AN ABSTRACT OF THE THESIS OF

Thomas Anthony Berkman for the degree of Master of Science in Geosciences presented on March 2, 1990.

Title: Surface - Subsurface Geology of the Middle to Upper Eocene Sedimentary and Volcanic Rock Units, Western Columbia County, Northwest Oregon.

Abstract approved:______________________________________

Alan R. Niem.

The middle to upper Eocene Tillamook Volcanics form the basement in the Rock Creek - Rocky Point area. These tholeiitic to alkalic basalts, basaltic andesites, and andesites were erupted as shield volcanoes seaward of the strandline ontop of an older deep-marine mudstone unit (Yamhill Formation) and an accreted portion of oceanic seafloor (lower Eocene Siletz River Volcanics). The subaerial flows are predominantly aphyric with subordinate plagioclase-augite porphyritic flows with pilotaxitic texture.

The overlying Hamlet formation (informal) is composed of three members which document a marine transgression over subsiding islands of Tillamook Volcanics in the middle to late Eocene. The stratigraphically lowest Roy Creek member is composed of basaltic boulder to cobble conglomerate grading upward into fossiliferous pebbly basaltic sandstone deposited around sea stacks and along a high-energy rocky coastline composed of Tillamook Volcanics.

Continued subsidence and transgression resulted in deposition of the Sunset Highway member of the Hamlet formation, which conformably overlies the Roy Creek

member. The Sunset Highway member consists of interbedded micaceous arkosic sandstone and siltstone with rare basaltic grit beds occurring near the top of the member. Molluscan fauna, faint low-angle cross-bedding, parallel laminations and bioturbation in these sandstones are interpreted to represent deposition in a high-energy inner shelf environment.

The upper Narizian (upper Eocene) Sweet Home Creek member conformably overlies the Sunset Highway member in western Columbia and eastern Clatsop counties and is composed of two lithofacies. The dominant lower facies consists of micromicaceous and carbonaceous silty mudstone which contains abundant Foraminifera indicative of outer neritic to upper bathyal water depths. Thin-bedded micaceous arkosic turbidite sandstones in nested channels of the upper facies are locally present near the top of the unit and represent deposits of a channelized shelf-slope break.

Abrupt sea level regression coupled with increased sedimentation rates due to tectonic unroofing in source areas in Idaho and Washington resulted in abrupt shallowing of sedimentation before deposition of the overlying Cowlitz Formation (C & W sandstone member). The C & W sandstone in cores from the Mist Gas Field and outcrops in the Rock Creek - Rocky Point area in Columbia County consists of massive to hummocky bedded sandstone with some bioturbated siltstone and coal formed in a delta front complex ranging from brackish-water swamps to storm-wave-dominated lower shoreface environments. Sandstone onlaps basement highs of Tillamook Volcanics (Nehalem arch), resulting in a complicated facies geometry with some intrabasinal basaltic detritus. Sedimentary structures, statistical grain size analysis, and lithofacies associations suggest that strong wave processes reworked the delta front sands during a transgression at the seaward edge of the system. Thickening-upward and shallowing-upward sequences record periods of westward deltaic progradation and increasing storm-wave energy.

C & W gas reservoirs consist of well-sorted, friable, fine-grained arkose to lithic arkose. Sandstone reservoir porosity and permeability average 31% and 1200 md, respectively. Porosity is dominated by primary intergranular pores which have been reduced by (1) compaction of ductile grains, (2) formation of minor mixed-layer clay rim cement, sparry calcite cement and authigenic pyrite, and (3) late stage precipitation of plagioclase, K-feldspar, and quartz overgrowths. However, partial dissolution of plagioclase feldspar has created some secondary porosity. Although arkosic sandstones have high porosities and correspondingly high permeabilities, chloritic cement in volcaniclastic-rich sandstones significantly reduces permeability without concomitant reduction in porosity.

The Cole Mountain basalt (informal) locally intrudes and overlies the Cowlitz Formation. These basalts to basaltic andesites have calc-alkaline affinities and consist of hypabyssal sills, submarine lava flows, and local peperites which are lithologically, chemically, and petrographically distinct from the slightly older Tillamook Volcanics.

The uppermost Narizian to Refugian (latest Eocene) Keasey Formation unconformably overlies the Cowlitz Formation in the study area. Volcanic and glauconitic sandstones at the base of the Keasey Formation mark the unconformity and reflect a period of slow sedimentation under slightly reducing conditions. The Keasey Formation predominantly consists of structureless, tuffaceous fossiliferous mudstone deposited by hemipelagic sedimentation on the middle to upper slope.

The informal Miocene (?) Ivy Creek formation locally disconformably overlies the Keasey Formation in the study area. The fluvially deposited Ivy Creek formation consists of a friable upper trough cross-bedded pebbly sand facies which overlies 9 m of blue organic-rich overbank clay. Local pebbly grits in matrix-support with buried flow-oriented rooted tree stems suggest that some debris flows entered the fluvial system from surrounding highlands. The unit may correspond to the middle Miocene Scappoose Formation.

Northwest-trending down-to-the-northeast high-angle faults, some with oblique offset, and a subordinate set of older east-trending faults are the dominant structural features of the Rock Creek - Rocky Point area. The faulting produces a dissected structural high or upthrown basement block of middle to upper Eocene Tillamook Volcanics. Upper Eocene sedimentary units flank the north and south sides with occasional perched sedimentary outliers along the volcanic crest.

Although source rock evaluations from this study indicate that the upper Eocene samples are thermally immature, it is possible that thermogenic "dry" gas at Mist migrated updip from more deeply buried Cowlitz shales and coals or equivalent Eocene strata in the adjacent Tualatin and Astoria basins.

SURFACE - SUBSURFACE GEOLOGY OF THE MIDDLE TO UPPER EOCENE SEDIMENTARY AND VOLCANIC ROCK UNITS, WESTERN COLUMBIA COUNTY, NORTHWEST OREGON

by

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I would also like to thank Leonard Farr of Portland State University, for helping me recognize and interpret many of the geologic problems we faced in this endeavor. Special thanks go to Mike Parker, fellow Dr. Niem graduate student, for moral support and helpful suggestions throughout this project and for critically reviewing the first draft. I would also like to thank Liz Coady for her support and encouragement during the final stages of this project. Finally, I would like to thank my parents, Judy and Peter, for their financial support during times of need and constant understanding throughout this thesis.

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INTRODUCTION

Geologic Problem

Since the discovery of commercial quantities of natural gas in May, 1979 near Mist, Oregon (Figure 1), the Clark and Wilson (C & W) sandstone of the upper Eocene Cowlitz Formation has produced more than 35 billion cubic feet of gas (Olmstead, 1989). This surprising discovery has proven the viability of hydrocarbon exploration in the Pacific Northwest, and stimulated considerable interest in the depositional environment and reservoir characteristics of these sandstones. New wells are being drilled at a rate of 8-12 per year with an astounding success ratio of over 50%. The field is currently producing at a rate of approximately 10 million cubic feet per day from small structural traps (Bob Jackson, 1989; pers. comm.). Armentrout and Suek (1985) believe that the production capability of the C & W sandstone is directly related to its mineralogy, textures, depositional environment, and diagenesis. They have postulated that an understanding of the sedimentological characteristics and origin of the C & W sandstone and similar Eocene reservoir-quality sandstones is critical to an exploration strategy for western Oregon and Washington.

Despite recent investigations by industry and academia, the interpretation of the depositional origin of the Cowlitz sandstones in northwest Oregon is controversial. It has been interpreted in the Columbia County surface as storm-dominated, shallow-marine shelf deposits (Timmons, 1981; Jackson, 1983; Shaw, 1986; Van Atta, 1971; Alger, 1985) and, alternatively, as deep-water sandstones, based on subsurface (well) data at Mist (Bruer, 1980). Whether the unit is a deep-marine fan or channel deposit or a

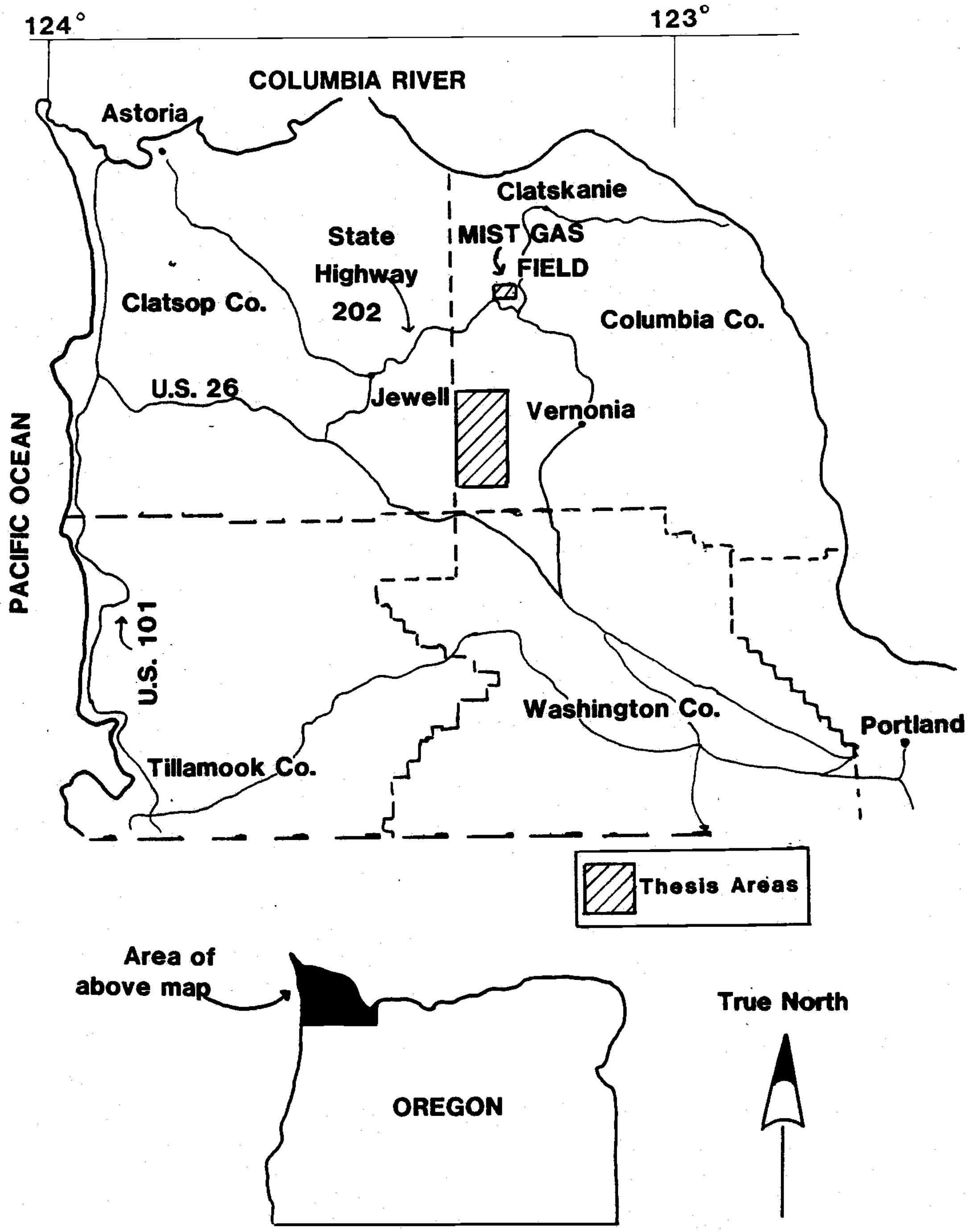


Figure 1. Map showing the location of the thesis areas in northwest Oregon.

shallow-marine sheet sandstone will affect the interpretation of the geometry and facies trends of the sandstone in the subsurface. This controversy is caused, in part, by the lack of integration of surface and subsurface data. In addition, the friability of the C & W sandstone has in the past permitted only poor recovery of well cuttings.

Recently, however, complete cores of the C & W sandstone from three wells in the Mist Gas Field have been provided to Dr. Alan Niem of Oregon State University and to Dr. Robert Van Atta of Portland State University by Jack Meyer of Oregon Natural Gas Development Corporation (ONGDC). These are the first continuously cored wells through the gas-producing C & W sandstone of the Cowlitz Formation that have been made available for study and comparison with surface outcrops (see Figure 2 for location of wells). These observation and injection wells are located in the depleted Bruer and Flora pools, which are currently being utilized by ONGDC in their underground natural gas storage project. This underground gas storage project has the potential to save ONGDC in excess of $19 million per year (J. Meyer, 1989, personal communication). The project, initiated in 1987, is nearing completion, culminating in a $20 million, 48-mile pipeline running from Mist to Portland.

These three wells thus have timely economic importance to ONGDC because they need to know detailed information pertaining to reservoir porosity/permeability trends and diagenesis. One important goal of this thesis is to relate diagenetic effects to depositional environment and facies. Diagenesis may enhance or degrade total porosity, thus affecting the volume of gas that can be stored in the reservoir.

ARCO is currently drilling step-out wells into the C & W sandstone for natural gas, and also actively exploring outside the boundaries of the Mist field in northwest Oregon and southwest Washington. They require information pertaining to the geometry and facies characteristics of the Cowlitz Formation in the surface and subsurface in order to enhance exploration strategies. By combining detailed subsurface

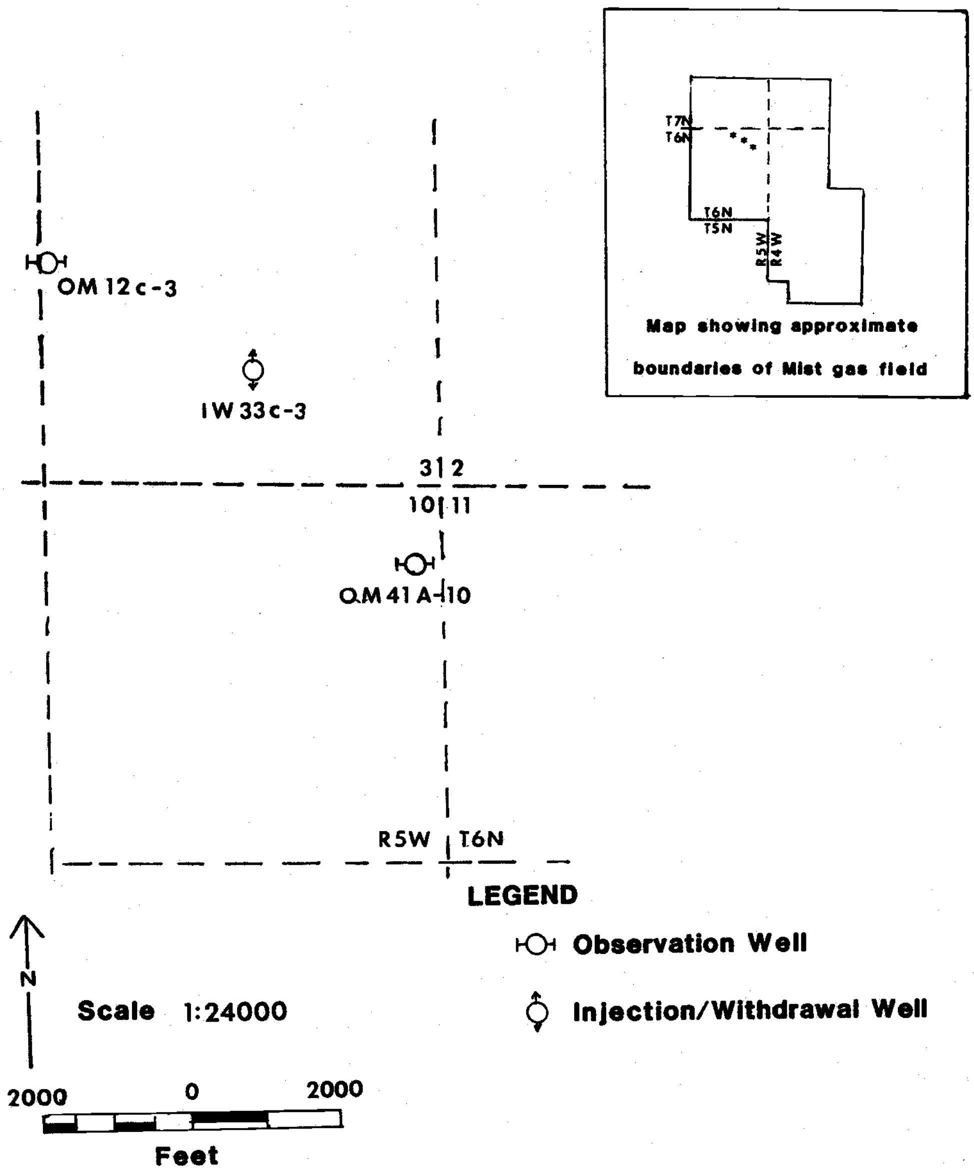


Figure 2. Location map of the three cored wells within the Mist Gas Field used in this study. Modified from map of Mist Gas Field, Ore. Dept. Geol. Min. Indus. (1988).

data from two of these wells (IW 33C 3 and OM 41A 10; Figure 2) with the closest surface outcrops of the C & W sandstone in Columbia County (Figure 1), a thorough study of the depositional environment and sedimentological characteristics of the Cowlitz Formation can be made. New logging roadcuts and extensive stream valley exposures of the Cowlitz Formation in western Columbia County (Figure 1) contain abundant sedimentary structures and lithologies that aid in the interpretation of the depositional environment and the geometry of the sandstone in the subsurface. Furthermore, geologic mapping of the Eocene strata is important in order to gain a broader understanding of the regional stratigraphy, Cowlitz facies changes, and structure south of the Mist field. This thesis study was conducted in cooperation with Drs. Robert Van Atta, and graduate student Leonard Farr at Portland State University. Farr mapped the adjacent area to the east in Columbia County and studied the other well (OM 12C 3) in detail. Leonard Farr and I also worked together to construct a model of the Cowlitz facies variation on the surface and between these three wells.

Purpose of Investigation

The objectives of the thesis investigation are:

1. to interpret the environments of deposition of the C & W sandstone and adjacent sedimentary units (e.g., Yamhill and Hamlet formations) in the surface and subsurface;
2. to correlate subunits of the Cowlitz Formation in the subsurface (wells OM 41A-10 and IW 33C-3) to the nearest Cowlitz outcrops (Rocky Point/Rock Creek area) and to produce a correlation diagram between the three wells;
3. to make a detailed geologic map at a scale of 1:18,000 of the Rock Creek-Rocky Point area in western Columbia County, including resolving the extent of

northwest-trending faults and determining the structural effects on rock units in the area;

4. to refine the stratigraphy of the Cowlitz Formation and adjacent upper Eocene units, including determining paleocurrent dispersal patterns, provenances, and facies variations;
5. to determine the diagenetic history of Cowlitz sandstones in the surface and subsurface and how these may affect reservoir porosity and permeability;
6. to evaluate the origin of the Tillamook Volcanics and other volcanic units in the study area and determine the stratigraphic relationships of these units to the Cowlitz Formation.

Location and Accessibility

The 25 square mile field area is located in western Columbia County, approximately halfway between Portland and Astoria (Figure 1). It is bounded on the west by the Clatsop/Columbia County line and is five miles north of U.S. 26 (Sunset Highway). The cores of Cowlitz Formation provided for this study are from wells located approximately eight miles north of the map area in the north-center of the Mist Gas Field (Figures 1 & 2) and were recovered from the original Bruer and Flora gas pools (Meyer, 1987; writ. comm.).

Access to the area is provided by State Highway 47, which passes north-south through Vernonia, located 4 miles east of the field area. From Vernonia, two paved roads (Rock Creek-Keasey road, and Timber Highway) lead to the east boundaries of the study area. Internal access is generally good; numerous new gravelled roads have been constructed near Rocky Point and are moderately well maintained and passable. These roads have been constructed by Longview Fibre Company, who owns most of the land and is currently logging in the area. In addition, several streams and creeks run through the interior and provide adequate foot access.

Much of the map area consists of forested low-lying hills, but extensive logging road cuts, quarries, natural cliffs, and creeks provide most exposures (Figure 3). Prominent geographic features include the unnamed peak above Rocky Point, which is the highest point in the field area at 1808 feet (Plate I). Rock Creek, which has good exposures, is the largest drainage in the thesis area. Rock Creek flows eastward from the Coast Range summit in Clatsop County and transects the middle of the field area trending east-west on the way to its confluence with the Nehalem River, the major drainage system in the northern part of the Oregon Coast Range. The former logging railroad depot of Keasey is located along Rock Creek in the field area. Some old houses now occupy this site. Clear Creek, Deep Creek, and Selder Creek also flow eastward across the field area. Maximum relief is 1000 feet in this densely vegetated region of the Oregon Coast Range.

Previous Work

The first geologic study of the sedimentary strata in the map area was conducted by Diller (1896), who examined the sedimentary rocks exposed in the bed of Rock Creek near Vernonia. A reconnaissance geologic map as part of an oil and gas investigation of the Northern Oregon Coast Range was published by Warren et al. (1945). They mapped undifferentiated Tertiary sedimentary rocks and the underlying Tillamook basalt in the study area at a scale of 1:143,000. In 1946, Warren and Norbisrath formally introduced the Cowlitz, Keasey, Pittsburg Bluff, and Scappoose formations for the previously undifferentiated upper Eocene and Oligocene strata in the upper

Figure 3. Aerial photograph of central portion (near Rocky Point) of field area looking northeast toward Mt. Adams (in far distant upper left of photograph). Also note extensive clear cutting in foreground by Longview Fibre Co.

Nehalem River basin. Many paleontologists have described the molluscan and foraminiferal assemblages of the rocks exposed in Rock Creek (e.g. McDougall, 1980).

Deacon (1953), in an unpublished Oregon State University master's thesis, noted major lithological differences (e.g.,coal-bearing fossiliferous strata in Washington) between the type Cowlitz Formation of southwest Washington and the upper Eocene Cowlitz strata of Warren and Norbisrath (1946) which overlie Tillamook volcanic rocks in Rock Creek. Deacon (1953) proposed an alternative name, Rocky Point formation, for these strata. This name was never formally introduced and, therefore, has not been adopted in later studies (Van Atta, 1971). Van Atta, in his 1971 Oregon State University doctorate thesis, completed the first detailed thin section petrography and sedimentary facies analysis of the Cowlitz, Keasey and Pittsburg Bluff formations.

Wells and Peck (1961) compiled a geologic map of Oregon west of the 121st meridian (1:500,000 scale) which differentiated the middle Miocene Astoria Formation but left other Eocene and Oligocene strata undifferentiated in Clatsop County. In Columbia County they described the upper Eocene Cowlitz and Keasey formations, the Oligocene Pittsburg Bluff Formation, and the upper Oligocene (subsequently revised by Van Atta and Kelty, 1985) Scappoose Formation. Van Atta (1971), Newton and Van Atta (1976), Jackson (1983), Timmons (1981), Nelson (1985), and Olbinski (1983) subsequently have mapped or described stratigraphic sections of the Cowlitz Formation and Tillamook Volcanics near the Rocky Point-Rock Creek area in greater detail, but the Columbia County region including the thesis area has not been mapped in detail. In their preliminary USGS open-file geologic map of the west 1/2 of the Vancouver sheet, Wells et al. (1983) compiled the most recent mapped geology of the field area before this study was conducted (Figure 4). Safley (1989) recently mapped the Tillamook Volcanics, Roy Creek conglomerate member, Sunset Highway member, and Sweet Home Creek member of the Hamlet formation as well as the Cowlitz (C & W) sandstone

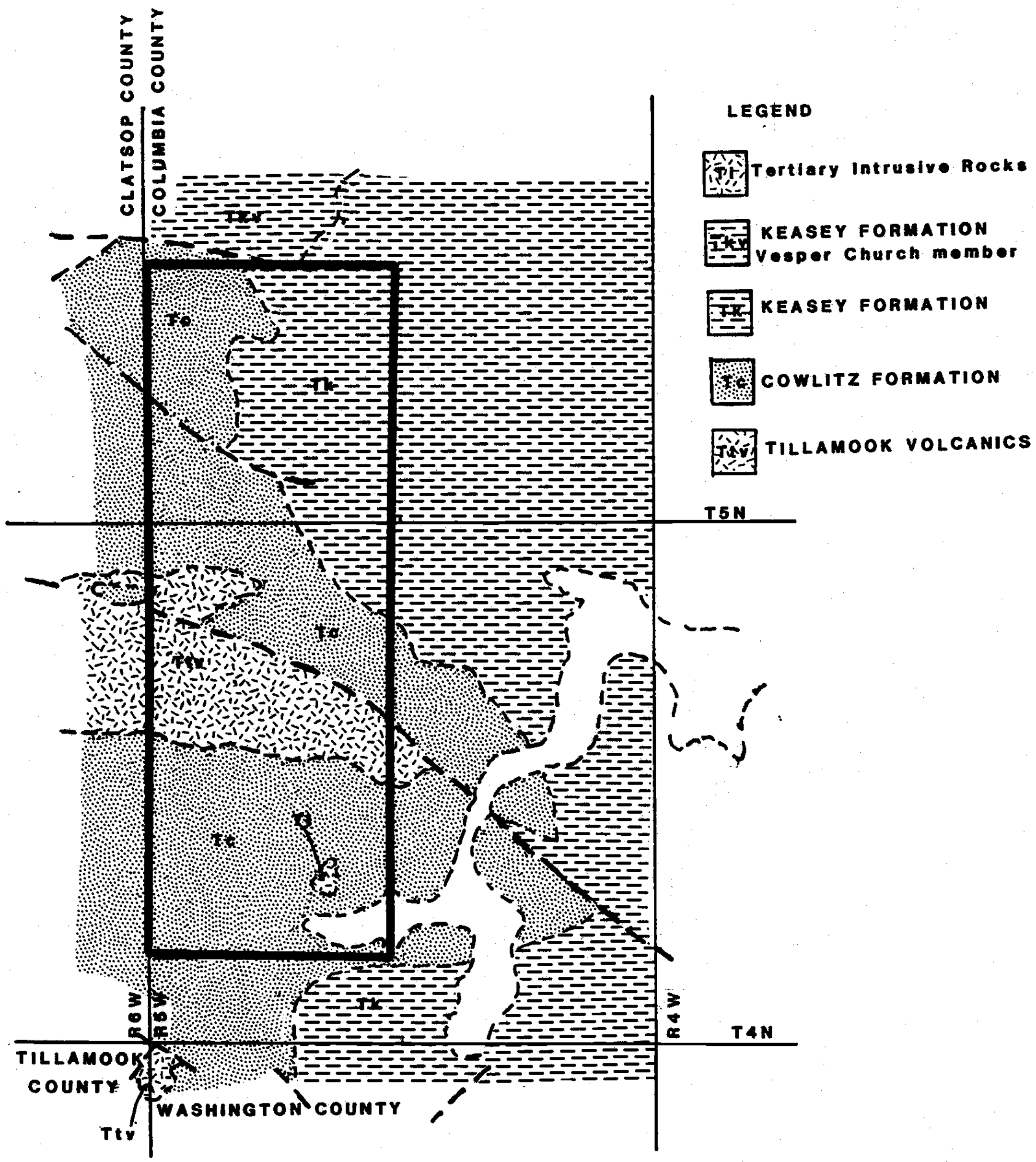


Figure 4. Previous geologic interpretation and map of thesis area (outlined). From Wells et al. (1983), after Newton and Van Atta (1976).

in the Green Mountain area immediately across the county line. Shaw (1986) recently compiled a detailed list of the bathyal and shallow-marine Foraminifera in the Cowlitz Formation (including Hamlet formation) in the study area and measured a composite section of the Cowlitz Formation in Rock Creek. However, he did not describe the sedimentary structures in any detail.

The depositional environment of the Cowlitz Formation has been incompletely studied in Columbia County, and disagreement regarding the depositional origin of Cowlitz strata still exists among geologists working in northwest Oregon. Bruer (1980), in his investigation of the depositional environment of the Cowlitz in the subsurface at Mist, proposed a deep-water origin for the sandstones based on bathyal Foraminifera in mudstones interbedded with the sandstones. He suggested that the gas-producing C & W sandstone was deposited in a narrow seaway between basaltic highs, analogous to the modern Strait of Juan de Fuca between the uplifted Eocene basalts of the Olympic Mountains and southern Vancouver Island. J. Meyer, (pers. comm., 1989) on the basis of electric and dipmeter log analysis, also has suggested that Cowlitz sands were deposited in deep water, possibly in channels surrounding Tillamook islands, and winnowed by marine currents. Alternatively, Alger (1985) suggested that Cowlitz strata in the subsurface at Mist were deposited in shallow water, possibly a shelf environment, on the basis of fossils and sedimentary structures. Dr. Robert Van Atta, Dr. Richard Thoms, and graduate students at Portland State University (i.e., Timmons, 1981; Jackson, 1983; Shaw, 1986) have studied Cowlitz Formation outcrops south of the Mist field in Columbia County, and Olbinski (1983), Nelson (1985) and Niem and Niem (1985) have studied Cowlitz Formation outcrops in Clatsop County and suggest deposition in a nearshore wave-dominated marine-shelf environment.

Methods of Investigation

Field Procedures

Field work was largely completed during three months in the summer of 1987 along with intermittent brief excursions during 1988 and 1989. Reconnaissance investigations and field trips were done in surrounding thesis areas, Clatsop County, Tillamook County, and southwest Washington. Mapping (Plate I) was accomplished using enlarged (1:18,000) parts of the 1979 Birkenfeld and Clear Creek U.S. Geological Survey 7 1/2 minute topographic maps assembled onto a base map. W.A.C. Corporation 1986 aerial photographs at a scale of 1:24,000 and 1:12,000 were invaluable as an aid to locating position during mapping, due to the addition of numerous new logging roads in the area. In addition, lineations interpreted on high-altitude photographs and low-angle oblique photographs that I took during a plane flight over the area in 1989, were plotted and field checked for possible structural significance.

Field work consisted of geologic mapping, description, and sampling of sedimentary and volcanic rock units. A shovel was an essential tool for creating fresh exposures in the deeply weathered and friable sedimentary rocks in the Coast Range. An outcrop map was prepared and updated each day during the mapping. Attitudes of rock units and orientations of structural features were measured with a Brunton Compass and slickensides plotted for rake and plunge on the map (Plate I). Measurement of representative stratigraphic sections was accomplished with a 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). Approximately 120 samples were collected for further laboratory study. All sample locations referred to in the text are presented in Appendix V. Samples were collected for a variety of purposes, including heavy mineral analysis for provenance and correlation, petrography, microprobe, SEM and EDX analysis for diagenetic investigations, X-Ray diffraction for clay mineralogy, X-ray radiography, grain size (sieve) analysis of sandstones, source rock maturation of mudstones, porosity and permeability, molluscan fossils, microfossils, palynology, trace fossils, and magnetic polarity and geochemistry of basalts. Many samples were sent to specialists or technical services for more precise identification or analysis. Representative well logs from the Mist Field were acquired from Northwest Natural Gas and ARCO Oil and Gas Company or purchased from Northwest Oil Report.

In addition, one thousand feet of core from three wells in the Mist Field were delivered from Bakersfield in frozen condition to Corvallis for study. This required careful preparation of a detailed budget proposal submitted to ARCO and Northwest Natural Gas for all technical and logistical problems encountered in cold-storing, cutting, mounting, photographing, storing, X-ray radiographing, and handling of core at Oregon State University School of Oceanography core repository. The core had to be kept cold (<35°F) due to the friable nature of the rock and the possibility of spontaneous disaggregation upon thawing which would have destroyed all sedimentary structures. During Spring and Summer, 1988, Leonard Farr and I cut, slabbed, and mounted the three cores, using a modified rock saw to account for variable core widths. One half of each core section was subsequently mounted in a pre-assembled, molded core box, holding three - three foot lengths of core (see: Cowlitz Formation) while the other half went into the original box. This permitted detailed core sampling of one half, at the same time preserving an archive half completely untouched. The archive half was then photographed two boxes at a time (i.e., 18 feet) using color film, tungsten filter and lighting in Oceanography's Marine Geology Core Laboratory. The core was then described and logged in detail, using ARCO's computer graphic core log generator program, and sampled according to the same procedures and purposes outlined above for the surface rocks.

Laboratory Procedures

Laboratory work included:

1. disaggregation of samples for microfossil recovery, using Quaternary-O treatment and wet-sieving (Appendix I) for Foraminifera and then mounted on gridded slides. Dan McKeel, as private consultant for ARCO, Plano, Texas, analyzed 11 samples for identification, age determination, and paleoecological information of Foraminifera (Appendices III and IV). Additional foraminiferal data was provided by ARCO Oil and Gas from cores OM 41A-10 and OM 12C-3. Smear slides prepared from disaggregated samples (30) were examined for calcareous nannofossils (coccoliths) and identified by Dr. David Bukry of the U.S. Geological Survey, Menlo Park California. Only two samples contained coccoliths. John Barron and Platt Bradbury, both of the U.S. Geological Survey, analyzed a single sample containing diatoms. Ellen Moore, Courtesy Professor of Geology, Oregon State University (formerly of the U.S. Geological Survey), identified molluscan fossils collected from 16 localities (Appendix II) and provided age and paleoecological information. Representative trace fossil photographs and samples from 11 cores and outcrops were identified by Dr. C. Kent Chamberlain (Appendix VIII) of University of Wisconsin, Eau-Claire (formerly of Valero Producing Company, Denver, Colorado).
2. separation of 3 and 4 phi size fractions of heavy minerals and preparation of 17 grain mounts (Appendix VI) for provenance and surface-subsurface correlation and facies

distribution using the gravity-funnel method and tetrabromoethane, following the method of Royce, (1970);

3. modal analysis and petrography of 38 sandstone and 8 basalt thin sections using feldspar staining techniques and impregnation of sandstone samples with blue epoxy resin to aid in porosity identification. Thin sections were prepared by Frank Padilla (UNOCAL Research lab, Brea, California), Quality Thin sections (Tucson, Arizona), and Ruth Lightfoot at Oregon State University. Composition of all samples was visually estimated and representative surface samples were selected for point counting. All subsurface samples were point counted (400 points per slide) using a mechanical stage, and results were plotted on Folk's sandstone classification (QFL) diagram (1974) and Dickinson and Suzcek's ternary diagrams (1979) to determine their plate tectonic setting.

4. source rock and maturation analysis of 17 Hamlet, Cowlitz, and Keasey mudstones from outcrop and core using Rock-Eval pyrolysis, vitrinite reflectance and TOC (performed by ARCO Oil and Gas Company, Plano, Texas);

5. major and trace element oxide chemistry of 8 basalt samples using X-ray fluorescence (XRF) by Dr. Peter Hooper at Washington State University. My preparation of the basalt samples involved crushing the fresh rock to chips and manually selecting and cleaning the least altered fragments for XRF analysis;

6. grain size analyses of 15 disaggregated core and outcrop samples using the Rotap shaker and nested sieves. Samples were disaggregated between thumb and forefinger to avoid crushing grains. Results were plotted on Folk's (1974) cumulative frequency graphs in order to determine statistical grain size parameters (e.g., median, sorting, kurtosis, skewness: Appendix VII) and to permit a comparison of surface and subsurface facies variations within the Cowlitz Formation and Hamlet formation members. The depositional environments of the sandstones were determined by plotting

the grain size data on binary statistical graphs (e.g., Friedman diagrams, Passega graphs);

7. detailed examination and photography of sedimentary structures using the X-ray radiograph for 6 core samples at Oregon State University School of Oceanography. Sedimentary structures preserved in the core could then be compared to surface sedimentary structures and lithologies in the map area;

8. X-ray diffraction analysis of 7 samples for clay mineralogy of sandstone matrix and of mudstones following the method of Jim Robbins at Oregon State University School of Oceanography using a Scintag fully automated diffraction system XDS with Peakfinder program. This analysis aided in diagenetic investigations and for the purpose of determining proper reservoir treatment processes for increasing porosity and permeability;

9. scanning electron microscopy (SEM) of 16 core and surface samples using an AMRAY 100A SN A-10 and attached Energy Dispersive X-ray analysis (EDX) with Al Soeldner (Department of Botany, Oregon State University), for determining diagenetic sequence of sandstones;

10. palynology studies of 2 selected mudstone samples performed by Ray Christopher of ARCO Oil and Gas Company, Plano, Texas. Additional palynological data was provided by ARCO for 2 core samples from OM41A-10;

11. electron microprobe analysis using a Cameca SX50 on 3 sandstone samples, including backscatter and image analysis to determine plagioclase and cement compositions and relative abundances with the help of Bill Gallahan, Oregon State University Department of Geology. Polished sections were prepared from billets by Lori Suskind of University of Oregon Department of Geology, Eugene, Oregon.

REGIONAL STRATIGRAPHY AND GEOLOGIC HISTORY OF NORTHERN OREGON COAST RANGE

A regional stratigraphic correlation chart for western Oregon is shown in figure 5. Lower to middle Eocene volcanic rocks form the core of the Coast Ranges of western Oregon and Washington. These rock units include the Roseburg, Siletz River, and lower Tillamook Volcanics in Oregon and the correlative Crescent Volcanics and Goble Volcanics mapped in the Grays River area in Washington (Duncan, 1982; Rarey, 1986; Wells et al., 1983). Geochemical analyses of pillow basalts in the Siletz River Volcanics show that these rocks are low-K_2O tholeiites with a composition virtually identical with basalts formed at oceanic ridges (Snavely et al, 1968; Glassley, 1974). However, the upper part of the Siletz River Volcanics is more alkalic and consists of pillowed flows and breccias along with some subaerial flows, analogous to the Hawaiian Islands or Iceland. Due to this stratigraphic variability, petrochemistry, and greater than normal oceanic crustal thickness (15 km or thicker), a seamount origin for these basalts has been postulated by Snavely et al. (1968). On the basis of a systematic age progression observed from K-Ar dating of basalts north and south of the Columbia River, Duncan (1982) suggested that during the early and middle Eocene oceanic crust and seamounts of the Siletz River Volcanics were erupted over a hot spot along the Kula - Farallon spreading ridge. Alternatively, these basalts may have formed contemporaneously with Kula - Farallon ridge reorganization or within an obliquely rifted North American Plate margin (Wells et al., 1984).

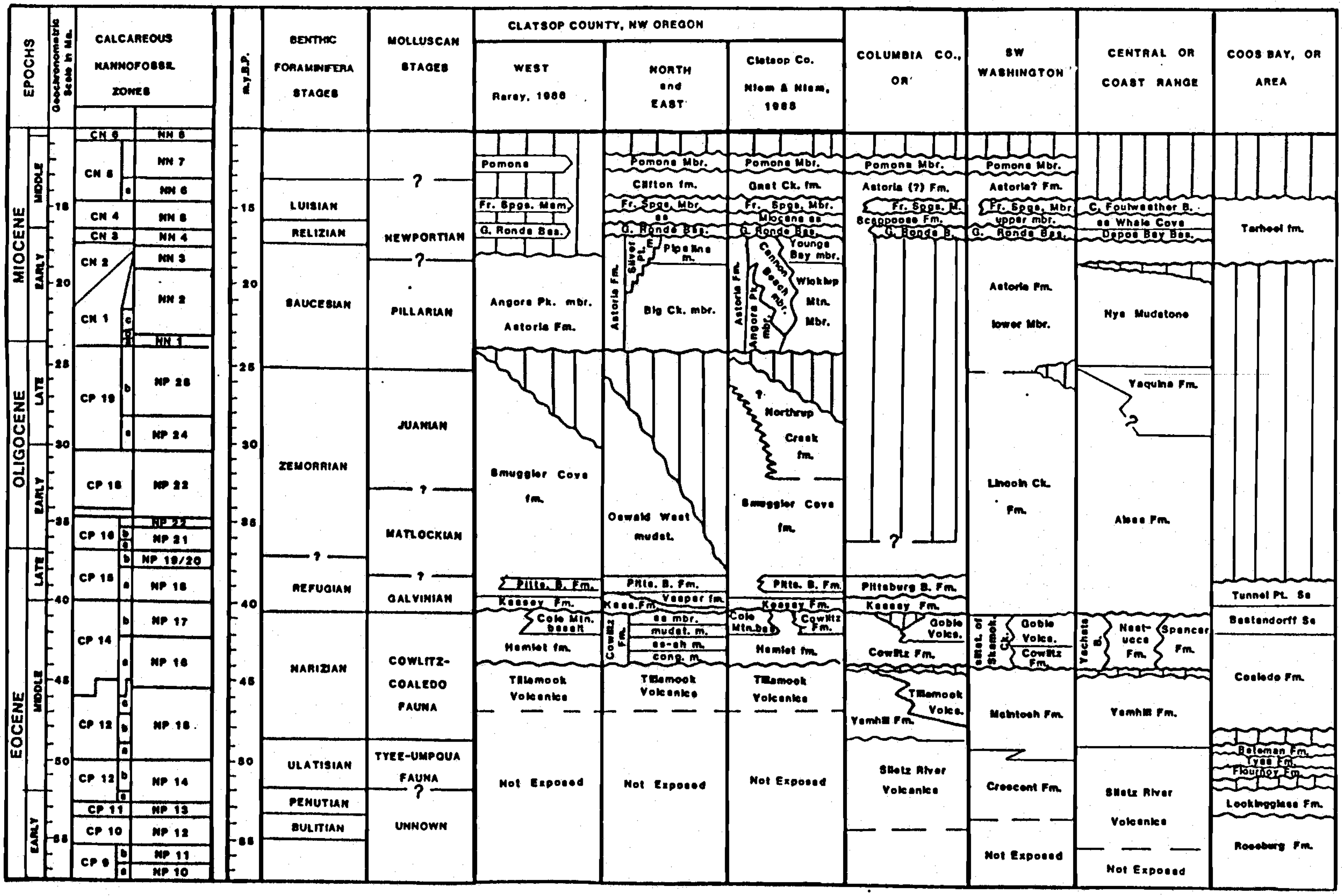


Figure 5. Correlation chart of Tertiary strata in western Oregon and southwest Washington. After Mumford (1988).

Subduction of the Kula and Farallon plates beneath the North American plate probably produced a trench that lay east of the Willamette-Puget Lowland during the early Eocene (Snavely et al., 1980; Niem and Niem, 1984). Deformed trench sediments typical of convergent margins are recorded in the southern Oregon Coast Range in the Roseburg Formation (Heller and Ryberg, 1983; Heller et al., 1987). By late middle Eocene, this oceanic ridge and seamount province was accreted to the North American continent and was accompanied by up to 50° clockwise rotation (Wells et al., 1984). This seamount-bearing oceanic crust may have clogged the trench, thus causing a westward shift of the subduction zone from its early Eocene position east of the Willamette Valley (Magill et al., 1984) to a position beneath the present outer continental shelf of Oregon (Snavely et al., 1980).

Renewed subsidence created a deep marginal or forearc basin on the newly accreted Coast Range basaltic crust. This marine basin extended from the site of the present Klamath Mountains on the south to the Olympic Peninsula (Snavely and Wagner, 1963; Niem and Niem, in press). Due to changes in relative motion between the North American and Pacific plates and transform faulting in late middle Eocene time, this region has undergone a complex tectonic and depositional history resulting in increasingly segmented shelf basins along the continental margin (Baldwin, 1974). Thick arkosic to lithic micaceous sand-rich middle Eocene deltaic and turbidite fan and ramp sequences (Tyee, Flournoy formations; Figure 5), derived from the continental margin and Idaho batholith sources to the east and southeast, were deposited in this developing forearc basin (Snavely et al., 1980; Heller and Ryberg, 1983; Chan and Dott, 1983; Heller et al., 1987). In the distal northern part of the basin there was renewed volcanism (Wolf Creek breccia of Cameron, 1980) and deep-marine hemipelagic mud sedimentation (e.g., lower Yamhill Formation of Snavely and Wagner, 1964; Chan and Dott, 1983).

Intermittent post-accretion "forearc" volcanism during plate reorganization and periods of extension in the middle to late Eocene formed the tholeiitic to alkalic Tillamook, Yachats, Cascade Head, and Cascade-derived Goble volcanics of the Oregon Coast Range (Figure 5). In the northern Oregon Coast Range, the Tertiary units have been deformed into a northward plunging anticlinal fold cut by numerous high-angle northeast- and northwest-trending normal, reverse, and oblique-slip faults (Niem and Van Atta,1973; Baldwin, 1974, Niem and Niem, 1985). The core of the fold or basement uplift consists of a 10,000+ foot thick sequence of middle to upper Eocene volcanics known as the Tillamook Volcanics (Snavely et al., 1970; Wells et al., 1983; Magill et al. 1982), which represent economic basement in the area (Niem and Niem, 1985; Bruer et al.,1984). At their base, these volcanics consist of tholeiitic pillow lavas and breccias, which grade to differentiated subaerial basaltic andesite to dacite flows and mud flow breccias toward the top of the section (Wells et al., 1983; Olbinski, 1983, Nelson 1985; Rarey, 1986). Field relationships and major element geochemistry suggest that the Tillamook Volcanics formed as oceanic islands on middle Eocene mudstone (Yamhill Formation) which in turn overlies an older accreted remnant of lower to middle Eocene oceanic crust (Siletz River Volcanics; Wells et al. 1983).

Several major transgressions and regressions are recorded in the overlying middle-late Eocene to middle Miocene sedimentary sequence (Niem and Niem, 1984; Armentrout, 1987). Eight volcanic and sedimentary formations totalling more than 6,000 feet unconformably wrap around the nose of the northward plunging northern Oregon Coast Range anticline (Wells et al., 1983; Niem and Van Atta, 1973). According to Snavely and Wagner (1964), Snavely et al. (1973,1980), and Wells et al.

(1984), this thick pile of shallow- to deep-marine, tuffaceous Tertiary strata and mafic volcanics accumulated in a marginal or forearc basin, probably associated with thermal subsidence of the Tillamook Volcanic pile (Rarey, 1986; Mumford, 1988). In Columbia County, from oldest to youngest, these units include: middle to upper Eocene Cowlitz and Hamlet formations, upper Eocene Goble and Cole Mountain basalts, upper Eocene Keasey Formation, upper Eocene to Oligocene Pittsburg Bluff Formation, upper Eocene to early Miocene Smuggler Cove mudstone, lower to middle Miocene Astoria Formation, middle Miocene Scappoose Formation, and the middle Miocene Columbia River basalts (Frenchman Springs and Grande Ronde basalts of Swanson et al., 1979; Niem and Niem, 1985; Figure 5). Of these, only the Tillamook Volcanics, Hamlet formation, Cowlitz Formation, Keasey Formation, possibly the Scappoose Formation, and local upper Eocene intrusions (e.g., Goble volcanics of Newton and Van Atta, 1976, or Cole Mountain basalt of Niem and Niem, 1985) occur in the study area (Figures 5 & 6, Columbia County section).

The oldest of these units in Columbia County is the upper Narizian (middle to upper Eocene) Cowlitz Formation (older terminology of Van Atta, 1971; Newton and Van Atta, 1976). At the type section in southwest Washington, the formation consists of deltaic to shallow-marine micaceous and arkosic sandstones, sub-bituminous coals, and deep-marine mudstones (Yett,1979; Armentrout and Suek, 1985; Buckovic, 1979). Similar lithologies crop out in northwest Oregon, but coals are uncommon and basaltic conglomerates as well as turbidite sandstones are present (Warren and Norbisrath, 1946; Van Atta, 1971; Olbinski, 1983; Nelson, 1985).

Recently, in order to conform to Weaver's (1937) original description of the type section in southwest Washington, Wells (1981) restricted the Cowlitz Formation to the sandstone-dominated unit (Olequa Creek member of Henriksen, 1956). This sandstone (C & W sandstone) and an overlying mudstone (upper Cowlitz mudstone) have also been included in the Cowlitz Formation in the Clatsop County surface and subsurface (Niem and Niem, 1985) and in the subsurface in Columbia County (Bruer et al., 1984; see Figure 6). The upper Cowlitz mudstone forms the seal for the gas at Mist (Alger, 1985). The Mist gas field is situated on the east flank of the northern Coast Range gravity high (Bromery and Snavely, 1964) or Nehalem arch of Armentrout and Suek (1985) which separates the Astoria basin on the west from the north Willamette basin on the east (Niem and Niem, 1985; Bruer et al., 1984). The gravity high is formed by the northward subsurface expression of the Tillamook Volcanics. The C & W sandstone thins rapidly across the northern Coast Range gravity high from 800 feet in the Mist field (Bruer, 1980; Meyer, 1988; personal communication) to less than 25 feet south of Jewell and pinches out into the bathyal Sweet Home Creek mudstone of the Hamlet formation in Clatsop County (Olbinski, 1983; Nelson, 1985; Niem and Niem, 1985; Rarey, 1986; Safley, 1989; see Figure 1 for geographic location).

The sedimentary unit between the Tillamook Volcanics and Cowlitz sandstone is informally referred to as the Hamlet formation in Clatsop County (Rarey, 1986; Niem and Niem,1985). This unit has been interpreted as a transgressive marine sequence and contains three mappable members (Rarey, 1986): a basal shallow-marine basaltic boulder conglomerate which unconformably overlies the Tillamook Volcanics (Roy Creek member); an overlying arkosic and basaltic shallow-marine sandstone (Sunset Highway member); and a thick turbidite-bearing mudstone unit (Sweet Home Creek member). These same informal members of the Hamlet formation crop out in Columbia County although they have previously been included within the older broader definition of the Cowlitz Formation in Oregon (Warren et al., 1945; Van Atta, 1971; Newton and Van Atta, 1976; Timmons, 1981; Shaw, 1986; Jackson, 1983; Figure 6).

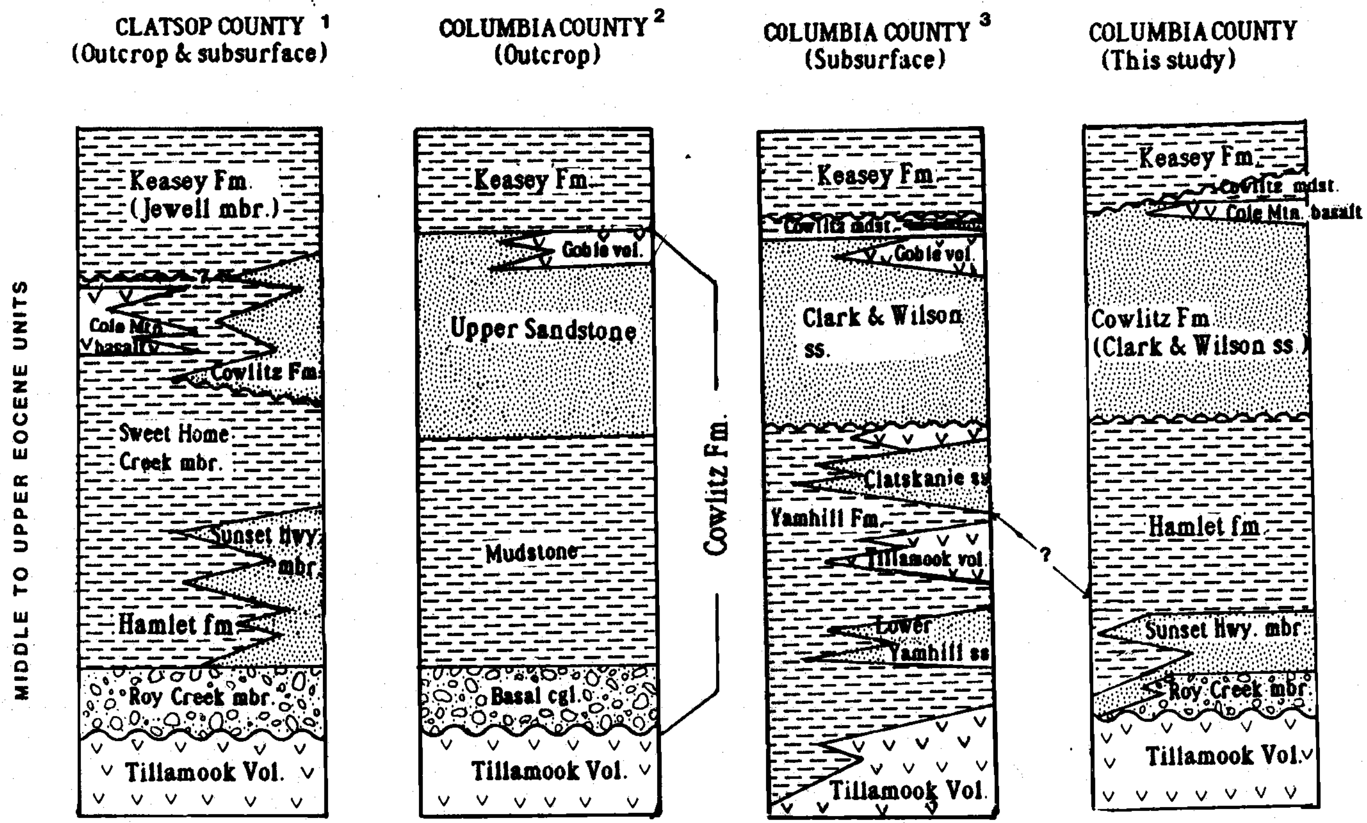


Figure 6. Correlation of middle to upper Eocene strata between Clatsop and Columbia counties, surface and subsurface. Data from: 1) Niem and Niem (1985), and Rarey (1986); 2) Timmons (1981) and Van Atta (1971); and 3) Bruer (1984).

In the Columbia County subsurface, the lower to upper Narizian dominantly mudstone unit between the Cowlitz Formation and Tillamook Volcanics has been called the Yamhill Formation (Bruer et al., 1984; Figure 6). Two sandstone bodies in the Yamhill in the subsurface have been informally referred to as the Clatskanie sandstone and lower Yamhill sandstone (Bruer et al., 1984). The Sunset Highway sandstone member of the Hamlet formation may equate to the Clatskanie sandstone and/or lower Yamhill sandstone of the Yamhill Formation of Bruer et al., (1984) below the C & W Sandstone in the Mist gas field (Figure 6). In previous mapping studies in southwest Columbia County (e.g., Van Atta, 1971; Newton and Van Atta, 1976), the Yamhill section has been included in the lower Cowlitz Formation.

The stratigraphic relationship of the Yamhill Formation of the Mist area to the Tillamook Volcanics is also a matter of some debate (for further discussion, see section on Hamlet formation nomenclature). Near the type locality along Mill Creek, in the central Oregon Coast Range, the Ulatisian to Narizian (early to late Eocene) Yamhill Formation appears to overlie the Siletz River Volcanics and to underlie flows of the Tillamook Volcanics (Wells et al., 1983), whereas in the Mist area subsurface, the Tillamook Volcanics underlie and interfinger with units assigned to the Yamhill Formation (Figure 6; Alger, 1985; Bruer et al., 1984). Two of the contributions of this thesis are (1) determination of how the Cowlitz Formation, members of the Hamlet formation, and Tillamook Volcanics, correlate between the surface and subsurface in Columbia and Clatsop counties, and (2) proposal for simplifying this stratigraphy (Figure 6).

Locally interstratified with and overlying the Cowlitz Formation in southwest Washington and in the northeast Oregon Coast Range are the upper Eocene Goble Volcanics (Henriksen, 1956; Van Atta, 1971; Newton and Van Atta, 1976;

Livingston, 1966; Wells, 1981; Figure 5). At the type locality near Goble, Oregon, this unit consists of subaerial and submarine basalt flows with minor pyroclastic rocks and has a total thickness of more than 4,600 feet (Wilkinson et al.,1946). A local late Eocene basalt intrusive unit, the Cole Mountain basalt (informal), of Clatsop County, equates geochemically and chronologically with the type Goble Volcanics (Rarey, 1986l; Mumford, 1988). This study and that of Farr (1989), show that scattered Cole Mountain basalt "intrusions" and flows exist in the map area, and therefore we are extending this terminology into Columbia and Washington counties. Upper Eocene volcanics at Cascade Head (north-central Oregon Coast) are interstratified with the Nestucca Formation and may be related to the same volcanic episode (Mumford, 1988; Barnes, 1981).

In the upper Nehalem River area, a thick sequence of tuffaceous siltstones of the Refugian (latest Eocene) Keasey Formation unconformably overlies the Cowlitz Formation and the Goble Volcanics (Niem and Van Atta, 1973; Figure 5). These bathyal siltstones were deposited in a forearc basin and received abundant volcanic detritus from the developing western Cascade calcalkaline arc to the east (Van Atta, 1971). Van Atta (1971) divided the Keasey Formation in Columbia County into three informal members: a basal thin, pebbly volcanic sandstone; a thick middle member of fossiliferous, tuffaceous siltstone; and an upper thin sequence of interbedded siltstone and fine-grained sandstone. In Clatsop County, Olbinski (1983) and Nelson (1985) separated the Keasey Formation into three different members, including a lowermost unit of laminated tuffaceous mudstone with minor sandstone clastic dikes which has been informally called the Jewell member (Olbinski, 1983; Nelson, 1985; Rarey, 1986; Niem and Niem, 1985; Mumford, 1988), a thick middle unit of thinly interbedded arkosic turbidites and siltstone which Olbinski (1983) informally referred to as the Vesper Church member, and an unnamed upper member of massive, tuffaceous siltstone. In their revision of the stratigraphy of informal units in Clatsop County, Niem and Niem (1985) included the upper massive part of the Keasey Formation within the informal Smuggler Cove formation (formerly Oswald West mudstone of Cressy, 1974; Niem and Van Atta, 1973; Figure 5). The type Keasey Formation lies within the thesis area and probably correlates with the Jewell member.

The late Refugian Pittsburg Bluff Formation overlies the Keasey Formation in the northern Oregon Coast Range. At the type locality in Columbia County, the unit has been separated into a lower structureless to thin-bedded, bioturbated, arkosic sandstone and siltstone unit and an upper unit of basalt conglomerate, arkosic and tuffaceous sandstone, glauconitic sandstone, tuffaceous siltstone, and minor coal beds (Warren and Norbisrath, 1946; Van Atta, 1971; Niem and Van Atta, 1973; Kadri, 1982). Niem and Niem (1985) appended the lower unit of the Pittsburg Bluff Formation as the informal Sager Creek Formation. The informal Northrup Creek formation is equivalent to the upper turbidite and mudstone unit of the Pittsburg Bluff Formation (formerly Oswald West mudstone, Niem and Niem, 1985). On the basis of molluscan fossils collected from this unit, Moore (1976), Olbinski (1983), and Peterson (1984), interpreted Pittsburg Bluff sandstone deposition to be in an open marine, sandy inner to outer shelf environment. Correlative units to the Pittsburg Bluff Formation include the lower part of the Lincoln Creek Formation of southwestern Washington and the lower part of the Alsea Formation of the central Oregon Coast Range (Figure 5; Armentrout and others, 1983).

The upper Pittsburg Bluff Formation apparently undergoes rapid facies changes laterally to the west where it is partly correlative with deep-marine mudstone of the Smuggler Cove formation (middle Oswald West mudstone of Cressy, 1974) along the coast (Figure 5; Penoyer, 1977; Peterson, 1984; Nelson, 1985). However, none of these younger units is exposed in the thesis area.

The Saucesian (lower to middle Miocene) Astoria Formation unconformably overlies the Smuggler Cove formation in Tillamook, western Clatsop, and Columbia counties (Cooper, 1981; Mike Parker, 1989; personal communication). The unit is widespread in northwest Oregon and has been informally divided into the following, lithologically distinct mappable members: 1) the fluvial-deltaic to shallow-marine Angora Peak sandstone (Cressy, 1974); 2) the shallow marine Wickiup Mountain member (Niem and Niem, 1985); 3) the Youngs Bay member, a submarine canyon head deposit (Niem and Niem, 1985), and 4) the Cannon Beach member, a deep marine turbidite mudstone and sandstone package. Currently, Mike Parker of OSU is mapping Astoria Formation facies distributions along the coast in Tillamook County. The lower to middle Miocene Astoria Formation does not crop out in the field area.

Intruding and unconformably overlying upper middle Eocene to middle Miocene sedimentary strata in northwestern Oregon are basalts of middle Miocene age. Flood basalts of the Columbia River Basalt Group (Grande Ronde, Frenchman Springs, and Pomona basalts) were erupted on the Columbia Plateau in eastern Oregon, Washington and Idaho during the middle Miocene, apparently flowed down an ancestral Columbia River and invaded the semi-consolidated Miocene, Oligocene, and consolidated middle to upper Eocene marine strata in the Astoria, Tillamook, Newport and Grays Harbor embayments (Beeson et al., 1979; Niem and Niem, 1984). Snavely et al. (1973) originally believed that these middle Miocene pillow basalts, breccias, sills and dikes along the coast were erupted from local vents. The origin of these coastal basalts is still controversial. Subaerial Columbia River (Grande Ronde) basalts in Columbia County are associated with arkosic sandstone and basalt cobbles of the Scappoose Formation (Ketrenos, 1986) as defined by Kelty (1981) and Van Atta and Kelty (1985). Previously, the Scappoose Formation was thought to underlie the Columbia River Basalts and was thought to be Oligocene in age (Warren and Norbisrath, 1946).

Major uplift of the Washington and Oregon Coast Range, subsidence of the Willamette Valley, and subsequent erosion of rock units was initiated in the late Oligocene and was well underway by the end of the late middle Miocene (Snavely et al., 1980; Niem et al.,in press). Periodic uplift of the Coast Range forearc ridge has been interpreted by Snavely et al. (1980) and by Wells et al. (1984) to be the result of pulses of oblique underthrusting of the Juan de Fuca Plate beneath the North American Plate. In addition, clockwise rotation (up to 22°) of this Coast Range block ("Willamette Plate") may have been associated with back-arc spreading and extension of the Basin and Range province (Wells and Coe, 1985).

Early workers in northwest Oregon considered the structure to be a relatively simple anticlinal fold with minor faults (e.g., Warren et al., 1945; Wells and Peck, 1961). Detailed mapping by Olbinski (1983), Nelson (1985), Rarey (1986), Peterson (1984), Mumford (1988), Safley (1989), Niem and Niem (1985), Jackson (1983), Kadri (1982), this study and that of Farr (1989) in southeastern Clatsop County and western Columbia County has shown that the structure is relatively complex. These studies show a series of major east-west shear zones and numerous northwest (right-lateral) and northeast (left-lateral) trending conjugate faults with oblique-slip displacements. Folds and east-west striking thrusts are minor. There have been several episodes of faulting including an early episode (late Eocene) of east-west faulting followed by late middle Miocene north-south compression which produced the conjugate fault system (Olbinski, 1983; Peterson, 1984; Rarey, 1986; Niem and Niem, 1985). Initial paleomagnetic studies on Miocene dikes suggest clockwise small block rotation (up to 11°) between oblique slip faults (Nelson, 1985). Extensive late Eocene northwest- and northeast-trending normal faults, some with right-lateral displacement, also occur in the subsurface at the Mist Gas Field (Alger, 1985; J. Meyer, 1987; pers. comm.; B. Jackson, 1988; pers. comm.). In addition, large-scale strike-slip faults that probably were active during Paleogene time have recently been documented or inferred throughout western Washington and Oregon (Heller et al., 1987). Wells et al. (1984) and Peterson (1984) suggest that much of the Miocene structure in the region is related to oblique subduction of the Farallon plate beneath the North American plate which produced north-south compression.

VOLCANIC UNITS

TILLAMOOK VOLCANICS

Nomenclature and Distribution

The Tillamook Volcanics were mapped by Warren et al. (1945) and formally named by Warren and Norbisrath (1946) for a thick sequence of middle to upper Eocene basaltic flows and subordinate tuffs and sedimentary interbeds in northwest Oregon. Since that time and especially in recent years, the distribution and origin of these volcanic rocks has received considerable attention (e.g., Snavely, 1970; Magill et al., 1981; Wells et al., 1983; Olbinski, 1983; Nelson, 1985; Rarey, 1986; Mumford, 1988; Safley, 1989). Therefore, an inclusive discussion of the origin of the Tillamook Volcanics would be redundant and is beyond the scope of this study. Interested readers are referred specifically to Mumford (1988) and Rarey (1986) for a thoughtful and comprehensive petrogenetic treatment of this unit. My objective here is to briefly summarize what is known about the Tillamook series and to add and compare any new pertinent geochemical, petrographic and lithologic information about the Tillamooks in the Columbia County surface based on this study. Unfortunately, the subsurface distribution and stratigraphic position of these rocks is poorly constrained from limited well and proprietary geophysical data.

The main Tillamook outcrop belt occurs in a rugged forested area known as the Tillamook Highlands, in Tillamook County, southwest of the thesis area. Warren and Norbisrath (1945) mapped two separate bodies of Tillamook volcanics; the main body in the Tillamook Highlands, and a smaller outlier centered around Green Mountain, in Clatsop County (Figure 7). In subsequent geologic mapping endeavors, those volcanic rocks at Green Mountain have been ascribed to the slightly younger upper Eocene Goble Volcanic series of the northeastern Oregon Coast Range by Wells and Peck (1961).

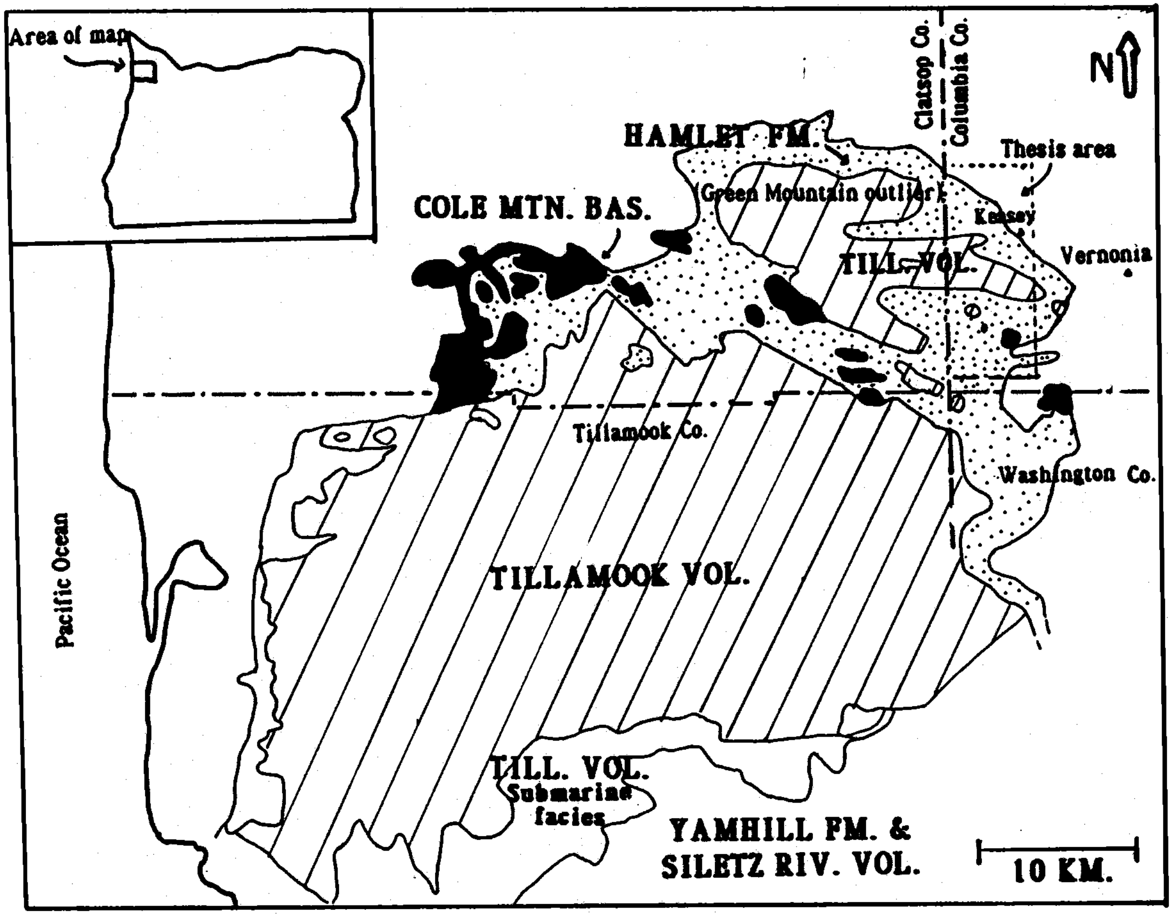


Figure 7. Generalized geologic map of part of northwest Oregon showing relationship of Hamlet formation (stippled) to Tillamook Volcanic highlands and "Green Mountain outlier" of Tillamook Volcanics. Also shown is distribution of Cole Mountain basalt. Part of Hamlet formation also contains rocks assigned to Cowlitz Formation. Modified from Rarey (1986).

Van Atta (1971) presented petrographic, lithologic and stratigraphic evidence similarly to correlate the "Green Mountain basalts" with the type Goble Volcanics of Goble, Oregon (Columbia County) and the Goble Volcanics of southwest Washington (Livingston, 1966). At the type locality, Goble Volcanics appear to overlie upper Narizian sedimentary rocks and underlie Refugian mudstones (Wilkinson et al., 1946). Newton and Van Atta (1976) subsequently mapped the volcanics at Green Mountain as Goble Volcanics, because they interpreted an interfingering relationship with the upper Narizian Cowlitz Formation at that locality.

On the basis of regional mapping, Snavely et al. (1970) proposed a three-fold subdivision of the Tillamook Volcanics. Snavely et al. (1970) recognized that the lower Tillamooks consist of lower Eocene tholeiitic pillow lavas, tuffs, and breccias interbedded with rare foraminifer-bearing siltstones. The middle unit is approximately 760 m of lower to middle Eocene tuffaceous siltstone with minor basaltic sandstone, tuff, breccias, and pillow lavas. The upper Tillamooks consist of at least 1525 m of middle to upper Eocene subaerial basaltic and basaltic andesite flows with rare sedimentary interbeds. Further mapping by Soper (1974) demonstrated continuity and equivalence between the lower and middle members of Snavely et al. (1970) to the Siletz River Volcanics and Yamhill Formation, respectively. Consequently, the Tillamook Volcanics were restricted to the upper unit of Snavely et al. (1970) and Wells et al. (1983). As later described in the Hamlet formation nomenclature section, the stratigraphic relationship of the Yamhill Formation to the Tillamook Volcanics is a matter of some debate.

A subsequent compilation map (unpublished) by Snavely and MacLeod led Wells et al. (1983) to separate the Tillamook Volcanics into a lower submarine basalt facies and a thick upper subaerial basalt package (Niem, 1989; pers. comm.). The lower member contains pillow basalts, breccias, and basaltic tuffs partly equivalent to the upper part of the middle member of Snavely et al. (1970), and the upper subaerial pile of basalt flows is directly correlative to the upper member of Snavely et al. (1970). Currently, Ray Wells of the U.S. Geological Survey is mapping in the Tillamook Highlands and expects to refine the stratigraphy of the Tillamook Volcanics and relationship with the Yamhill Formation in that area (Wells, 1989, pers. comm.).

Regionally, the Tillamook Volcanics cover an area of approximately 1300 km^2 in the northern Oregon Coast Range. Furthermore, deep exploratory wells in Columbia and Clatsop counties have bottomed in volcanic rocks with similar chemistry, petrography, and stratigraphic position as the Tillamook Volcanics (Bruer et al. 1984; Martin et al., 1985; Meyer, pers. comm. 1988). Regional gravity studies in the northern Oregon Coast Range indicate that Mist is located on the eastern flank of a gravitational high composed of Tillamook and Grays River volcanics (Armentrout and Suek, 1985; Kadri, 1982). Therefore, the area in northwest Oregon and southwest Washington floored by middle to upper Eocene volcanics exceeds roughly 5,000 km^2. The substantial area, plus the fact that lower Tillamook basalts are interbedded with Eocene bathyal mudstones while the upper subaerial facies is locally unconformably overlain by shallow-marine basalt conglomerates, led Mumford (1988) to conclude that the Tillamooks document the emergence and subsidence of a moderately large volcanic oceanic island (see: Tectonic Setting).

Exposures of Tillamook Volcanics in Columbia County are limited to the northeastern margin of the outcrop belt (Figure 7). These volcanics should be considered part of the "Green Mountain outlier" because they are uplifted fault blocks of Tillamook Volcanics separated from the main volcanic outcrop area (Tillamook Highlands to the south) by a down-faulted pull-apart depression of the Hamlet formation (this study; Safley, 1989; Niem and Niem, 1985). The Tillamook Volcanics are well exposed in the center of my field area (Plate 1), as an east-west trending elevated basement uplift. High rainfall in the Coast Range combined with the resistant nature of the unit creates steep-sided forested hills and canyons such as along Rock Creek (Plate 1). In general, the westward-thickening Tillamook Volcanics outcrop pattern demarcate north-dipping overlying Eocene sedimentary rocks to the north and lithologically similar south-dipping sequences to the south (Plates 1 and 2). The Tillamook Volcanics represent economic basement in the thesis area with a minimum stratigraphic thickness of 1,100 m based on outcrop calculations. As mentioned previously, the subsurface stratigraphy is incompletely understood in Columbia County.

In their regional cross section, Bruer et al. (1984) showed volcanics tentatively assigned to the Tillamooks underneath C & W sandstone of the Cowlitz Formation but above "Yamhill" sandstone. However, the "Yamhill" of Mist is probably partly equivalent to the Hamlet formation mapped on the surface in Columbia and Clatsop counties (Figure 6). This subsurface relationship may be a function of: 1) the basalt encountered in wells is actually local sills and dikes of middle Miocene Columbia River or upper Eocene Cole Mountain basalt; 2) unrecognized faulting causing repeated sections and miscorrelations; or 3) apparent interfingering of Tillamook Volcanics with sedimentary rocks in part of the Mist Gas Field. Additional basalt geochemical and stratigraphic work needs to be undertaken in the subsurface before any final conclusions can be drawn. There is no surface stratigraphic evidence for marine sedimentary interbeds in the upper Tillamook Volcanics (Niem and Niem, 1985; Rarey, 1986; Olbinski, 1983; Nelson, 1985; Safley, 1989; Mumford, 1988; Farr, 1989; this study). However, as previously noted, correlative Grays River Volcanics overlie and may interfinger with type Cowlitz strata in southwest Washington (Wells, 1981). Therefore, although Tillamook Volcanics represent economic basement to the south of Mist, it is possible that sporadic Tillamook eruptions continued to occur during deposition of C &

W sandstone of the Cowlitz Formation farther to the north. This subject will be addressed in greater detail in the section: Cowlitz Formation.

Contact Relations

The lower contact of the Tillamook Volcanics is not exposed in the thesis area. The upper contact is represented by a regional nonconformity with the upper Eocene basaltic Roy Creek conglomerate member of the Hamlet formation. This contact is observed in two places (locality 809; at Rocky Point, and locality 142) and is planar to undulatory and erosional in both places. However, the Tillamook Volcanics in my area contain a few debris flows with basaltic cobbles which closely resemble those observed in Roy Creek conglomerates, potentially creating complications in separating the two units (Mumford, 1988; Jackson, 1983). In general, the dip of Tillamook Volcanic platy basaltic andesite flows is greater by a few degrees than that of the overlying gently dipping basaltic and arkosic sandstones of the Hamlet formation (Mumford, 1988; this study; Plate I). In addition, basalt clasts of the overlying Roy Creek conglomerate are geochemically, lithologically, and petrographically identical with the Tillamooks, supporting evidence for an erosional contact. Nelson (1985) and Olbinski (1983) showed in a quarry in Clatsop County that the Roy Creek conglomerate (their Cowlitz unit, Tc1) truncated debris flows and basalt dikes.

Lithology

In general, the Tillamook Volcanic subaerial facies exposed in my area is identical to that described by Safley (1989) and Olbinski (1983) in the adjacent areas for equivalent volcanic rocks exposed in the Green Mountain outlier. They predominantly consist of blocky dense dark-grey microporphyritic basalt to basaltic andesite flows, minor andesite flows toward the top of the sequence, and some debris flow breccias. These flows range from 5 to 15 m thick, a few separated by red paleosols, and may display crude columnar jointing (Figure 8). Platy jointing typical of andesite lavas was best observed in Rock Creek (locality 188) and in the more siliceous flows (ie.,60% SiO_2, locality 22). Conversely, the rocks with more basaltic compositions display crude columnar jointing and blocky weathering. Where a complete flow can be observed, the basal section consists of rubbly, very angular, weathered basalt breccia, thick (8-10 m) dense flow interior, and vesicular flow top. Dense flow interiors are dark grey (N3) to grayish black (N2), weathering to light brown (5YR 6/4) to dark yellowish orange (10 YR 6/6). The yellowish color is probably due to surficial weathering and oxidation of iron-bearing framework minerals and basaltic glass to limonite, goethite, and hematite and alteration of plagioclase to clay minerals. Most flows are aphyric to microporphyritic, containing tiny (2 -4 mm length) lath-shaped plagioclase microphenocrysts visible only with a hand lens. Augite microphenocrysts are typically much smaller and less abundant. Porphyritic flows are rare, however one porphyritc basalt (locality 24) near the top of the section contains approximately 30% plagioclase phenocrysts averaging about 5 mm length.

Almost no sedimentary interbeds are observed in the Tillamooks in my area, although basalts in one quarry (locality 22) contain very thin yellowish shale interbeds delineating the attitude of the flow. However, Jackson (1983) reported a few fluvial basalt conglomerate and sandstone interbeds in the Tillamook Highlands to the southeast, and Mumford (1988) found 6 thin (3 m thick) areally restricted volcaniclastic interbeds in the volcanics in his area in southeast Clatsop County. In addition, Wells (1989, pers. comm.) collected thin lithic sandstones from the Tillamook Volcanics in the Tillamook Highlands. I mapped one fine-grained arkosic sandstone outlier along a

Figure 8. Exposure of blocky subaerial flows of middle to upper Eocene Tillamook Volcanics separated by reddish paleosol. Rock hammer for scale. Locality 214 (at Rocky Point).

ridgecrest in the center of the Tillamook Volcanics in my area (locality 115), however, lithologic, petrographic, and paleontologic resemblance to overlying Sunset Highway member sandstones suggested to me that this isolated exposure of Sunset Highway sandstone was down-faulted into its current isolated position surrounded by outcrops of Tillamook basalt (Plate I).

Mumford (1988) and Rarey (1986) reported that debris flows are rare in the Tillamook Volcanics in their areas. However, debris flows appear to be slightly more common in my area and Safley (1989) reported numerous small dikes and debris flows (10% of the section) on Green Mountain. Debris flows were observed in three locations in the Tillamook volcanics in western Columbia County (includes my area and Farr's adjacent thesis area) and appear to represent two end member types. The more common type was observed along the Columbia County mainline just below the Rocky Point quarries (locality 905; Farr's area) and at locality 23. These consist of highly weathered blocks of vesicular, aphyric, and porphyritic basalt and basaltic andesite in a volcaniclastic silty clay matrix support. Commonly, the rounded to subrounded basalt clasts have been so weathered that they resemble the grey silty matrix. This type of debris flow may have been contemporaneous with volcanism (i.e. lahars), initiated as thick super-concentrated matrix supported flows able to transport large cobbles and boulders of mafic material off steep volcanic flanks and deposited in mass (Fisher and Schmincke, 1982).

The other type of debris flow was observed in only one locality (80). This roadcut exposure contains several alternating 2-3 m thick layers of poorly sorted purple (5 P 4/2), yellow (5 Y 8/4) and greenish-grey hard shaley mudstone containing lapilli size or smaller subangular to subrounded fragments of highly weathered basalt clasts and carbonaceous plant matter (Figure 9). Two of the matrix-rich layers are separated by an undulatory red paleosol. The crude stratification and poor sorting suggest that this

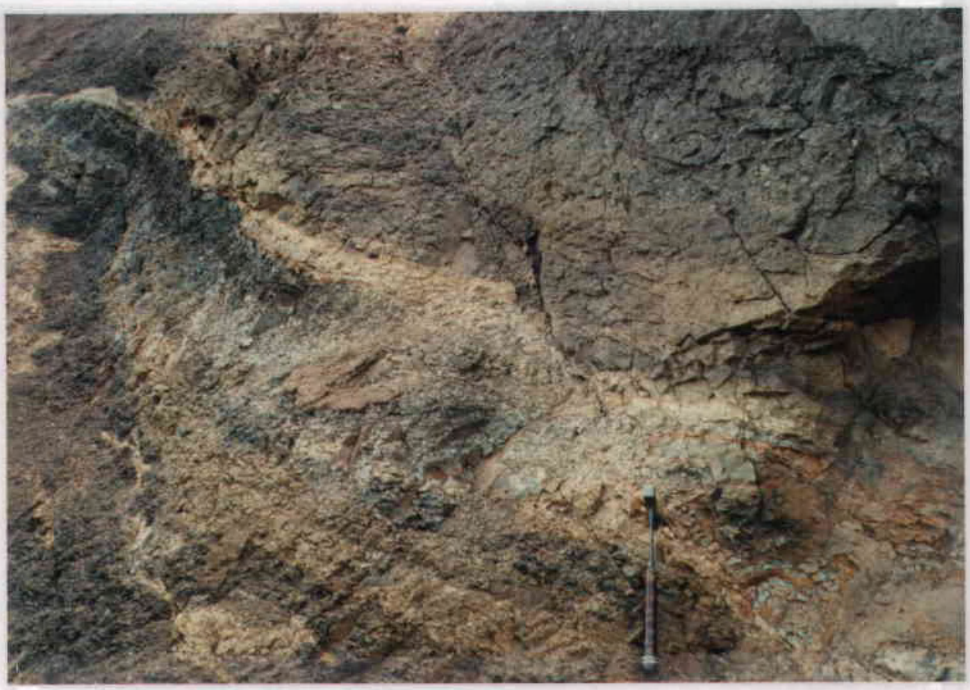


Figure 9. Debris flow in Tillamook Volcanics. Note crude stratification and poor sorting suggestive of "sheet" flow. Rock hammer for scale. Locality 80.

deposit represents a high discharge sheet flow which may have originated as a hyperconcentrated, channelized flash flood of weathered flows and soils off steep volcanic highlands (i.e.,Green Mountain). The debris flow deposit dips approximately 10° north and is limited in areal extent, suggesting flow down narrow incised canyons (Safley, 1989). The altered nature and small size of these vescular clasts is suggestive of mafic pyroclastic material that was exploded in local phreatic eruptions and subsequently reworked. Therefore, this type of flow may represent volcaniclastic sedimentation somewhat intermediate in sediment/water ratio between stream flow and debris flow (Smith, 1986).

Both types of debris flows occur stratigraphically near the top of the section. Nelson (1985) and Olbinski (1983) also mapped debris flows near the top of the section around Green Mountain. Mumford (1988) suggested that low primary dips in the Tillamook Volcanics and tholeiitic petrochemistry in the main Tillamook Highlands to the south is congruent with eruption from a low-relief shield volcano. However, the presence of debris flows and some andesitic lavas implies moderate relief and possible steepening of a differentiated shield volcano at Green Mountain during the late stages of Tillamook eruptions.

Rarey (1986), Olbinski (1983) and Nelson (1985) described the occurrence of possible eroded cinder cones and spatter cones in Tillamook Volcanics. Although no direct evidence of these features was observed in my area, scoriaceous basalt clasts were encountered in two Cowlitz Formation core samples (see: Cowlitz Petrography section) providing further evidence for explosive basaltic volcanism during late Eocene time (e.g.,Goble or Grays River volcanics). Several workers have described and mapped dikes in the Tillamooks (Safley, 1989; Mumford, 1988, Olbinski, 1983; Nelson, 1985). Wells (1989, pers. comm.) has mapped numerous basaltic dikes as well as dacite intrusions, flows, and rare ignimbrite flows in the upper subaerial part of the Tillamook Highlands to the southwest; however, none of those features was observed in my area.

In fault zones, the basalts are extensively hydrothermally altered. In a quarry along the Rock Creek mainline (locality 47), a shear zone approximately 40 m wide is exposed in basalt. This basalt flow is so altered to chlorite and clay minerals it resembles a greenish waxy mudstone or greenstone. Basalt amygdules in this rock contain the secondary minerals, chalcedony, calcite, zeolites, and rare euhedral fluorite crystals (Van Atta, pers. comm.; 1988). Rarey (1986) performed X-ray diffraction analysis on a zeolite in Tillamook basalt and found it to be thomsonite. He concluded that thomsonite is probably the most common zeolite to occur in the upper Tillamook Volcanics. Mumford (1988) was able to identify analcime, and wairakite from further X-ray diffraction analysis on zeolites from amygdules in his area.

Petrography

Six samples of Tillamook Volcanics were petrographically examined. The samples were chosen from the interior of flows in order to obtain the freshest samples possible. Sample locations (Appendix V) were selected with the purpose of sampling various features from all parts of the Tillamook outcrops, and for comparing petrographic characteristics with geochemical data.

Pilotaxitic flow texture is the typical petrographic characteristic of Tillamook Volcanics and was identified in all 6 of the Tillamook thin sections examined. Safley (1989) recognized intersertal texture in a few porphyritic basalt samples which he interpreted to represent more viscous flow. No intersertal texture was observed in any Tillamook samples from this study. The pilotaxitic texture is characterized by alignment of abundant needle-like plagioclase microlites. Five of the 6 thin sections were microporphyritic, with plagioclase phenocrysts and glomerocrysts of plagioclase and augite ranging from 1 to 3 mm long. Phenocryst abundance ranges from 7-15% of the total rock. Plagioclase phenocryst compositions determined using the Michel-Levy method range from andesine (An 45) to labradorite (An 62). Plagioclase phenocrysts are both lath-shaped and euhedral in outline and commonly exhibit albite, Carlsbad, and combined Carlsbad-albite twinning. Many plagioclase crystals are normally compositionally zoned but others have skeletal outlines indicative of rapid growth (Lofgren, 1974). A few plagioclase phenocrysts are rimmed with tiny dark glass blebs which are probably mafic melt inclusions (Tsuchiyama, 1985) (Figure 10).

Clinopyroxene phenocrysts are much less common, although large glomerocrysts of plagioclase with augite are observed in sample 754 (location 159). Augite phenocrysts are typically smaller than plagioclase phenocrysts (<2 mm in diameter), are commonly complexly twinned, and some occur with plagioclase in irregularly shaped glomerocrysts. Augite is recognized by its characteristic stubby rectangular prismatic shape, yellow to pale yellow-green color, inclined extinction and moderate birefringence. Augite in Tillamook samples is usually partially altered to chlorite and smectite clay. Titaniferous augite, usually recognized by its violet-brown tint and strong pleochroism, was found in only 1 thin section. Opaque micro-phenocrysts also occur but are very small (1mm) and comprise less than 2% of the total rock. They are commonly subhedral to euhedral and are probably magnetite or ilmenite.

The characteristic pilotaxitic groundmass in Tillamook basalt flows consists of abundant plagioclase microlites set in a dark mesh of intergranular opaque minerals magnetite-ilmenite (from 1-3 mm diameter) and subhedral to euhedral augite crystals. Needle-like plagioclase microlites are commonly strongly aligned, range in length from 0.2 to 0.8 mm and form 20-70% of the groundmass (Figure 10). They have slightly more calcic An contents (An 55-65) than the plagioclase phenocrysts. Tiny opaque

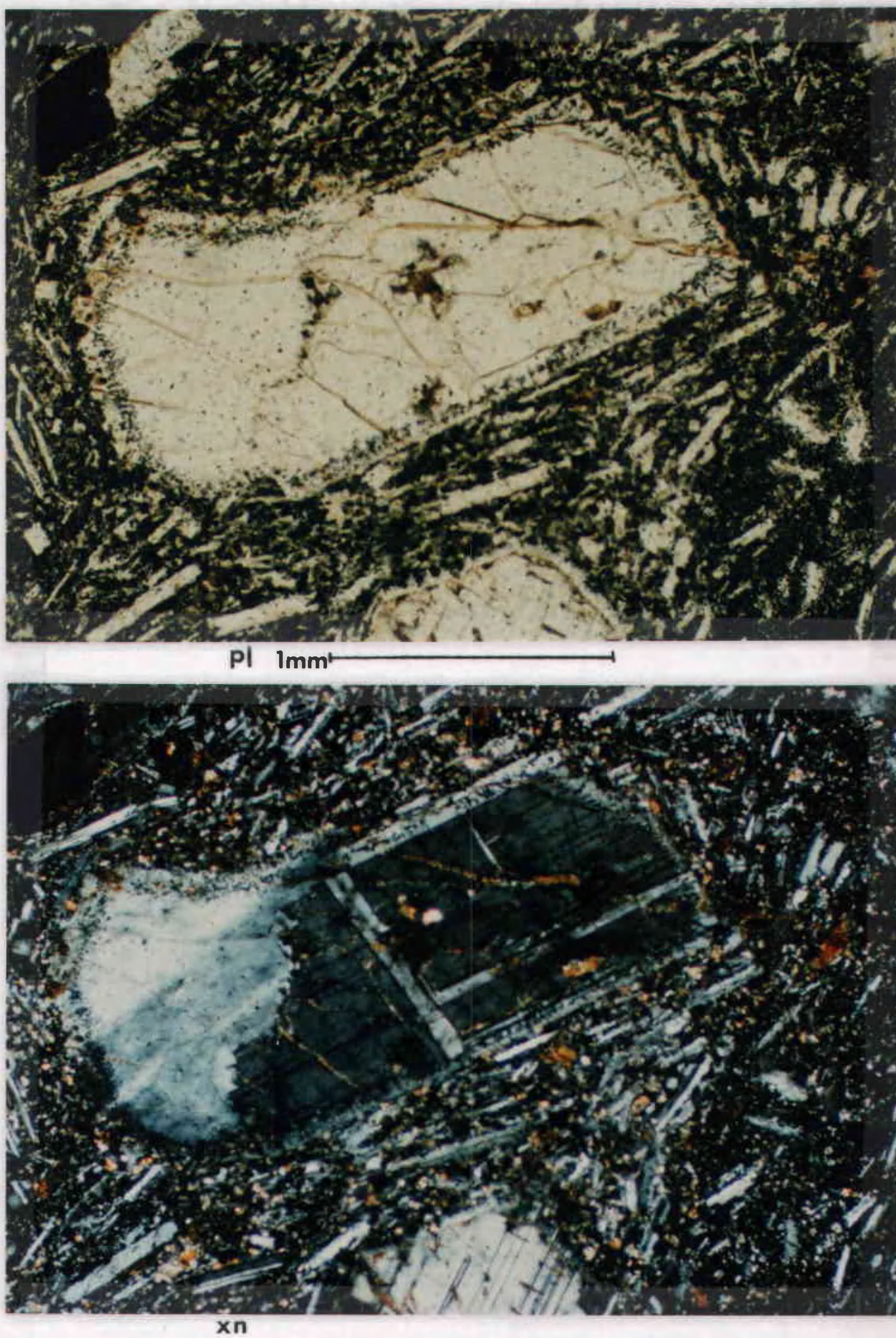


Figure 10. Plagioclase phenocryst rimmed by tiny dark glass blebs which may indicate rapid crystallization. Note opaque minerals (magnetite/ilmenite), interstitial clay, and pilotaxitic flow texture characteristic of Tillamook Volcanics. Sample #754 (locality 159).

crystals of magnetite/ilmenite comprise 5 to 20% of the groundmass, and augite comprises from 10 to 25%. Reddish brown smectitic clay tentatively identified as nontronite (Mumford, 1988) commonly rims plagioclase microphenocrysts and selectively replaces plagioclase cores but also occurs in the interstitial space between the primary minerals in the crystalline groundmass (Figure 10). This clay is not pervasive in any thin section but appears to be more abundant in the more porphyritic samples, where it comprises 5-15% of the sample. In porphyritic samples, the clay is most likely the product of alteration of calcic plagioclase and interstitial glass.

One andesitic flow (SiO_2- 59.61%) in thin section (locality 22) is unusual in that it exhibits alternating light and dark-grey discontinuous flow banding approximately 2-5 mm thick (Figure 11). The trachytic flow texture consists of laths of plagioclase and grains of pyroxene set in an altered finely crystalline to cryptocrystalline mesostasis. This flow texture was observed in both the light and dark bands, indicating flow separation rather than magma zonation (Hibbard, 1981). Microphenocrysts consist of skeletal plagioclase and lesser augite much like the other Tillamook basaltic flows seen in thin sections. However, plagioclase microphenocrysts and phenocrysts are not as well aligned as the plagioclase microlites. Plagioclase microlites comprise about 70% of the groundmass in the lighter bands and only about 30% in the darker bands. The 70% value is among the highest percentage of microlites reported for the upper part of the Tillamook Volcanics (Jackson, 1983; Rarey, 1986; Mumford, 1988; Safley, 1989; Olbinski, 1983; Nelson, 1985). Tiny opaque minerals (less than .05 mm) are abundant in the dark bands, comprising up to 20% of the sample, but are much less common in the light bands (6-10%). Much of the groundmass in this sample is thought to be an altered brownish-black basaltic glass (tachylite), imparting a dark glassy appearance to the thin section. No fresh sideromolane was observed. The glass is probably altered to orange palagonite, chlorophaeite and clay and composes approximately 20% of the light

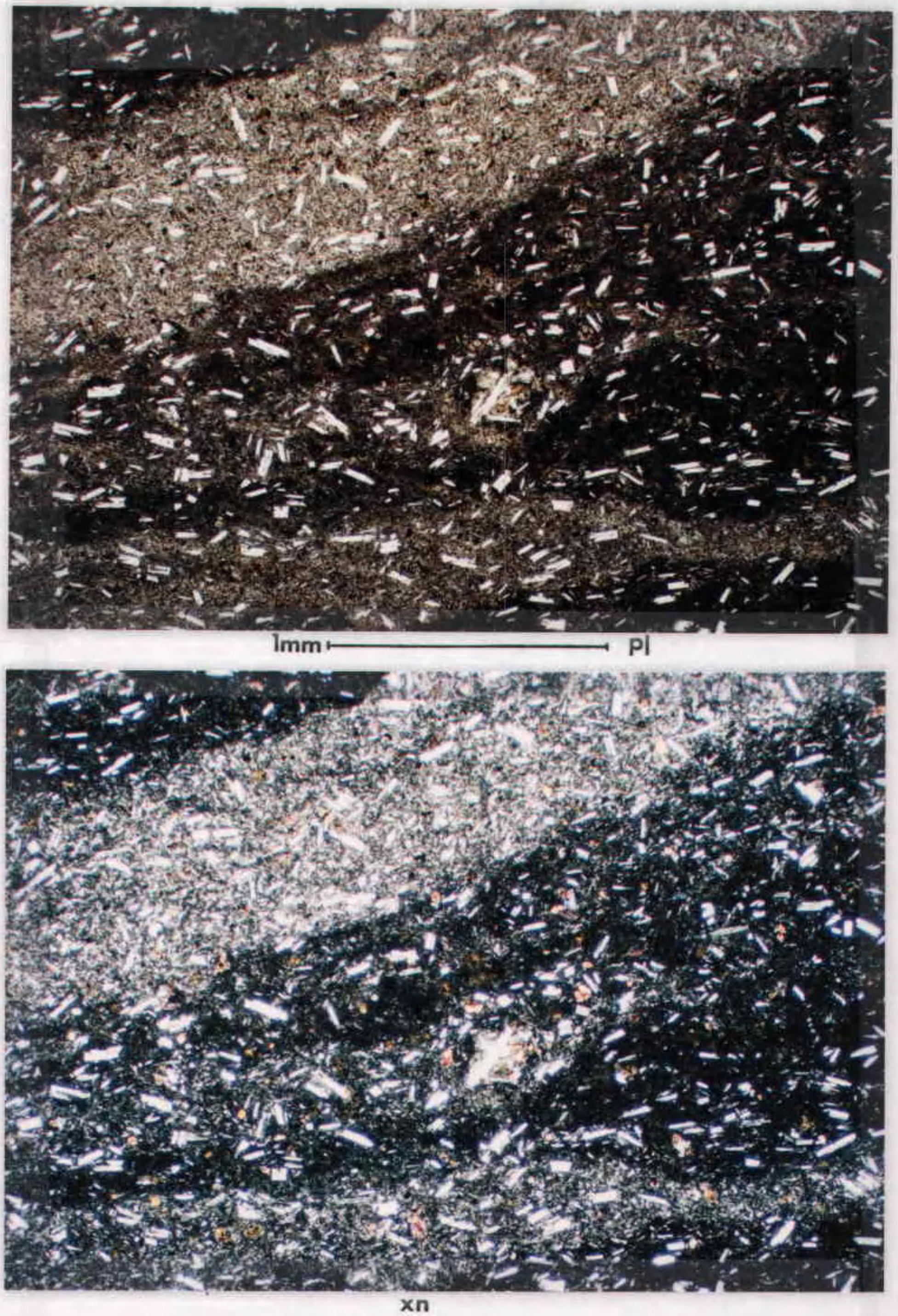


Figure 11. Trachytic flow texture in glassy andesite sample from fractionated uppermost Tillamook Volcanics. Note alternating light and dark banding due to abundance of plagioclase microlites in light bands, and altered glassy dark bands. Sample #764 (locality 22).

bands, but up to 65% of the dark bands. Olbinski (1983) reported a similar texture from an andesitic Tillamook sample in his area; however, he attributed the dark color to a very high percentage of tiny opaque minerals in the groundmass.

Age

Kris McElwee of the School of Oceanography, Oregon State University, as part of her doctoral dissertation has performed K-Ar radiometric dating on several Tillamook Volcanic samples from Mumford (1988), Safley (1989), Rarey (1986) and Farr's (1989) field areas from Clatsop and Columbia counties. For a thorough discussion concerning Tillamook Volcanic K-Ar dates and associated complications, readers are referred to Mumford (1988). Although I have no additional age information from this study, a brief synopsis of their findings follows.

Safley (1989) found that different laboratories (U.S. Geological Survey versus Oregon State University School of Oceanography) provided different ages (37.1 +/- 0.4 versus 40.1 +/- 1.2 Ma) for the same sample. The oldest K-Ar date obtained by McElwee for the Tillamook Volcanics is on the order of 42 Ma; however, most of the age determinations fall between 35 and 39 Ma or late Eocene (Mumford, 1988). Biostratigraphic zonations on calcareous nannofossils collected from the overlying Hamlet formation fall into subzone CP 14a and 14b (Rarey, 1986). According to the time scales proposed by Berggren et al. (1985) and Armentrout et al. (1983), CP 14a is older than 42 Ma. Thus, the radiometric ages are inconsistent with biostratigraphic data. This indicates that the either the radiometric ages are too young or that the absolute ages assigned to middle Eocene to early Oligocene calcareous nannoplankton zones need to be revised. However, recent $^{39}Ar/^{40}Ar$ radiometric dating of upper Tillamook Volcanics by McElwee (1989, pers. comm.) has yielded consistent 42-43 Ma dates for the upper Tillamooks. This suggests that there is a problem with the K-Ar dating of the samples, either through some type of argon loss or potassium exchange and inhomogeneity (Mumford, 1988; Safley, 1989). Whole rock K/Ar dates from the lower part of the Tillamook Volcanics in Tillamook County range from 43 to 46 Ma (Magill et al., 1981); thus the unit is middle to upper Eocene.

On the basis of similar K-Ar dates and major element geochemistry from basalt sampled on Green Mountain with those from the Tillamook Highlands, Safley (1989) and Mumford (1988) concluded that the two basalt sequences are equivalent. This information is particularly important because Tillamook Volcanics in my area are interpreted to represent economic basement and are laterally continuous with those "Green Mountain basalts" in Safley's area.

Regional Correlation

Regionally, several formations correlate with the middle to upper Eocene Tillamook Volcanics (Figure 5). These include the Yachats Basalt of the central Oregon Coast (Snavely and MacLeod, 1974) and the basalt at Cascade Head (Barnes, 1981). However, the Yachats Basalt and the basalt at Cascade Head represent local younger basaltic late Eocene eruptive centers (>32 Ma; K. McElwee, 1989; pers. comm.) that may not represent economic basement in those areas, while the Tillamook Volcanics erupted over a wide area and are economic basement (Wells et al., 1983; Niem and Niem, 1985). On the basis of similar chemistry, petrography, stratigraphic position, and biostratigraphic age bracketing, Rarey (1986) and Wells (1985) correlated upper Tillamook Volcanics with the Grays River area Goble Volcanics and Unit B basalt of Wolfe and McKee (1972) in southwest Washington. Further subsurface information in Clatsop County near Mist indicates that the Tillamook Volcanics and Grays River

Volcanics may be nearly identical geochemically (Jackson, 1989; pers. comm.). However, in northwest Oregon, Tillamook Volcanics appear to underlie Cowlitz sandstone, whereas in southwest Washington Grays River Volcanics interfinger and may overlie strata of the Cowlitz Formation (Wells, 1981). This apparent stratigraphic inconsistency has very important implications regarding hydrocarbon exploration in northwest Oregon and southwest Washington. Wells drilled in the Coast Range frequently encounter basalt at many stratigraphic levels, and the exploration geologist needs to know which flows represent economic basement.

COLE MOUNTAIN BASALT

Nomenclature and Distribution

Rarey (1986) and Mumford (1988) informally proposed the name, Cole Mountain basalt, for a 210 to 250 m thick sequence of upper Eocene basaltic and andesitic intrusive, invasive (?) and minor submarine basalts that crop out in southern Clatsop and northernmost Tillamook counties. The proposed type section is at Cole Mountain along an unnamed logging road in the extreme southwest corner of section 12, T4N, R9W, and northernmost part of section 13, T4N, R9W. The distribution of Cole Mountain basalts in Clatsop Clatsop is further shown by Niem and Niem (1985) and Safley (1989).

In the thesis area, Cole Mountain basalt is limited to two isolated exposures in the southern part of the area (Figure 7; Plate I). However, Farr (1989) has mapped new significant exposures southeast of my area in southern Columbia and northernmost Washington counties (Figure 7), bringing the total area covered by this unit in excess of 65 km^2.

Previous mapping studies in the thesis area have included the Cole Mountain basalt in Tillamook Volcanics (Newton and Van Atta, 1976; Warren and Norbisrath, 1945) , Goble Volcanics (Timmons, 1981; Van Atta, 1971), or as undifferentiated Tertiary intrusions (Beaulieu, 1973; Wells et al., 1983). Petrographic, geochemical, biostratigraphic, and stratigraphic evidence from Rarey (1986), Mumford (1988), Safley (1989), Farr (1989), and this study indicate that the Cole Mountain basalt is younger and chemically distinct from the Tillamook Volcanics. The Cole Mountain basalt of my area matches field and laboratory descriptions given by Rarey (1986), Mumford (1988), and Safley (1989) for Cole Mountain basalt identified in those areas.

In Clatsop County, Cole Mountain basalt occurs close to the contact between mudstones of the Sweet Home Creek member and the Jewell member of the Keasey Formation (Mumford, 1988). In my area, however, Cole Mountain basalt sills and submarine flows are thinner (15-50 m) and occur between the Sweet Home Creek mudstone of the Hamlet formation and C & W sandstone of the Cowlitz Formation (locality 17), or interstratified with upper Cowlitz mudstones near the Keasey contact (locality 11) (Plate I). The apparent attenuation of part of the unit in my area may reflect substantial downcutting and erosion associated with the Keasey unconformity (Figure 6). In any case, Cole Mountain basalt straddles the boundary between upper Narizian Cowlitz sandstones and Hamlet mudstones and lower Refugian Keasey mudstones, which constrains the unit to a latest Narizian/earliest Refugian age. Whole-rock K-Ar age determinations of selected Cole Mountain basalt samples have been performed but have not been reliable, possibly the result of considerable alteration and authigenic mineral growth causing lack of reproducible results (Mumford, 1988).

Through reconnaissance field work and sampling of Goble Volcanics in the type area along the Columbia River, Rarey (1986) demonstrated that Cole Mountain basalt is chemically and stratigraphically correlative to type area Goble Volcanics. As noted previously, Goble Volcanics are reported to interfinger with upper Narizian sedimentary rocks of the Cowlitz Formation at the type locality (Wilkinson et al., 1946). Rarey (1986) postulated that the submarine Cole Mountain basalt is an invasive equivalent to the subaerially erupted Goble Volcanics (discussed further in next section).

Lithology and Implications for Mode of Emplacement

Cole Mountain basalt is poorly exposed in thc thesis area and limited to two exposures separated by approximately 1.7 km: localities 11 and 17 (Plate I). These outcrops exhibit some of the characteristic features of Cole Mountain basalt as described by Rarey (1986), Mumford (1988) and Safley (1989). The larger Cole Mountain exposure (locality 11) consists of a well-excavated quarry containing approximately 50 m of dark grey (N3) to grayish black (N2), microporphyritic to porphyritic, amygdaloidal, glassy pillowed basaltic andesite (53.03% SiO_2) encased in deep-marine upper Cowlitz mudstone. Plagioclase phenocrysts are small and blocky, 1 to 5 mm in diameter, and comprise up to 20% of total rock. Augite also occurs less commonly as microphenocrysts and with plagioclase in glomerocrysts. Plagioclase phenocrysts are partially altered to chlorite and smectitic clays, particularly along fractures and cleavage planes. Oblong amygdules are filled with white zeolites and chalcedonic silica. No vesicular flow top was observed.

At the quarry base, the lava is characterized by densely packed ellipsoidal pillows 2-3 m in diameter, which have chilled margins with glassy rinds, radial to irregular fracture patterns, and dense interiors. The middle part of the quarry contains many lenticular lava tubes up to 3 m across. A spectacular "war bonnet" structure is exposed at the upper, back part of the quarry (Figure 12). War bonnet structures resemble fanning radial columnar jointing, typical of filled lava tubes or very large mega-pillows (Niem, 1987; pers. comm.). Trend and plunge of the war bonnet structure and pillows gives a flow direction of S10W, dipping approximately 17°, the inferred paleoslope. War bonnet structures have also been reported by Mumford (1988) and Farr (1989) from Cole Mountain basalt in their areas and seem to be characteristic of that unit.

Many thin layers of pillows in the lower and middle parts of the quarry contain interstitial irregular nodules of sugary-textured to smooth, medium grey (N5) chert up to 25 cm diameter. SEM and EDX analysis performed on these nodules confirms a silica composition but rules out origin from diatomaceous ooze. Interstitial sediment is a

Figure 12. "War bonnet" structure, or fanning columnar jointing in submarine flow of upper Eocene Cole Mountain basalt. Locality 11.

common feature in pillow basalts (Snyder and Fraser, 1963). One of the three following explanations is generally given for the presence of this material: 1) contamination from below the extrusive lava sheets; 2) infiltration and precipitation from later deposits or contemporaneous precipitation; or 3) mixing during intrusive flow into water-rich mud (Snyder and Fraser, 1963). At locality 11, there is a diminution in the amount of interstitial sediment upward in the sheets of pillowed lava, which would not be the case if this was a shallow intrusion into mud. Furthermore, if this siliceous material was originally a mudstone it would be primarily composed of clay minerals and micas. The pure silica composition indicates that it probably represents a later chemical precipitate.

Rarey (1986) and Mumford (1988) reported irregular thin pillowed sills and thin beds of pillow basalt in Sweet Home Creek mudstones that characterize the basal part of the Cole Mountain basalt. There exists the possibility that this outcrop also represents a sill-like intrusion or a shallow igneous invasive flow into moist sediments (upper Cowlitz mudstone). However, this outcrop contains a volumetrically thick (50 m) package of closely packed pillows and lava tubes which would be unlikely in an intrusive or invasive body (Hanson and Scheickert, 1982). The upper contact with upper Cowlitz mudstone is planar to undulatory, but not highly irregular, signifying a conformable depositional surface. Vitrinite reflectance values (R_o=.41) of the overlying mudstone (sample 780) 3 m above the contact indicate that the sediments were not significantly heated (compared with other mudstone analyzed samples: see Source Rock Analysis) indicating that this mudstone has not been baked by the underlying basalt. Therefore, the basalt in this quarry probably represents a small submarine extrusion of lava onto wet semiconsolidated seafloor sediments. Because the basalt is enclosed in deep-water mudstones containing a bathyal foraminferal assemblage (McKeel, 1988; writ. comm.), the lava must also have been extruded in deep-water. Safley, (1989) described similar pillowed basalts but noted highly irregular contacts with the Sweet

Home Creek mudstones. He interpreted these basalt bodies as shallow-level irregular sills. Accordingly, sill-like bodies reported by Safley are microgabbroic to gabbroic, suggesting slow cooling; in contrast, the analogous basalt in my area is microporphyritc and glassy. It should be noted, however, that the small size and limited extent of the outcrop seems to dispute a submarine flow origin because subaqueous eruptions usually are more extensive and contain significant hyaloclastite (Kokelaar, 1982).

Due to the limited exposure, it could not be inferred where this unit occurs stratigraphically (in the upper or lower part of the Cole Mountain basalt unit). Mumford (1988) reported that the lower and middle parts of the Cole Mountain basalt have a massive appearance, whereas the middle and upper parts contain large pillows and war-bonnet" jointing similar to features observed in outcrop locality 11.

The other exposure of Cole Mountain basalt (locality 17) is a hyaloclastite facies characteristic of some Cole Mountain basalt (Rarey, 1986). It consists of highly altered, brecciated, vesicular basaltic rock intercalated with marine Hamlet siltstone and mudstone. Approximately 50% of the 17 m thick outcrop is composed of mudstone and mudstone inclusions within amygdaloidal basalt. The outcrop physically resembles a thorough mixture or homogenization of sedimentary and basaltic material, resulting in massive, slightly pillowed (?) and brecciated beds of water-laid fragmental debris or peperite. The debris consists of subangular medium-grey (N5) glassy basaltic fragments (1-2 cm in diameter) cemented in a matrix of chalcedony, zeolites and calcite. All three minerals are present in approximately equal amounts between subangular to angular basalt grains. Amygdules and vesicles are commonly filled with drusy pyrite cubes, probably the result of hydrothermal (deuteric) alteration. Mumford (1988) has also recognized abundant amygdules containing minor supergene copper-silver mineralization associated with vesicular Cole Mountain basalt intrusions in his area.

These features all suggest intrusion or injection of hot magma into water-saturated uncompacted muds, causing fragmentation and steam-blasting near the water-sediment interface (Snavely, 1973). Fluidization of sediments is commonly associated with peperites and is usually indicated by reconstituted sediments with loss of sedimentary structures and intervention of exogenous material (i.e. zeolites and calcite) between the host and igneous body (Kokelaar, 1982). Peperites have also been described in Cole Mountain basalt in Clatsop County (Mumford, 1988; Rarey, 1986).

A 2 m thick red oxidized zone interpreted to represent a paleosoil is well exposed in the upper part of the exposure on top of this thick disorganized basalt breccia. However, red oxidized zones conceivably can develop in shallow oxygenated water where they may represent a redeposited soil (pedolith). Mapping relations suggest that the paleosoil (?) may directly underlie nearshore arkosic C & W sandstone, which may indicate that this Cole Mountain basalt represents eruption in shallow-water or near the strand line of an island or shoreline that existed in middle to upper Eocene time. Alternatively, sea level regression or uplift of Hamlet strata may have resulted in a very short period of subaerial exposure during the late Eocene and unconformity before deposition of Cowlitz strata. A third possibility is that this red oxidized feature may represent a late middle Miocene paleosol. Paleosols have been described on the Keasey Formation and Columbia River Basalt in Columbia County (Niem and Van Atta, 1973; Van Atta, 1971).

Rarey (1986) speculated that some Cole Mountain basalt may represent invasive flows of Goble Volcanics of the northeast Oregon Coast Range which foundered into water-saturated sediments of the Sweet Home Creek member. This peperite outcrop exhibits features which suggest that it may represent a remnant of an eroded point of invasion of lava flows (Goble?) that fed shallow-level invasive and submarine basalt flows such as the Cole Mountain basalt at outcrop locality 11. Subaerial Goble Volcanic flows and Cole Mountain basalt in Columbia County are more than 30-50 km apart and have not been connected by surface mapping or subsurface exploratory wells (Bruer et al., 1984; Niem and Niem, 1985; Timmons, 1981; this study). However, it is possible that large parts of the Cole Mountain basalt or Goble Volcanics in Columbia County have been removed by erosion during the Keasey unconformity (Mumford, 1988).

Petrography

Three thin sectins of Cole Mountain basalt from the 2 exposures in the thesis area were petrographically examined. One of the thin sections is from the peperite at locality 17 and the other 2 are from the pillowed outcrop at locality 11. Mineral abundances were visually estimated. All Cole Mountain basalt samples have been effected to some extent by weathering and deuteric clay alteration, precluding accurate petrographic and geochemical analysis of the altered samples.

Texturally, all samples are porphyritic and microporphyritic and/or glomeroporphyritic, with plagioclase phenocrysts and minor augite phenocrysts arranged in an intersertal to altered hyalopilitic glassy groundmass. Although porphyritic, plagioclase in Cole Mountain basalt shows a complete crystal size gradation from small microlites (0.2-1.5 mm) to phenocrysts (Figure 13). Plagioclase phenocrysts are generally subhedral and exhibit patchy Carlsbad and albite twinning. Phenocryst size ranges from 0.5 to 3 mm in length. Plagioclase phenocrysts comprise 18% and 27% of the samples (705 and 702, respectively). Large glomerocrysts (up to 2.5 mm) consist of intergrown euhedral plagioclase in irregular clusters. Most plagioclase phenocrysts are normally zoned in two or three stages rather than a "tree ring" zonation (Figure 13). Maximum extinction angles determined from Michel-Levy method of albite-twinned plagioclase indicate an An_{51} to An_{62} (labradorite) composition.

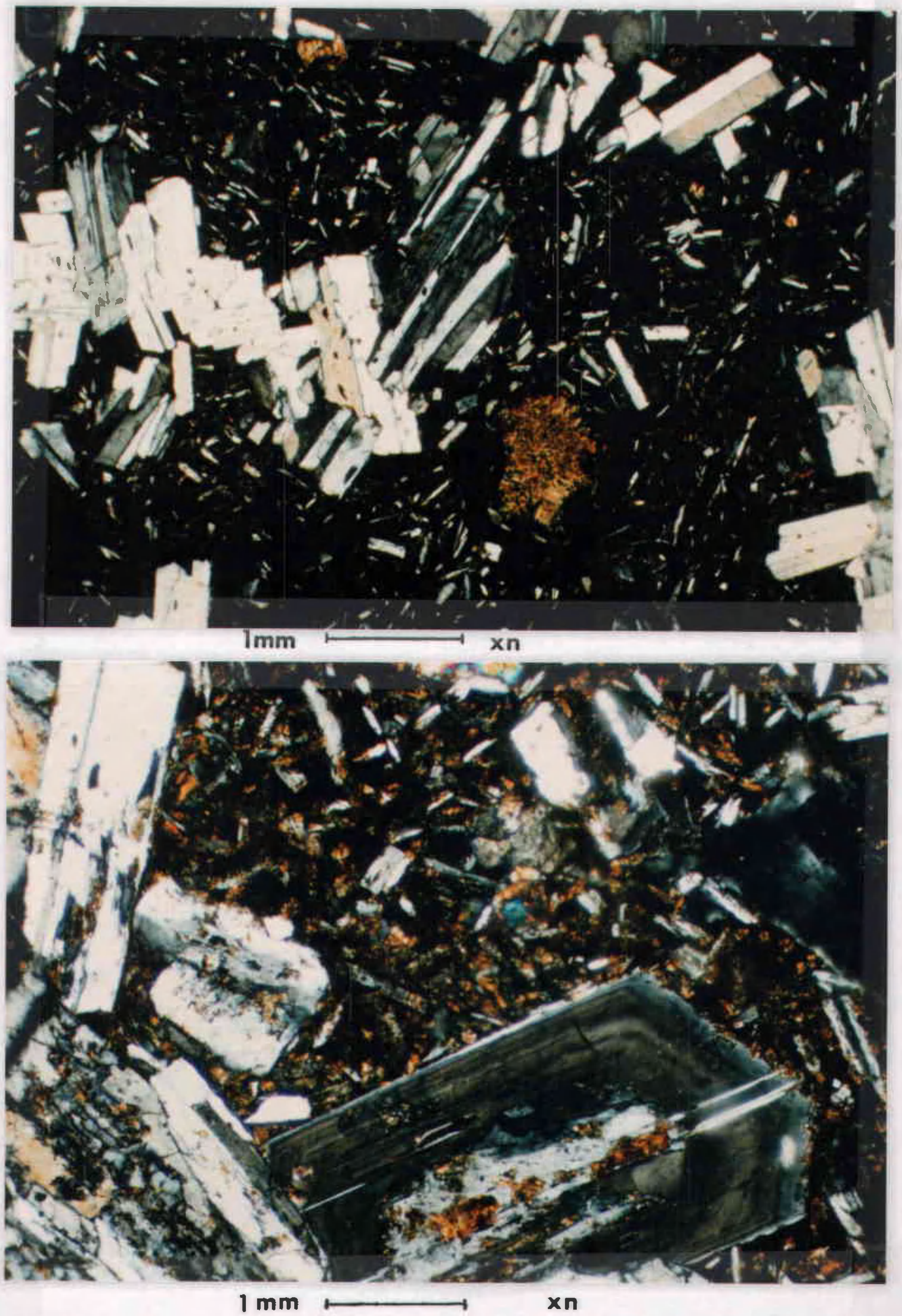


Figure 13. Photomicrographs of Cole Mountain basalt. a) Glomerophenocryst of intergrown labradorite set in a groundmass of randomly arranged plagioclase microtes, altered glass and secondary clays. Note vesicles filled with radiating nontronite clays. b) Oscillatory zoned plagioclase with sieved interior texture filled with brownish-orange clays. Sample #702 (locality 11).

Unfortunately, no zoned crystals were properly oriented for determination of core and mantle compositions, however, Mumford (1988) reported calcic cores (An_{58}) and calcic andesine rims (An_{47}). Commonly the plagioclase grains have sieved interior textures (Figure 13) commonly associated with resorption and partial dissolution (Tsuchiyama, 1985). Some plagioclase interiors contain small spheroidal inclusions, rimmed with radiating brownish-orange chlorite or iron-rich smectite (nontronite) or chlorophaeite clays (Figure 13). These clays are interpreted to represent altered volcanic glass (Tsuchiyama and Takahashi, 1983). Clay development is also preferentially developed along plagioclase cleavage planes.

Augite also occurs as euhedral phenocrysts ranging in size from 0.3 to 2 mm across and form 2-15% of the samples. Augite in Cole Mountain basalt is typically partially replaced by chlorite and nontronite clays. Opaque microphenocrysts are less abundant in Cole Mountain basalt than in Tillamook Volcanic samples, comprising from 1-2%. They are generally too small for positive identification but are probably magnetite and/or ilmenite.

The intersertal to hyalopilitic groundmass consists predominantly of randomly oriented plagioclase microlites in a dark glassy matrix with nontronite-filled vesicles, tiny augite crystals and minor tiny opaque minerals (Figure 13). Microlites comprise approximately 30% of the groundmass. Fresh glass is rare and most has altered to fibrous birefringent clay minerals, probably chlorite. Amygdules comprise from 5-8% of Cole Mountain thin sections and are greenish brown chlorite and nontronite. Plagioclase microlites in Cole Mountain basalt are lath shaped and can generally be distinguished from the flow aligned needle-like plagioclase microlites in Tillamook basalts (see Figures 10 and 11).

Mumford (1988) described rare seriate textures and Safely (1989) reported microgabbroic to gabbroic textures for some Cole Mountain basalt intrusions, but this was not observed in my thin sections of the pillowed flows or peperitic breccia.

The peperite at locality 17 consists of altered, glassy basalt grains (60%) cemented by sparry calcite (18%) and zeolite (20%) with trace amounts of augite. Early sparry calcite cement partly replaces and rims basalt grains and partly fills intergranular pore spaces; zeolites then filled the remaining pore spaces (Figure 14). Zeolites exhibit a fibrous radiating habit and appear to be of two different types. Early zeolite cement partly fills pore spaces and appears as colorless, prismatic crystals or as radiating fibrous aggregates, similar to the crystal form of laumontite (Phillips and Griffen, 1981). A late-stage fibrous radiating zeolite fills the remaining pore spaces and is tentatively identified as thomsonite, considered to be the most common zeolite in Cole Mountain basalt (Rarey, 1986). Alternatively, these may represent two different forms of the same zeolite. Zeolites are characteristically found in vesicles, amygdules, and fissures in mafic volcanic rocks where formed by late hydrothermal processes (Phillips and Griffen, 1981).

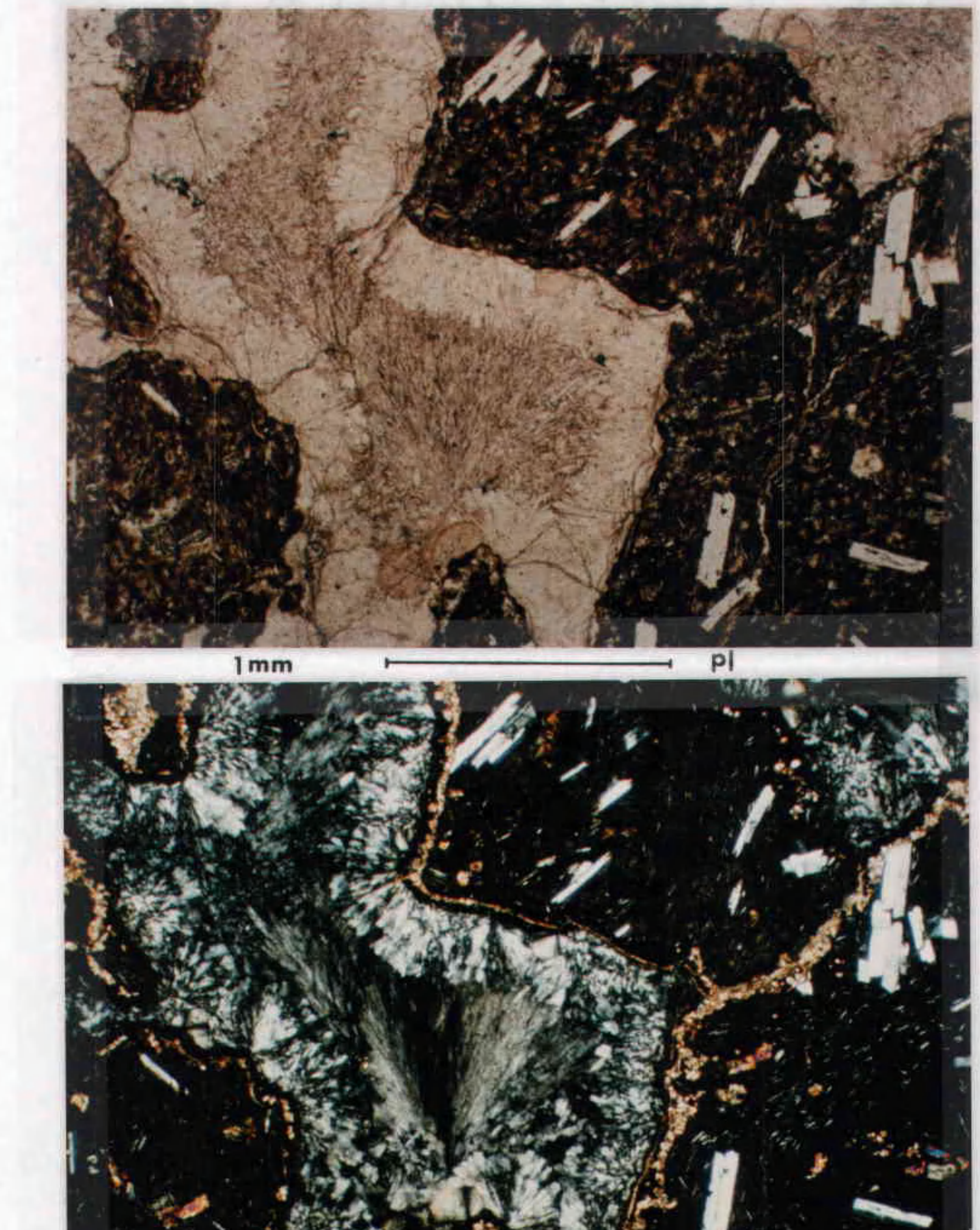


Figure 14. Photomicrograph of peperite (sample 901) from locality 17. Note early sparry calcite cement and late fibrous radiating zeolite pore fill. Note slightly different crystal habit of zeolite in rim versus center of pore.

GEOCHEMISTRY OF VOLCANIC ROCKS

Introduction

Volcanic rocks in the Washington and Oregon Coast Ranges and particularly in northwest Oregon have been extensively sampled and analyzed for major element geochemistry (i.e., Snavely et al., 1968; Snavely and Wells, 1984; Snavely et al., 1973; Beeson et al., 1979; Cameron, 1980). Rarey (1986), compiled over 100 basalt geochemical analyses from widely spaced localities from the work of Mumford (1988) and Safley (1989), and from theses by Nelson (1985), Olbinski (1983), Jackson (1983), and Timmons (1981). All of these samples were analyzed by X-ray fluorescence (XRF) under the direction of Dr. Peter Hooper at Washington State University using a Phillips XRF instrument, thus establishing an internally consistent analytical data base. Using this data base, Rarey (1986), Mumford (1988) and Safley (1989) were able to delineate separate geochemical fields for Tillamook Volcanics and Cole Mountain basalt. In addition, Mumford (1988) and Rarey (1986) plotted geochemistry samples outside their thesis areas and defined fields for Columbia River Basalt in northwest Oregon, and Goble Volcanics and Grays River Volcanics of southwest Washington. Mumford (1988) and Rarey (1986) also presented extensive investigations into the relationship between geochemistry of Tillamook and Cole Mountain basalts and tectonic setting and petrogenesis of the Eocene volcanics in the Nehalem River Basin of northwest Oregon. Because of the thoroughness of their work, limited investigations on basalt petrogenesis were undertaken in this study.

Data Reliability.

This study contributed 7 additional basalt major and trace element analyses, also performed under the direction of Dr. Peter Hooper of Washington State University using the International Basalt Standard and the newly-installed automated Rigaku X-ray fluorescence unit. See Methods of Investigation section for sample preparation proceedures. Sample locations are shown on Plate I and are listed in Appendix V.

Because of the two varying machines used in the analyses (Phillips for Rarey, 1986; Mumford, 1988; Safley, 1989; Jackson, 1983; and Timmons; 1981) nomogram correction factors were calculated by Westinghouse Hanford Company in 1987. The purpose of these correction factors is to convert and compare major element data sets from the older Phillips analyses to the new Rigaku data sets, or vice versa. However, recent evidence suggests that these correction factors are unreliable. Specifically, Hooper and Tolan have demonstrated from thousands of XRF reanalyses using the new Rigaku unit versus the older Phillips instrument that there is no consistent variation of major elements between the machines (Tolan, 1990; pers. comm.). Therefore, the correction factors supplied by Westinghouse in 1987 were not applied to XRF analyses on volcanic rocks from the thesis area. According to Tolan (1990; pers. comm.) complex instruments such as a XRF machine often require a period of adjustment and familiarization before producing consistent results. For this reason, although XRF samples that were run immediately after installation of the Rigaku have the potential for statistical variability, major and trace element abundances generated in the last year (i.e., my samples) are statistically comparable with those from the previous Phillips unit with no correction factor (Tolan, 1990; pers. comm.).

Data Set

Generally, I attempted to attain geochemical data on the same samples which were thin sectioned in order to correlate mineralogy with major element variation within the sample group. Geochemical results (Table 1) were plotted on several Harker variation diagrams and volcanic rock classification plots in order to discriminate between different generic basalt types in my area. Geochemical data have proved to be a valuable tool for helping to identify unknown basalts with similar appearance in the Coast Range. No attempt was made to resolve detailed basalt stratigraphy within units utilizing geochemical data in the thesis area.

Figure 15 shows several Harker silica variation diagrams of the volcanic units in the thesis area. The figure shows that the probable Tillamook Volcanic samples from my area plot well within the established Tillamook Volcanic fields of Rarey (1986), and the two samples suspected to be Cole Mountain basalt plot within the Cole Mountain basalt field. Although some scatter exists among the data, the Tillamook fields are generally tightly clustered and well defined. One of the samples (#749) registered as Tillamook Volcanics is a basalt cobble from the Roy Creek member conglomerate which unconformably overlies the Tillamook Volcanics. The nearly identical chemical composition of this clast and Tillamook Volcanics indicates derivation from a Tillamook source (Table I).

Rarey (1986) and Safley (1989) reported two distinct groupings of Tillamook Volcanics based on Harker variation diagrams for basalts and andesites from their areas. Group I basalts from Safely (1989) have SiO_2 values from 49% to 55% and chemically classify as basalt and basaltic andesite (Cox, 1979). Group II samples have SiO2 percentages from 58% to 66% and classify as basaltic andesite and andesite. Samples from group I have lower K_2O, Na_2O, and higher MgO, CaO, and TiO_2 percentages

Table 1. Major element oxide data determined by X-ray fluorescence of Eocene volcanic rocks and Roy Creek basalt conglomerate clast in thesis area.

Major Oxide

Normalized results (weight %)

	[------------Tillamook Volcanics------------]						[-Roy-] Creek cgl	[--Cole Mountain-----] basalt		
Sample #'s	753	764	902	803	706*	Ave.	749	702	785	Ave.
SiO_2	50.62	59.61	50.12	50.00	66.55	52.59	50.64	53.26	59.26	56.26
Al_2O_3	15.67	16.27	16.83	16.56	15.05	16.33	20.67	17.63	16.35	16.99
TiO_2	3.28	1.63	3.10	3.23	0.85	2.81	3.98	1.34	1.50	1.42
FeO**	11.69	7.67	10.78	11.53	5.46	10.41	11.60	8.72	7.72	8.22
MnO	0.192	0.229	0.192	0.198	0.162	0.202	0.105	0.220	0.141	0.181
CaO	9.99	4.68	9.89	9.41	0.66	8.49	5.07	9.94	6.91	8.43
MgO	4.42	1.76	3.91	4.34	0.41	3.60	1.23	5.40	3.14	4.27
K_2O	0.60	2.43	1.01	0.97	9.07	1.25	2.39	0.24	0.68	0.46
Na_2O	2.93	5.12	3.45	3.31	1.65	3.70	3.46	2.99	4.03	3.50
P_2O_5	0.597	0.601	0.725	0.470	0.146	0.598	0.848	0.266	0.277	0.272

* Highly weathered and altered sample not included in average. ** Total Fe.

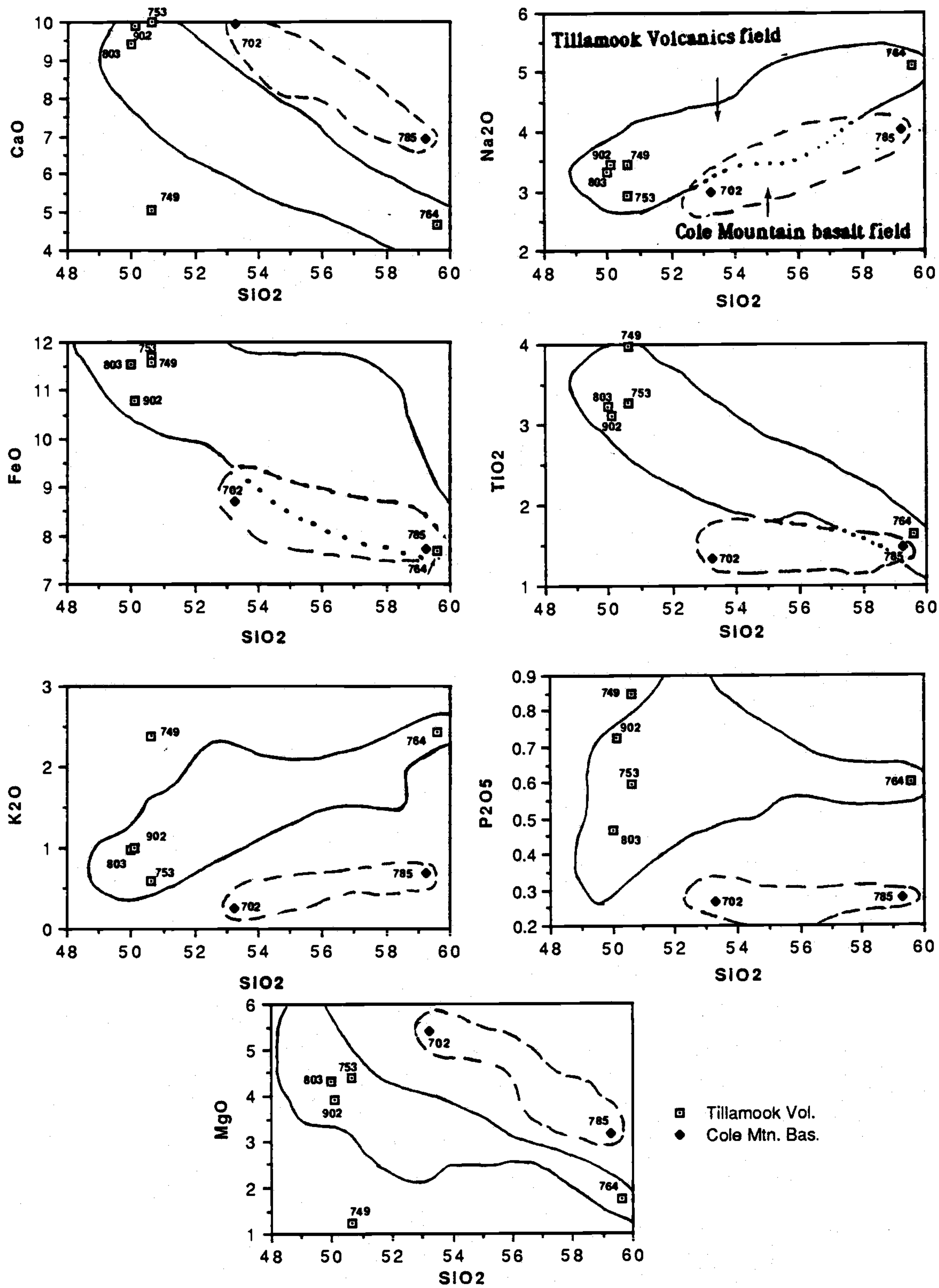


Figure 15. Harker silica variation diagrams of middle to upper Eocene volcanic rocks in thesis area. Fields for Tillamook Volcanics and Cole Mountain basalt smoothed from Rarey (1986). Note how sample 749 plots outside of Tillamook Volcanic field due to weathering of clast in Roy Creek mbr.

than group II samples; however, they are along the same chemical trends established for Tillamook Volcanics (Rarey, 1986). Four of the 5 Tillamook Volcanic samples from my area plot within Group I, while the other (#764) plots within the more silicic Group II. The four samples from Group I have tightly grouped SiO_2 values ranging from 50.00 to 50.64, with a mean of 50.34%. These samples classify as basalts (Cox, 1979). No Tillamook samples from this area plot as basaltic andesites.

Sample #764, a flow banded glassy sample, has a significantly higher silica value than the other 4 Tillamook samples (59.61%), which classifies it as an andesite (Cox, 1979). This sample also had the highest total alkali (K_2O and Na_2O; Figure 16) consistent with the andesite classification and suggests that the high SiO_2 value was not the result of alteration of primary glass and plagioclase (Cox, 1979). Sample 764 is from a quarry located near the highest peak in the field area at 550 m (1809 feet; Plate I). Safley (1989) demonstrated that the flows from the upper part of the Green Mountain outlier have higher SiO_2 values than those sampled from lower in the volcanic section. My results from limited data also show this to be so. Safley (1989) also suggested that the flows underlying Green Mountain tend to be more silicic and differentiated than in the main Tillamook Volcanics in the Tillamook Highlands (Figure 7). However, Tillamook Volcanics in my area are directly adjacent and continuous with those on Green Mountain yet they have predominantly low SiO_2 values. Evidence from this study suggests that only the uppermost part of the Green Mountain outlier in Columbia County contains andesitic flows. Safley (1989) and Mumford (1988) argued that these flows may represent a later, more differentiated or fractionated part of the volcanic center. The fact that the rocks fall into two distinct geochemical subgroups requires either (1) two magma chambers responsible for the basalts at Green Mountain; or (2) a significant amount of time between eruptions to allow magma evolution and fractional crystallization within one chamber. However, Rarey (1986) found a nearly continuous

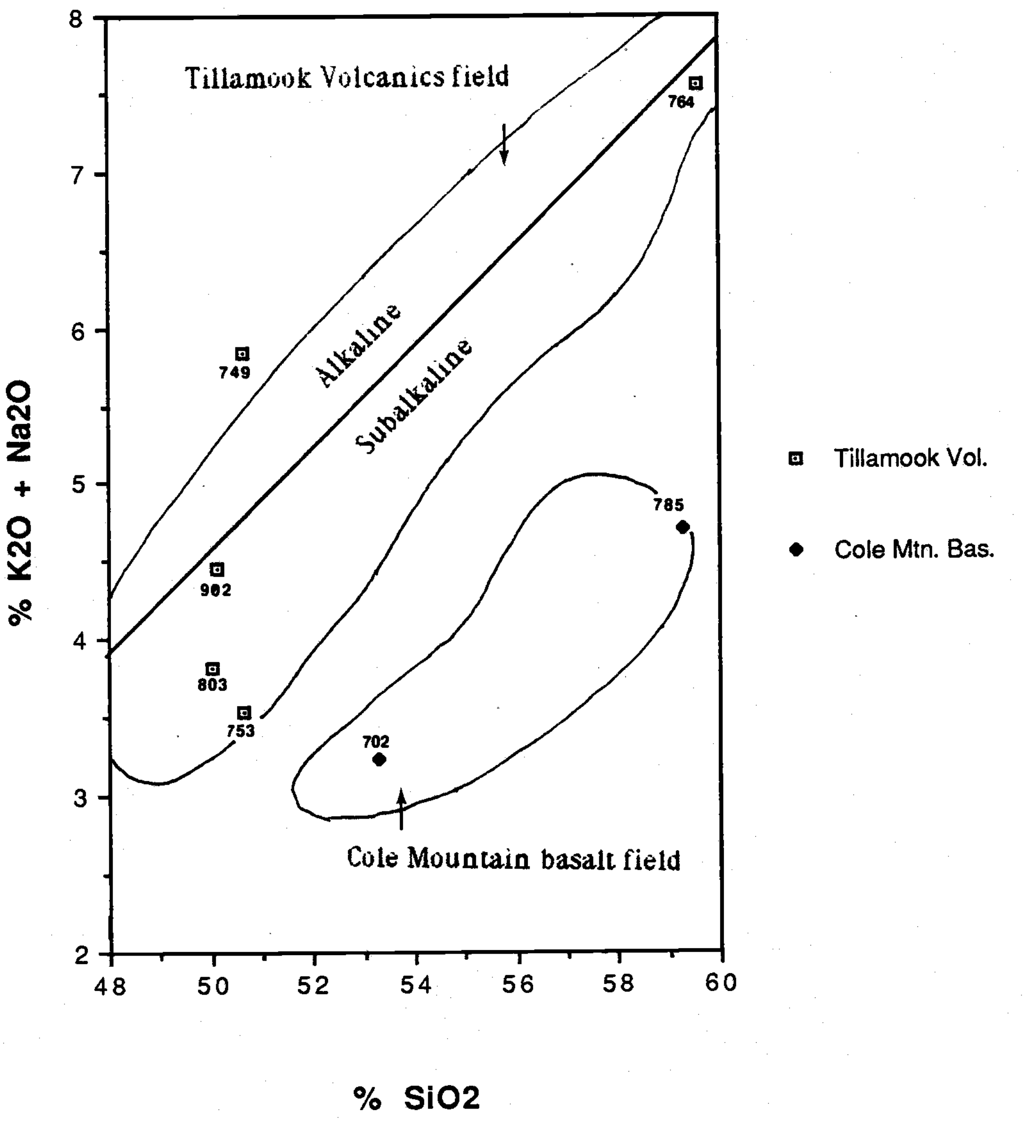


Figure 16. Silica versus total alkali diagram, after Irvine and Barager (1971). Note that Tillamook Volcanics and Cole Mountain basalts are subalkaline, however, Tillamook Volcanics plot nearly along the line separating alkaline from subalkaline. Tillamook Volcanics and Cole Mountain basalt fields slightly modified (smoothed) from Rarey (1986).

fractionation trend occurs when all the previous samples from Clatsop and Columbia Counties are considered. Wells (1989; pers. comm.) and Wells et al. (1983) show that fractionated and more silicic-rich flows (e.g.,dacites and even ignimbrites) occur at the top of the Tillamook Volcanics in Tillamook County to the south.

Cole Mountain basalt from the thesis area was plotted on Harker variation diagrams with Tillamook Volcanics in order to facilitate comparison (Figure 15). In general, Cole Mountain basalt samples can be distinguished from Tillamook Volcanics by higher SiO_2, MgO, CaO values, and lower values of TiO_2, K_2O, P_2O5, FeO,and Na_2O (Figure 15). Cole Mountain basalt sample 785 has a similar SiO_2 value as Tillamook sample 764 (59.26% and 59.61% respectively); however, 785 is higher in MgO, CaO, and lower in TiO_2, K_2O, P_2O5, FeO,and Na_2O. The much lower TiO_2 and FeO in Cole Mountain basalt is reflected in the lower abundances of the opaque minerals ilmenite/magnetite in the groundmass. In the classification scheme of Cox (1979), one Cole Mountain basalt sample (785) plots as an andesite, and the other (702) plots as a basaltic andesite.

On the silica versus total alkali (K_2O and Na_2O) diagram of Irvine and Barager (1971), 4 out of 5 Tillamook Volcanic samples and both Cole Mountain basalt samples from the thesis area plot in the subalkaline field (Figure 16). However, this diagram also shows that 1 Tillamook Volcanic sample (#901) is alkaline and the other 4 plot nearly along the line subdividing alkaline from subalkaline rocks. Cole Mountain basalts plot substantially below the Tillamook field in the subalkaline area. Subalkaline rocks can be divided into tholeiitic and calcalkaline trends, using the AFM (total alkalies-total iron-total magnesium) ternary diagram of Irvine and Barager (1971), which shows the Tillamook Volcanics to be tholeiitic in nature, and Cole Mountain basalts to be calcalkaline (Figure 17). The "iron enrichment" plot of Miyashiro (1974) is also used to distinguish tholeiitic from calcalkaline trends. This diagram (Figure 18) also shows that

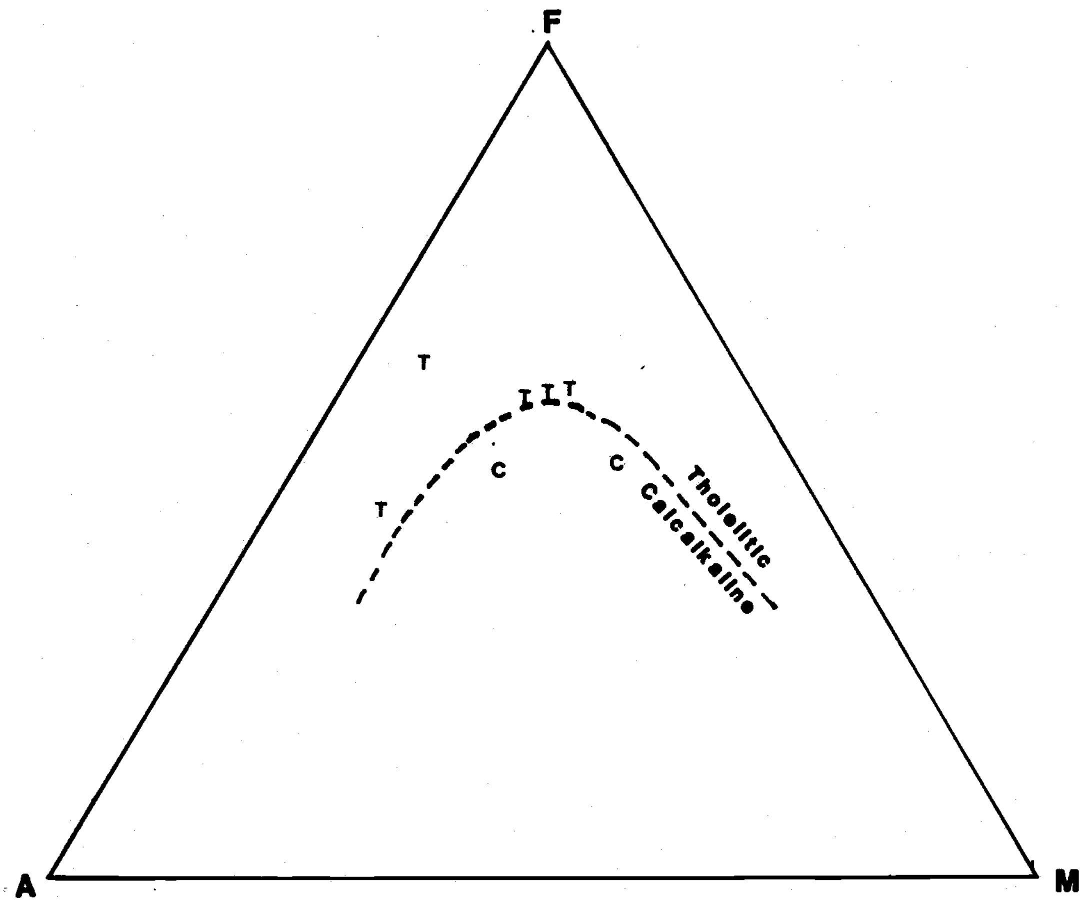


Figure 17. AFM (total alkalies-total iron-total magnesium) diagram of Irvine and Barager (1971) showing that the Eocene Tillamook basalts (T) are tholeiitic whereas the Eocene Cole Mountain basalts (C) plot as calcalkaline.

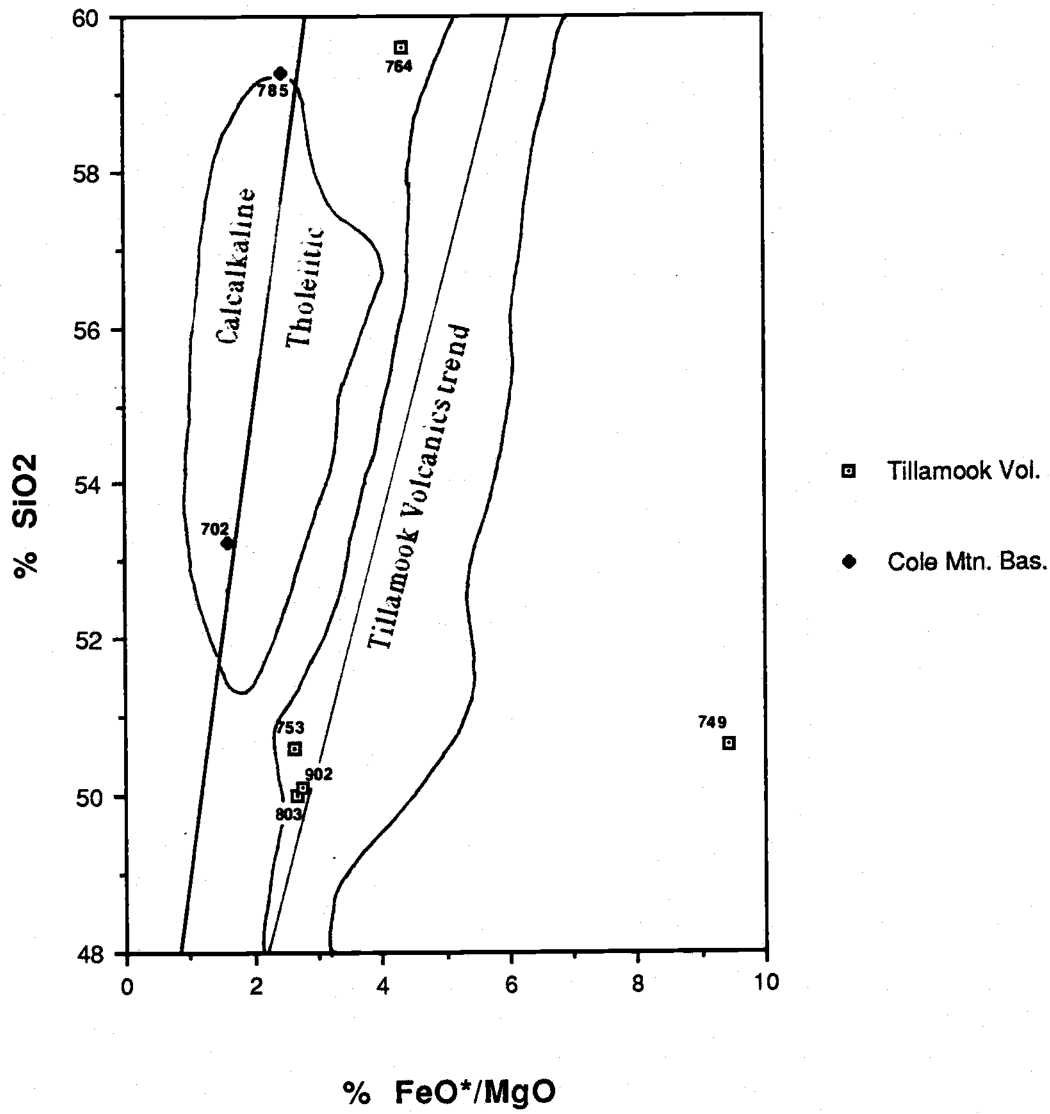


Figure 18. "Iron-enrichment" plot of Miyashiro (1974), also showing Tillamook Volcanics to be tholeiitic whereas Cole Mountain basalt falls within the calcalkaline field nearly along the line subdividing calcalkaline from tholeiitic. Fields for Tillamook Volcanics and Cole Mountain basalt slightly modified (smoothed) from Rarey (1986).

all the Tillamooks from the field area are tholeiitic in composition, whereas both Cole Mountain basalt samples follow a more calcalkaline trend. One sample (#749) contained an anomalously high concentration of FeO/MgO (nearly 9.5%). This sample was a plagioclase-phyric cobble in the Roy Creek conglomerate. The high FeO/MgO ratio is suspected to be due to surficial weathering and iron enrichment from alteration of ferromagnesian minerals to iron oxides and iron-rich clays. This sample also contained an unusually high percentage of Al_2O_3 (20.67%), K_2O, and low values of CaO (Table 1), probably a function of leaching of Ca cations from plagioclase grains and concomitant enrichment in immobile aluminum and potassium-rich clays (e.g. illite) and oxides.

Trace Element Comparison

Trace element comparison of the Tillamook Volcanics versus the Cole Mountain basalt have not been done by previous workers (e.g.,Rarey, 1986; Mumford, 1988; Safley, 1989). However, the 5 limited Tillamook basalt samples versus the 2 Cole Mountain basalt samples suggest that Tillamook samples overlap the range of the Cole Mountain samples in Ni, Cr, V, Rb, Pb, La, and Ta (Table 2). Tillamook Volcanic samples are considerably higher than Cole Mountain basalt in Ba, Zr, Sr, Y, Nb, and Ce, and slightly higher in Ga, and Zn, whereas Cole Mountain basalts are comparatively enriched only in Sc and Cu. Whether these trends are regional awaits further analysis.

Table 2. Trace element data determined by X-ray fluorescence of Eocene volcanic rocks and Roy Creek basalt conglomerate clast in thesis area.

Trace Elements (PPM) **Sample**

	[------------Tillamook Volcanics------------]					[-Roy-] Creek cgl	[--Cole Mountain-----] basalt		
Sample #'s	753	764	902	803	706*	Ave.	749	702	785	Ave.
NI	13	5	16	4	8	9.5	6	57	6	32
CR	35	0	10	5	0	12.5	9	74	5	40
SC	25	13	24	26	8	24	28	29	26	28
V	310	46	221	276	5	213	284	238	217	228
BA	277	563	253	221	977	329	535	127	278	203
RB	16	58	21	20	202	29	44	7	25	16
SR	589	437	577	529	85	533	452	373	362	368
ZR	246	477	235	232	568	298	340	153	175	164
Y	39	66	40	37	64	46	54	23	30	27
NB	49.5	99.2	49.2	46.5	106.7	61.1	70.5	13.3	15.9	14.6
GA	25	27	21	26	16	25	32	21	21	21
CU	20	2	37	31	1	23	31	156	124	140
ZN	111	138	114	108	114	118	115	76	89	83
PB	3	9	2	4	8	5	5	4	4	4
LA	26	64	46	14	84	38	60	16	17	17
CE	72	139	80	58	135	87	122	29	42	36
TH	5	9	1	5	12	5	6	2	2	2

* Highly weathered and altered sample not included in average.

TECTONIC SETTING

Chemical discriminant diagrams using major and trace elements between volcanic rocks from differing tectonic environments have become popular since the early 1970's (i.e., Pearce et al., 1975; Pearce and Cann, 1973). The most reliable diagrams are those utilizing wide data bases from unaltered Cenozoic volcanic rocks in established tectonic settings. The MgO-FeO-Al_2O_3 ternary diagram of Pearce et al. (1977) and the TiO_2-MnO*10-P_2O_5*10 diagram of Mullen (1983) were used to establish the tectonic setting of the volcanic rocks in the thesis area (Figure 19). On the diagram of Pearce et al. (1977) (Figure 19a), three out of four samples determined to be Tillamook Volcanics plot within the field for spreading center island, similar to results obtained by Rarey (1986), Mumford (1988), and Safley (1989) for their samples of Tillamook Volcanics. Pearce et al. (1977) intended this diagram to be used only for non-alkaline rocks. Therefore, only tholeiitic rocks as defined by MacDonald and Katsura (1964) and which have SiO_2 values from 51 to 56% should be considered. However, Pearce et al. (1977) found that they can extend the SiO_2 range from 50 to 60 wt.% using the same diagram with some success. Therefore, I also plotted two samples which have higher silica values (59%).

Although Pearce et al. (1977) compiled over 8,000 sample analyses to define the fields in this diagram, the spreading center field was constructed based on limited number of analyses from volcanic rocks from Iceland and the Galapagos Islands. However, the spreading center island field is significant, because only a few analyses from ocean floor and island plotted in the field for spreading center island. Therefore, Tillamook basalts geochemically resemble those tholeiites from Iceland or the Galapagos Islands, rather than normal oceanic islands (i.e., Hawaii) or oceanic crust. Cole Mountain basalt analyses plot in the orogenic field on this diagram, which is defined by

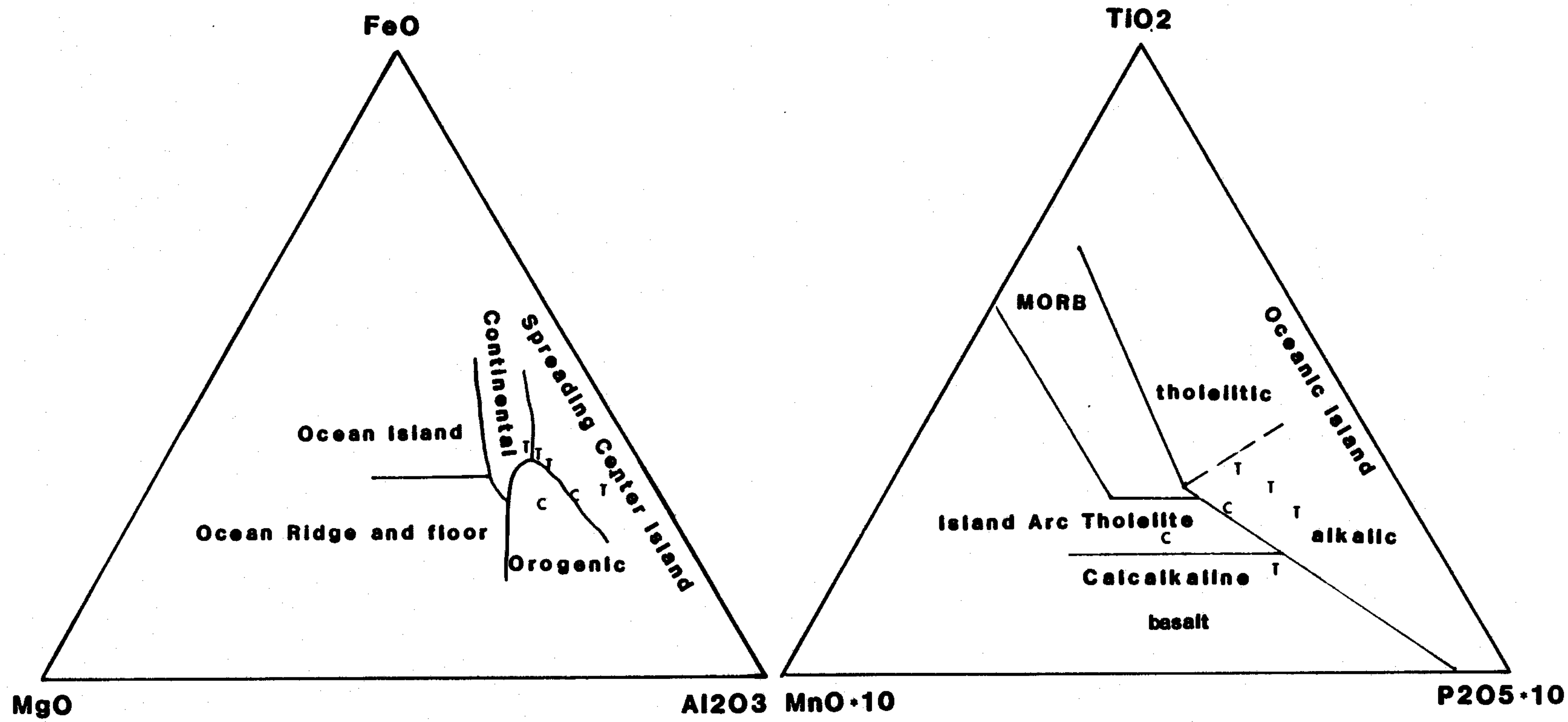


Figure 19. A. After Pearce et al. (1977). Most Tillamook Volcanics (T) plot within Spreading Center Island, and Cole Mountain basalt (C) plot within or near the Orogenic field. B. After Mullen (1983). Tillamook Volcanics (T) plot as Alkalic Oceanic Island basalts, whereas Cole Mountain basalts are Island Arc Tholeiitics and/or Alkalic.

Pearce et al. (1977) from rocks from the Cascade Arc and subduction-related active continental margins.

Three of four analyses of Tillamook Volcanics from the thesis area plot in the oceanic island field on the MnO-TiO_2-P_2O_5 diagram of Mullen (1983) (Figure 19b), whereas the two Cole Mountain basalt analyses plot in or near the island arc tholeiite field. This diagram is for oceanic basaltic rocks with 45% to 54% SiO2; however, all unaltered samples were considered in this study. The island arc field was constructed by Mullen (1983) incorporating volcanic arc rocks from the Cascade Range. Therefore, this diagram also shows that Tillamook Volcanics have closer affinities to oceanic islands, when contrasted to the "Cascade-like" Cole Mountain basalt. Mumford (1988), following the method of Christiansen and Lipman (1972), used a plot of CaO/Na_2O + K_2O versus SiO_2 ratio to show that Cole Mountain basalt samples have a higher calc-alkali index (63) compared with Tillamooks which have a calc-alkali index of 55 1/2. This index is similar to Peacocks (1931) alkali/lime index and is defined as the value of SiO_2 where the curve intercepts at a ratio of 1.0 (Petro, 1979). Mumford (1988) found that Tillamook samples define a suite within the field for a extensional tectonic setting (50-56) as defined by Christiansen and Lipman (1972) and Petro et al. (1979), whereas the Cole Mountain basalt is shown to have been erupted in a compressional setting (calc/alkali index of 60-64). In addition, Jackson (1983) showed that Tillamook Volcanics are enriched in the light rare earth elements (LREE) and have La/Yb ratios typical for alkali basalts such as lava from Iceland. In comparison, Cole Mountain basalt has "primitive" chemistries (low abundances of rare earth elements: Table 2) comparable with those of early western Cascade volcanism (Mumford. 1988). In summary, both major element discriminant diagrams used in this study and many lines of evidence gathered from several workers show that the Tillamook Volcanics have similar geochemical affinities with basalts formed in extensional oceanic spreading center island tectonic settings, while Cole Mountain basalts are geochemically and petrogenetically similar to volcanic rocks formed in compressional island arc tectonic settings. Thus, the Cole Mountain basalt and Tillamook Volcanics were generated and extruded in significantly different tectonic regimes.

On the basis of major element variations, distribution, thickness, and facies relationships, Snavely (1987) considered the Tillamook Volcanics to represent in-situ eruption of an oceanic island close to a terrestrial source on top of an older accreted portion of tholeiitic seafloor (Siletz River Volcanics). Mumford (1988) compared the dimensions of the "Tillamook island" to modern oceanic islands and suggested that the moderately large size (5000 sq km) may signify several coalesced shield volcanos formed over local eruptive centers. The middle to upper Eocene Tillamook volcanics were erupted in a complex forearc setting during Kula and Farallon plate and ridge reorganizations, involving a westward shift of the subduction zone, and westward migration of the arc front from the Eocene Challis-Clarno position in eastern Oregon and Idaho to its western Cascade position at about 42 ma (Mumford, 1988; Wells and et al., 1984). In contrast, Cole Mountain basalt and its Goble Volcanics equivalent (Burr, 1978) was emplaced in the latest Eocene forearc to arc region of the newly developing western Cascade calcalkaline arc (Rarey, 1986, Mumford, 1988).

SEDIMENTARY UNITS (Except Cowlitz Formation)

HAMLET FORMATION

Nomenclature

In northwest Oregon the stratigraphic nomenclature is currently being redefined, and this study is a continuation of that revision. This has partly been the result of the discovery of gas at Mist and the associated subsurface information but is also due to a better understanding of stratigraphic relationships, age control, and facies changes of units from surface mapping (i.e., Niem and Niem, 1985; Wells, 1989; mapping in progress). Rarey (1986), Mumford (1988), Safley (1989), and Niem and Niem (1985) proposed the name Hamlet formation for a thick (200m to 900m) marine sequence of late Narizian mudstones, siltstones, sandstones and basal basaltic conglomerates in the Nehalem River basin of northwest Oregon. In Clatsop County those rocks have previously been mapped as undifferentiated Tertiary sedimentary rocks (Warren et al., 1945; Wells and Peck, 1961) and as Eocene volcanic rocks (Beaulieu, 1973) correlative with the Cowlitz Formation in Columbia County. In Columbia County and this thesis area, these strata have previously been mapped as undifferentiated marine sedimentary rocks (Wells and Peck, 1961), as Cowlitz Formation (Warren and Norbisrath, 1946; Van Atta, 1971; Newton and Van Atta, 1976; Jackson, 1983; Wells et al., 1983, Timmons, 1981; Shaw, 1986), or as the Nehalem and Rocky Point formations in Rock Creek (Deacon, 1953). In previous nomenclature of Warren and Norbisrath (1946) in the upper Nehalem River Basin (includes my area), the Cowlitz Formation was comprised of a basal conglomerate, a lower shale, an upper sandstone, and an upper shale. The Hamlet formation separates the basal conglomerate, lower mudstone, and a lower sandstone from the upper sandstone and mudstone, and breaks them out as members of this new formation. The distribution of the Hamlet formation on the surface and in the subsurface in Clatsop County is shown by Niem and Niem (1985) and Martin et al. (1985).

The reasons for naming and describing this sequence of rocks in Clatsop County as the Hamlet formation, rather than the Yamhill Formation or Cowlitz Formation, has been discussed in detail by Rarey (1986), Mumford (1988), and Safley (1989). However, for the purpose of substantiating the nomenclature used in this study, the use of Hamlet nomenclature will be briefly reiterated here. Within my thesis area, which is directly adjacent to Hamlet rocks mapped and described in Clatsop County (Safley, 1989; Niem and Niem, 1986), Hamlet lithologic assemblages have been identified. Therefore, and for the reasons outlined below, I propose to extend the Hamlet formation nomenclature used in Clatsop and Tillamook counties into Columbia County.

The Cowlitz Formation was proposed by Weaver (1912) for a 60 m section of Eocene (Narizian) sandstones and minor siltstones and coals in southwest Washington ("Big Bend locality"). He subsequently expanded the definition to include a 1,300 m thick, late Narizian, predominantly sandstone section along Olequa Creek in southwest Washington (Weaver, 1937). Subsequently, the Cowlitz Formation nomenclature has undergone many significant changes over the past 70 years. For a more detailed discussion of Cowlitz nomenclature problems, readers are referred to the section in the thesis, Cowlitz Formation. In 1981, Wells (1981) restricted the Cowlitz Formation in the Willapa Hills of southwest Washington to a sequence of upper Narizian sandstones (essentially the Olequa Creek section of Weaver, 1912). In addition, Bruer et al. (1984) restricted the Cowlitz Formation in the subsurface at Mist to the Clark and Wilson (C & W) sandstone and overlying late Narizian mudstone. These important restrictions make the Cowlitz in northwest Oregon similar to the sandstone-rich section in southwest Washington as originally defined by Weaver (1937).

In their subsurface cross section, Bruer et al. (1984) show that there is a regional unconformity at the base of the Cowlitz Formation (sandstone member). In addition, surface exposures, well logs, and cores from the Mist Gas Field (this study) also show an abrupt change from deep-water mudstones (Hamlet formation) to deltaic, shallow-marine sandstones. Thus, there is some evidence for an unconformity at the base of the sandstone. According to the Code of Stratigraphic Nomenclature (1983), a formation should not have an unconformity in it. Hamlet nomenclature simplifies use of the term Cowlitz Formation to refer to those mappable, friable, arkosic and micaceous sandstones (and upper mudstone member) which crop out in southwest Columbia County and are the reservoir rock in the Mist Gas Field. For those reasons, the term Hamlet formation is a logical departure from the old, broader definition of the Cowlitz Formation of Warren and Norbisrath (1946) and Newton and Van Atta (1976) in Columbia County and use of the Cowlitz Formation has been rejected for those predominatly mudstone-rich rocks in the Clatsop and Columbia county (this study) surface.

Bruer et al., (1984) have included the siltstones, conglomerates, and sandstones which occur below the C & W sandstone in the Mist Field in the Yamhill Formation rather than in the Cowlitz Formation. However, the term "Yamhill Formation" has been rejected for these upper Narizian rocks exposed in Clatsop and Columbia Counties for the following reasons. The type section of the Yamhill is located along Mill Creek further south in the central Oregon Coast Range, and the strata contain older Ulatisian to "upper" Narizian Foraminifera (Gaston, 1974). Data from this study, Rarey (1986), Mumford (1988), and Safley (1989), show that the microfauna in the Hamlet mudstones ("shale" member of Warren and Norbisrath, 1946) is different and younger than the microfauna in the type Yamhill Formation, which is lower Narizian (McKeel, pers. comm., 1987). Furthermore, micropaleontologic evidence is mounting (McKeel, 1988, pers. comm.), that the strata between the Tillamook Volcanics and the C & W sandstone in the Mist field should be also be called Hamlet formation, rather than the older Yamhill. In addition, southwest of the field area, Wells et al. (1983) have restricted the Yamhill Formation to mudstones which overlie the Siletz River Volcanics and underlie the Tillamook Volcanics. In the field area, Hamlet rocks only overlie Tillamook Volcanics.

Therefore, the cross section of Bruer et al. (1984) has introduced misleading nomenclature into the stratigraphy of northwest Oregon. Bruer et al. (1984) were apparently influenced by several workers in the Tualatin Valley region and near the type Yamhill section (e.g., Al Azzaby, 1980; Schlicker and Deacon, 1967) who mapped lower Narizian Yamhill Formation on top of "Tillamook Volcanics" and below the upper Narizian Spencer Formation. However, Rarey (1986) pointed out that the "Tillamook Volcanics" near the type section of the Yamhill (near Gaston) are lithologically and chemically identical to nearby outcrops of Siletz River Volcanics and lower Narizian basalt sills (i.e., they contain olivine, abundant zeolites and pillows). They are, therefore, the older Siletz River Volcanics and not correlative to the thick younger (late Narizian) sequence of subaerial flows mapped as Tillamook Volcanics in the Tillamook Highlands. The situation in the Tualatin Valley, however, is not as clear. This area and the region around the Tillamook Highlands are currently being mapped by Ray Wells of the USGS and T. Popowski of Oregon State University who will hopefully solve the apparent stratigraphic nomenclature problem of the Yamhill Formation.

The major advantage of using the Yamhill nomenclature for the Mist subsurface is that it tends to simplify subsurface correlations between the Willamette Valley and the Nehalem River Basin (e.g. Bruer's cross section). Also, where the Tillamook Volcanics are absent or interfinger with Narizian sedimentary rocks it is difficult to distinguish Hamlet mudstones from Yamhill mudstones. This situation occurs in a few wells in the Mist field (Dahleen, 1987; pers. comm.) and also in scattered localities in the Tillamook Highlands (Wells, 1989; pers. comm.). Perhaps micropaleontologic evidence would help to distinguish these units in those cases. It is apparent that further work (including acquiring additional drill hole data) in the Tualatin and Willamette valleys needs to be undertaken in order to effectively correlate and delineate Yamhill stratigraphy between the Nehalem River Basin and the Willamette Valley.

Disadvantages of including the basal conglomerate and "shale" members of Warren and Norbisrath (1946) in the Yamhill Formation are numerous: 1) strata younger than the type section would be added to the formation (i.e., the formation would have new members); 2) lithologies, depositional environments, and faunas not represented in the type section would be added to the formation; 3) the Yamhill Formation would overlie and underlie a 3,000 m thick sequence of subaerial and subaqueous basalts and cross a significant regional unconformity at the top of the volcanic sequence (Wells et al, 1983, this study). This unconformity covers an area many hundreds of square kilometers in Clatsop, Tillamook, Washington and Columbia counties. 4) The Yamhill would both overlie and be laterally equivalent to lithologically similar mudstones in the upper Narizian Nestucca Formation which has been mapped by Snavely and Vokes (1949) and Snavely et al. (1969, 1970) in the Newport and Tillamook embayments as overlying the Yamhill (Rarey, 1986).

The Hamlet is laterally correlative to the Nestucca Formation mapped in Tillamook County (Wells et al., 1983). While the Nestucca mudstone does have some lithologic similarities to the Hamlet, it has some important differences (i.e., the Nestucca mudstone tends to be distinctly bedded with light colored tuff layers (Snavely and Vokes, 1949)). This led Wells (pers. comm. 1989), who is currently mapping in this area for the U.S.Geological Survey, to conclude that these upper Eocene rocks should not be called Nestucca Formation.

Another less appealing nomenclatural alternative is calling the mudstones and interbedded silty sandstones that crop out in the field area, the Spencer Formation. Spencer Formation is mapped to the south of the field area in the Willamette Valley and upper Tualatin Valley and is laterally correlative to the Cowlitz sandstones of southwest Washington (Figure 5). In addition, the depositional environments and age of the mudstone in the upper Spencer are similar to Hamlet mudstones described in Clatsop County and this study (Baker, 1988). However, important lithologic and stratigraphic differences exist. The mudstones of the Spencer occur in the upper part of the unit and grade eastward and upward in the subsurface into tuffs and flows of the eastern Willamette volcanic facies (Baker, 1988). Spencer rocks thicken basinward (Willamette and Tualatin) to the south and east, in contrast with the mudstones of the Hamlet, which makeup part of the thick section filling the Astoria basin to the west. Thus, while the Spencer is partly correlative to the Hamlet, it is not part of the same depositional province. Also, most of the Spencer Formation is a shallow-marine sandstone-dominated unit, whereas the Hamlet formation is dominated by mudstone (Rarey, 1986; Mumford, 1988; this study). It is possible that the ancestral western Oregon Coast was segmented in late Eocene time (Baker, 1988; Schlicker and Deacon, 1967).

Distribution

The Hamlet formation has been divided into three mappable members to aid in depositional and structural interpretations of the unit (Rarey, 1986; Niem and Niem, 1985). In the study area, the basal Roy Creek member consists of 0-30 m of basaltic sandstone and conglomerate (Figure 20). To the west in Clatsop County, the unit appears to thicken markedly, where it has a maximum thickness of 125 m (Rarey, 1986; Mumford, 1988; Safley; 1989); (unit Tc_1 of Nelson; 1985; Olbinski, 1983). Overlying

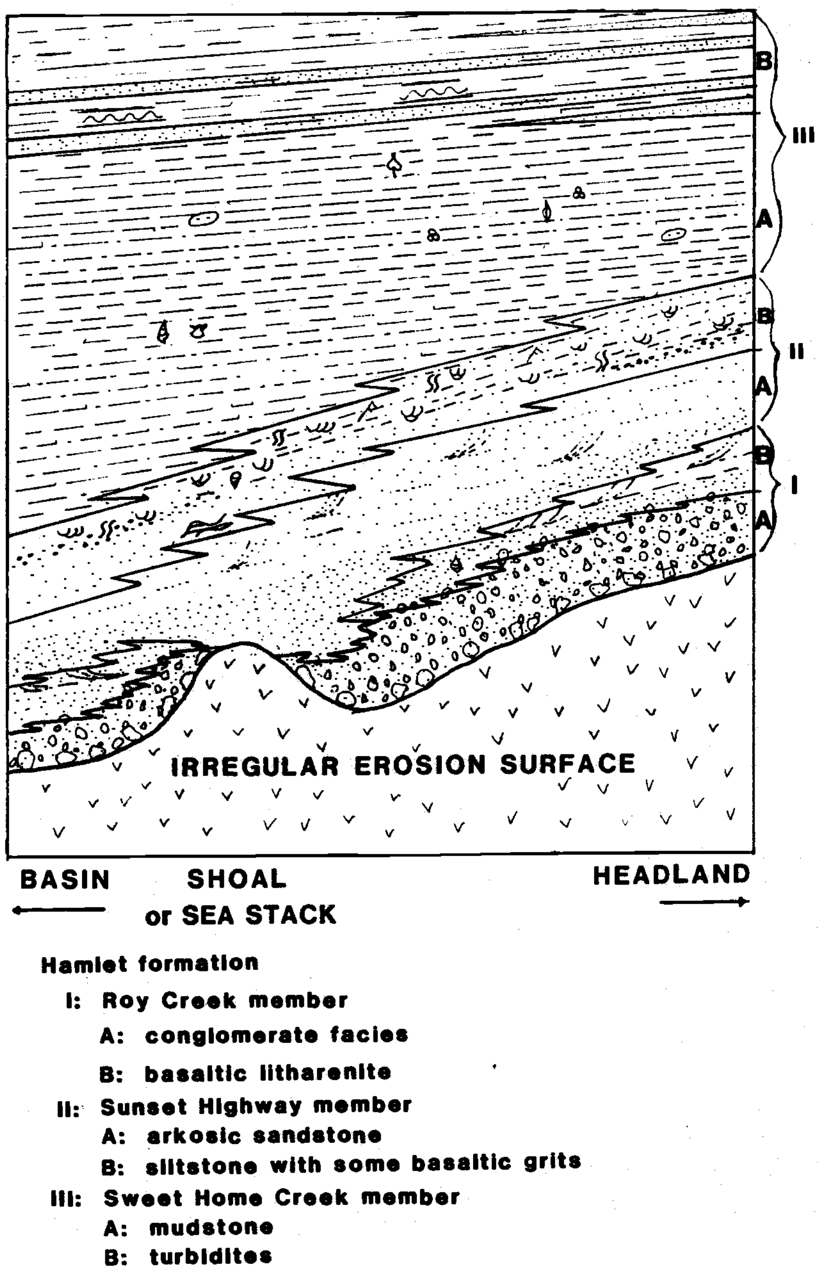


Figure 20. Hamlet formation stratigraphy and model for deposition. Modified from Miller and Orr, 1988.

this unit are the Sunset Highway and overlying Sweet Home Creek members (Rarey, 1986). The Sunset Highway member consists of interbedded basaltic and arkosic sandstones and siltstones whereas the Sweet Home Creek member is dominated by mudstone with minor thin-bedded turbidite sandstones (Figure 20). All three members crop out in the thesis area, although they are thinner and poorly exposed in Columbia County. Figure 6 compares the mapped stratigraphy of the Hamlet formation between Clatsop and Columbia counties. The Hamlet formation crops out in an arcuate pattern around the Tillamook Volcanics in northern Tillamook, southern and eastern Clatsop, southern Columbia, and northern Washington counties (Figure 7). The type locality is near the town of Hamlet in Rarey's field area, where good exposures of the unit occur on several unnamed logging roads (N 1/2 sec. 16, T4N, R8W) and along Sweet Home Creek.

The type section of the Roy Creek member is located near Roy Creek in a Southern Pacific Railroad cut in Tillamook County (Rarey, 1986). The base of the member is defined as the top of the Tillamook Volcanics; the upper boundary is the point where basaltic sandstones or basalt conglomerates no longer dominate the section. Within the thesis area the Roy Creek member is overlain by interbedded arkosic and basaltic sandstones and siltstones of the Sunset Highway member. The proposed type section of the Sunset Highway member (Mumford, 1988; Safley, 1989) is along Sunset Highway, 2 km east of Elsie, where it overlies and interfingers with mudstones and turbidites of the Sweet Home Creek member. Small but fresh exposures of the Sweet Home Creek member along Sweet Home Creek in Clatsop County are designated as the proposed type section (Rarey, 1986).

Within the thesis area the best exposures of the Roy Creek member occur in Rock Creek in two localities around the periphery of the Green Mountain outlier of Tillamook Volcanics in the center of the area: (Rock Creek measured section at 6-16 m and locality

161) . Other small discontinuous exposures of the Roy Creek member occur in section 18 along the jeep trail traversing the Tillamook Volcanic high (localities 105 and 106), near borrow pit quarry (locality 45) and north of the Rock Creek mainline in section 6 (locality 130). Perhaps the best exposure of the conglomerate and lower contact is 0.2 km east of the thesis area at Rocky Point in Leonard Farr's (1989) field area. Here the contact with the underlying Tillamook Volcanics is well exposed along a Columbia mainline roadcut. The Roy Creek conglomerate member is generally erosionally resistant, well-indurated and calcite cemented.

The Sunset Highway member is poorly exposed in the field area but scattered exposures occur in fresh roadcuts, ditches and stream beds. Weathered Sunset Highway sandstones are discontinuously exposed along the jeep trail traversing the Tillamook Volcanic high on the south (localities 107 and108), west of the quarries at Rocky Point (localities 87 and 88), in Rock Creek (locality 162), and along the Rock Creek mainline (localities 50, 128, and 129). Other exposures of the Sunset Highway member occur along the Eastside Grade (locality 103 and 77) and an isolated down-faulted block surrounded by Tillamook Volcanics (locality 115; Plate I). From limited outcrop data in the thesis area, the Sunset Highway member averages about 30 m in thickness. Sunset Highway member distribution is limited to western Columbia, northern Tillamook, and eastern Clatsop County (Mumford, 1988).

The Sweet Home Creek member is exposed in several localities in the field area, although due to its weathered lithologic character, it commonly forms low forested hills and valleys with thick soils. The freshest exposures are located in Rock Creek near Keasey (Plate I) and in a recent roadcut near Rocky Point (localities 25 and 26). Weathered exposures are common along logging road cuts in the center of the field area near the Eastside Grade (localities 112, and 113). Incomplete exposures and moderately complex faulting make it difficult to determine the thickness of the Sweet Home Creek mudstones. In the Banzer 34-16 well to the north of the field area in the south part of the Mist field, the equivalent (?) age Eocene mudstone unit is about 500 m thick. Within the thesis area, approximate thicknesses estimated by outcrop pattern and strikes and dips range from 130 to 300 m.

Age and Correlation

The Hamlet formation is late middle Eocene to late Eocene (late Narizian) in age, based on fossil control and regional correlation (Niem and Niem, 1985). Foraminifera collected from mudstones of the Sweet Home Creek member in the study area were assigned to the middle to late Narizian stage by Dan McKeel (1988, writ. comm.). Rarey (1986) and Mumford (1988) collected a number of age diagnostic foraminiferal and calcareous nannofossil assemblages from the Sweet Home Creek member to the west of the thesis area in Clatsop County. All foraminiferal assemblages from Rarey's area were assigned to the late Narizian, although McDougall (Mumford, 1988) assigned Foraminifera from Mumford's area to the late Narizian to early Refugian stages. These stages are late middle to late Eocene in age (Figure 5). Coccoliths from the lower to middle part of the Sweet Home Creek member were assigned to subzone CP-14a or 14b, which is correlative to the late Narizian foraminiferal stage (Rarey, 1986; Niem and Niem, 1985). The uppermost part of the Tillamook Volcanics may be as young as 40 to 42 m.y. (late Narizian) based on radiometric age dating by Kris McElwee (pers. comm., 1989). Thus, the Hamlet formation is age bracketed between the overlying Keasey (Refugian) strata and the underlying late Eocene Tillamook Volcanics, which further demonstrates a late Narizian age for the Hamlet formation.

The Roy Creek member is correlative to the conglomerate member of the upper Narizian Cowlitz Formation of Warren and Norbisrath (1946). Molluscan fossils collected from the Roy Creek member by Mumford (1988) are not age diagnostic but are correlative with the middle Eocene Cowlitz-Coaledo fauna (Moore, pers. comm.; *in* Mumford, 1988). Wells and others (1983) on their compilation map show similar widespread unnamed upper Eocene basaltic sandstones and conglomerates overlying the Tillamook Volcanics and underlying Refugian mudstones southwest of the thesis area which can be considered equivalent to the Roy Creek member, substantiating that this is probably a middle to late Eocene unit.

Based on lithology and stratigraphic position, the Sunset Highway member is equivalent to the "heterolithic facies" of Jackson (1983) in the Wolf Creek measured section in Tillamook County, Shaw's (1986) Sunset Camp section in Washington County, Tc_2 of Olbinski (1983) and Nelson (1985) in Clatsop County, and the "shale member" of the Cowlitz Formation of Warren and Norbisrath (1946) and of Van Atta, (1971) in the upper Nehalem River basin of Columbia County. Evidently, these Sunset Highway member lithologies were recognized and studied in some detail in northwest Oregon, but these authors had utilized the older Cowlitz Formation nomenclature.

The Hamlet formation can be placed into a regional correlation framework based on stratigraphic position and age restrictions indicated by foraminiferal and calcareous nannofossil assemblages of the Sweet Home Creek member. The following units are in part age equivalent: the Nestucca Formation and the Spencer Formation in northwest and central-west Oregon, the Coaledo Formation of southwest Oregon, and the Cowlitz Formation of southwest Washington. The upper Sweet Home Creek mudstone of Clatsop County is time equivalent with the Cowlitz sandstone of northwest Oregon in Columbia County (Niem and Niem, 1985). Mumford (1988) and Rarey (1986) showed that type area Yamhill strata contain additional fauna that were assigned to the lower or middle part of the Narizian stage and therefore are older and distinct from the "Cowlitz" fauna.

Roy Creek Member

Lithology

In the thesis area the basal Roy Creek Member (Thr) of the Hamlet formation consists of basaltic and basaltic andesite boulder to pebble conglomerate, coarse-grained to pebbly basaltic sandstone, and subordinate fine-grained, well indurated basaltic sandstone (Plate I). The unit generally represents a fining-upward marine sequence which unconformably overlies Tillamook Volcanics. The basal conglomerate is generally massive with poor stratification and no imbrication of clasts. Boulders and cobbles of Tillamook Volcanics in the unit range in size from 15 to 150 cm diameter. The largest clasts (150 cm) were observed at Rocky Point (Figure 21), below the Rocky Point quarry. The very large size of these basalt clasts suggests minor transport and close proximity to the source, which is interpreted as sea stacks or headlands of Tillamook basalt (see: depositional environment) from the adjacent Green mountain outlier and the Tillamook highlands.

Roy Creek conglomerate varies from 2 to 15 m thickness in Columbia County but thickens dramatically to the west in Clatsop and Tillamook counties (Rarey, 1986; Mumford, 1988; Safley, 1989). Jackson (1983) measured 30 m of cobble to boulder conglomerate in Washington County, Rarey reported up to 100 m of interstratified cobble to boulder conglomerate and pebbly basaltic sandstone at the type section in Tillamook County, and Warren and Norbisrath (1946) estimated the thickness of the "basal conglomerate" as more than 200 feet, at a location three miles west of Timber. My study and that of Farr (1989) show that the Roy Creek member is not ubiquitous over the Tillamook Volcanics in Columbia County, although it has a regional sheet-like geometry around the periphery of the Tillamook Highlands (Niem and Niem, 1985; Wells, 1989;

Figure 21. Exposure of basal Roy Creek basalt conglomerate member. Note massive structure and very large size of some clasts. Also note overlying medium-grained basaltic sandstone. Locality: Rocky Point, below Rocky Point quarry.

pers.comm.). In addition, a few mudlogs from deeper wells drilled in the Mist Gas Field report encountering Tillamook basalt without any intervening conglomerate (Jackson, pers. comm., 1989). Sunset Highway arkosic sandstones have been observed within 30 m of the nearest outcrop of Tillamook Volcanics with no conglomerate or basaltic sandstone of the Roy Creek member in between (Plate I; Figure 5). However, this may be an artifact of poor exposure and/or faulting. Obviously, the thickness of the conglomerate is variable, and the pinch and swell characteristics of the unit are consistent with the interpreted rocky shoreline or pocket beach between headlands depositional environment (see that section).

The conglomerate usually occurs at the base of the Roy Creek member and consists of clast-supported, rounded to subrounded, moderately sorted boulders and cobbles of aphyric to plagioclase and augite micro-phyric basalt and basaltic andesite. Lesser amounts of vesicular and amygdaloidal (scoriaceous) basalt also occur. Clasts are dense dark-grey (N3), weathering to dark yellowish -brown (10 YR 4/2), and are in framework support in a basaltic sand-silt matrix. Light grey to buff flow banded clasts form about 10% of the clasts and probably indicate a more silicic source. Nelson (1985) and Olbinski (1983) reported more silicic compositions (up to 70% silica) of some conglomerate clasts from the "Green Mountain outlier" 3 to 12 km to the west of my area. Olbinski (1983) and Safley (1989), also in the Green Mountain area, noted abundant vesicular clasts (up to 20%).

A coarse-grained to pebbly basaltic sandstone overlies and interfingers with the conglomerate. In places (locality 161; Rock Creek), this pebbly sandstone has been observed directly overlying Tillamook basalt. The resistant sandstone is very well indurated, poorly sorted, and "dirty" olive-grey (5Y 3/2). Pebbles, in both matrix and clast suppprt, are well rounded and up to 0.7 cm diameter. Along the stream-cut bank (locality 161), a faint stratification can be observed on a natural "shelf", and one thin section shows a slight elongation and alignment of larger basalt clasts. The lithic sandstone and conglomerate of the Roy Creek member are locally fossiliferous (e.g., Rock Creek) consisting of numerous abraded oyster and mollusc shells. The disarticulated nature of the wave abraded and broken fossils inhibited recovery of whole specimens for positive identification. Rarey (1986) reported one unbroken shallow-marine Gastropod *Scurria* from his area and Mumford (1988) and Safley (1889) were able to recover the gastropods *Crepidula* and *Calyptreae*, and pelecypods *Brachidontes* and *Macrocallista* from the conglomerate in their field areas to the west. These fossils are characteristic of rocky, high energy, shallow-marine environments (Ellen Moore, 1988; pers. comm.). In addition, Farr (1989) collected a few molluscan fossils in medium-grained basaltic sandstone directly above the conglomerate at Rocky Point (Figure 21), and Van Atta (1971) described crab carapaces from the conglomerate in the upper Nehalem River Basin from the Rocky Point quarry.

Abundant 1 cm diameter tubular vertical burrows were found (locality 161) in the pebbly sandstone. According to Chamberlain (1989, writ. comm.):

> "these burrows have striations (scratch marks), meniscate back-fill, are in one piece (with striae), have a cone-in-cone on the outer wall with shale layering; also have shale slippage striae (micro-slickensides). These were probably produced by burrowing crustaceans."

Chamberlain also notes that they compare favorably with *Thalassinoides*, which is common in the lower to middle shoreface depositional environment.

A fine- to medium-grained, tightly cemented medium-grey (N5) sandstone was found in one locality along the Rock Creek measured section (sample 749), interbedded between the Tillamook Volcanics and the basaltic conglomerate. This outcrop was concretionary (calcareous concretions averaging 10 cm diameter), nonfossiliferous, and contained some paper-thin carbonaceous plant matter along parting planes. One concretion contained an especially well-preserved and coiled vitreous tubular burrow cast (*Thalassinoides*) in its center. Rarey (1986), Safely (1989), and Mumford (1988) reported fine-grained, moderately-sorted basaltic sandstone near the top of the Roy Creek member in their field areas. They also noted that the unit weathered into large ellipsoids that resembled basalt outcrops from a distance. This lithology most closely approximates the outcrop described above from Rock Creek.

Clasts in the conglomerate are lithologically and geochemically nearly identical to lavas of the underlying Tillamook Volcanics (Table 1) (Rarey, 1986), which overwhelmingly points to the Tillamook Volcanics as the primary source for the locally derived conglomerate.

Contact Relations

The Roy Creek member nonconformably overlies the Tillamook Volcanics. This unconformity is evidenced by the fact that nowhere in the field area do the two units interfinger. The contact, when exposed (locality 161; Rock Creek, 809; Rocky Point), is undulose to planar and abrupt (Figure 21). Also, in Rock Creek (locality 161), platy Tillamook Volcanic flows dip northward at 22° while the overlying sandstone dips more gently northward at 18°. Additionally, provenance study shows that the conglomerate represents basal lag deposits from the eroded volcanic pile. Evidently, following Tillamook subaerial eruptions, there was a period of erosion and subsidence, resulting in transgression and deposition of the Hamlet formation on the thick basalt edifice. The upper part of the Roy Creek member grades rather abruptly into arkosic Sunset Highway member sandstone in the thesis area (adjacent to locality 161), and into the Sweet Home Creek mudstone to the west in Clatsop County (Rarey, 1986).

Wells (1989, pers. comm.) has mapped basaltic conglomerate beds interfingering with the Tillamook Volcanics in the Tillamook Highlands to the south and west of the thesis area. However, these older conglomerates are probably local channelized nonmarine interbeds within the Tillamook Volcanics and not the distinctive Roy Creek unit, which contains marine fauna and forms a fairly continuous sheet overlying the volcanic basement.

Petrography and Diagenesis

Three thin sections of Roy Creek strata were examined petrographically. In addition, a basalt clast (749) from the basal conglomerate was analyzed for major and trace element geochemistry by X-ray fluorescence (Tables 1 and 2). One of the thin sections (755) was cut from the basaltic pebbly medium-grained sandstone facies (Figure 22), another from the fine- to medium-grained lithic sandstone near the contact with Tillamook Volcanics (750), and the third was of a basalt clast from the conglomerate (749). The medium-grained samples have a framework composition of 85-95% basaltic rock fragments, 3-8 % plagioclase (labradorite) with carlsbad twinning, 1-2 % potassium feldspar, 3-5% quartz, 1-2 % mica, 2-3 % chlorite, 2-3 % augite, and 5-10 % opaque minerals (mostly magnetite and ilmenite). Pyrite cubes are present in trace amounts in the clay matrix. Basaltic rock fragments consist of 30-50% pilotaxitic fine-grained clasts, 20-30% plagioclase porphyritic pilotaxitic clasts, 5-15% intersertal clasts, and 5-7 % vesicular clasts (Figure 22). The vesicular rock fragments are interpreted to represent scoria fragments, diagenetically altered to chlorite and smectite. Opaque basaltic glass (tachylite) and scoriaceous fragments are present in minor amounts and are indicative of an explosive phreatic eruptive source. Alternatively, these vesicular fragments could

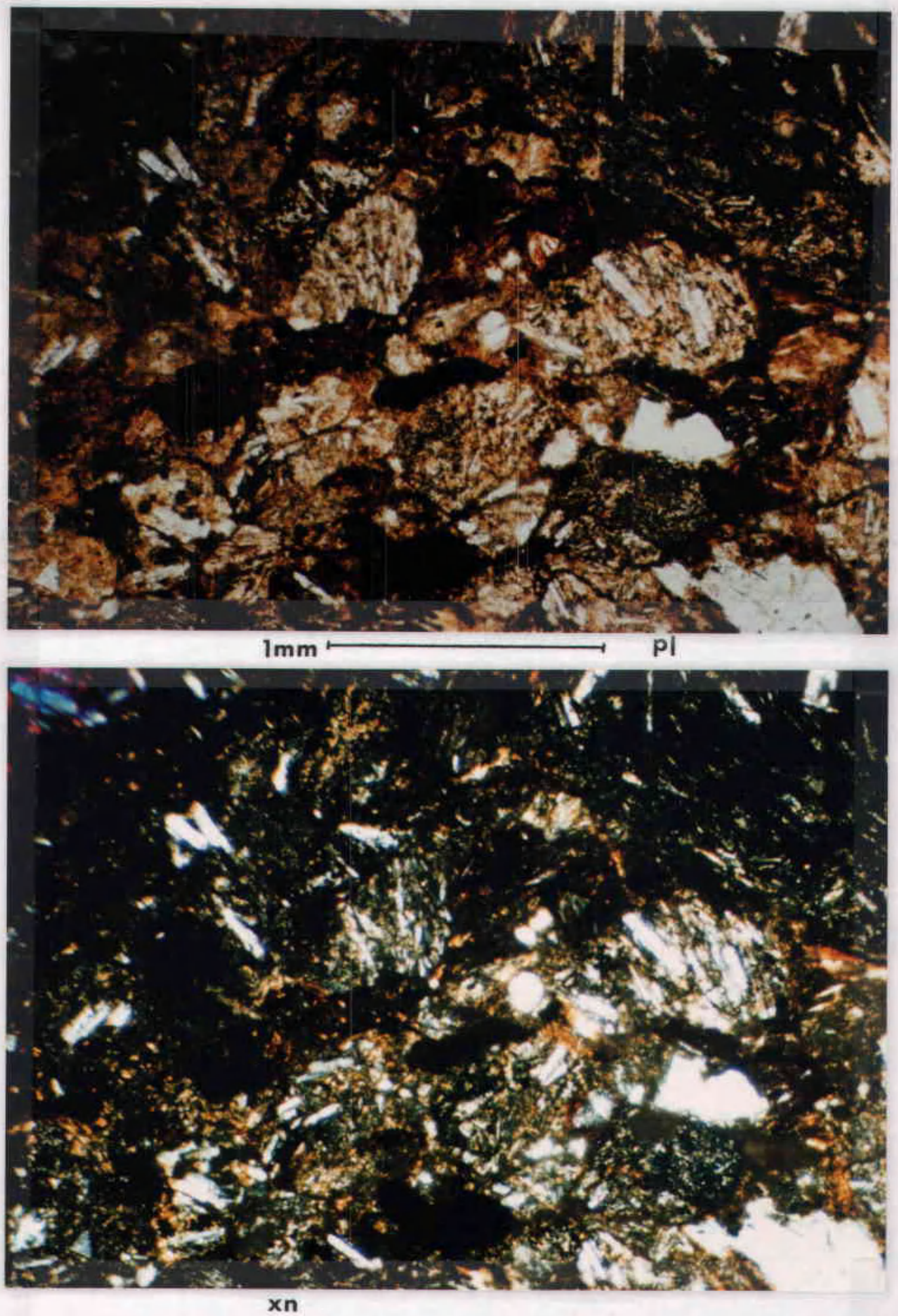


Figure 22. Photomicrograph of pebbly medium-grained basaltic litharenite. Note abundant basaltic rock fragments with pilotaxitic flow texture and extensive clay coats. Sample 755 (locality 161).

represent the frothy glassy tops of lava flows. However, because the Tillamook Volcanics in the Green Mountain area have been shown to have higher silica values (up to 70%; Nelson, 1985; Safley, 1989; Olbinski, 1983; this study), and contain some debris flows, the former hypothesis is preferred. Rarey (1986) and Olbinski (1983) have pointed out the occurrence of eroded remnants of cinder cones in the Tillamook Highlands and Green Mountain outlier, respectively. In addition, no frothy, vesicular flow tops were observed in the field area.

Most larger volcanic grains are subrounded to rounded. However, the smaller feldspar, quartz, and augite grains are typically subangular in the sandstone. Sorting is poor to moderate. Median grain size is fine to medium sand, but the larger grains are coarse-sand to pebble size. The fine-grained sample (750) shows a bimodality between fine-, and lesser medium-grained sand, probably due to sediment mixing by burrowing organisms. There is a slight elongation and alignment of larger grains within one thin section, defining a crude stratification in the outcrop.

Brown clay rims and iron oxide cement comprise 10-15% of the sample. However, due to extreme weathering and diagenetic alteration effects, it is difficult to tell if the clay represents depositional matrix or if it is "pseudo-matrix", a product of post-depositional crushing and subsequent alteration of detrital grains. Because of the tendency of volcanic and plagioclase grains to chemically breakdown and because clay rim cements are in contact with large grains, Roy Creek lithic sandstones probably contain abundant "pseudo-matrix". Therefore, these samples are texturally submature due to the absence of detrital clay matrix, but are compositionally immature because they consist of mostly unstable volcanic rock fragments (Folk, 1974). Roy Creek sandstones thus classify as litharenites according to Folk's 1974 classification diagram (Figure 23) but are more precisely called, basaltic litharenites. This classification scheme ignores the large clay

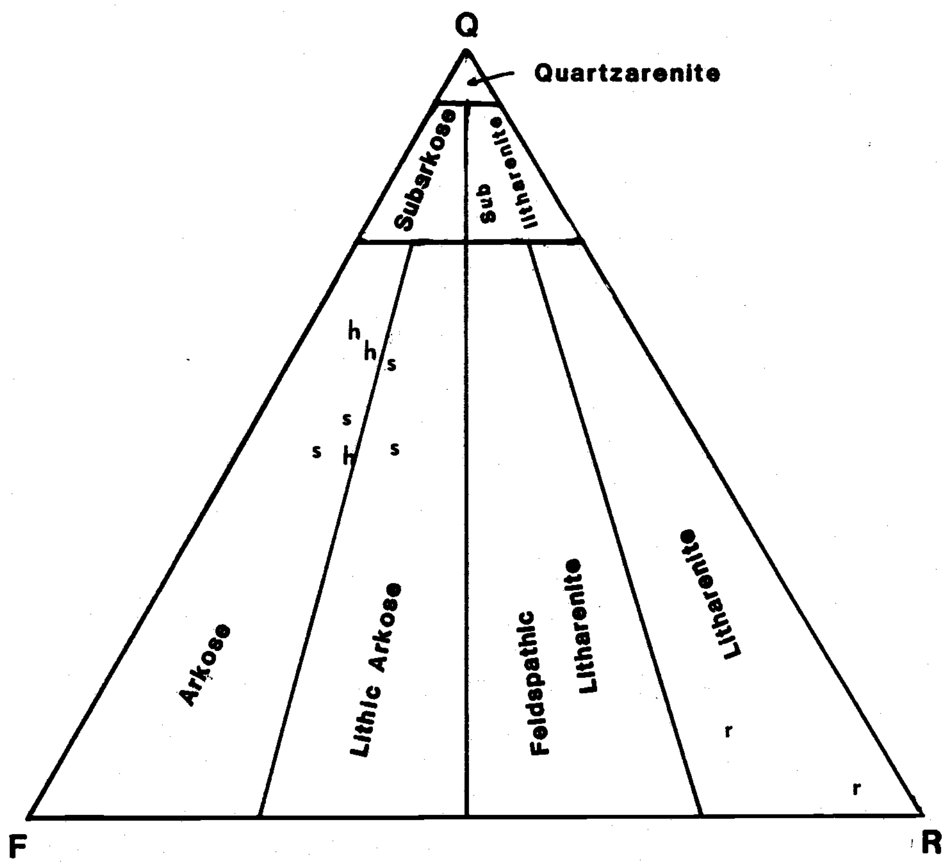


Figure 23. Folk's (1974) ternary classification diagram showing Roy Creek sandstones (r), Sunset Highway sandstones (s), and turbidites from Sweet Home Creek member (h).

fraction in these samples because the clay present is diagenetic and the samples were relatively "clean" at the time of deposition.

Most of the diagenetic features observed in thin sections and SEM photographs of the Roy Creek member are analogous to the Paleocene to Eocene Umpqua Group lithic sandstones of southwest Oregon described by Galloway (1974) and Burns and Ethridge (1977), and readers are referred to Rarey (1986), Mumford (1988), and Safley, 1989) for a further comprehensive and detailed discussion of Roy Creek member diagenesis.

Commonly, intergranular basalt cores have altered to orange-brown smectite clay, and less commonly, chlorite (Figure 22). In addition, all large grains of basalt are rimmed by thin clay coats, which have in turn been stained or oxidized reddish-brown by hematite, limonite, and goethite. Smectite clay also fills intergranular pores as a pervasive cement and imparts an orange tone to the thin section. Mumford (1988) performed SEM and EDX analyses on similar clay from Roy Creek basalt sandstones in his field area in Clatsop County and determined it to be nontronite, an iron-rich smectite. He also discovered from petrographic analysis that this clay occasionally developed radiating crystal habit. This feature was not observed in my samples, however, possibly due to smaller pore size and/or obliteration by weathering effects. Alternatively, the large amounts of earlier formed smectite (nontronite) clay rims may have inhibited growth of radiating chlorite crystals in these samples (Safley, 1989). Some green clasts are amygdules derived from weathered vesicular basalt lava clasts and consist of radiating nontronite clay and/or chlorite. Isotropic brownish material (chlorophaeite) in the groundmass of some basalt grains is probably slightly altered basaltic glass (tachylite; Figure 22). Alteration of basaltic glass to yellow palagonite is present in one thin section.

Sparry calcite cement is less common (5-10 % of sample) and is usually associated with alteration of basaltic rock fragments and plagioclase and also partially fills primary interparticle pores surrounding the larger basaltic grains. Mumford (1988) suggested that the calcite probably resulted from dissolution of soluble aragonite molluscan shell fragments that was subsequently reprecipitated in adjacent intergranular pore spaces (Galloway, 1974). The abundance of fossil fragments in the Roy Creek sandstones supports this origin for some pore-filling calcite. However, sparry calcite also commonly forms from partial grain dissolution by pore waters and mobilization of calcium from volcanic rock fragments and calcic plagioclase to be reprecipitated as less soluble crystals in intergranular pores (Mathison, 1984). In addition, Surdam and Boles (1979) suggest that early diagenetic changes in organic matter are one of the major sources of HCO_3^- and that the distribution of organic matter in sediments is probably the limiting factor for carbonization reactions. The relative amounts of calcite in Roy Creek sandstones, therefore, may indicate that a moderate amount of organic matter was deposited with the sediments. Where present, early calcite cement completely fills pore spaces, preventing signficant compaction and further diagenetic reactions from taking place.

Paragenetic relationships observed in thin section show that calcite cement directly postdated formation of clay rim cements on grain surfaces and typically forms early in the diagenetic sequence of volcaniclastic sandstones (Galloway, 1974). With deeper and later burial, smectite and chlorite were precipitated from pore fluids and alteration of adjacent volcanic clasts in primary intergranular pores. Mumford (1988) reported rare zeolite (clinoptilolite-heulandite) in some pore throats from Roy Creek sandstones which indicates an even later stage of diagenesis (Mathisen, 1984), but this zeolite was not observed in my thin sections . Zeolite, calcite, smectite, and chlorite precipitation probably resulted from the abundance of chemically unstable basaltic and fossil fragments in the lithic sandstones.

Where calcite is not present, some evidence of compaction exists. This is mostly in the form of altered volcanics in tight, tangential grain to grain contacts, but also from some squashed mica flakes, minor pseudomatrix, and ductilly deformed carbonaceous debris. Although compaction accounts for some of the porosity reduction, chemical diagenesis in the form of authigenic chlorite, nontronite clay, and calcite cement almost completely obliterate porosity, resulting in only a trace percentage (<1%). No secondary porosity was observed.

In summary, the main sequence of diagenesis observed for Roy Creek sandstones involve: 1) growth of authigenic clay rims, 2) mechanical crushing, 3) formation of authigenic pore fill calcite cement, and 4) further formation of authigenic smectite and chlorite cements. These observed diagenetic features are compatible with burial depths of 1000 to 1500 m according to Galloway's (1974) depth criteria for similar Tertiary volcaniclastic sandstones in wells from the Pacific Northwest and southeast Alaska. Authigenic clay rims and coats began to form first from glassy volcanic lava fragments at shallow depths up to several hundred meters, along with minor dissolution of plagioclase and volcanic rock fragments shortly after burial. The relict rims and coats preserve the original grain form and suggest that significant authigenic clay had formed before the grains were extensively dissolved. Although mechanical compaction features are observed, the fact that clay rims and coats can still be observed indicates that significant amounts of additional compaction did not occur with depth. With greater depth of burial, probably around 400 to 900 m (Mathison, 1984), pore-filling sparry calcite was precipitated, cementing sandstones that already contained pore-lining clays and some intergranular porosity. Continued dissolution of volcanic fragments and plagioclase occurred during this stage. The growth of chlorite and smectite clay probably reflects even greater depth of burial, and was the last stage of diagenesis before telogenetic oxidation of iron-bearing minerals and basalt rock fragments occurred in the weathering zone by groundwater solution after uplift and erosion of the present Coast Range.

Depositional Environment and Provenance

The basalt conglomerate, with well rounded to subangular clasts, and broken marine pelecypods and gastropods, probably represents high energy, storm-dominated, nearshore to pocket beach gravels derived from sea cliffs or sea stacks analogous to the modern Oregon and Washington basaltic coastlines (Figure 20). Due to its proximal position along a high-energy, active plate margin, the Roy Creek member records the complex interaction between volcanic, tectonic, wave, and tidal processes. This depositional regime is characterized by "pocket beaches" between steep sided rugged basalt headlands. In this environment, one would expect the conglomerate to pinch and swell; boulder conglomerate would flank the headlands, and the sandstone facies would prevail in the intervening beaches and quiet bays.

Although several examples of rocky coast clastic sedimentation have been recognized (Dott, 1974; Kumar and Sanders, 1976; Ruxton, 1970), few studies have treated nearshore depositional processes in these settings in detail. One of the earlier efforts to describe wave-worked gravels was made by Clifton (1973), who distinguished them from stream or river gravels based on sedimentary structures and fossils, utilizing examples from Quaternary terrace deposits along the southern Oregon coast.

The Roy Creek member fining upward sequence is very similar to that described by Miller and Orr (1988), for the Tertiary strata of the Scotts Mills

Formation (Marquam Member) now exposed in the foothills of the western Cascades, northeast of Salem. The Oligocene Marquam Member consists of intrabasinal conglomerate and basaltic sandstone and has been interpreted to have been deposited unconformably upon the Little Butte Volcanics along a storm-dominated rocky coastline (Miller and Orr, 1988, 1986).

The Roy Creek Member contains some very large boulders (up to 125 cm), which are too large to have been transported and rounded in a fluvial setting. It is possible, however, that some of the clastic detritus from the pebble-cobble conglomerate facies could have been carried by rivers during floods or in debris flows (Olbinski, 1983) and discharged into the nearshore marine environment. However, the predominance of a single volcanic rock type in the conglomerate precludes a significant fluvial contribution (e.g., mixing of several volcanic lava sources) for these strata. Harms et al. (1975) pointed out that fluvial gravels typically display large-scale trough cross-laminations, have lenticular geometries, and contain down-current imbrication, none of which is characteristic of conglomerates of the Roy Creek member.

Field mapping from this study and that of Safley (1989) show that the Roy Creek member was deposited on an irregular topography of Tillamook basalt flows and breccias (Figure 20). Regional relief on the basalt is as high as 150 m, with local relief up to 30 m along nearly vertical faces and slopes. This suggests that the Tillamook "islands" formed a steep, rugged terrain shortly before and during Roy Creek deposition. Following the analysis of Dott (1974), based on empirically derived current data and flume experiments, rounded clasts 150 cm in diameter require breaking waves 7 to 8 m high to initiate and maintain movement in littoral settings. Boulders in the Roy Creek conglomerate are partially rounded up to about 80 cm diameter, while the largest boulders (150 cm) are subrounded to subangular.

This implies that waves of at least 5 m pummeled the paleoshoreline, probably during winter storms and/or tsunamis, effectively rounding pebbles and boulders. Volcanic beach sand and and some silt then infiltrated into the beach gravels, constituting the detrital matrix between basaltic pebble-boulder clasts.

The overlying medium- to coarse-grained basaltic sandstones are also interpreted to have been deposited in a wave-dominated, nearshore to inner shelf environment. They are faintly stratified to structureless and contain abundant broken molluscan fauna and *Skolithos* ichnofauna (escape burrows), indicative of high energy nearshore conditions (Chamberlain, writ. comm., 1989). Safley (1989), reported some trough and hummocky micro-ripple cross-stratification in the Roy Creek sandstone facies in the adjacent study area to the west. However, these sedimentary structures were not observed in the thesis area. The fining-upward sequence of conglomerate to coarse- and medium-grained sandstone reflects progressively deeper water and/or lower energy conditions during deposition of the Roy Creek member, which is a characteristic of hummocky cross-stratified sequences (Dott and Bourgeois, 1982). Relative depth changes in nearshore, coarse-grained sequences probably reflect changes in the balance between sediment supply, basin subsidence, and eustatic sea-level changes (Leithold and Bourgeois, 1984). During Roy Creek rocky coast sedimentation, these changes are directly affected by subsidence and erosion of the Tillamook unconformable surface on the basal transgressive facies.

Sunset Highway Member

Lithology

The Sunset Highway member of the upper Narizian Hamlet formation was proposed by Mumford (1988), Rarey (1986), and Safley (1989) for an approximately 50 m thick sequence of micaceous, arkosic and lithic fine-grained sandstones and siltstones, cropping out in Clatsop County and overlying the Roy Creek member and underlying and interfingering with the Sweet Home Creek mudstone member. In Columbia County, this unit is poorly exposed, finer grained, and not as thick (this study; Farr, 1989). Furthermore, identification of the member is complicated by lithologic similarity to the C & W sandstone and difficulty in establishing stratigraphic sequence due to faulting (Plate I). However, there are a few localities (Rocky Point, and locations 161, 27, 108) where arkosic and lithic sandstones of the Sunset Highway member can be observed or inferred to be directly overlying Roy Creek lithic sandstones and conglomerates, and underlying mudstones of the Sweet Home Creek member. During low summer water levels, the Sunset Highway member is also exposed in a small fresh cut along the bed of Rock Creek (locality 161).

In these places, the Sunset Highway member is a very fine- to medium-grained, micaceous, arkosic and lithic sandstone and siltstone. In the field area, most weathered logging roadcut exposures of the unit predominantly consist of sandy siltstone to silty fine-grained sandstone. These lithologies are similar to the overlying Sweet Home Creek mudstones, which demonstrate a gradational lithologic change from sandstone to mudstone. At the type section along the Sunset Highway, 10 km to the southwest, Mumford (1988) and Safley (1989) showed that coarse-grained basaltic sandstones and grit interbeds are more common upsection in the Sunset Highway member. Mumford (1988) interpreted some of these poorly sorted and matrix-supported pebbly sandstones to represent debris flows derived from the underlying Tillamook Volcanics that flowed onto the adjacent shallow-marine shelf. At locality 27, (north of Rocky Point in a tilted fault block), the unit contains intercalated, rounded to subangular basalt pebbles in a faintly laminated, well-cemented, medium- to coarse-sand matrix. These basalt pebbles are lithologically similar to those of the underlying Roy Creek member and thus indicate a proximal Tillamook Volcanic source for these beds. Parallel laminations and faint graded bedding, however, suggest that this outcrop is not a debris flow. Unfortunately, due to local faulting, stratigraphic control within the Sunset Highway member was not established for locality 27 (Farr's area).

In the bed of Rock Creek, basal Sunset Highway sandstones are exposed adjacent to the Roy Creek member (locality 161). Here, the unit consists of well sorted, moderately well indurated, fine-grained, micaceous, arkosic sandstone. At locality 103, along the Eastside Grade, the Sunset Highway member also consists of fine-grained, laminated, friable arkosic sandstone, much like the C & W. This outcrop is along strike with locality 161, and low in the section. Thus, from limited available outcrop data, this study also shows that the lower Sunset Highway member is cleaner and more arkosic than the upper part. However, although coarse basaltic interbeds are locally present, the upper part of the Sunset Highway member is predominantly an arkosic, micaceous siltstone.

Sunset Highway sandstones are sparsely to moderately fossiliferous (molluscan shell fragments). Molluscan fossils identified by Ellen Moore (1988, writ. comm.) include pelecypods, *Acila (Truncacila) decisa* (Conrad) and a gastropod *Scaphander* sp. Mumford (1988) and Safley (1989) reported locally abundant molluscan fossils from the Sunset Highway member in Clatsop County, and Jackson (1983) found molluscan fossils in his equivalent heterolithic facies of the "Cowlitz Formation" in Washington and Tillamook counties, unlike the overlying Cowlitz sandstone.

Bioturbation and burrowing are common and have generally obliterated primary sedimentary structures (Figure 24). The moderately indurated sandstones are medium grey (N3) when freshly exposed in stream cuts, weathering to pale buff or yellow in logging road cuts. These sandstones tend to be more indurated than the ovelying more friable and laminated to cross-bedded Cowlitz sandstones. The muddy siltstones are slightly darker grey (N4) when fresh, but also weather to a pale buff or yellow color (10YR 5/6).

The Sunset Highway member is thinly (1 mm) horizontally laminated to low angle (10°) trough cross-laminated, but may also appear massive (Figure 24). The low-angle cross-bedding (< 5-10°) may represent storm-wave formed hummocky cross-stratification as described by Dott and Bourgeois (1982). However, full-scale hummocks and swales were not observed, so positive identification of hummocky cross-stratification was not possible. Starved ripple laminations were observed (locality 115) in interlaminated very fine- and fine-grained sandstone. Carbonaceous plant matter is fairly abundant, both as comminuted dark black matter along bedding planes and as rare fossil leaves. Sunset Highway member sandstones and siltstones are generally weakly cemented by authigenic clays and iron oxides. The clay-rich character of the sedimentary unit results in rapid weathering, erosion, and poor exposure.

The lower contact of the unit is defined by a relatively abrupt and distinct lithologic change from micaceous arkose and lithic arkose to basaltic litharenite and conglomerate (Roy Creek member). Although the contact is not exposed in the field area, it can be constrained to within a few meters along Rock Creek (locality 161). The contact between the two members is interpreted to be conformable based on similarity of attitudes and composition. Sunset Highway basaltic sandstones differ from basaltic sandstones of the Roy Creek member in that they tend to be more poorly sorted, are in

Figure 24. Exposure of northeast-trending fault contact between faintly laminated bioturbated very fine-grained arkosic sandstones of Sunset Highway member and blocky, weathered Sweet Home Creek mudstones. Locality 88.

an arkosic sandstone matrix, are more friable, and display better stratification and primary sedimentary structures (Mumford, 1988; Safley, 1989; this study).

The upper contact of the Sunset Highway member with the Sweet Home Creek member is partly gradational (Mumford, 1988) but may also be distinct. This contact is exposed in two places in the field area; however, abrupt contacts and different bedding attitudes in one of the outcrops (locality 140) indicate that the two members are juxtaposed by faulting (Figure 24). Along the Selder Creek road (Plate I), a gradational relationship between very-fine grained, arkosic, carbonaceous sandstone/siltstone, and thicker, poorly laminated, micromicaceous mudstone demonstrates a comformable contact between the Sunset Highway member and the Sweet Home Creek member.

Detailed geologic mapping (Rarey,1986; Mumford,1988; Safley 1989), subsurface log correlation (Martin et al., 1985), and measured stratigraphic sections show that the Sunset Highway member thins rapidly to the west in Clatsop County and eventually pinches out into deep-water Sweet Home Creek mudstones in the eastern half of R8W about the longitude of the Nehalem River. Toward the east and south, the Sunset Highway member also pinches out into mudstones of the Hamlet formation (Farr, 1989). Therefore, the Sunset Highway member is not as widespread in northwestern Oregon as either the Roy Creek or Sweet Home Creek members of the Hamlet formation.

Petrography

Four thin sections of Sunset Highway strata were analyzed petrographically. The samples range from silty, very fine-grained micaceous sandstones to medium-grained arkosic and lithic arkosic sandstones. Deep surficial weathering resulted in oxidation of pore-filling clays and iron-bearing framework minerals and volcanic rock fragments to secondary iron oxides of hematite, goethite, and limonite. Late stage, telogenetic oxidation of iron-bearing clay mineral's (smectite) by surface weathering and deep circulating meteoric groundwater has largely masked and destroyed previously formed diagenetic features in thin section. This expandable clay matrix results in an overall yellowish brown color to most weathered outcrops and thin sections of Sunset Highway sandstones and siltstones. Consequently, most thin sections are in poor condition preventing a thorough diagenetic analyses. Mumford (1988) and Safley (1989), however, were able to identify five separate stages of diagenesis for cleaner and fresher Sunset Highway member samples. Some diagenetic replacement features that could be observed in Sunset Highway sandstones include chlorite and calcite replacing plagioclase and volcanic rock fragments, and smectite clay as an alteration from chlorite. Chlorite occurs as both detrital flakes and as alteration products probably from biotite.

Six heavy mineral grain mounts were prepared from Sunset Highway samples. The heavy mineral assemblage of the Sunset Highway member is dominated by epidote, zircon, and hornblende, with trace quantities of tourmaline, garnet, mica and clinopyroxene. For further discussion of heavy minerals and comparison with C & W sandstones, readers are referred to the section; Heavy Minerals of the Cowlitz Formation.

The arkosic sandstones are composed of moderately sorted, subangular to subrounded grains of quartz, plagioclase, and potassium feldspars, micas (mostly biotite, with minor muscovite), assorted heavy minerals, chert, and associated basaltic, rare plutonic, sedimentary, and metamorphic rock fragments (Figure 25). Metamorphic lithics in Sunset Highway sandstones are usually polycrystalline strained quartz with microcrenulated or sutured boundaries, but low grade phyllite fragments are present in one sample (766). One sample (777) contains a large clast of micro-micaceous siltstone which is interpreted to be intrabasinal in origin.

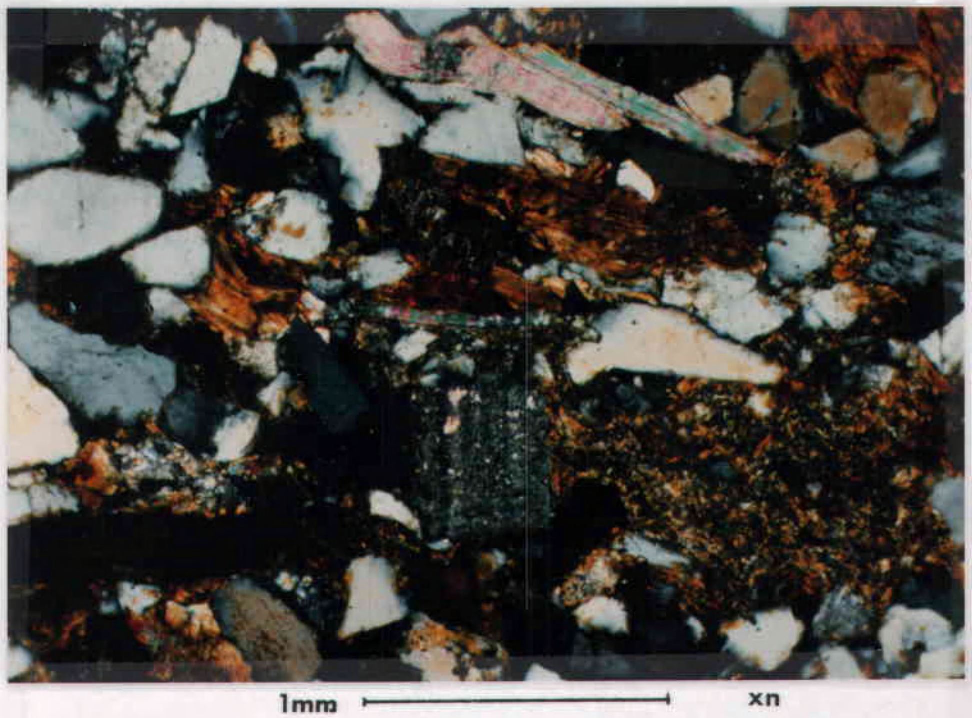


Figure 25. Photomicrograph of arkosic Sunset Highway member. Noe subangular to subrounded monocrystalline quartz, K-feldspar, albite twinned plagioclase, micas, and orange smectite clay rim cement surrounding altered basaltic grain.

On Folk's (1974) ternary QFL diagram, these rocks classify as arkose and lithic arkose (Figure 23). However, these sandstones would be more precisely identified as plagioclase arkoses, rather than "traditional" potassium feldspar arkoses. This is in contrast with C & W sandstones, which usually contain a higher percentage of potassium feldspar (15-20%), and lesser amounts of lithic fragments (3%). Arkosic sands form due to high relief and rapid erosion of uplifted granitic and metamorphic source areas. Volcanic and sedimentary lithic grains reflect sources of sedimentary or volcanic cover. Therefore, Sunset Highway deposition is time-transitional between local uplift and erosion of Tillamook Volcanics (i.e. Roy Creek member) and more distal extrabasinal arkosic sedimentary input, because it contains both lithic and significant arkosic micaceous contributions.

Quartz occurs as both monocrystalline unstrained (25-40%) and polycrystalline (4-7%) forms, with straight extinction (Figure 25). Quartz is typically subangular, probably of first cycle origin; many contain tiny euhedral mineral inclusions (zircon and apatite). Some quartz grains display undulose or strained extinction indicative of a metamorphic source (Folk, 1974). The polycrystalline quartz grains may also have undulose extinction typical of hydrothermal or vein quartz. Quartz grains are interconnected along straight common boundaries with minor small quartz matrix filling in between larger grains. Mumford (1988) and Safley (1989) reported secondary quartz overgrowths on some rounded quartz grains, but this was not observed in my thin sections. However, most quartz grains are rimmed by a thin layer of clay minerals and iron oxides. This clay coating significantly reduces permeability by narrowing or occluding pore throats.

Plagioclase is the dominant feldspar (15-20%), with orthoclase and microcline also present (10-15% and 2-3%, respectively). Plagioclase grains commonly display albite twinning or less commonly combined Carlsbad-Albite twinning. Composition ranges from oligoclase to andesine (An_{26} to An_{44}). Potassium feldspar identification was aided by feldspar staining. Both plagioclase and potassium feldspar grains commonly exhibit a dusky appearance due to partial decomposition to clay minerals. This characteristic, plus cleavage, helped distinguish untwinned feldspar from clear undaltered quartz. Some dissolution of plagioclase grains results in secondary interparticle porosity; however, this contribution to total effective porosity is probably not significant.

Mica forms the next most common clast (10-15%). Biotite comprises 8% of the rock and is either brown and stubby, or green and elongate. Characteristic "birds-eye" speckled appearance is observed in fresh grains. However, the biotite is more commonly altered to iron-oxides and chlorite and has frayed ends which reduces the effectiveness of primary porosity. Muscovite is less common (3-7 %) and exhibits a thin, elongate shape. Mica flakes are commonly split and ductilly deformed between brittle detrital quartz and feldspar crystals, providng evidence for moderate compaction and depth of burial. However, most grain contacts are tangential, and compaction features such as crushed quartz grains and pressure solution were not observed. Micas and carbonaceous plant matter are commonly aligned subparallel with one another along bedding planes. Mica content is variable in Sunset Highway sandstones, and the presence of large quantities of compacted mica can result in reduction of permeability and porosity by blocking pore throats and expanding into pore space.

Glauconite, chert and unidentifiable fragments account for approximately 2-5% of Sunset Highway sandstones. Although Sunset Highway arkosic sandstones are generally loosely packed and weakly cemented, the presence of iron-oxides and secondary clay cement prevents reliable assessment of reservoir rock potential.

Depositional Environment

An open shallow-marine to middle shelf environment is postulated for deposition of the Sunset Highway member. This interpretation is based collectively on lithofacies, stratigraphic sequence, sedimentary structures, and fossil data. The abundance of carbonized plant debris, traces of glauconite, molluscan fossils, and low-angle trough cross-laminations, parallel laminations, and bioturbation all attest to a marine origin for these sandstones. One silty very fine-grained lithic sandstone (sample 752; Appendix III) yielded marine Foraminifera, sterrasters/statoliths (fish scales) and also contained large quantities of glauconite. One pelecypod (7-11-1; Plate I; Appendix II) was recovered from the Sunset Highway member and identified by Ellen Moore (wri. comm., 1988), as *Acila (Truncacila) decisa* (Conrad). *Truncacila* lives today in the eastern Pacific at depths between 5 and 200 m. Jackson (1983) collected *Pitar* and *Brisaster* from his heterolithic facies which Thoms (in Jackson, 1983) interpreted to be peferentially found in subtidal, shallow-marine environments. This environment was moderately high energy, wave-dominated, and influenced by storms. Although a classic hummocky cross-stratification (HCS) sequence as described by Dott and Bourgeois (1982) and Harms et al. (1975) was not preserved, some partial sequences of HCS such as swaley and low angle cross stratification were observed. Wavy bedforms, consisting of ripple cross-laminated silty sandstone strata capped by thin mudstone drapes, are similar to the upper part (fxb) of a hummocky sequence (hmfxb) as described by Dott and Bourgois (1982) for the Coaledo Formation in southern Oregon (see: Cowlitz Formation, Figure 45). Commonly these laminae are disrupted by subvertical burrows of *Thallasinoides*., typical of lower shoreface deposits. These burrows in the upper part of the sequence probably indicate recolonization of the substrate by infauna after a period of storm sand deposition (Reading, 1978). These features and style of cross-stratification are reminiscent of HCS and imply that the inner shelf was periodically swept by storms during deposition of Sunset Highway member sandstones.

Although features positively indicative of deltaic influence such as a feeder channel and levee deposits were not found, a major river system may have been located nearby, delivering extrabasinal arkosic sediments to the marine environment where they were reworked and winnowed by longshore and shelf currents and storm waves. In contrast, the basaltic sandstones and grits interbedded with the arkosic sandstones were of local derivation from the subsiding Tillamook volcanic pile. These volcanic islands were situated to the west and south in the depositional basin and were still emergent and possibly active at this time, as evidenced by occasional basaltic debris flow deposits interbedded in the Sunset Highway member (Mumford, 1988). Deposition occurred in the offshore transition and shoreface zones on a beach to offshore shelf profile.

Many Sunset Highway very fine- to fine-grained sandstones are moderately to extensively bioturbated, which is typical for modern middle shelf deposits off the Oregon coast (Kulm et al.,1975). The bioturbated strata represent periods of slower rates of deposition, which allow an infauna time to homogenize the sediment. However, flaser bedding and starved ripple laminations in some beds are indicative of wave-influenced deposition, and therefore reflect variations in the "energy" of the depositional environment and sediment supply. These beds are typically discontinuously laminated. Such fluctuations are associated with a transition zone at or near fair weather wave base (Reineck and Singh, 1980). The silty sandstones and mudstones of the Sunset Highway member probably reflect deposition farther offshore in a low-energy neritic environment where muds and silts normally settle out of suspension, indicating an overall transgression during Sunset Highway deposition.

Kulm et al. (1975) recognized similar areas of mud and silt deposition on the modern middle to outer continental shelf of Oregon.

Grain size analysis (see: Cowlitz Formation; Figure 62) shows that some arkosic sandstones of the Sunset Highway member are medium-grained, moderately sorted, coarsely skewed, and generally leptokurtic. The coarse-skewed nature of these sediments reflects the ability of high energy storm events to transport coarser grained material from nearshore farther out onto the shelf and winnowing of the fines (e.g., clay and silt). Storms cause a lowering of the wave base, thus increasing the energy and the coarseness of the transported sediment into an otherwise low energy (silty-muddy) environment on a shallow shelf.

Sweet Home Creek member

The Sweet Home Creek member of the Hamlet formation was informally proposed by Rarey (1986) for a 100 to 400 m thick mudstone-dominated unit that crops out along Sweet Home Creek in southwest Clatsop County (sec. 20 and 29, T4N, R8W). Along with the Roy Creek and Sunset Highway members of the Hamlet formation, the Sweet Home Creek member was previously included in the Cowlitz Formation in southern Clatsop, western Columbia, and northwestern Tillamook counties (Nelson, 1985; Olbinski, 1983; Jackson, 1983; Shaw, 1986; Timmons, 1981; Wells et al.,1983), or as undifferentiated upper Eocene to Oligocene sedimentary rocks by Wells and Peck (1961). Measured thickness of the Sweet Home Creek member in southwestern Columbia County exceeds 120 m, and map relations elsewhere in the field area indicate maximum thicknesses of approximately 207 m.

Age

Fresh Sweet Home Creek mudstones locally contain abundant marine foraminifera indicative of an upper Narizian zonal stage (Appendix III). According to Dan McKeel (writ. comm., 1988), consultant for ARCO Oil and Gas, mudstones collected from Rock Creek and elsewhere in my thesis area (samples 734, 776, 742, & 743; Plate I), contained microfauna which constitute a typical and distinctive "Hamlet" assemblage. Specifically, the presence of "spiny" spherical radiolaria and the foraminiferal species *Pseudoglandulina nallpeensis* indicates that these mudstones are older than the C & W sandstone, while the species *Cibicides natlandi* is restricted to an upper Narizian stage.

Rarey (1986) collected coccoliths from Hamlet mudstones along Sweet Home Creek which are typical of calcareous nannofossil subzones CP-14a and CP-14b, correlative to the middle to late Narizian foraminiferal stage (Figure 5). Accordingly, the Hamlet assemblages from this study were found to be different and in part younger than type Yamhill Formation, which is Ulatisian to upper Narizian in age (Gaston, 1974). This agrees with foraminiferal data collected by Rarey (1986) and Mumford (1988) from Hamlet mudstones in Clatsop County and from Yamhill mudstones in Tillamook County and demonstrates an equivalence between the two widely separated Hamlet formation localities. Furthermore, these findings were corroborated by two different micropaleontologists (i.e., McKeel and Rau) who conducted their research independently. Perhaps most importantly, the Hamlet assemblages are similar to strata which Bruer et al. (1984) called Yamhill below the C & W sandstone in the Mist field. According to McKeel (written comm., 1988), evidence is mounting that the "Hamlet formation" lies between the Tillamook Volcanics and the C & W sandtone in the Columbia County subsurface. Recent mapping south of Columbia and Clatsop counties by Wells (1989; pers. comm.) indicates that the type Yamhill lies beneath and lateral to the Tillamook Volcanics.

Lithology

Micro-micaceous and carbonaceous mudstone comprise most of the Sweet Home Creek member; however, silty mudstone is common and local micaceous arkosic turbidite sandstones occur near the top of the member. In Clatsop County, Mumford (1988) reported that local thin beds of basaltic turbidite sandstone and associated thin rhythmically bedded arkosic turbidite sandstones occur in the lower part of the unit. Basaltic turbidites are not present in my area; however thin bedded arkosic turbidite sandstones do occur in two locations (locations 66 and along Rock Creek) near the upper contact with the C & W sandstone. Therefore, these arkosic turbidite sandstones are probably not restricted to any particular stratigraphic horizon in the Sweet Home Creek member.

The well-indurated Hamlet mudstone is medium bluish grey (5 B 5/1) to greyish black (N 2) when fresh, weathering to a chippy yellowish brown (10 YR 6/4) or light brown (5YR 6/4; Figure 24). They are generally structureless but may also be moderately well laminated to thinly bedded. Mica content varies considerably from being randomly disseminated to continuous sheets of fine mica concentrated along bedding planes. A few coarse mica flakes (3-4 mm) and large whole fossil leaves can be found in silty laminated mudstones. One fossil leaf found in Selder Creek (locality 175) identified as*Cercidiphyllum "Katsura"* by Ries (1989, pers. comm.) is testimony to a warm subtropical climate during the middle to upper Eocene. Hamlet mudstones are sparsely fossiliferous but locally contain pelecypods *(Macoma)* and gastropods *(Conus)* identified by E. Moore (1988; writ. comm.) along with the small hook-shaped trace fossil *Helminthoida*.. The large distinctively coiled arenaceous foraminifera *Cyclammina pacifica* is very common and can be seen without the aid of a hand lens, even in weathered hand samples. Small ovoid calcareous concretions and lensoidal concretionary ledges are common throughout the unit. Hamlet clay-rich mudstones erode easily, fill topographic lows and valleys, and are prone to slumping. Consequently, fresh roadcut exposures do not last for more than a couple of years.

Along the banks of Rock Creek, a thick sequence (120 m) of the Sweet Home Creeek member is discontinuously exposed (Figure 26). Unfortunately, because the lower contact is faulted against Keasey mudstone (Plate I), stratigraphic position can not be well established. The base of the Rock Creek measured section begins in medium-grey, micromicaceous, indurated mudstone. This interval was very productive of

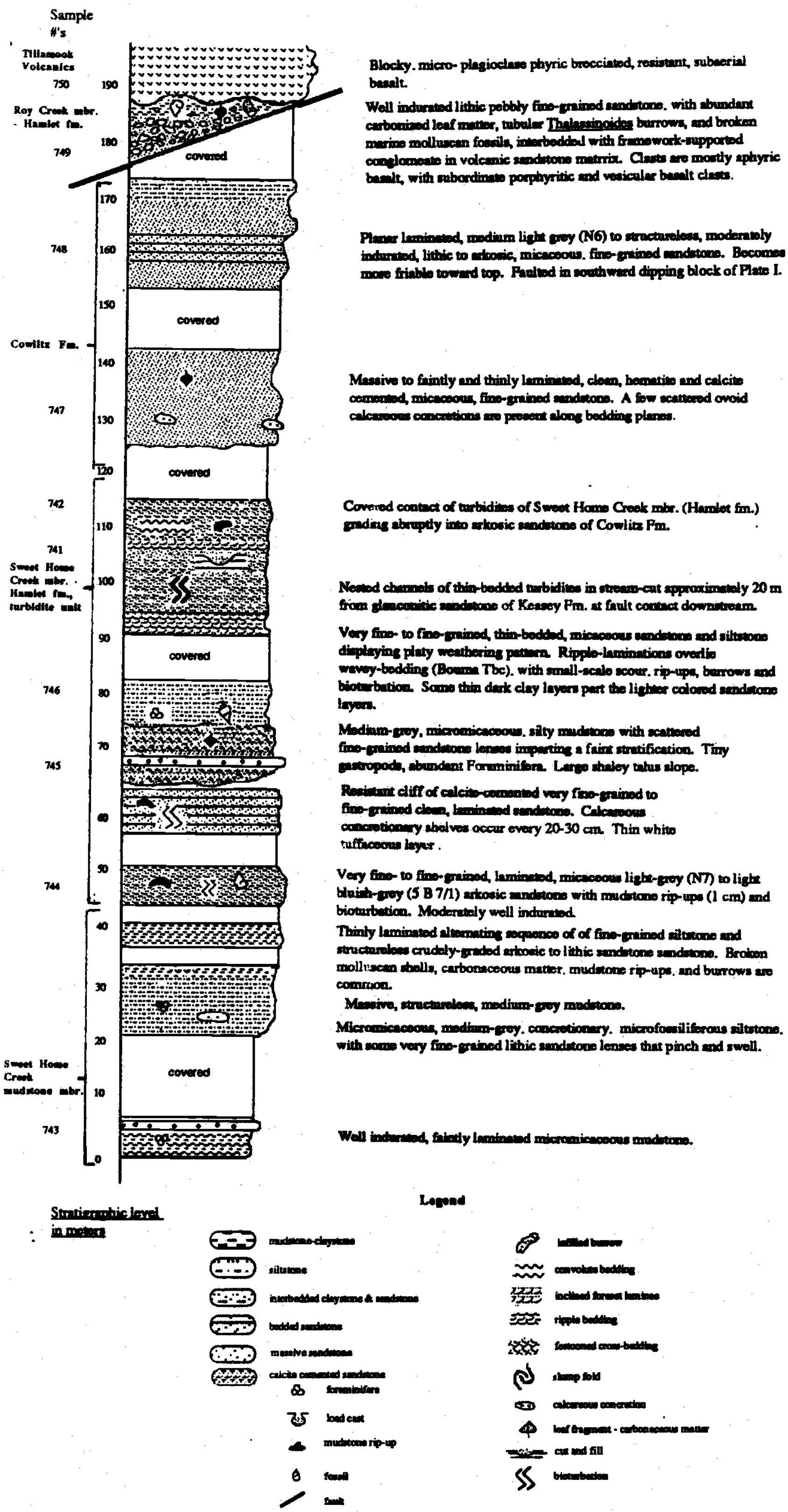


Figure 26. Rock Creek measured section.

Foraminifera (Sample 743; Appendix III). A laterally continuous 25 cm thick concretionary ledge in the mudstone is laterally continuous.

The mudstone becomes siltier and coarsens upward, containing intercalated discontinuous and wavy very fine-grained lithic sandstone lenses. Tiny mica flakes and fine-grained sandstone lenses aligned with bedding impart a faint stratification to the outcrop. From 43 to 48 m, a rather abrupt lithologic change occurs, manifested by thinly laminated beds of fine-grained siltstone alternating with weakly normally graded sandstone beds. The sandstones range from 5 to 20 cm thick, whereas the thicker mudstone beds vary in thickness from 10 to 30 cm. The well-cemented, light bluish-grey sandstones contain broken molluscan shells, disseminated carbonaceous matter, and 2 cm diameter irregular brown mudstone rip-ups. Sandstone beds have sharp basal contacts marked by rare groove casts and internally display parallel laminations overlain by ripple laminations (Bouma Tbc). Upper contacts with shale are gradational (Bouma Tb-e). Further up section (50 - 55 m), the sandstone becomes very fine- to fine-grained and micaceous, displaying platy weathering, ripple laminations and wavy-bedding, with small scale scour surfaces, rip-ups, and bioturbated tops. Some thin dark clay layers are interbedded with lighter colored sandstone.

The upper part of the Hamlet section contains flame structures and other soft sediment deformation features (Figure 26). This sequence of sedimentary structures is characteristic of Bouma sequences Tbcd for turbidite deposits, as described by Bouma (1962) and Middleton and Hampton (1976). In contrast with the underlying structureless mudstone, this interval was relatively nonproductive of Foraminifera. A possible explanation for the paucity of Foraminifera is that rapid sand/silt deposition combined with short elapsed time between storm events prevented deposition of much hemipelagic foraminifera-bearing muds. The preceding line of evidence strongly suggests a turbidity current origin for this 70 m thick sequence of sandstone, siltstone and mudstone.

Many Sweet Home Creek "mudstones" contain a significant proportion of silt and even sand size particles, along with thin sandy interbeds. Along Clear Creek, just below the contact with the Cowlitz Formation near an irregular intrusion of Cole Mountain basalt (locality 139), small Hamlet exposures consist of rhythmically bedded sandstone and chippy mudstone, with a sandstone/mudstone ratio of near 1:1.

The high mica content of Hamlet mudstones helps distinguish these rocks from Keasey Formation mudrocks in fresh outcrops. In addition, Keasey mudstones contain a higher percentage of tuffaceous and glauconitic components, glass shards, basaltic grit, have less sand, and are more fossiliferous (Van Atta, 1971; Rarey, 1986; Mumford, 1988; this study). However, in small weathered exposures, microfossil data and stratigraphic position are the most reliable indicators for differentiating between the two units.

Contact Relations

The contact of the Sweet Home Creek member with the underlying Sunset Highway member is conformable and depositional. This is evidenced by similar structural attitudes between the two members (Plate I), similar megafaunas and microfaunas with no age break, and a gradational facies change between silty sandstones of the Sunset Highway member and silty mudstones of the Sweet Home Creek member. The gradational nature of the contact can be observed in outcrops along Selder Creek road (Plate I). The sequence grading from littoral Roy Creek conglomerate, through shallow-marine Sunset Highway member arkosic sandstones, and overlying deep-water Sweet Home Creek member mudstones reflects a regional transgression or local deepening trend of uninterrupted shelf to slope sedimentation.

In the Columbia County field area, the Narizian C & W sandstone overlies the Sweet Home Creek member, whereas the Refugian Keasey Formation (Jewell member) overlies the Sweet Home Creek member in Clatsop County (Rarey, 1986; Mumford, 1988). Consequently, the nature of the contact in the two areas may also be dissimilar. Because of similar bedding attitudes, gross lithology and depositional environments (deep-water mudstones) between the two units, Mumford (1988) concluded that there did not appear to be a major unconformity between Sweet Home Creek mudstones and the Jewell mudstone member of the Keasey Formation in southern Clatsop County. Because Cowlitz sandstones pinch out into bathyal mudstones of the Sweet Home Creek member in Clatsop County (Nelson, 1985; Safley, 1989; Niem and Niem, 1985), Clatsop County probably represents a more distal depositional environment (Figure 27). In deeper parts of a depocenter, unconformable contacts commonly merge and become conformable (Miall, 1984). An analogous situation is the Sunset Highway member pinch out and facies change into Sweet Home Creek mudstones from Mumford's (1988) area in south-central Clatsop County to Rarey's (1986) area in southwest Clatsop County (Figure 5). In Columbia County, the Hamlet/Cowlitz contact becomes unconformable due to proximity to the basin edge which is easily affected by shoreline retreat and subsequent erosion.

In Columbia County subsurface, stratigraphic evidence suggests that the Hamlet contact with the overlying C & W sandstone is unconformable. In their regional correlation diagram of Clatsop and Columbia counties, Bruer et al. (1984) show a regional unconformity at the base of the C & W sandstone at the contact with the "Yamhill". As mentioned previously, the "Yamhill Formation" of the Mist field is probably the lateral and subsurface equivalent of the Hamlet formation. The

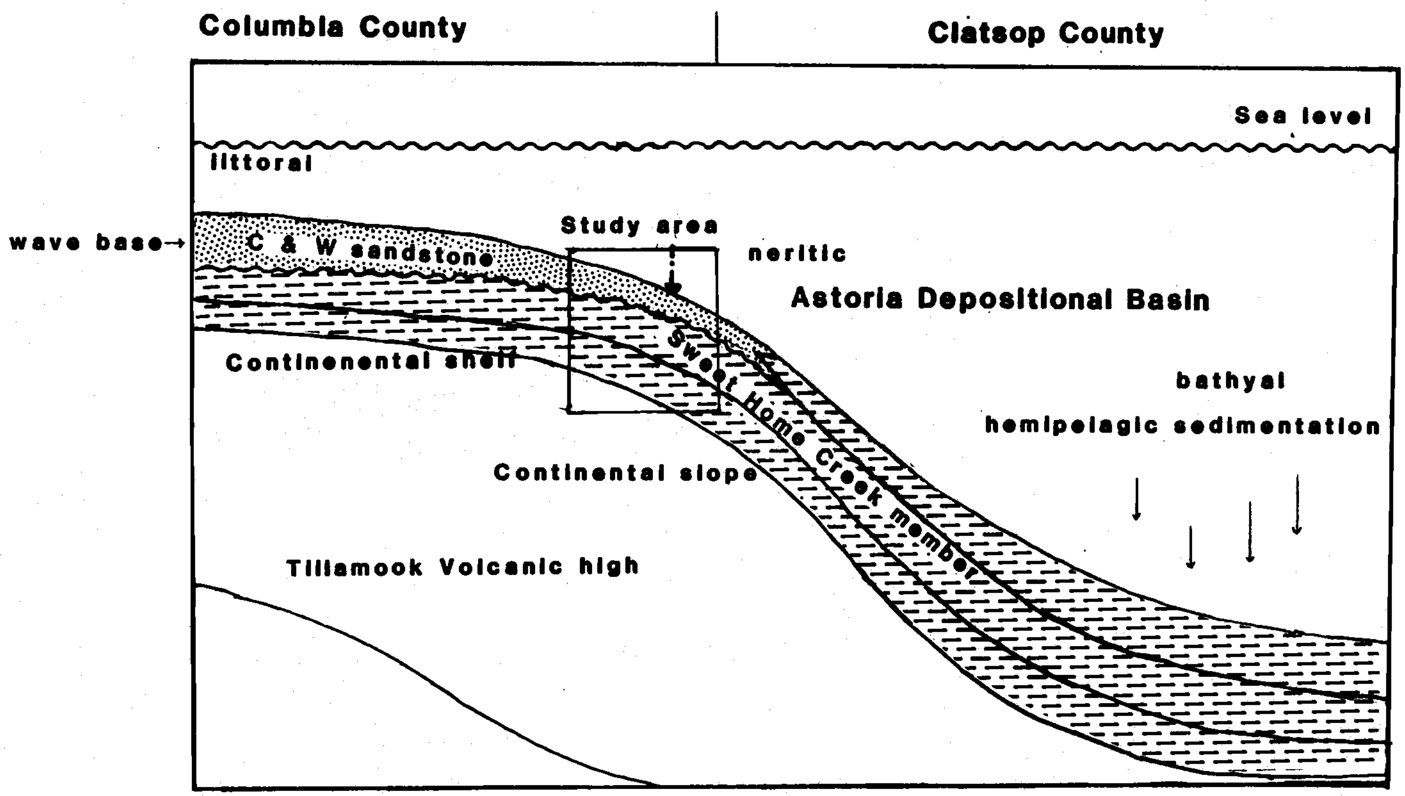


Figure 27. Schematic reconstruction of Astoria-Nehalem depositional basins during late Eocene (Cowlitz) time, illustrating relationship between the study area and equivalent but deeper marine deposits in Clatsop County.

unconformity is noted in electric logs and seismic lines of the Mist field, because part of the Hamlet formation (near the top) appears to be truncated (B. Dahleen, pers.comm., 1989). In addition, Hamlet deep-water mudstones are overlain by Cowlitz sandstones which are interpreted to represent deltaic to shallow shelf deposition. A pronounced or sharp lithologic break is always encountered. In addition, McKeel (writ. comm., 1988) found little similarity between foraminiferal assemblages recovered from Hamlet mudrocks in my area and foraminiferal assemblages from C & W sandstones in the Mist field. This upper Narizian unconformity may have been a temporary zone of sediment bypass or subaerial exposure during an episode of low relative sea level stand. Comparison with worldwide relative coastal onlap curves suggests that the unconformity may be partly related to changes in sea level (see: Relationship of Depositional Cycles to Geologic History, Figure 95).

The Hamlet formation is interpreted to be the product of deposition during a transgression. Typically, a cycle of relative rise and fall of sea level consists of a gradual relative rise, a period of stillstand, and a rapid relative fall of sea level (Vail et al., 1977). The abrupt fall at the end of the cycle tends to produce an unconformity that will separate the sequence from the overlying one of the next cycle.

In the field, the sharp contact of the Cowlitz sandstones over the Hamlet mudstone member is exposed in one location (localitiy 1) and nearly approximated in another (Rock Creek section), yet no structural evidence (i.e., dissimilar bedding attitudes) exists for a pronounced angular unconformity of tectonic origin. Therefore, the abrupt nature of the contact is more likely manifested by a nondepositional hiatus and/or shallowing of sedimentation during and possible before deposition of basal C & W arkosic sandstone. Examination of electric logs from the Mist field show an abrupt coarsening-upward funnel-shaped SP curve near the Hamlet/Cowlitz contact, interpreted to represent a transitional facies of bathyal mudstone grading rapidly upward into storm-deposited, cross-bedded arkosic C & W sandstones (Figure 28). Funnel-shaped curves are characteristic of regressives cycles of deposition, in this case concomitant with Cowlitz deltaic or shelf progradation out onto a subsiding offshore or prodelta platform (Bigelow, 1987).

Petrography and Clay Mineralogy

Three thin turbidite sandstone beds from Rock Creek were examined petrographically. In addition, one mudstone sample was analyzed by X-ray diffraction for identification of clay minerals. The moderately well sorted sandstone samples are nearly identical to Sunset Highway arkosic sandstone samples in mineralogy and texture, suggesting that these sandstones may, in part, be a deeper water lateral equivalent to the shallow-marine Sunset Highway sandstone (Mumford, 1988). However, the Sweet Home Creek member samples are very fine- to fine-grained, whereas Sunset Highway sandstones are very fine- to medium-grained and tend to be cleaner. All three Sweet Home Creek turbidite sandstone samples plot on Folk's ternary classification diagram as an arkose (Figure 23), whereas the Sunset Highway member contains some basaltic sandstone beds which plot as feldspathic litharenites.

The micaceous arkosic nature of Sweet Home Creek sandstones probably indicates increased extrabasinal contribution. Detrital mineralogy of these sandstones consists of subangular grains of monocrystalline unstrained quartz (40%), plagioclase feldspar (20%), lesser potassium feldspar (14%), biotite (10%), muscovite (3%), chlorite (3%), opaque iron oxides (5%), pyrite cubes (2%), and rare volcanic, sedimentary, and metamorphic rock fragments (2-3%) (Figure 29). One thin section (742) contained a few sedimentary clasts interpreted to represent rip-ups from the underlying Sunset Highway member that were transported by turbidity currents

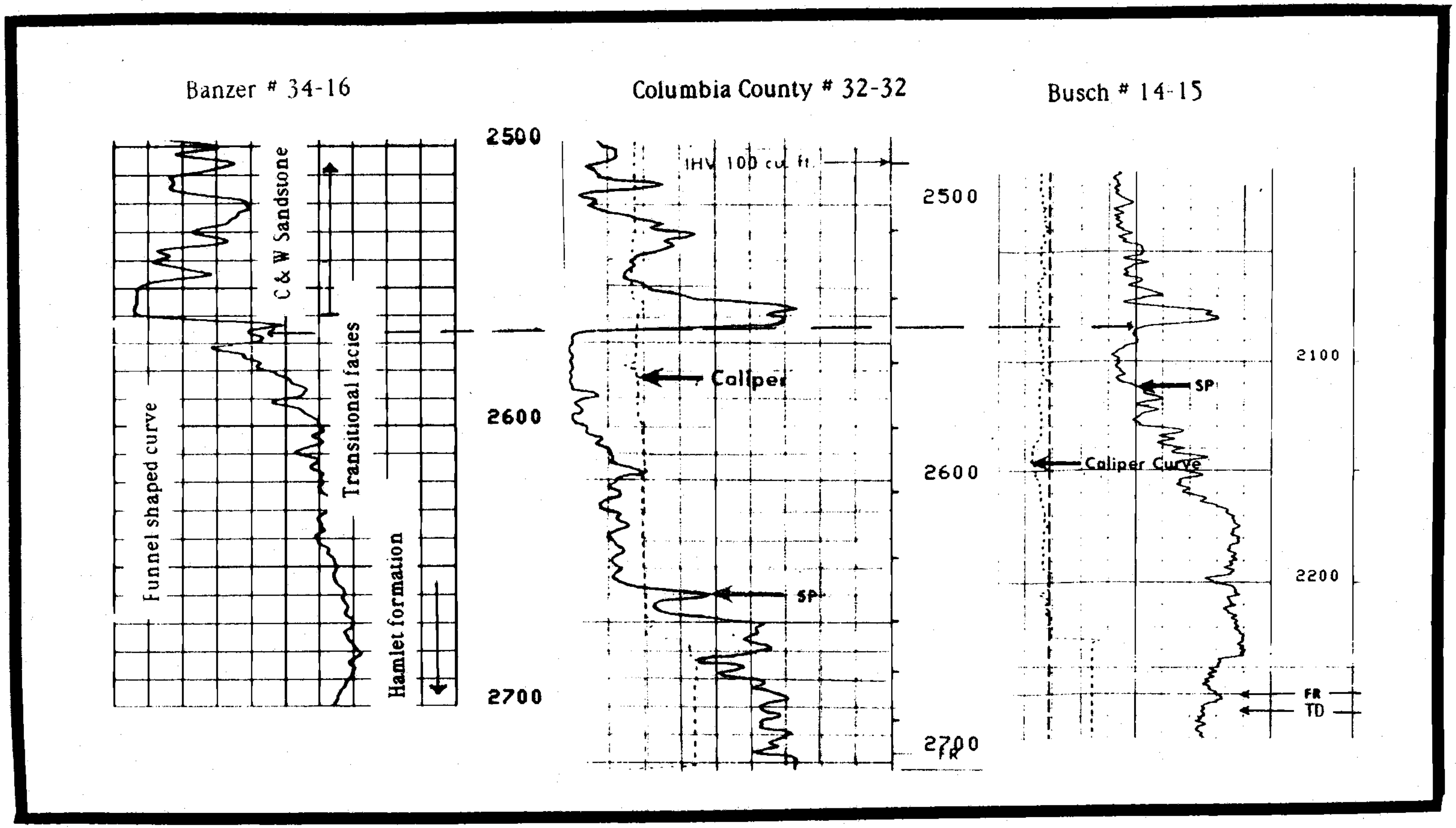


Figure 28. Portions of 3 electric logs from Mist Gas Field showing funnel shaped SP signatures and short transitional facies interpreted to represent rapid coarsening upward trend at end of Hamlet ("Yamhill") deposition.

downslope into a deep-water environment. Accordingly, this sample contained a higher percentage (5-10%) of detrital clay matrix and silt size particles.

Due to the fine detrital clay matrix in the Sweet Home Creek member, the samples are texturally immature (Folk, 1974). Textural maturity reflects the type of physical processes and length of time during which these processes acted on the grains in different depositional environments. Texturally immature sediments tend to accumulate in environments where either current action is weak or deposition and burial are very rapid so that sediments do not have a chance to be reworked (winnowed and sorted) by currents. A turbidity current origin into a deep basin would be such an environment because of the rapid burial and turbid nature of the transporting agent.

Many framework micas and feldspars have been partially or wholly replaced by clay minerals which have been rendered a yellowish brown color upon weathering in the vadose zone to opaque iron oxides, imparting a muddy appearance to the thin sections. Stringers of dark brown carbonaceous plant matter are common and are aligned parallel with bedding, as are the mica flakes (Figure 29).

X-ray diffraction was performed on a Sweet Home Creek mudstone sample from the Rock Creek measured section (743) following the method of J. Robbins (in prep., 1989) at Oregon State University school of Oceanography. The magnesium-saturated sample was heated at 65°C in a dessicator filled with ethylene glycol for 5 hours before scanning. Then the sample was heated for 1 hour at 550°C and scanned again in order to expand the smectite layers and collapse kaolinite structure if present. The first scan shows a very pronounced peak at 17.59 angstroms and lesser peaks at 10.17, 8.56 and 7.30 angstroms (Figure 30). The second scan shows that the first order 17 angstrom peak shifted to a broad peak at 10 angstroms, characteristic of the expanding clay, smectite (Brindley and Brown, 1980). However, this partially masks a small illite peak, also at 10 angstroms. The illite peak does not shift upon heating but

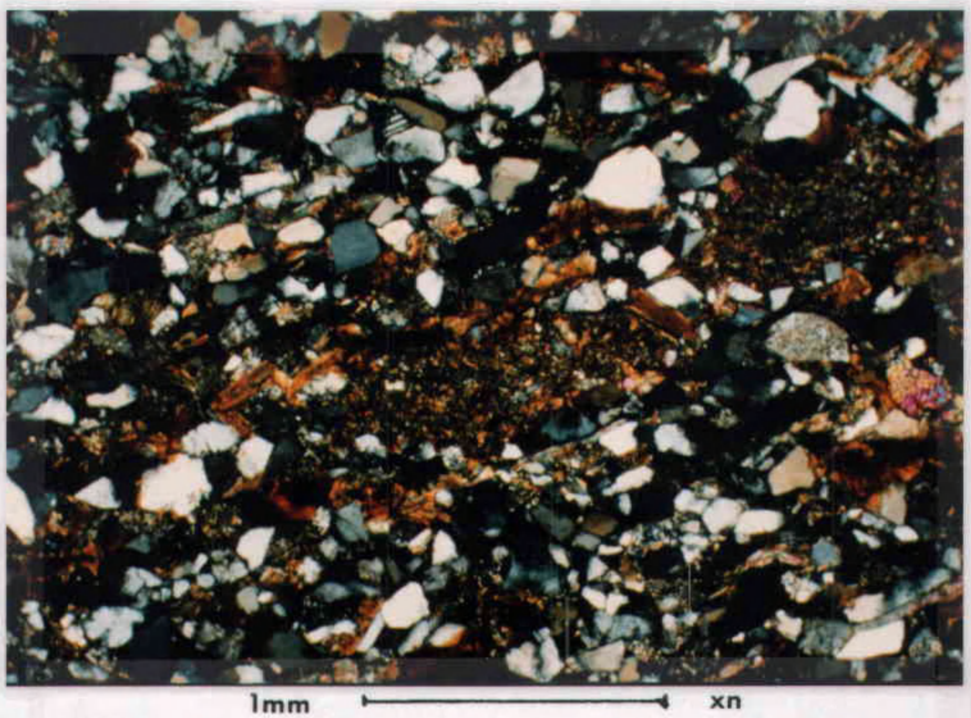


Figure 29. Photomicrograph of Sweet Home Creek member thin bedded fine-grained quartzose-feldspathic sandstone turbidites. Note alignment of carbonaceous plant matter and mica flakes and birefringent yellowish orange smectite clay rim cement.

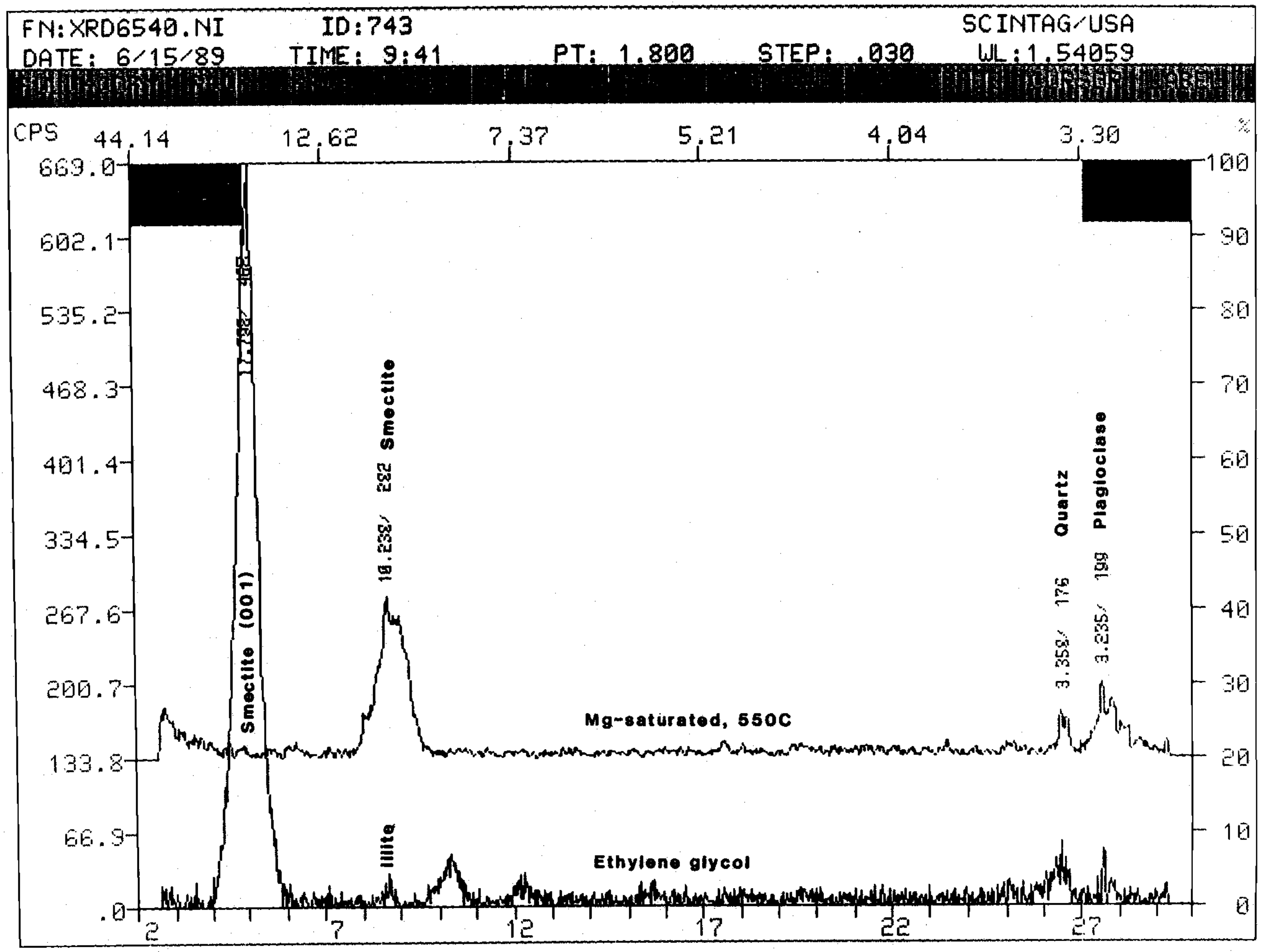


Figure 30. X-ray diffraction pattern of mudstone from Sweet Home Creek member.
Sample 743 (Rock Creek section).

instead grows slightly in intensity as water interlayers are removed. The presence of the 2° peak at 3.35 angstroms confirms the presence of illite; however, this double peak also suggests that some quartz is present in the sample (Figure 30). The very small peak at 7 angstroms disappears with heat treatment, indicating that kaolinite and/or chlorite is present in very minor quantities. The peak at 8.56 angstroms disappeared upon heating and may be a hydrous zeolite. The smaller peaks at 3.23 and 3.37 anstroms are probably quartz and plagioclase feldspar.

Smectite clay minerals have a high Si : Al ratio (2 : 1), and usually form by weathering of alkaline soils in an arid microenvironment developed on volcanic bedrock (Glassman, 1982). In these environments, smectite is a common alteration and weathering product from rocks rich in Ca^+, Mg^+, and Fe^+ such as intermediate to mafic igneous rocks (i.e.,basalt). These rocks contain mafic ferromagnesium minerals (eg. pyroxene), calcic plagioclase and glass and have high Si to Al ratios. Mobilized Mg and Fe in their structure can enter smectites expanding lattice structure. It is possible that the abundant smectite in the Sweet Home Creek mudstone sample is derived by this process from weathering of volcanic sources, such as the Tillamook Volcanics. However, arid climates are most conducive for smectite formation because there is little leaching and removal of Ca, Mg, and Fe cations released by hydrolysis (Keller, 1970). Because the climate during middle to upper Eocene time was subtropical and humid (Ries, 1989), alternative sources of smectite should be considered as possible contributors (e.g. arid eastern Oregon volcanic sources). Colwell et al. (in press), postulate that abundant smectite forms from volcanics on the drier lee side of the tropical Solomon Islands.

Smectite can form diagenetically in oceans by alteration from other clay minerals as Biscayne (1965) showed in cores from the Atlantic Ocean. It has been shown experimentally that illite may be stripped of K^+ ions, degraded and converted to montmorillinite (smectite). However, smectite derived in this manner is probably not significant for the Sweet Home Creek member, because smectite formed by weathering of framework silicates appears to be relatively stable in the open marine environment, and thus indicates provenance (Mackenzie and Garrells, 1965). Accordingly, smectite clays in the marine Sweet Home Creek member were probably derived from weathering of the underlying Tillamook volcanics and/or eastern Oregon Clarno Volcanics.

Kaolinite clays are reported to form in low latitude humid climates. The presence of trace quantities of kaolinite in Sweet Home Creek mudstones probably reflects extensive tropical weathering and leaching of late Eocene volcanic units in the source area of the Hamlet formation (Tillamook Highlands). Therefore, the presence of kaolinite also indicates a deeply weathered Tillamook Volcanic source for mudstones of the Sweet Home Creek member. Smectites can also be transformed to kaolinite by extensive leaching and heating and cooling cycles in tropical soil microenvironments (Colwell et al., in press).

Minor illite in the Sweet Home Creek member reflects the micro-micaceous character of the Sweet Home Creek mudstones and probably originated from degradation of large mica flakes from sandy portions of the unit and the underlying Sunset Highway sandstone member. Thus, illite in the Hamlet mudstones is thought to be a detrital fine-grained mica weathered from granitic terranes and transported via an ancestral river system. Therefore, the illite represents a nonvolcanic provenance unlike smectite and kaolinite and probably is not a product of in situ diagenesis.

Depositional Environment

The Sweet Home Creek member was deposited in outer neritic to upper (?) bathyal depths by slow hemipelagic clay-silt sedimentation. This interpretation is made collectively on the basis of microfossil (mainly foraminiferal) data, lithology, and stratigraphic position. Nearly 40 different species of foraminifers were picked from mudstone samples which made possible fairly accurate paleoenvironmental determinations (Appendix III). Water depths according to McKeel (writ. comm., 1988) ranged from 50 to 6000 meters; however, those depths represent the extreme environmental tolerances of the species and probably not true depths of deposition. McKeel interprets some Hamlet foraminiferal assemblages (734) to represent slope deposits, whereas others (743) are representative of the shelf-slope break (i.e., 200 m water depth). According to McKeel, more complete faunal recoveries in two Hamlet samples (734 & 742) may extend paleodepths to middle bathyal. However, even extending paleodepths to middle bathyal conflicts somewhat with the conclusions of Mumford (1988), Rarey (1986), and Safley (1989), whose foraminiferal assemblages indicate lower or middle bathyal deposition for Sweet Home Creek mudstones in their respective areas in Clatsop County.

This discrepancy may simply be a function of different paleoenvironmental interpretations by different micropaleontologists. However, comparison of Foraminifera checklists from Mumford (1988) with those from my area, indicates that there are minor differences in microfossil assemblages. Therefore, a more plausible explanation based on regional stratigraphic relationships and paleogeography is that Hamlet mudstones underlying the C & W sandstone in Columbia County were deposited in shallower depths (outer shelf and slope) and that equivalent deposits several kilometers to the west in Clatsop County were basinward and deeper (e.g., lower to middle slope; Figure 27). Evidence for this lies in the very thick, predominantly late Narizian mudstone mapped in the center of the Astoria basin (Rarey, 1986; Niem and Niem, 1985; Bruer et al., 1984). In going from outer neritic/upper bathyal depths to middle bathyal depths in a distance of 8 kilometers, a narrow and moderately steep continental slope is inferrred.

The thick lower sequence of thinly bedded to structureless micaceous silty mudstones and siltstones of the Sweet Home Creek member is lithologically similar to the fine-grained massive middle to upper slope deposits off the Oregon coast today (Kulm and Scheidegger, 1979). On the other hand, the sequence of laminated turbidite sandstones in the Sweet Home Creek member are of limited areal extent, which may be evidence for minor channels cut into the slope in which turbidity currents moved sand down-slope. However, these turbidites are thin-bedded, mud-rich, do not display classical Bouma sequences and large-scale channels, thickening upward sequences with coarse pebbly sandstone (Figure 31), and hence do not resemble turbidites deposited in inner submarine fans and upper fan canyons (Mutti and Ricci Luchi, 1975; Normark,1978; Walker, 1984).

The regional transgression recorded by the Hamlet formation may have caused most sand to be retained in estuaries and deltas, preventing development of prograding submarine fans and sand-rich turbidites (Bigelow, 1987). The presence of sandy turbidite interbeds near the top of the Sweet Home Creek member may indicate a shoaling upward trend within the upper part of the unit which is further supported by foraminiferal data collected by Mumford (1988) and which may herald the approach of the Cowlitz delta. Mumford (1988) suggested that Sweet Home Creek turbidites may have been deposited in shallow sea gullies carved into the outer shelf to upper slope. The Sweet Home Creek member may be somewhat analogous to the middle Eocene Elkton Formation of the southwest Oregon coast, in the sense that it is transitional between shallow-marine arkosic sandtones (Sunset Highway member) and possibly deeper marine deposits (Keasey Formation). Elkton siltstones display numerous small

Figure 31. Exposure of Sweet Home Creek member thin bedded arkosic turbidites in Rock Creek. Note cross-cutting relationship of beds interpreted to represent nested channels cut into the shelf-slope break. Fanny pack is 30 cm diameter for scale.

sandstone-filled channels, thin-bedded turbidites and lenticular sand bodies (Dott and Bird, 1979), similar to the strata observed in Rock Creek (Figures 31 and 26).

Safley (1989) suggested that these turbidites represent gravity-driven interflows originating on the shelf, possibly setup by storms (Stowe, 1986) as noted by hummocky and swaley cross-stratification observed in the underlying Sunset Highway member. However, sediment may bypass the shelf to be deposited in the slope in other ways as well, within low density-stratified turbid layers by direct discharge of mud-charged rivers (Stowe, 1986; Harlett and Kulm, 1973).

KEASEY FORMATION

Nomenclature

The Keasey Formation was originally described by Schenck (1927) for sandy tuffaceous, bluish grey fossiliferous shale exposed along Rock Creek near Vernonia in western Columbia County, Oregon (within my field area). The most characteristic exposures of the dark, sandy Keasey shale were stream cuts between the old logging railstations of Tara and Keasey. In 1937 Weaver estimated thickness of 1,200 feet (387 m) for the Keasey Formation and listed some characteristic molluscan fossils. He divided the Keasey into a lower dark-colored sandy shale member and an upper shaly sandstone member which comprised two-thirds of the formation. In 1943 Weaver published an important monograph summarizing existing knowledge of the Tertiary megafaunas of Oregon and Washington, including the Keasey.

In their geologic report of the upper Nehalem River Basin, Warren and Norbisrath (1946) expanded Schenck's original definition of the Keasey Formation to include younger beds that crop out farther downstream along Rock Creek, as well as elsewhere in the general vicinity of western Columbia County. They noted that Keasey strata are exposed at intervals for about 2 miles (3.2 km) downstream from Cowlitz Formation exposures, and subdivided the Keasey into three informal members: 1) a lower dark shale member with variable thickness (type Keasey); 2) a thick middle unit of tuffaceous and concretionary siltstone; and 3) a thin upper member of stratified tuffaceous sandy shales. Van Atta (1971) noted that the members of Warren and Norsbisrath (1946) can be defined only in a limited area in Columbia County and informally subdivided the Keasey into three different members: 1) a basal thin pebbly volcanic sandstone; 2) a thick middle member of structureless, fossiliferous, tuffaceous siltstone; and 3) an upper thin sequence of interbedded siltstone and fine-grained sandstone. Since that time, Van Atta (1987; pers. comm.) has included the lower sandstone unit in the Cowlitz Formation.

In Clatsop County, Olbinski (1983) and Nelson (1985) informally proposed the Jewell member of the Keasey Formation for a sequence of laminated to thinly bedded, locally glauconitic mudstones near Jewell. The Jewell member is lithologically similar and probably correlative to the lower two members of the Keasey Formation as defined by Warren and Norbisrath (1946); however, it tends to be thinner, better laminated, darker colored, and contains rare clastic dikes and beds of arkosic sandstone (Rarey, 1986; Mumford, 1988). Van Atta's (1971) upper member of the Keasey has been renamed the Sager Creek formation (formerly Vesper Church member of Oswald West formation) in Clatsop County (Niem and Niem, 1985).

Distribution

The Keasey Formation is particularly well exposed in the northeastern part of the map area (Tk on Plate I). The fine-grained smectitic Keasey unit is prone to weathering and erosion and is topographically expressed as low hummocky hills and valleys due to frequent slumping and landsliding. In addition to natural cliff exposures or stream-cuts along Rock Creek (the type locality), there are excellent fresh logging roadcut exposures of the Keasey Formation in the field area. The most accessible exposures occur along the Columbia County Mainline, constructed in 1983 by Longview Fibre Co. This road traverses the east side of the area in a north-south direction (Plate 1). Numerous exposures of the upper Keasey Formation are represented along this road to the north of the Rock Creek bridge (Plate I). Other fresh to weathered roadcut exposures occur along Ivy Creek road (T5N, R5W, Secs.20, 29), Deep Creek road (T5N, R5W, Secs. 20), and several spurs off these logging roads (Plate I).

Fresh outcrops of the lower Keasey Formation are well exposed along Rock Creek, Selder Creek, and along the Selder Creek road (e.g., localities 44 and 125). Based on bedding attitude and area of outcrop distribution, approximately 500 - 900 m of Keasey Formation is exposed in the thesis area; however, the thickness of this unit seems to vary considerably and the absence of the upper contact in the study area precludes accurate estimates of total thickness. West of my area in Clatsop County, Mumford (1988) estimated 300 m for the Jewell member, and Olbinski reported a thickness of 365 m northwest of the thesis area. Martin and others (1985) show a thickness of over 900 m in the subsurface of central Clatsop County. In the OM 41A-10 well in the Mist field (Columbia County), I estimate the Keasey Formation to be 406 m thick.

Lithology

The Keasey Formation in the study area primarily consists of structureless or poorly laminated to thin bedded, tuffaceous silty mudstone. The tuffaceous character is confirmed by: 1) abundant altered glassy shards visible only in thin section; 2) rare thin (less than 1 cm) light grey (N7) tuff beds in outcrop; 3) some highly pumiceous zones in a few exposures, and 4) general low specific gravity of the bleached white to light grey mudstone. Individual tuff beds have also been reported in the Jewell member in Clatsop County (Rarey, 1986; Mumford, 1988). Fresh mudstone exposures are dark grey (N3) to medium dark grey (N4), weathering to a bleached very pale orange (10 YR 8/2) to grayish yellow (5Y 8/4). Weathered Keasey roadcuts are mantled with several feet of chippy talus. Thin resistant concretionary ledges and small (10 cm diameter) to large (150 cm diameter) ovoid to irregularly shaped calcareous concretions are common and concentrated in scattered layers parallel to bedding. However, spheroidal weathering in the Keasey results in outcrops containing many concentric iron-stained rings of mudstone which can easily be mistaken for concretions. Keasey mudstones are generally mica free and only slightly carbonaceous, which helps distinguish them from the underlying micromicaceous and carbonaceous Sweet Home Creek mudstone of the Hamlet formation.

The mudrocks of the Keasey Formation are locally quite fossiliferous, containing abundant mollusks such as scaphopods (*Dentalium*, curved smooth, and ribbed), gastropods, and pelecypods (Appendix II; Moore, 1988; writ. comm.). Specifically, the high diversity of turrid gastropod species is one of the most outstanding characteristics of the fauna (Hickman, 1976). However, fresh Keasey mudstones also contain an unusual diversity of non-mollusk groups. The groups represented include benthonic and planktonic Foraminifera (McKeel, 1988; writ. comm.; McDougall, 1980), crinoids (Moore and Vokes, 1953), asteroids, corals, brachiopods, and crustaceans (Hickman, 1976). In addition, disaggregation of Keasey mudrocks from my area yielded echinoid remains and spines, calcareous nannoplankton (coccoliths), radiolarians, pyritized diatoms, fish scales, ostracodes, sharks teeth, sponge spicules (Appendix III) (McKeel, 1988; writ. comm.), and trace fossils (*Helminthoida*) indicating a deep-water environment (see: Depositional Environment). Coarse sand size snail-like coiled specimens of the foraminifer, *Cyclamina pacifica* are common even in weathered outcrops and easily visible in hand specimen without the use of a hand lens.

Stratigraphically, there appear to be some characteristic lithologic and faunal differences between the lower and upper parts of the Keasey, although this distinction is not always obvious on cursory examination. Upper Keasey mudstones tend to be massive, more concretionary, tuffaceous, and weather to dark yellowish orange (10 YR

6/6). The lower Keasey is much thinner (<200 m), poorly laminated to laminated, slightly more micaceous, glauconitic, basaltic, and pumiceous than the upper part. In addition, the characteristic recurring mollusk assemblage in the type section along Rock Creek is defined by "*Turicula columbiana*", which does not occur in the middle and upper members (Moore, 1988; writ. comm.).

The lower Keasey is lithologically diverse and consequently more interesting than the uniform massive tuffaceous upper Keasey. In particular, parts of the basal Keasey are distinctively composed of moderately to highly glauconitic mudstones that include 12 - 25 cm thick glauconitic sandstone interbeds. Glauconite is generally disseminated throughout the lower Keasey Formation; however, it seems to be especially concentrated at the lower contact, where sandy mudstone beds contain up to 90% glauconite (e.g., Rock Creek locality 906; locality 156). Glauconite "pellets" are dark green to black, coarse sand to pebble size, and well rounded to ovoid. Glauconitic sandstones in the lower Keasey Formation exhibit a compositional spectrum from nearly pure glauconite sandstones to micaceous, arkosic sandstones texturally resembling well sorted C & W sandstones but containing up to 20% glauconite. This latter facies appears to be confined to the extreme basal part of the unit and typically occurs as discrete beds 1 - 2 m thick alternating with tuffaceous mudstone. The lower Keasey Formation at the type locality along Rock Creek is somewhat an exception in that it tends to be slightly more micaceous and sandier than usual. In addition, in Rock Creek the highly glauconitic facies of the Keasey Formation occurs approximately 50 to 100 m upsection (200 m downstream) from the contact with the Cowlitz rather than at the base.

Pumice is prevalent in both the lower and upper Keasey (Mumford, 1988) as large irregular white fragments (up to 0.8 cm diameter) randomly dispersed in dark Keasey mudrocks (e.g., locality 162).

Clastic dikes and rare channelized arkosic sandstone interbeds have been reported as a distinguishing feature of the Jewell member in nearby Clatsop County (Rarey, 1986; Mumford, 1988). However, 1 thin (12 cm) pebbly clastic dike was observed in my area near the Keasey type locality (locality 163), and Farr (1989) has recently discovered similar arkosic clastic dikes farther east in Columbia County. These clastic sandstone dikes probably formed through rapid loading of sandstone bodies within the Keasey, with subsequent liquefaction and remobilization causing sand to be injected upward into fractured Keasey mudstone during early burial.

Scattered thin (1 - 2 m) basaltic pebbly turbidite sandstone beds also occur in the lower Keasey Formation. They are similar to the glauconitic facies in that they are most abundant at the basal part of the Keasey but also occur at higher stratigraphic levels within lower Keasey mudstones. However, glauconitic and basaltic beds are generally mutually exclusive. In the thesis area the basaltic turbidite beds are characterized by well rounded basaltic pebbles in clast support, limited in areal extent and displaying lenticular geometries. Basaltic sandstones have also been reported from the Jewell member, where they are fine-grained, graded, and occur in the "upper middle" part (Mumford, 1988). However, this study and Farr (1989) report abundant basaltic pebbly sandstone beds in basal Keasey outcrops. A fresh road cut (locality 44) exposes a typical example of this facies, which consists of 1.5 m of weakly normally graded basaltic pebbly sandstone, containing large parallel flute casts (5 x 10 cm) scoured into chippy mudstone (Figure 32). The flute casts, graded bedding, and lenticular geometry of this deposit suggest turbidity current deposition in small submarine paleochannels.

The generic name, Keasey Formation, has been retained for Refugian mudrocks in my area, rather than adopting the informal Jewell member of Olbinski (1983) in the adjacent Clatsop County area. Furthermore, this study indicates that there are significant lithologic and biostratigraphic similarities between the Jewell member of the

Figure 32. Exposure of large parallel flute casts in pebbly basaltic turbidite sandstone bed in lower Keasey Formation. Underlying Refugian chippy mudstone is fossiliferous and tuffaceous. Locality 44.

Keasey Formation described in Clatsop County (Rarey, 1986; Mumford, 1988; Niem and Niem, 1985) and the type Keasey in Columbia County.

Contact Relations

The upper contact of the Keasey Formation with the Pittsburg Bluff Formation is not exposed in the thesis area. A pronounced regional unconformity has been reported at the base of the Keasey in the Mist Gas Field 5-10 miles north of my field area (Bruer et al. 1984; McKeel, 1983). The erosional nature of the contact is evidenced in well log correlation which indicate parts of upper Cowlitz mudstone are truncated by the Keasey Formation. Structure contour maps of the base of the Keasey show considerable relief and indicate deposition over an irregular eroded surface (J. Meyer, 1989; pers. comm.). In addition, most of the major faults mapped in the subsurface in the Mist area offset the Cowlitz Formation but are truncated by the overlying Keasey Formation (Alger, 1985).

Mumford (1988) and Rarey (1986) suggested that glauconite at the base of the Keasey marks a minor unconformity or diastem between the Jewell member and the underlying Sweet Home Creek member or Cole Mountain basalt in Clatsop County. Glauconite has long been recognized by geologists as having sedimentological significance as an unconformity indicator. However, the mere presence of glauconite is not sufficient to indicate an unconformity because it may also reflect a period of slow sedimentation in a marine environment (Burst, 1957).

In my area, the Keasey/Cowlitz contact is observed in a few places, and in each place Keasey strata overlie Cowlitz sandstones with apparent structural conformity. In fact, locality 156 records a 3 m thick transitional contact from "clean" arkosic C & W sandstone into Keasey mudstone containing interbedded glauconitic sandstone layers with minor ovoid (22 cm) calcareous concretions. Well-sorted 10 - 25 cm thick mixed glauconitic arkosic sandstone layers are regularly intercalated every 9 cm with glauconitc mudstones, grading upward into sparsely glauconitic tuffaceous mudstones of the lower Keasey Formation. These fine-grained glauconitic sandstones at the contact texturally resemble arkosic micaceous Cowlitz (C & W) strata. For this reason, the decision regarding whether to include them in the uppermost Cowlitz Formation or basal Keasey is potentially ambiguous. Modal analyses of C & W sandstone core and outcrop from upper parts of the Cowlitz Formation indicate that only trace amounts of glauconite are present (Table4). In addition, Farr (1989) has described similar well-sorted sandstones from the lower Keasey which are composed almost entirely of plagioclase, unlike the potassium feldspar-rich C & W. Therefore, I interpret these arkosic glauconitic sandstones to represent reworked C & W sandstone with an additional volcanic source contributing the abundant plagioclase and thus choose to place them in the lower Keasey Formation.

In the Mist Gas Field, the caprock for the C & W sandstone is the deep-marine upper Cowlitz mudstone (see: core IW 33C-3, Appendix XII). This unit is characterized by slightly more resistive and irregular electric log signatures than the monotonous straight line resistivity signatures of the Keasey Formation (Figure 33). The upper Cowlitz mudstone, between the C & W sandstone and the Keasey Formation, approaches 335 m thickness at the center of the Mist Field, but thins rapidly or is cut out by the Keasey unconformity toward the south, where it attains a maximum outcrop thickness of 0 - 17 m in the thesis area (Plate I). In fact, the upper Cowlitz mudstone is not present between the C & W sandstone and the Keasey Formation in most of the field area (Plate I).

In addition, the thickness of the C & W sandstone also seems to vary considerably in northwest Oregon, from a maximum of 300 m at Mist (subsurface), to

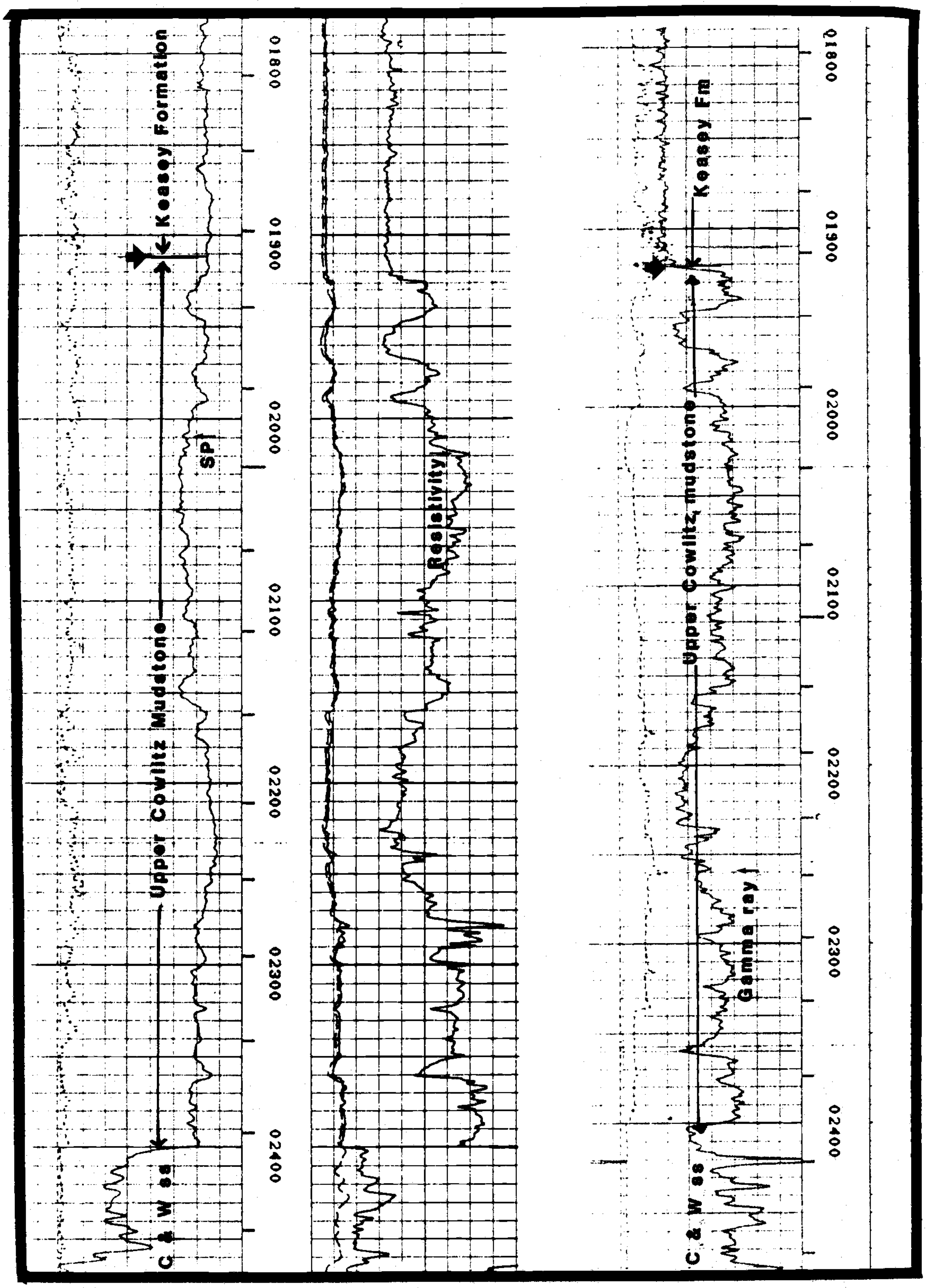


Figure 33. Portions of geophysical well logs from OM 41A-10 well in Mist Gas Field (see Figure 2 for location). Note irregular electric log signature of upper Cowlitz mudstone compared with smooth, flat SP and resistivity signatures of the Keasey Formation. Also note the abrupt decrease in the gamma ray log at the Cowlitz/Keasey contact due to the tuffaceous Keasey mudstones.

150 m in the north part of my area, to less than 15 m in the southwest part (Plate I). Some of the thickness variability of the C & W sandstone may be attributed to complex and dynamic depositional conditions along a storm-dominated Eocene shoreline. However, the thinning and attenuation of both the upper Cowlitz mudstone and the C & W sandstone in the field area may also be a function of the erosional "Keasey unconformity". Pebbly basaltic turbidite sandstones in the lower Keasey (Figure 32; locality 44) attest to high-energy currents and irregular topography developed on the deep seafloor during the earliest Refugian. These turbidites consist predominantly of Tillamook Volcanic detritus, which may be the product of Tillamook uplift and subsequent erosion at that time. The unconformity with the Keasey may be related to this renewed uplift and subsidence.

In summary, although there is no outcrop evidence for a regional angular unconformable contact other than glauconite between the Keasey and the Cowlitz formations in southern Columbia County, the abrupt changes in fauna, lithology, inferred paleobathymetry, the presence of glauconite and reworked Cowlitz deposits at the base of the Keasey, and apparent thinning of upper Cowlitz facies, all suggest that this contact is unconformable, although perhaps of relatively small magnitude (i.e., short time). The cause of this unconformable relation is speculative, because erosional unconformities are usually associated with subaerial exposure (Reineck and Singh, 1980). However, the late Eocene in Oregon was a time of complex and dynamic plate configurations (Snavely, 1987), concomitant with the beginning of western Cascade and Coast Range volcanism, subsidence and development by warping of many small basins within the forearc, and inundation of the forearc basin by the "Keasey sea". These developments may have resulted in an irregular seafloor topography, a sedimentation hiatus, and possibly creation of the Cowlitz/Keasey submarine unconformity.

Age

The Keasey Formation in the thesis area is uppermost Narizian to lower Refugian in age. This age is indicated by *Cibicides haydoni* (Appendix III) (Dan McKeel, 1988, writ. comm.). This species is restricted to the lower Refugian in California; however, in the Willamette Valley it occurs in both the lower Refugian and upper Narizian sporadically (Dan McKeel, 1988; writ. comm.). Two Keasey samples also contained coccoliths which were assigned to Zone CP14 or CP15 (upper Narizian-Refugian; Figure 5) based on the range of *Cribrocentrum reticulatum* (Bukry, 1988; wri. comm.). Unfortunately, the samples lacked the guide species *Discoaster barbadiensis* and *Isthomolithus recurvus* which would have narrowed the range considerably. Molluscan fossils identified by E. Moore (1988; Appendix II) were not particularly age diagnostic. However, bathyal gastropods of the family Turridae are considered to be indicative of the Refugian Keasey Formation (Hickman, 1976). Many micropaleontologists now place all of the Refugian in the late Eocene, whereas molluscan specialists rarely separate the two foraminiferal stages and feel the Refugian includes the early Oligocene (E. Moore, 1988; writ. comm.). The question of the age of the Refugian stage is bound up in unresolved international biostratigraphic controversy over the location of the Eocene-Oligocene boundary.

Age assignments made by Kristin McDougall for the Jewell member in Clatsop County (Mumford, 1988) are identical to those of the type lower Keasey Formation along Rock Creek (McDougall, 1980); some samples were assigned to the upper Narizian, while the rest were considered to be Refugian. Thus, the type Keasey and Jewell member appear to be age equivalent. On this basis, McDougall (*in* Mumford, 1988) concluded that the lower Jewell member straddles the upper Narizian/lower

Refugian (Eocene/Oligocene) boundary. However, it is possible that erosion reworked Cowlitz Formation Narizian microfossils during Refugian time (Niem and Niem, 1985). For this reason, some subsurface workers in upper Eocene stratigraphy prefer to make the Cowlitz/Keasey formational break, in part, on the basis of the first Refugian microfossils (Alger, 1985; Meyer, 1988; pers. comm; McKeel, 1988; writ. comm.). Specifically, highest Narizian strata are marked by the highest occurrences of *Cibicides natlandi* in neritic to upper bathyal facies and *Bulimina microcostata* in the upper middle bathyal (McKeel, 1983).

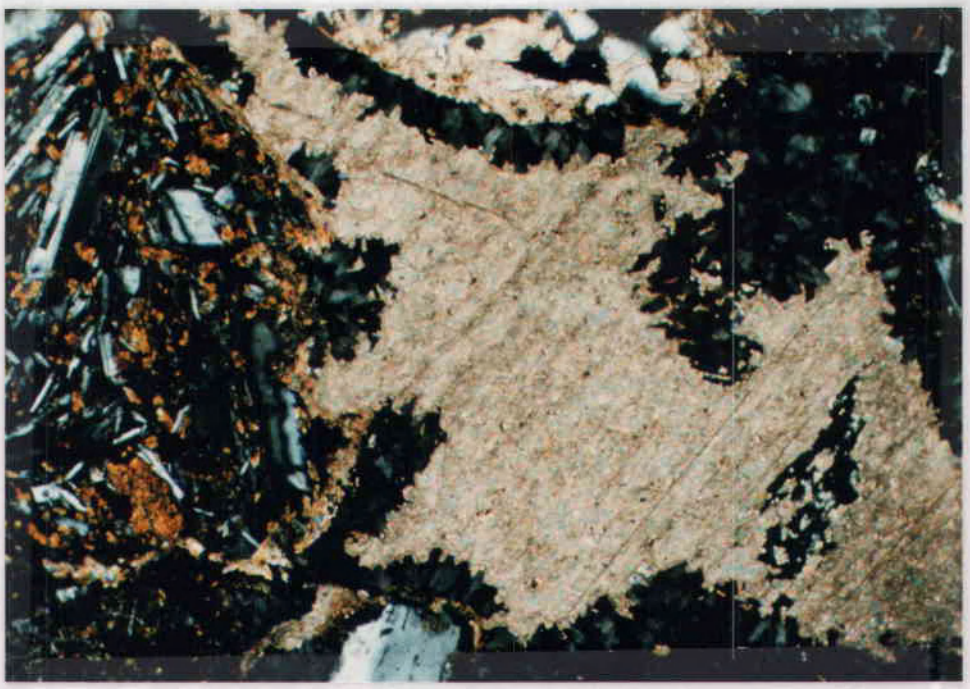
Petrography, Diagenesis and Clay Mineralogy

Four thin sections from the Keasey Formation were examined. The thin sections of basaltic and glauconitic sandstones were sampled from the coarser facies of the basal Keasey. In addition, SEM and EDX analyses wwere made on one basaltic turbidite from the Keasey, and X-ray diffraction was performed on one mudstone sample for clay mineralogy determination.

A basaltic turbidite interbed in the lower Keasey mudstone (sample 720; locality 44: Figure 32) was studied in detail. This poorly to moderately sorted sample contains 72% framework clasts, 17% cement, and 5% matrix. Clasts range from medium sand to pebble size; however, median grain size is very coarse sand to pebble, with 0.7 to 0.9 sphericity (Pettijohn et. al., 1973). The sample is texturally submature to mature because the clasts are well rounded but not well sorted. The sandstone is compositionally immature due to the predominance of volcanic rock fragments and is classified as a volcanic-arenite (Folk, 1974).

Most detritus in the sample is relatively fresh and exhibits only mild alteration, permitting reliable provenance determinations. Of the detrital volcanic clasts, approximately 45% are aphyric basalt clasts with pilotaxitic flow texture, 15% are porphyritic pilotaxitic clasts, 15% have intersertal texture, and 5% contain equigranular to porphyritic textures (Figure 34). The pilotaxitic basalt clasts generally have strong alignment of plagioclase microlites and a high percentage of opaques in the groundmass. Many of these clasts also contain augite and glomerocrysts of augite with plagioclase. Thus, the volcanic clasts are texturally and lithologically identical with Tillamook Volcanics (compare Figures 10 and 34). Clasts with intersertal and equigranular texture are reminiscent of Cole Mountain basalt (or Goble Volcanics) textures described in this thesis and by Safley (1989). Approximately 9% of the volcanic clasts are very finely crystalline and glassy and may reflect a more silicic composition commensurate with the beginning of western Cascade arc volcanism, or differentiated upper Tillamook Volcanics (see: Tillamook Volcanics Petrography). The remaining mineralogy is composed of medium sand size particles of angular plagioclase (6%), strained monocrystalline quartz (3%), and pyroxene (augite) (2%). Glauconite and calcite-replaced molluscan shell fragments are present in trace quantities. Detrital plagioclase in the sample exhibits combined albite/carlsbad twins and Carlsbad twinning: An content ranges from An50 to An60 (andesine to labradorite), typical of Tillamook and Cole Mountain basalt.

Clast composition is dominated by Tillamook Volcanic fragments, which probably reflects steepening and erosion of a submarine or subaerial basement high or irregular topography developed on the continental slope (see: Depositional Environment). The possibility of continued Tillamook eruptions during Keasey time is considered improbable due to inconsistency with mapped Keasey and Hamlet stratigraphy overlying the Tillamooks and the contribution of Cole Mountain and Cascade-dervied volcanic detritus in the sample.



1mm

xn

Figure 34. Photomicrograph of pebbly basaltic turbidite bed in Lower Keasey Formation. Note clay-altered, flow-aligned clasts probably derived from Tillamook Volcanics. Also note diagenetic zeolite and late-stage calcite filling intergranular pores. Sample 720 (locality 44).

Detrital matrix is difficult to determine in the sample but is estimated at only 5%, in the form of fine-sand size feldspars, opaque minerals and augite. Pseudomatrix is also considered to be minor due to lack of clay and the fresh unaltered condition of the framework clasts with sharp grain boundaries. The paucity of matrix indicates moderately high depositional porosity, allowing pore fluid migration and precipitation of extensive diagenetic cements, similar to what Chan (1985) described in early to middle Eocene sandstones of the southern and central Oregon Coast Range. The "clean" condition of the thin section allowed for a paragenetic sequence for diagenetic phases to be worked out.

This sample has undergone significant diagenesis and cementation somewhat similar to that described by Galloway (1979) and Burns and Ethridge (1979) for Tertiary volcaniclastic sandstones in the Pacific Rim, which has largely served to obscure all primary porosity and permeability. Early diagenesis (stage 1) began shortly after burial with formation of thin clay rim cements around framework clasts. Some compaction and grain rotation probably occurred during this stage. Virtually all the larger rock fragments in the sample are lined with very thin smooth brown clay coats parallel to the grain surface. Clay rims are typically formed by illuviation of colloidal material onto the grains and form at shallow to intermediate depths of burial (323 to 1300 m; Galloway, 1979).

The next stage (stage 2) of diagenesis was in *situ* alteration of lithic fragments and plagioclase. Groundmass in some basalt grains has partially altered to a yellowish-brown birefringent and fibrous chloritic or smectitic clay. Many glassy volcanic rock fragments have devitrified and are totally replaced by smooth opaque clay. However, their volcanic origin is recognized by scattered relict plagioclase laths and retention of the original grain form.

Increasing diagenetic alteration typical of intermediate depths of burial (i.e., 960 to 3225 m; Galloway, 1979) produced an incomplete pore-filling cementation stage. This phase (stage 3) is represented by precipitation of authigenic zeolite cement which lines and partially fills pore spaces (Figure 34). In some instances, it appears that the zeolite has also partially replaced clay coats at grain contacts. The tabular habit, biaxial positive optic figure, and weak birefringence suggest that the zeolite may be clinoptilolite-heulandite.

With greater depths of burial, a late stage (stage 4) sparry calcite cement completely infilled the center of the pores and replaced many volcanic rock fragments and some plagioclase feldspars (Figure 34). In places, calcite cement seems to have incorporated broken clay rim pieces. Broken clay rims may have resulted from dissolution of original grains and subsequent collapse of the surrounding rims (Chan, 1985) and/or compaction of the grains.

Some features indicative of mechanical crushing and compaction during burial are present in the form of crushed and fractured plagioclase feldspars parallel and perpendicular to cleavage planes, strained quartz with warped subparallel lines, and some broken clay rim cements. Compaction of the loose volcanic sand probably progressed until extensive zeolite and calcite cement produced a rigid, lithified rock. Some secondary porosity is developed by partial leaching and dissolution of detrital grains and selective leaching of feldspar phenocrysts as well as calcite cement dissolution (or incomplete cementation). However, total estimated porosity does not exceed 5%.

According to Boles (1980), paleotemperatures of about 100° C are adequate for zeolite formation. Organic maturation indexes from vitrinite reflectance analyses, Tmax, and source rock character (see: Source Rock Analysis) indicate thermal immaturity (Roberts, 1989; writ. comm.) and hence paleotemperatures considerably less than 115°

C for most of the late Eocene section in the thesis area. Therefore, other factors beside temperature alone had important influences on diagenesis. The abundance of Ca-rich detritus (plagioclase and mafic volcanic fragments) as well as the Ca-rich diagenetic phases (Ca-rich zeolites and calcite) indicate that the original bulk sandstone composition and the Ca^{++} ion concentration of pore fluids were very important factors in the resulting diagenetic history of these rocks (Chan, 1985).

Sample 769 (locality 163) is a very poorly sorted highly altered sample containing approximately 30% basaltic rock fragments, 20% sedimentary clasts, 20% plagioclase, 5% quartz, and 3% pyroxene. Glauconite and heavy minerals are present as accessory minerals. This sample is compositionally similar to the previously described thin section (720) in consisting of basalt grains with birefringent clay rims cemented by zeolite. However, sample 769 lacks sparry calcite cement, and average clast size is fine to coarse sand. Larger clasts tend to be basaltic and well rounded, whereas finer grained plagioclase, monocrystalline quartz, and pyroxene framework clasts are subangular. Basaltic clasts have a groundmass which is altered to pseudomatrix and dark brown iron oxide stained smectitic clays, preventing a thorough diagenetic assessment. The extremely poor sorting, mudstone rip-ups and abundant clay matrix in this sample suggest turbidity current transport down steep submarine slopes.

Sandstone sample 751, from a 1 m thick green massive sandstone (locality 156) contains 90% glauconite (Figure 35). Glauconite is well rounded, medium to coarse sand size, and well sorted with clay rims and "smectite" (?) completely filling pores between grains. Glauconite is recognized by "granular" texture and green color in both ordinary and polarized light. Rounding does not necessarily indicate abrasion, as this glauconite was probably produced as fecal pellets *in situ* in a slightly reducing

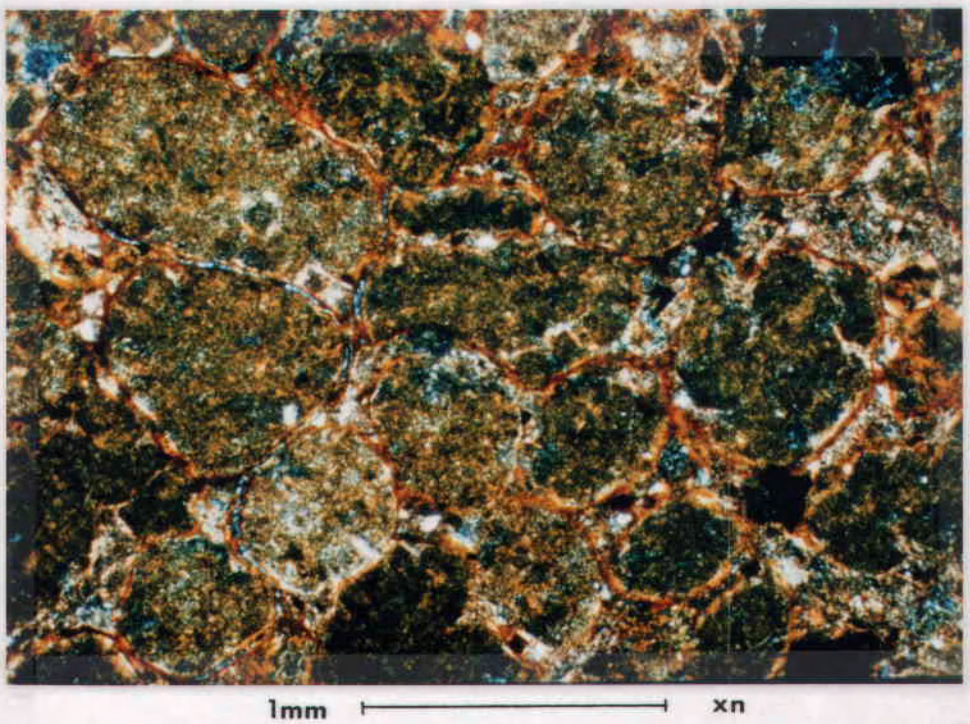


Figure 35. Photomicrograph of coarse-grained glauconitic sandstone interbed typical of basal Keasey Formation near unconformable contact with C & W sandstone. Note how some clay-rimmed glauconite grains have been mildly squashed by burial compaction. Sample 751 (locality 156).

environment (Scholle, 1979; Burst, 1957). Minor subangular plagioclase (5-7%) is present as detrital matrix.

Sample 767 (locality 41) is a thick sandy siltstone, containing mostly iron stained birefringent clays preferentially oriented with some angular plagioclase, minor quartz, and glauconite as fine sand size detrital particles. Extreme changes are noted in overall birefringence of the clays as the stage is rotated with crossed polarizers, an indication of fissility of the sample formed during burial compaction.

The clay size fraction was separated from a tuffaceous mudstone (sample 774; locality 174) for X-ray diffraction analysis. Preparation methods and identification of clays by X-ray diffraction were discussed in the petrography and clay mineralogy section of the Sweet Home Creek member. The diffractogram (Figure 36) shows that the sample consists of nearly 100% smectite, with a small peak at 8.33 that is probably a hydrous zeolite (clinoptilolite). The X-ray diffraction patterns are generally similar to those for Sweet Home Creek mudstone samples (Mumford, 1988), except zeolite is present in greater quantities in Keasey mudstones. Although illite and kaolinite are present in minor quantities in Sweet Home Creek mudstones, these clays are absent in Keasey sample 774. The lack of illite probably reflects the fact that Hamlet mudstones are micromicaceous and derived in part from a granitic source (e.g., Idaho Batholith) in contrast with the tuffaceous Keasey derived from the western Cascade arc.

Smectite in the Keasey probably reflects a volcanic source terrane, similar to smectite formation in the Sweet Home Creek member. Smectite is commonly derived from weathering of poorly drained soils developed on volcanic bedrock (Glasmann, 1982). The presence of silicic fragments in the Keasey may indicate weathering of volcanic topography in warm humid climates during development of the western Cascades arc. However, glass shards (Appendix III), pumice fragments, and basaltic sandstones in the Keasey may indicate smectite formed through devitrification and later

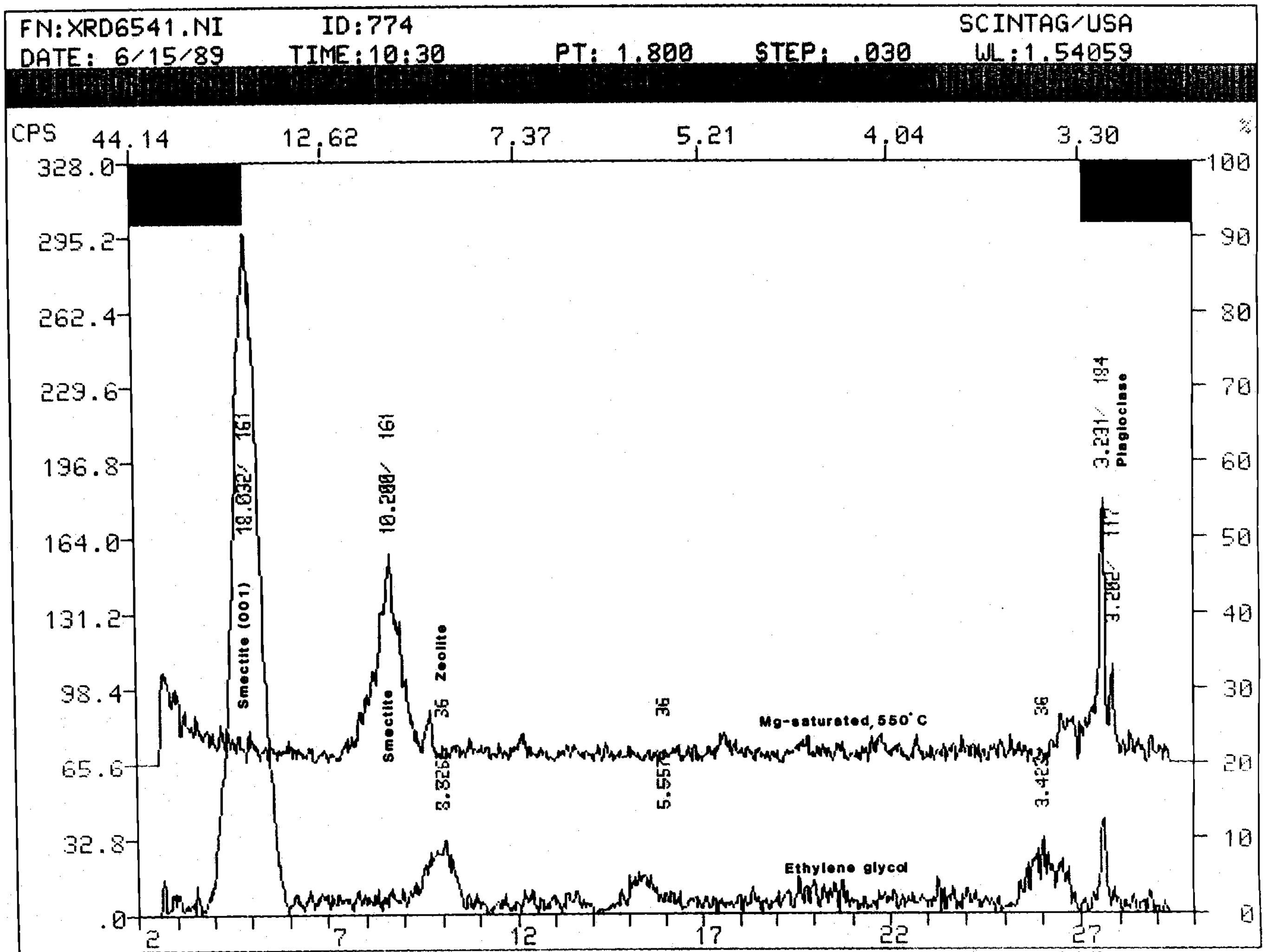


Figure 36. X-ray diffractogram of mudstone sample 774 (locality 174) from middle Keasey Formation. Note collapse of 18 angstrom smectite peak upon heating and shift to 10 angstroms. Also note small peak at 8.3 angstroms, consistent with zeolite.

diagenetic alteration of volcanic rock fragments. This is consistent with abundant clinoptilolite in the Keasey, which commonly forms by devitrification of volcanic glass and mild metamorphic alteration of tuff or ash deposits (Phillips and Griffen, 1980).

Depositional Environment

Two localities within the Keasey Formation contained paleoecologically diagnostic foraminiferal assemblages (samples 724 and 774: Appendix III). In addition, molluscan fossils (Appendix II) identified by E. Moore (1988; writ. comm.) provided some constraints on environmental interpretations. Upper bathyal depths in the lower Keasey (locality 125) are indicated by the Foraminifera *Cassidulina globusa*, and by *Costate uvigerina* in the middle to upper Keasey (locality 174) (McKeel, 1988; writ. comm.). Foraminifera collected in the lower Keasey (locality 125) constitute a slope assemblage in contrast with the upper Keasey assemblage which is characteristic of the shelf-slope break. This apparent shallowing-upward trend near the top of the Keasey in southwest Columbia County may be a precursor to deposition associated with the overlying shallow-marine Pittsburg Bluff sandstone (Moore, 1976; Olbinski, 1983).

Paleobathymetric ranges provided by E. Moore (writ. comm.; 1988) for the molluscan fossils collected in the Keasey mudstone are not as simply interpreted. The spiny pearly gastropod *Bathybembix columbiana* (locality 44; Plate 1) is a cool deep-water genus, and is a characteristic form from the Keasey Formation (Moore, 1988; writ. comm.). However, several of the molluscan species collected from the same or nearby outcrops (i.e., localities 44 and 174) have modern equivalents which live in shallow, oxygenated water. For instance, the pelecypod *Acila (Truncacila) nehalamensis* G. D. Hanna collected from the Keasey lives today in the eastern Pacific at depths between 5 and 200 m. These shallow - water molluscan fossils are interpreted to have been transported postmortem from a shelf setting into a deeper water (bathyal) slope environment. Graded, channelized basaltic coarse-grained sandstones are interbedded with these thick, massive fossiliferous mudstones and probably represent turbidity flow transport and deposition off local older Tillamook Volcanic highs on the outer shelf or upper slope, or off the nearby "Nehalem Arch" of Armentrout and Suek (1985). Rip ups, flame structures, and graded fine-grained silty sandstones in the lower Keasey along Rock Creek near the contact with the Hamlet formation (Plate I) all attest to high sedimentation rates and a turbidity current or mass flow origin for this facies.

On the other hand, formation of glauconite is favored by slightly reducing conditions and low sedimentation rates, such as on isolated uplifted or topographic highs on the outer continental shelf (Kulm et al.,1975; Burst, 1957). Mumford (1988) suggested that glauconite rip-ups in the Keasey were transported downslope from outer shelf settings into a bathyal environment. However, some nonfossiliferous Keasey mudstones yielded glauconite "floods" upon disaggregation (see sample 751: Appendix III) and probably represent *in situ* glauconite production and slow deposition by hemipelagic and biogenic sedimentation near the oxygen minimum zone (Douglas and Heitman, 1979). Glauconite also forms on the continental slope off the southern California borderland and some occurs in graded beds that were swept off isolated highs into adjacent slope basins in late Miocene strata (Niem, 1989; pers. comm.).

The predominance of tuffaceous material (glass shards, pumice fragments, and smectitic clays) reflects settling of fine ash and clay altered ash through the water column, while discrete tuff beds may represent reworked turbidity currents or base of slope contourites (Mumford, 1988). These tuff beds probably signify the onset of western Cascade calcalkaline explosive volcanism.

In summary, sediment textures and composition in the Keasey Formation are related to both sediment source and to depositional processes. Irregular seafloor topography resulted in dominantly hemipelagic sedimentation on the continental slope, occasionally interrupted by coarse influx of clastic (basaltic) material from bank and ridge tops of Tillamook Volcanics. Consequently, the Keasey Formation (especially lower Keasey) records a complex array of dynamic slope and basin environments ranging from outer shelf to deep slope, anoxic to oxygenated (fossiliferous), and from slow sedimentation rates characterized by glauconitic mudstones to areas of rapid sedimentation rates characterized by thick tuffaceous detritus.

IVY CREEK FORMATION

The name, Ivy Creek formation, is informally proposed for an Oligocene (?) nonmarine clastic deposit that occurs locally in the drainage basin of the upper Nehalem River (Plate I). Nearly continuous fresh exposures of the unit occur at the designated type locality (T5N R5W Sec. 28, NE 1/4) along the recently constructed (1983, by Longview Fibre Co.) Columbia County mainline. Other small exposures of this deposit can be observed in small logging roadcuts immediately adjacent to the type locality (Plate I). The informal name, Ivy Creek formation, is selected because Ivy Creek is the nearest (within 0.5 km) distinctive geographical feature to the formation (Plate I). The 17 m thick unit is easily separated into two facies consisting of: 1) a 8 m sequence of tuffaceous claystone grading into pebbly blue woody peat-rich clay; and 2) a thick (9 m) sequence of abundant cross-bedded coarse-grained to pebbly lithic volcanic sand and pebble gravels (Figure 37). The Ivy Creek formation is inferred to rest disconformably upon indurated Keasey mudrocks, although the contact is not exposed (Plate I).

Lithology and Sedimentary Structures

A measured section of the Ivy Creek formation (informal) shows the two distinctive lithofacies (Figure 37). The section begins in highly carbonaceous and woody peat-rich medium bluish grey (5 B 5/1) clay . The massive unconsolidated clay is generally structureless, poorly indurated, and contains pebbles of tuffaceous mudstone and nodules of partially lithified clay in matrix support. At 4.3 m, the silty clay contains mud dessication cracks indicative of periods of subaerial exposure. The upper part of this lower facies (from 6 to 8 m) consists of moderate blue (5 B 5/6) pebbly, gritty clay containing woody debris in the form of lignitic chunks, roots, tree

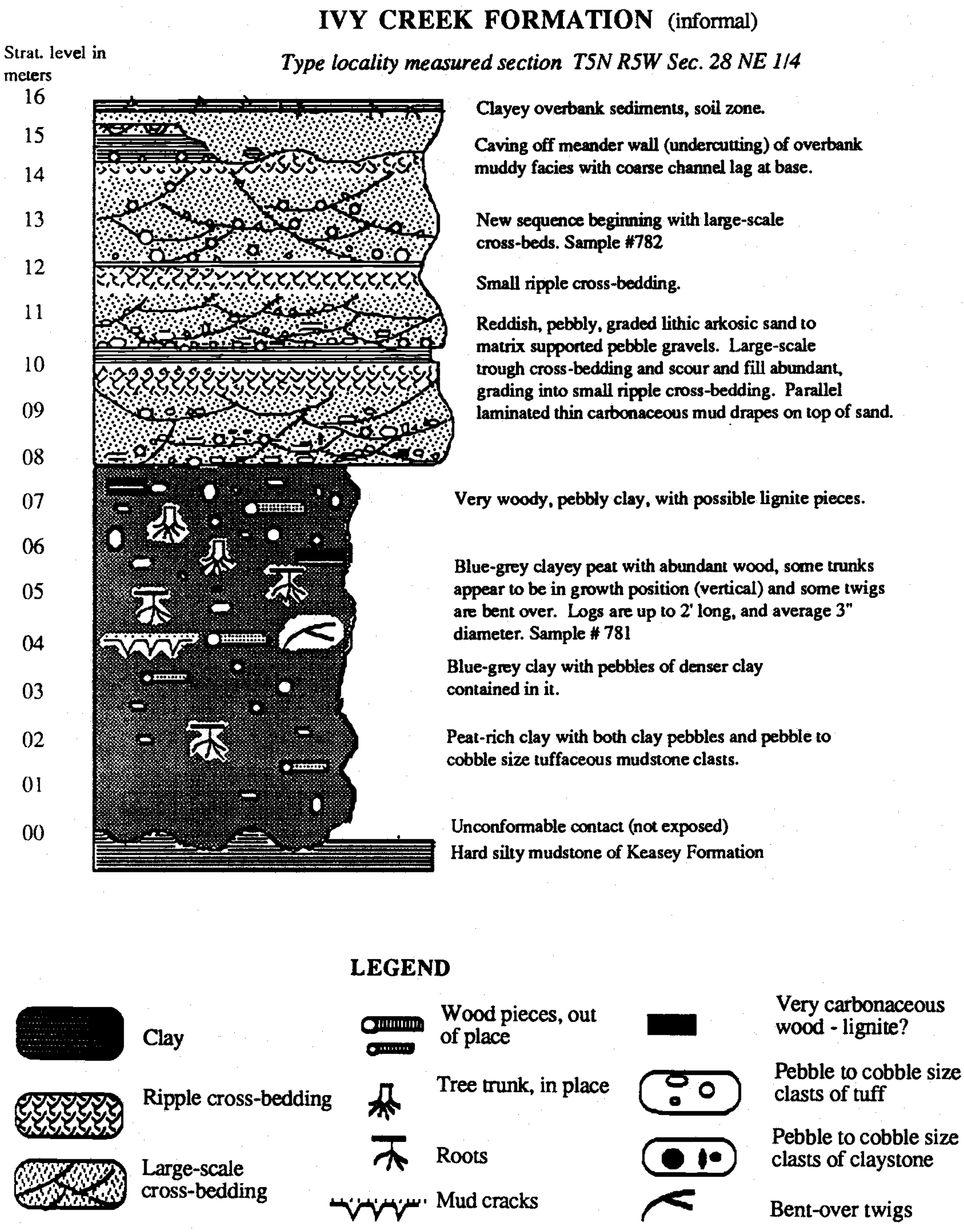


Figure 37. Ivy Creek formation (informal) measured section. Note separation into lower and upper lithofacies.

trunks, and abundant large wood pieces up to 45 cm long. Some of the blunted vertical stumps and thin tree stems appear to be in growth position and/or bent over in direction of the paleoflow of the pebbly mudstone.

At 8 m, the lithology changes abruptly from a carbonaceous pebbly clay-dominated sequence to a trough cross-stratified coarse-grained and pebbly lithic sand sequence about 9 m thick (Figure 37). The trough cross-stratified pebbly sand appears to have scoured and back-filled at the underlying contact with the blue-grey mud. Graded trough cross-beds have volcanic pebbly lag deposits at the bases, which fine upward within a set of cross strata to lithic and arkosic coarse-grained sand (Figure 38). Trough cross sets become smaller upward in the sequence and range from 22 to 50 cm in diameter, averaging 40 cm. A composite trough coset (McKee and Weir, 1953) grades into a thin sequence (15 cm) of small ripple cross-bedding in fine to medium-sand, capped by thin silty mud drapes and parallel laminated mud. The mud marks the top of a genetically related fining-upward sequence which is incompletely repeated three times. Within the upper sequence, large slump blocks of mud and mud rip-ups occur within the pebbly sand (Figure 39). These blocks consist of cohesive sandy organic-rich muds and are interpreted as cavings off channel walls (Figure 39).

Age

The Ivy Creek formation is tentatively assigned either a middle Oligocene or a post middle Miocene age. The Oligocene age is based on stratigraphic position above the upper Eocene Keasey Formation, and palynological analysis (Appendix IX) of clay sample 781 (Figure 37) performed by Ray Christopher of ARCO Oil and Gas (1989; writ. comm.) who suggested the middle Oligocene age. According to Christopher, the presence of several constituents (e.g., *Pachysanda* sp., Triporate type A of Piel,

Figure 38. Exposure of large-scale trough cross-bedding in fluvial Ivy Creek formation (informal), showing graded volcanic pebbly lags and fining-upward sequence. Locality 172.

Tricolpate A of Hopkins, *Graminidites* sp., and *Arecipites* sp.) indicate a post-Eocene (i.e., Oligocene) age for the deposit.

Due to lithologic similarity to the middle Miocene Scappoose Formation, I asked Christopher (1989; pers. comm.) if any of the pollen forms stretched into the Miocene. Unfortunately, there is a paucity of published palynological data for the Miocene of the Pacific Northwest. In addition, most ages based on pollen are the result of changes in climate rather than in evolution. However, Christopher (1989; pers.comm.) indicated that the sample lacks certain guide species identified from the late Oligocene of British Columbia (Piel, 1971). Christopher's "gut feeling", based on lithocorrelation and palynological analysis, remains that the deposit is middle Oligocene.

However, the Oligocene "call" by Christopher should be considered tentative or suspect for several reasons. First, the only Zemorrian (Oligocene) deposits known in the northern Oregon Coast Range are the deep-marine mudstones of the Smuggler Cove and Northrup Creek formations in Clatsop County (Niem and Niem, 1985), which crop out only 8 - 10 km west of these Ivy Creek formation fluvial deposits. The shallow-marine Pittsburg Bluff sandstone includes Zemorrian age sandstones and siltstones 8 km to the north and east of this unit (Moore, 1976). Secondly, the Ivy Creek formation is suspiciously poorly indurated (sand, gravel, and clay) for a deposit as old as Oligocene. Furthermore, the unit is nearly flat lying and not dipping like other Oligocene units in the northern Oregon Coast Range (Niem and Niem, 1985).

The Ivy Creek has lithologic affinities with the Pliocene Troutdale Formation, a fluvial deposit of the ancestral Columbia River (Niem and Van Atta, 1973). Therefore, further correspondence with Christopher was necessary to determine the likelihood of pollen reworking from Oligocene deposits. Christopher (1989; pers. comm.) indicated that pollen is often reworked; however, the diversity and preservation of large fern spores in Ivy Creek clay argues against long distance transport (i.e. reworking).

However, reworked marine diatoms do occur in the mudstone sample (781) (Barron, 1988; writ. comm.).

Nomenclature and Possible Scappoose Equivalence

Exposures of flat lying Ivy Creek are limited to a series of terrace-like outcrops along a part of the mainline that traverses a ridgeline. Outcrops flanking the ridgecrest consist entirely of Keasey mudrocks (Plate I). According to published accounts of Columbia County and eastern Clatsop County stratigraphy, several formations might overlie the Keasey. The Pittsburg Bluff, Sager Creek, Northrup Creek and Scappoose formations all have been reported to unconformably overlie the Keasey Formation at different localities (Warren and Norbisrath, 1946; Niem and Niem, 1985; Van Atta, 1971; Armentrout et al., 1983; Timmons, 1981; Kadri, 1982).

However, the Pittsburg Bluff Formation is predominantly a tuffaceous silty, fine-grained tuffaceous quartzo-feldspathic shallow-marine sandstone (Niem and Niem, 1985; Van Atta, 1971; Olbinski, 1983). In addition, surface exposures of the well indurated Pittsburg Bluff sandstones and sandy siltstones in Columbia and Clatsop counties are reported to be bioturbated and support a rich shallow-marine molluscan fossil assemblage (Moore, 1976), unlike the unconsolidated fluvially deposited Ivy Creek.

The Sager Creek formation (Vesper Church unit of Olbinski, 1983; Nelson, 1985) and the Northrup Creek formation have also been reported to unconformably overlie the Keasey Formation in the subsurface of Columbia and Clatsop counties (Niem and Niem, 1985; Dahleen, 1988; pers. comm.). However, the Sager Creek formation is a deep-marine channelized sequence of thin-bedded turbidite sandstones and laminated mudstones. Surface exposures of Sager Creek and Northrup Creek formations consist of well indurated highly carbonaceous and micaceous laminated mudstone and thin, very fine-grained arkosic sandstone (Goalen, 1988; Niem and Niem, 1985).

Conversely, the middle Miocene Scappoose Formation (particularly the lower Scappoose) of Columbia County as described by Kelty (1983) and Van Atta and Kelty (1985) superficially bears striking resemblance to the Ivy Creek formation (informal). The Scappoose Formation consists of two lithofacies; a basal nonmarine lithofacies and an overlying shallow-marine lithofacies. The nonmarine fluvial lithofacies consists of a basal poorly indurated, framework-supported, pebble to boulder conglomerate (Van Atta and Kelty, 1985) with dispersed gravel lenses in trough cross-bedded, medium to coarse-grained, micaceous lithic arkose sand beds. The basalt conglomerate contains clasts with middle Miocene Columbia River Basalt chemistry (Van Atta and Kelty, 1985). A nonmarine carbonaceous, tuffaceous, micaceous mudstone subfacies intertongues with the arkosic sand and is also contained in the fluvial channel sand as rip-up clasts and large slump blocks.

The upper marine siltstone lithofacies is tuffaceous and fossiliferous and intertongues with the fluvial arkose (Van Atta and Kelty, 1985). In their redefinition of the boundaries of the Scappoose Formation, Van Atta and Kelty (1985) showed through mapping, petrography, and geochemistry of the basalt clasts that the Scappoose Formation lies disconformably on both the Keasey and Pittsburg Bluff formations and interfingers with the Yakima Basalt (now Grande Ronde Basalt) of the Columbia River Basalt Group (CRB). Based on the interfingering relationship with CRB, Van Atta and Kelty (1985) revised the age of the Scappoose from Oligocene (Warren and Norbisrath, 1946) to middle Miocene.

Similarities between the lower Scappoose lithofacies and the Ivy Creek formation are numerous. Both formations consist of trough cross-bedded to conglomeratic sand with associated carbonaceous mud. Both are fluvially derived and rest disconformably (in places) on the Keasey Formation. However, there are important lithologic differences and missing key stratigraphic relationships in the Ivy Creek area which serve to dissuade the author from including this deposit within the Scappoose Formation. First, no CRB outcrops have been reported to exist within 5-10 km of this exposure (Kadri et al., 1983; Van Atta, 1988; pers. comm.). Therefore, an interfingering relationship with CRB cannot be established. Petrography of the pebbly lithic sand facies in the Ivy Creek formation was attempted in order to determine the provenance of the basalt clasts. However, due to extreme weathering (up to 2 m) of the exposed gravels and pebbly sands, thin section petrography of the pebbly sand facies is inconclusive to permit positive identification as CRB's. However, it is apparent that some of the basalt clasts exhibit pilotaxitic flow texture typical of middle to late Eocene Tillamook Volcanics (see: Tillamook Volcanics Petrography). These volcanic pebbles are typically bleached white in hand sample, in contrast with fresher CRB clasts of the Scappoose conglomerate and gravels.

Furthermore, the mudstone facies of the Scappoose Formation is considerably more indurated, micaceous and laminated than the unconsolidated blue clay of the lower Ivy Creek. In addition, the Ivy Creek formation has been assigned a middle Oligocene age based on palynological analysis by Ray Christopher of ARCO (1989; writ. comm.), whereas the Scappoose Formation has been shown to be middle Miocene in age (Van Atta and Kelty, 1985).

In conclusion, due to lithologic and stratigraphic resemblance to the Scappoose Formation, it can not be unequivally proven that the middle Oligocene (?) or post middle Miocene (?) Ivy Creek formation is a previously undescribed deposit. Indeed, further investigation of lithologically correlative exposures in Columbia County may render the Ivy Creek formation a "Scappoose equivalent". For example, Van Atta has included similar unconsolidated fluvial muds and cross-bedded sands and gravels near Mist in the Scappoose (Niem, 1989; pers. comm.). However, for the purpose of avoiding future misleading nomenclatural problems and because the deposit contains an interesting different facies assemblage with new palynological biostratigraphic evidence, the name Ivy Creek formation is tentatively assigned for this series of outcrops in southern Columbia County.

Depositional Environment

The sequence of carbonaceous clay with abundant woody debris abruptly overlain by trough cross-stratified to ripple-laminated coarse-grained graded pebbly sand capped by laminated mud probably represents a fluvial deposit (Reineck and Singh, 1980; Walker and Cant, 1986; Reading, 1978). Specifically, the upper Ivy Creek facies consisting of 3 repeated fining-upward cycles containing channel lag deposits which grade to large-scale trough cross-bedding and small ripple cross-bedding covered by a mud drape, resembles an idealized point bar sequence of a meandering river channel (Reineck and Singh, 1980). Deposition on point bars results from lateral migration of a meandering river during flooding. Point bar deposits have been described in detail by a number of workers (e.g.,Miall, 1978; Fisk, 1944; Harms et al, 1963) who have described the variability of these volumetrically important deposits.

Shape and size of point bars vary dramatically with the size of the river. For a river the size of the Mississippi, a point bar sequence can be as thick as 20 to 25 m (Fisk, 1944). Also, the preserved vertical sequence of a point bar depends upon the style of river migration (i.e., by avulsion, cut-off, or by the growth phase of a meander). The lithology and grain size of point bar deposits depends upon the grain size available. If rivers are carrying gravel to sand size material, the fining-upward change is from gravel, coarse sand to fine sand, and silt on the top. The limited areal extent of the Ivy Creek formation suggests that these deposits probably did not originate from a major meandering river system (i.e., Columbia River). However, Ivy Creek point bar deposits are characteristically coarse-grained, which indicates that a coarse-grained sediment source must have been nearby. Accordingly, the clast composition resembles surrounding Coast Range units (i.e., Tillamook Volcanics, Keasey mudstones) which suggest a small drainage basin like the present Nehalem River.

Cross-bedding (megaripple bedding) is the major current-formed bedding in point bars and results predominantly from deposition during floods (Reineck and Singh, 1980). In an idealized point bar sequence such as displayed in the upper Ivy Creek lithofacies, megaripple bedding grades upward to a zone of small-ripple bedding, overlain by sets of horizontal (parallel) stratification. Parallel stratification has been interpreted to represent flow in the upper flow regime (Harms and Fahnestock, 1965). However, the position of these horizontal laminations on top of current ripple bedding in a point bar deposit more likely represents deposition of suspension clouds due to decrease in water turbulance or current velocity in the lower flow regime (Reineck and Singh, 1980).

Silty and clayey layers are sometimes present as flood basin suspension deposits in an abandoned point bar if they are not eroded before the next depositional event. Furthermore, the ideal point bar sequence is not always developed because of fluctuations of the energy of the environment during a flood phase, complicating the overall fining-upward sequence. In the Ivy Creek formation, these clayey layers are very thin, less than 8 cm in thickness.

In general, point bar deposits are characteristically discontinuous and lenticular. Coarse-grained point bar deposits such as the Ivy Creek formation result from streams with low sinuosity (1.4 to 1.7) and typically show more complex facies differentiation than sand-silt point bar deposits (Reineck and Singh, 1980). Directions of cross-bedding in these deposits is quite variable due to control by local flow conditions. This is consistent with paleocurrent determinations from trough-cross bedding in the Ivy Creek formation, which show high variability in direction and no consistent orientation.

The lower part of the Ivy Creek formation, with thick deposits of blue-grey pebbly clay with abundant decayed lignitic plant matter, represents a flood basin with associated overbank flow deposition. Flood basins are flat areas adjacent to active or abandoned stream channels (point bars). Because they are low- lying, they are poorly drained and represent the long-continued accumulation of fine suspended sediment, where sedimentation rates are very slow (Reineck and Singh, 1980). The thickness of flood plain deposits depends upon the rate of shifting meandering channels and rate of subsidence.

In a humid climate flood basins are low, wet and thickly vegetated allowing for thick accumulations of plant matter. During overbank flows, the accumulated organic matter may be incorporated in peat layers associated with silty clayey sediments. Because of repeated exposure, flood basin deposits are subject to frequent periods of dessication. This pattern of flood deposition is recorded in the lower Ivy Creek, documented by the thickness of the clay and mud dessication cracks (6.5 m; Figure 37).

The occurrence of some tuff pebbles suspended in the massive clay and bent over rooted twigs and stems (up to 1 m long) suggest that part of the massive clay origin may be water-saturated debris flows of tuffaceous Keasey pebbles derived from the surrounding hills that flowed onto the flatter stream floodplain.

The palynomorph assemblage (Appendix IX) from the lower lithofacies is well preserved, moderately diverse, and consists entirely of terrerstrial plant fossils (Ray Christopher, 1989; writ. comm.). The assemblage is dominated by fern spores (especially *Laevigatosporites ovatus, L.* sp., and *Polypodiumsporites* sp.,) and contains gymnosperm pollen and angiosperm pollen. The abundance of large delicate fern spores suggests deposition in close proximity to the source, consistent with *in situ* plant growth in a flood basin.

Bordering the flood basin and the stream channel are typically natural levee deposits (Reineck and Singh, 1980). Levees gently slope from the river bank into flood basins away from the channel. Levees are formed by deposition of sediment when flood waters of a stream overtop its banks, resulting in deposition of bedload sediment near the channel. Natural levees are able to support much rooted vegetation. Thus, much plant debris and organic matter is incorporated by floods into levee sediments. Small levee deposits are present in the upper Ivy Creek formation in the form of slumped mudstone blocks formed by the river channel undercutting its levee walls (Figures 37 and 39).

Figure 40 shows a schematic aerial sketch of the interpreted sedimentological features during Ivy Creek deposition. A moderate flood plain was developed on the sides of a meandering river channel. Humid climate combined with occasional floods built up vegetated natural levee deposits. As the water overtopped its riverbank during very high floods, and incised mud-rich highlands, debris flows were initiated which carried woody debris and pebbly tuffaceous grit out over the vegetated flood plain, bending over rooted tree limbs and burying tree stumps.

Regional Implications

The fluvially deposited Ivy Creek formation, situated 145 m above the floor of the Nehalem River valley (Plate I), may be a remnant of a large fluvial deposit of the ancestral Nehalem River. Thus, it may record a transition from a former marine basin to a high relief eroded land area and commencement of uplift of the northern Oregon Coast

Figure 39. Exposure of large slump blocks of mud and pebbly sand in Ivy Creek formation (informal) interpreted as cavings off fluvial channel walls due to undercutting by erosive stream activity. Locality 172.

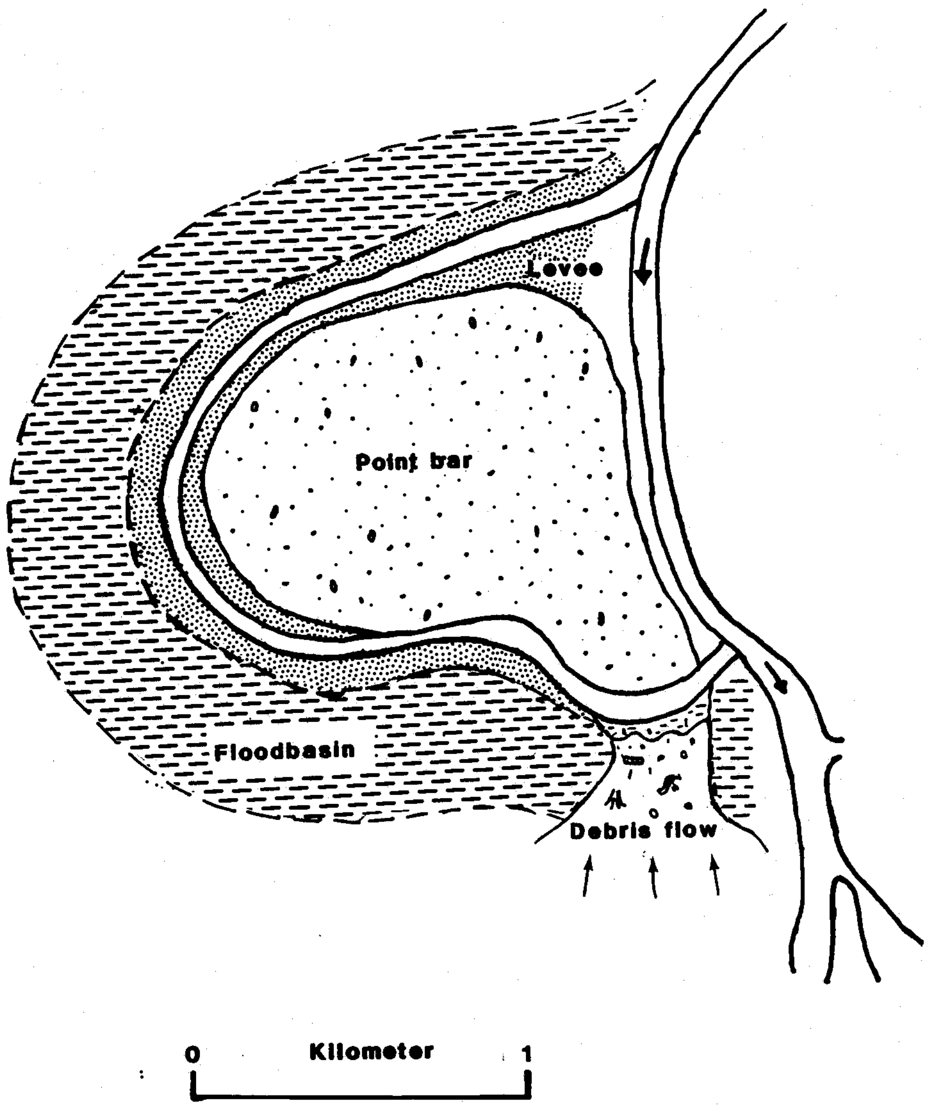


Figure 40. Schematic sketch of fluvial system during Ivy Creek deposition. Flood basin and debris flow correspond to lower Ivy Creek lithofacies, whereas point bar and levee correspond to upper Ivy Creek lithofacies.

Range during the middle Oligocene and/or late middle Miocene. Alternatively, the Ivy Creek deposit may record deposition of an ancestral and throughgoing Columbia River, before it was diverted north along its present course by the Tillamook uplift. Previously, uplift of the Oregon Coast Range has been considered to have begun in the late Oligocene and accelerated in the late middle Miocene (Snavely, 1987; Niem and Niem, 1984).

A sample of mudstone (781; Figure 37) from the lower Ivy Creek facies was initially examined for freshwater diatoms by Bradbury of the USGS (1988, writt. comm). Interestingly, the sample contained no freshwater forms, but Barron (1988; writ. comm) reported sparse fragments of the marine centric diatoms, *Coscinodiscus* and *Stephanopyxis* (or *Pyxidicula*). In addition, Kris McDougall (*in* Barron; writ. comm. 1988) identified the foraminifers *Bolivinia scabrata* Cushman and *Bermudez* as well as fish otoliths (scales) from the sample. According to McDougall, if the Bolivina species is in place, outer neritic water depths (100 - 200 m) are suggested.

Clearly, a marine origin for the Ivy Creek is considered extremely unlikely due to persuasive evidence from sedimentary structures, facies relationships, tree stumps in growth position, lithology and terrestrial palynology collectively indicating fluvial deposition. However, the presence of a few broken marine diatoms and two late Eocene or younger neritic Foraminifera suggest considerable reworking from the adjacent upper Eocene and Oligocene Keasey or Pittsburg Bluff formations. This is significant because it indicates the erosive nature of initial Ivy Creek deposition associated with degradation and incising commensurate with Coast Range uplift. Perhaps further detailed mapping in Columbia County will delineate additional exposures of this interesting but enigmatic deposit and hence provide important information pertaining to resolving the complex tectonic history of the northern Oregon Coast Range.

SURFACE - SUBSURFACE ANALYSIS OF CLARK AND WILSON SANDSTONE (COWLITZ FORMATION)

DISTRIBUTION AND DESCRIPTION

Nomenclature

A brief discussion of Cowlitz Formation nomenclature has already been provided under the section: Hamlet formation nomenclature. This discussion focuses in greater detail on those strata in the Pacific Northwest which have historically been referred to as Cowlitz Formation.

The Cowlitz Formation has undergone many significant changes since the name was initially proposed by Weaver (1912) for a 60 m section of Eocene sandstones, minor siltstone and coals exposed in bluffs on the west side of the Cowlitz River at the "Big Bend locality" one and one-half miles east of Vader, in southwest Washington. On the basis of molluscan fauna collected there, the Cowlitz Formation was considered to be slightly older than the typical marine upper Eocene Tejon formation of California. In a later paper presented at the Pasadena meeting of the Cordilleran Section of the Geological Society of America, Weaver (1937) expanded the definition of the type Cowlitz to include a 1,300 m thick late Narizian predominatly sandstone section exposed along Olequa Creek in southwest Wahsington. In the geologic report, Weaver (1937) described in detail the Tertiary formations and stratigraphy of the southwest Washington region (Cowlitz Formation and Metchosin volcanics), presenting maps, measured sections and a complete list of Tertiary faunal localities. He also implied that the lower part of the Cowlitz formation was exposed along Stillwater Creek southwest of Vader, but did not describe it at that time.

The results of a detailed collection and study of the Foraminifera from the Cowlitz River bluffs locality were presented in a paper by Beck (1943), who confirmed the Eocene age of the Cowlitz River strata by correlating the Cowlitz Formation in part with the Coaledo formation of Oregon and the Tejon and Poway formations of California. Beck critized Weavers amendment of the type Cowlitz because the Olequa Creek section was not included in the original definition and would necessitate two type localities for the Cowlitz Formation. Beck (1943) consequently limited the type Cowlitz Formation to beds exposed along the Cowlitz River.

More detailed mapping near the type section led Henrickson (1956) to subdivide the middle to upper Eocene Cowlitz Formation into four mappable members. In order of stratigraphic position, they are: 1) the Stillwater Creek member, consisting of marine and near-shore tuffaceous siltstones, mudstones, and sandstones, with minor thin basalt flows and basaltic sediments; 2) the locally restricted Pe Ell volcanics member, composed of lapilli tuff, agglomerate, breccia, and thin tuffaceous siltstones; 3) the Olequa Creek member, composed of brackish-water, marine, and terrestrial siltstones, sandstones, mudsones, and intecalated coal beds; and 4) the Goble volcanics member, which consists of basalt flows, flow breccia , and subordinate pyrotclastic rocks, which interfingers with sediments of the Olequa Creek member. With Henrickson's (1956) appendum of 5,400 feet of Stillwater Creek strata to the type section, the type Cowlitz represented the thickest predominantly marine Eocene section exposed in the Pacific Northwest. Henrickson interpreted the Cowlitz Formation to rest comformably on volcanic rocks of middle Eocene age.

Later investigations of Eocene sedimentary and volcanic rock units in southwest Washington by Livingston (1966), Buckovic (1979), Wells (1981) and Armentrout et al (1983) led to the redefinition of the Stillwater Creek strata as the McIntosh Formation, and the separation of the Goble Volcanics and the siltstone of the Skookumchuck Creek formation from the sandstone-dominated Cowlitz Formation.

On the basis of similarity of its molluscan fauna with that of the Washington type Cowlitz Formation, Warren and Norbisrath (1946) mapped the Eocene strata above the Tillamook Volcanics in the upper Nehalem River Basin of northwest Oregon as the Cowlitz Formation. However, Warren and Norbisrath did not compare the lithology of the Oregon upper Eocene beds to the type Cowlitz Formation of Weaver (1937). In their geologic report of the upper Nehalem River Basin, Warren and Norbisrath (1946) described the Cowlitz Formation as consisting of a basal conglomerate, a lower shale, an upper sandstone, and an upper shale.

Warren and Norbisrath similarly mapped the Cowlitz/Keasey contact along Sunset Highway (U.S. Highway 26; Figure 1) within the Keasey Formation (between the lower and middle members) because they considered fauna contained in the "lower" Keasey member to be Eocene. They pointed out; however, that although the contact may actually represent the boundary between the lower and middle Keasey members, the "lower" Keasey strata at the Sunset Highway locality was lithologically similar to the Cowlitz map unit.

In his unpublished Oregon State University master's thesis, Deacon (1953) suggested that the Oregon upper Eocene strata mapped as Cowlitz Formation by Warren and Norbisrath did not bear sufficient lithologic resemblance to the type Cowlitz of Weaver (1937) in southwest Washington to enable extension of the name "Cowlitz" into northwest Oregon. Deacon (1953) informally proposed the name Rocky Point formation for late Eocene strata in the upper Nehalem River Basin, specifically for exposures along Rock Creek (in this study area) and along the Nehalem River. The type locality of the 550 feet thick Rocky Point formation was on Rock Creek about a quarter of a mile downstream from Keasey Station (Plate I). The Rocky Point formation consisted of three major lithologic units: a lower member of basaltic conglomerate and medium grained sandstone; a micaceous middle siltstone member containing resistant, coarse sandstone beds; and an upper micaceous, concretionary sandstone member that weathers light brown.

Van Atta (1971) in his Oregon State University doctoral thesis, favorably compared the Rocky Point formation with the type Cowlitz of southwest Washington and recommended retainment of the Cowlitz terminology for the upper Eocene strata of the upper Nehalem River Basin. Since that time, numerous workers in western Columbia and eastern Clatsop counties have applied the Cowlitz Formation terminology to middle to upper Narizian sedimentary strata (i.e., Timmons, 1981; Jackson, 1983; Shaw, 1986; Olbinski, 1983; Nelson, 1985; Wells et al., 1983, Newton and Van Atta, 1976).

Recently, in order to conform to Weaver's (1937) original decription of the sandy type section in southwest Washington, Wells (1981) restricted the type Cowlitz Formation to the sandstone-dominated unit (Olequa Creek member of Henriksen, 1956). This sandstone (C & W) and an overlying mudstone (upper Cowlitz mudstone) have also been informally included as members of the Cowlitz Formation in the Clatsop County surface and subsurface (Niem and Niem, 1985) and in the subsurface in Columbia County (Bruer et al.,1984; Figure 6). These important restrictions make the Cowlitz in the upper Nehalem River Basin a distinctive mappable unit which correlates with the reservoir rock (C & W sandstone) at the Mist Gas field and the type locality in southwest Washington. For this reason, the lower two lithologic members described and mapped by Deacon (1953) in Rock Creek (and elsewhere in the field area) as Cowlitz Formation have hereupon been included in the Hamlet formation, whereas the upper member of Deacon represents the C & W sandstone of the Cowlitz Formation.

Distribution

The Cowlitz Formation (C & W sandstone member) covers approximately 11.4 square kilometers of the study area, and is well exposed along several streams and logging road cuts (Plate 1). C & W sandstone is the most widely distributed unit in the thesis area. The best outcrops of Cowlitz Formation sedimentary rocks in the area are exposed along the Columbia County mainline from the bridge at Fall Creek (T4N, R5W, Sec. 9 SE 1/4) to the contact with the overlying Keasey Formation (T4N, R5W, Sec. 15 NW 1/4). Other excellent C & W sandstone exposures occur along the Eastside Grade (T4N, R5W, Sec. 5 SE 1/4), on the banks and stream bottoms of Rock Creek (T4N, R5W, Sec. 5 NW 1/4), Clear Creek (T4N, R5W, Sec. 20 S 1/2), Deep Creek (T5N, R5W, Sec. 19 N 1/2), north of Selder Creek (T5N, R5W, Sec.31 NE 1/4), and near or along the Boeck Ranch Jeep trail (T5N, R5W, Sec. 30). C & W sandstone crops out in a series of faulted exposures striking generally east-west and dipping gently from 10 to 20 degrees. Large fault blocks of Tillamook Volcanics demarcate north dipping C & W strata to the north, from south dipping C & W to the south of the Tillamook Volcanic outlier (Plate I).

Regionally, the outcrop belt of C & W sandstone forms an arcuate but discontinuous pattern around the eastern periphery of the Tillamook Volcanics-Hamlet formation in Columbia, Clatsop, and Washington Counties (Figure 41). To the west, Cowlitz strata crop out in a narrow band just north of Green Mountain (Olbinski, 1983), to the east, C & W strata are exposed near Rocky Point and in the Nehalem River (Farr, 1989) and in the south in Washington County, C & W strata is exposed in stream cuts of the Reeher Park and Wolf Creek sections (Jackson, 1983).

Thickness

In most parts of the Mist Gas Field subsurface, the C & W sandstone member maintains an approximate thickness of 283 m when unfaulted (Meyer, 1989; pers. comm.). However, the thickness of the sand around the periphery of the producing

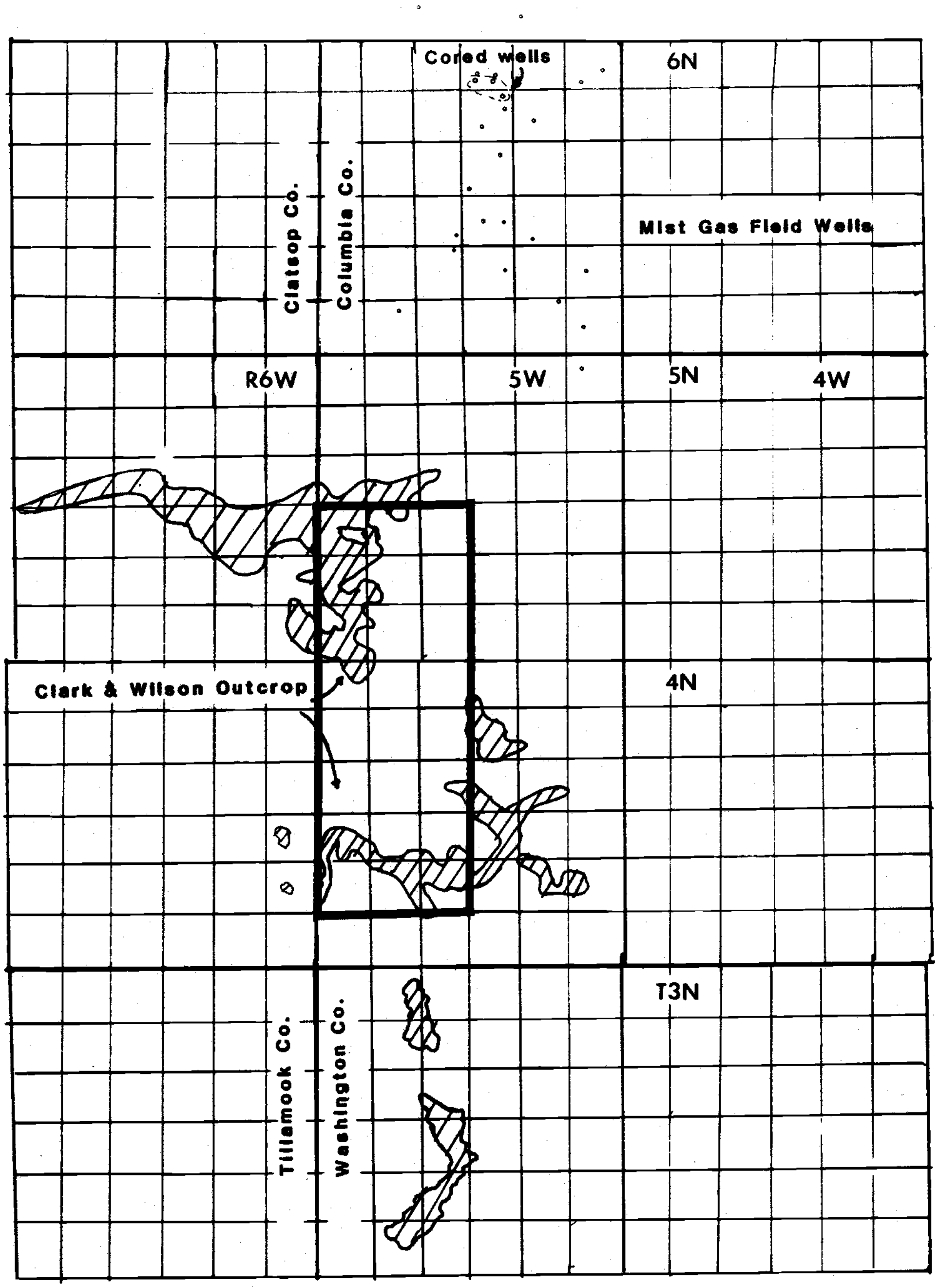


Figure 41. C & W sandstone outcrop distribution in northwest Oregon showing relationship to Mist Gas Field. Note general north-south elonation of outcrop. Field area outlined in black. Data from this study, Farr (1989), Olbinski (1983), Safley (1989), Jackson (1983), and Nelson (1985).

field is quite variable. For instance, in the northwest portion of the Mist Gas Field at well OM 12C-3, the total sand thickness is 100 m due to deposition and pinchout against the Tillamook Volcanics, whereas nearly 320 m of C & W sandstone is present in the thicker east part of the field (Jackson, 1989; pers. comm.). Similarly, the upper Cowlitz mudstone attains 320 m thickness in the center of the Mist Gas Field, but pinches out to the south due to the Keasey unconformity. In the thesis area, the upper Cowlitz mudstone ranges from being entirely absent in most of the thesis area, to only 6.5 m thick in section 28.

In the field area, the C & W sandstone ranges from approximately 16 m thickness (T4N, R5W Sec. 30) to nearly 134 m thickness (T4N, R5W, Sec. 28), and averages approximately 106 m thickness from partial measured stratigraphic sections and outcrop calculations. It is thinner than in the subsurface at the Mist Gas Field 15 km to the north due to erosion by the overlying unconformity of the Keasey Formation and general pinching out to the south and southwest.

Age and Correlation

The sedimentary rocks that are mapped as Cowlitz Formation in the study area and in the cores from the Mist Gas Field are assigned to the upper Narizian stage of Mallory (1959) on the basis of Foraminifera (Appendix IV) (McKeel, 1988; writt. comm.). Washed plugs from the cores OM 41A-10 and OM 12 C-3 were examined for biostratigraphic analysis by Dan McKeel (consultant for ARCO Oil and Gas Co.). Upper Narizian is indicated in the upper Cowlitz mudstone from core OM 41A-10 by the presence of *Cibicides natlandi*, *Karreriella contorta*, and *Lenticulina welchi*. See Appendix IV for the full list of Foraminifera. C & W sandstone is typically devoid of diagnostic foraminifera, however, Narizian undifferentiated is indicated by the arenaceous species, *Trochammina*. Molluscan fossils collected from lithofacies of surface Cowlitz exposures were non age diagnostic or identifiable (Appendix II).

Regionally, the Cowlitz Formation in the study area correlates with other formations in the Pacific Northwest that are assigned an Upper Narizian age (Figure 5). These formations include: the C & W sandstone in the Mist subsurface (Bruer et al., 1984), type Cowlitz Formation in southwestern Washington (Henricksen, 1956; Wells, 1981; Weaver, 1937), upper part of the Hamlet formation in Clatsop County (Niem and Niem, 1985; Rarey, 1986), the Spencer Formation in the east-central Coast Range (Baker, 1988; Al Azzaby, 1980) the Nestucca Formation of the central Oregon Coast and the Coaledo Formation of the southern Oregon Coast (Baldwin, 1974; Chan and Dott, 1986).

The above upper Eocene formations (except Nestucca Formation) of the Oregon Coast Range are similar to the described lithofacies of the Cowlitz Formation in the study area. These similarities are: fine to medium grained parallel-laminated, cross-laminated, hummocky cross-stratified and massive, micaceous arkosic sandstones; interbedded micaceous carbonaceous siltstones and bioturbated mudstones, and locally interbedded volcaniclastic deposits. Each of these formations is interpreted to have been deposited in a nearshore wave-dominated marine to brackish water deltaic environment.

Lithology and Sedimentary Structures of Surface Exposures

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

1) a thick sandstone lithofacies - composed of thick bedded to cross-laminated, micaceous, arkosic, very fine-to medium-grained sandstones and interbedded siltstones (Tc_1); and

2) a thin upper mudstone lithofacies - silty, laminated to thickly bedded, carbonaceous, micaceous siltstones and mudstones (Tc_2).

In the field area the upper mudstone facies is very thin and poorly exposed, and hence is not subjected to the same rigorous treatment in this discussion as the sandstone lithofacies (C & W sandstone). The mudstone is exposed in only two outcrop areas, one in the north and one in the south (Plate I). In the southern localities (11, 12) near the quarry of Cole Mountain basalt (Plate I), the medium dark grey (N4) mudstone is finely laminated, micaceous, silty, and contains abundant paper thin mud pecten *Propeamussium* indicating deep (2650 to 3900 m) quiet water (Moore, 1988; writ. comm). In the north part of the map area (localities 149, 153) the unit is massive, silty, very micaceous, and microfossiliferous. In general, the upper Cowlitz mudstone is characterized by suspension deposition, lack of wave-generated sedimentary structures, and *Helminthoida* trace fossils referrable to the *Nereites* ichnofacies (Frey and Pemberton, 1984). Weathered exposures of upper Cowlitz mudstone occasionally exhibit a "speckled" appearance, probably the result of bioturbation by infauna. Typically, these mudstones contain both light and dark colored mica, abundant carbonaceous matter, and iron staining, resulting in a reddish tan color. Fresh upper Cowlitz mudstones are typically medium grey (N5) and thinly laminated. In the field, the distinction between the upper Cowlitz mudstone and the Keasey is made primarily on the presence or absence of mica. In addition, the Keasey Formation is more tuffaceous, glauconitic, and not as well laminated as the upper Cowlitz mudstone. Upper Cowlitz mudstones harbor an upper Narizian microfossil assemblage, in contrast with the Refugian Keasey Formation (McKeel, 1988; writ. comm.).

In outcrop, the C & W sandstone member of the Cowlitz Formation is characterized by a lithologically distinctive sequence of friable sheet-like sandstones. The outcrop distribution of these sandstones in northwest Oregon is shown in Figure 41. Fresh exposures of C & W sandstone consist of medium light grey (N6) to medium grey (N5) arkosic, micaceous, carbonaceous, fine to medium-grained sandstone. However, rapid and deep weathering (up to 2 m) into exposed outcrops restricts fresh exposures to recently excavated roadcuts and streamcuts, where reducing conditions slow the oxidation of iron-bearing minerals and the constant erosive action of the current continually exposes new fresh surfaces. More common roadcut and slope exposures of C & W consist of weathered very pale orange (10 YR 8/2) to pale yellowish orange (10 YR 8/6) sandstone with liesegang banding (iron oxide staining) imparting a streaky to layered ring-like appearance to the rock.

However, even in small weathered exposures, the extremely porous, "reservoir quality" of the C & W makes the unit generally distinguishable from other sandstone map units. In particular, the arkosic, well-sorted nature, extreme friability, abundant cross stratification, and lack of fossils serve to distinguish most C & W outcrops from the stratigraphically lower but molluscan-bearing and more indurated lithic Sunset Highway member sandstone of the Hamlet formation.

Mica content varies dramatically in the C & W, from sandstones with very little mica (2%), to highly micaceous sandstones containing sheets of oriented mica flakes coating bedding planes. Mica consists of fine to very coarse-grained flakes of biotite and lesser muscovite that are up to 5 mm in diameter. Mica content is probably related to the hydrodynamic conditions present at the depositional site. Shelf hummocky cross-stratified (HCS) sequences typically exhibit higher mica contents than upper shoreface deposits due to remobilization of mica from the foreshore and shoreface (Dott and Bourgeois, 1982). Carbonaceous matter is also very abundant in the C & W in the form of finely comminuted to coarse-grained plant detritus, and some black carbonized woody fragments up to 2 cm in length. Both mica and carbonaceous debris are preferentially concentrated along primary bedding structures or cross-bedding planes.

Carbonate concretions are also present in various shapes and sizes (some up to 1.5 m in diameter), but do not seem to be restricted to any particular stratigraphic level. Carbonate cemented zones can be very thin (a few centimeters) and localized or thick (up to 1.5 m) and extensive.

The Cowlitz Formation shelf sandstones were deposited during a transgression culminating in deposition of the deep-marine upper Cowlitz mudstone. Two coarsening-upward vertical successions interpreted to represent shelf progradation (see Depositional Environment) are contained in the Cowlitz outcrop area. Close scrutiny of outcrop and cores reveals significant internal variability of C & W sandstones, allowing for interesting facies comparisons and analysis (Figure 42). On the basis of this internal variability, the C & W sandstone (core and outcrop) is subdivided into a number of lithofacies types representing genetically related packages on the basis of sedimentary structures, lithology, bed thickness, bounding surfaces, grain size, and burrow intensity and type. These lithofacies F, H, and B are shown on Figure 42. All of these lithofacies, plus 3 additional lithofacies are present in the core from the Mist Gas Field (see Core Description).

Heterolithic Lithofacies F generally consists of small-scale ripple laminated sandstone with abundant siltstone interbeds and contorted bedding. Lithofacies B comprises bioturbated interbedded sandstone and siltstone, with rare laterally

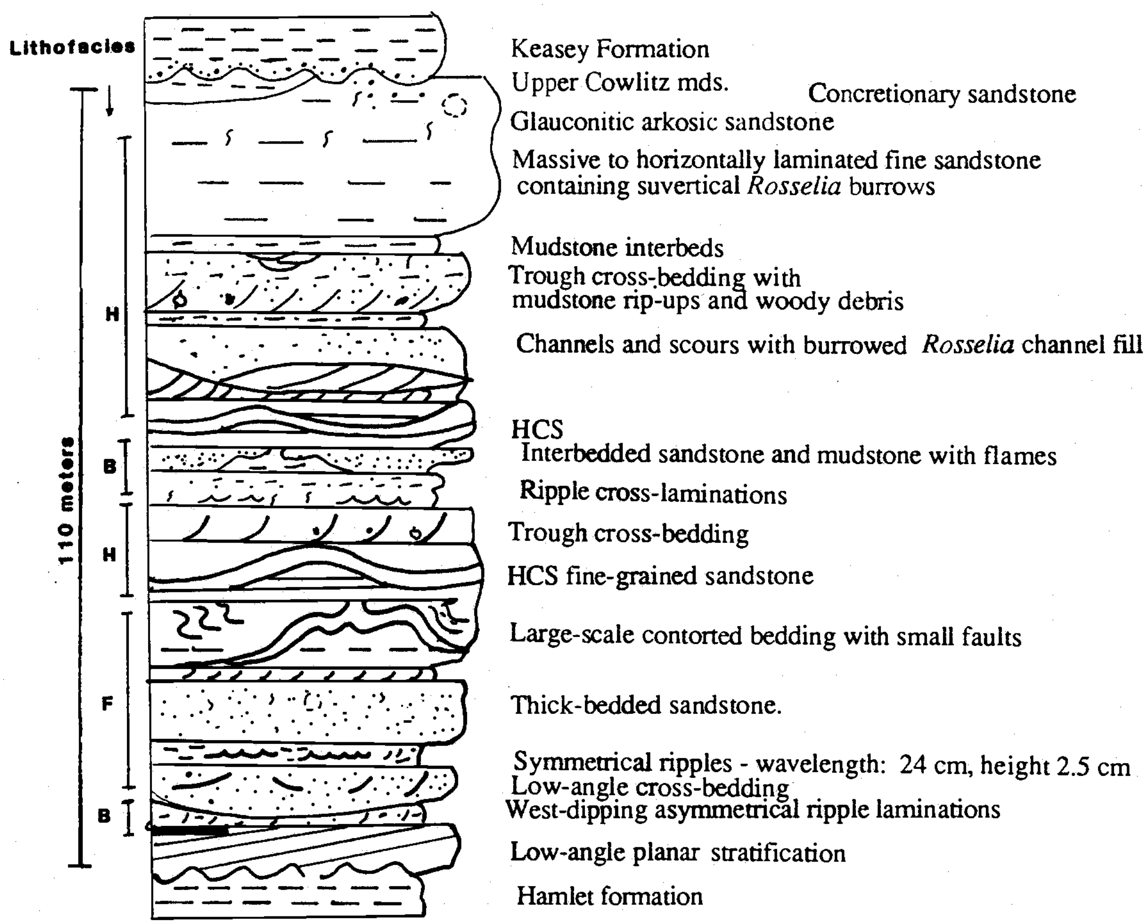


Figure 42. Generalized composite stratigraphic section through C & W sandstone (outcrop). Note designations of lithofacies and 2 coarsening-upward sequences in C & W sandstone representing shelf progradation.

continuous coal beds. Lithofacies H is a trough cross-bedded to hummocky cross-stratified facies with high sand to shale ratios and represents the "cleanest" reservoir sandstone in the C & W (Figure 42).

Unfortunately, lack of continuous exposures and a modest amount of structural complexity prevented measuring of a complete C & W outcrop section containing both upper and lower contacts. Therefore, facies trends and sequences within the C & W are documented by available measured sections and by relating lithologies to mapped stratigraphic position. A composite generalized section through the C & W outcrop area is provided in Figure 42, and location map of measured sections through the Cowlitz (and Hamlet formations) is provided in Figure 43.

Lower heterolithic facies of the Cowlitz Formation are well exposed along the Selder Creek measured section (Appendix XI), the lower part of the Fall Creek section (Appendix X), and along the banks of Deep Creek (locality 146). This facies (Lithofacies F) is characterized by a "transitional" sequence of interbedded sandstone and siltstone. Although this transitional sequence occurs in basal C & W sandstone, it also occurs stratigraphically higher in the Cowlitz as the base of subsequent coarsening-upward cycles. Excellent representative exposures of lower Cowlitz lithofacies also occur in Farr's area (1989) south of Rocky Point along the Columbia County mainline (Plate I; T4N, R5W, Sec. 22 SW 1/4).

Sand-shale ratios in the lower C & W vary from 2 to 1 to 4 to 1, whereas the C & W further upsection (Lithofacies H) exhibits sand-shale ratios on the order of 6 to 1 to 20 to 1.

The heterolithic Selder Creek section is dominated by repetitive cycles of planar bedding to low-angle cross-laminations in well sorted, arkosic, micaceous sandstone beds averaging 2 m thick alternating with medium bluish gray (5 B 5/1) to dark greenish grey (5 G 4/1) micromicaceous sandy siltstone beds (Appendix XI). Each planar to

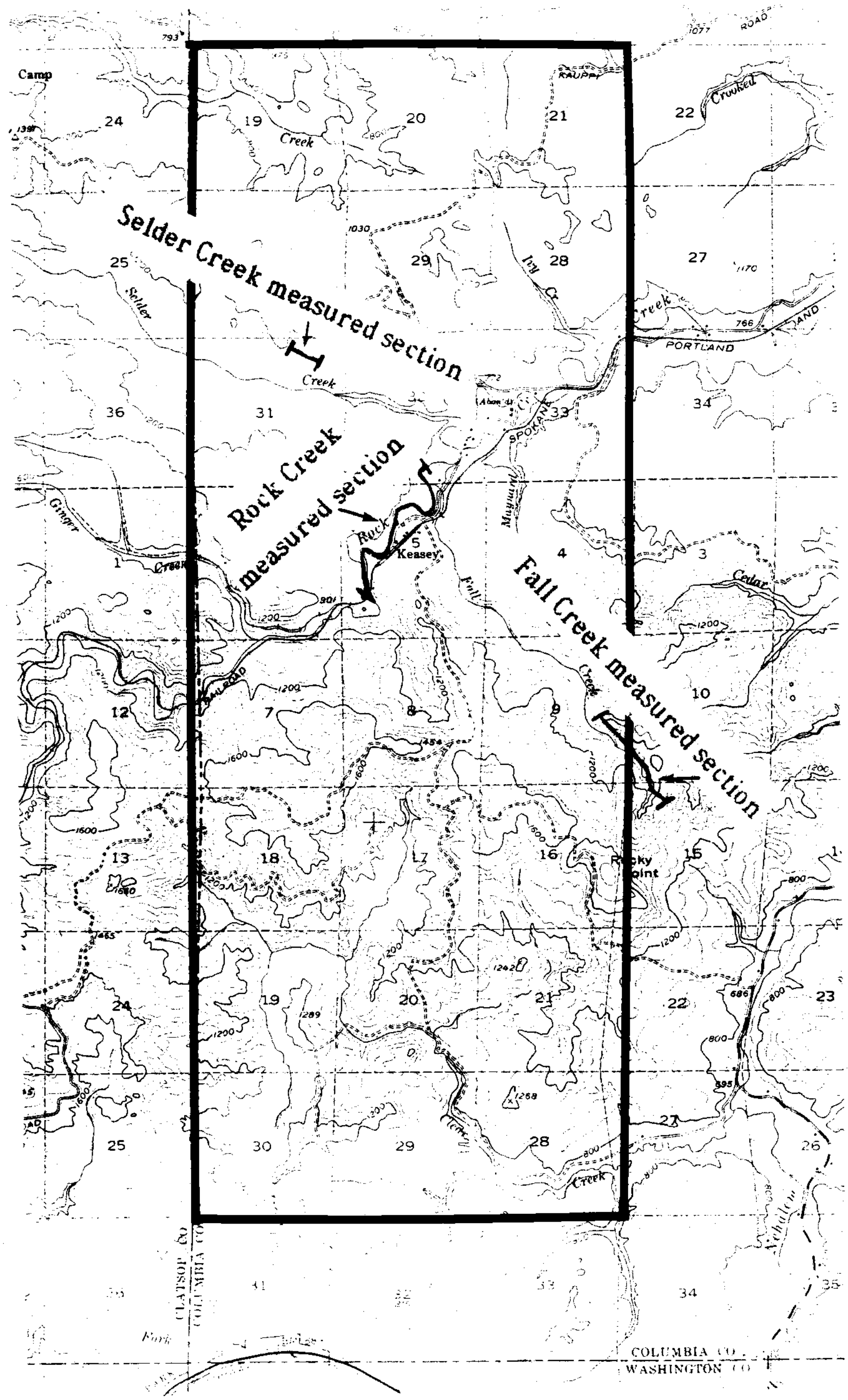


Figure 43. Location map of measured stratigraphic sections in Hamlet and Cowlitz formations in field area (see Appendices X, XI, and Figure 26).

ripple cross-laminated interval displays slight grading upward from fine to very fine-grained sandstone, into a rather abrupt transition with the overlying sandy siltstone subfacies. The sandy siltstone beds range from 10 cm to 60 cm in thickness and have sharp upper and gradational to sharp lower contacts with the thicker grayish orange (19 YR 7/4) fine- to medium-grained sandstones.

Primary sedimentary structures displayed by the silty sandstones include thinly interlaminated sand and silt, both asymmetrical and in phase (climbing ripple) symmetrical wave-ripple and starved-ripple laminations with second order truncations, and subordinate even to discontinuous wavy subparallel laminations.

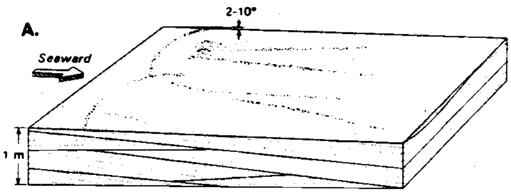
This facies (Lithofacies F) is also well displayed in Farr's Columbia Mainline section (1989) and in core OM 41A-10 (see Plate IX). Bioturbation is common in the sandy siltstones, along with comminuted plant debris and tiny mica flakes. Asymmetrical ripple laminations from the Selder Creek section have foresets yielding slightly different current directions, from N40°W to N 75°W, with the average being N55°W. In contrast, paleocurrent directions from the large-scale low-angle cross beds in the fine-grained sandstone are variable, from N80°W, to S20°W (see Depositional Environment; Figure61)

The sandtone packages display large-scale low-angle cross beds resembling portions of amalgamated hummocky cross stratified sequences (Dott and Bourgeois, 1982; Walker, 1984). These relatively clean quartzofeldspathic sandstones have erosional or scoured bases with low relief into the underlying carbonaceous ripple-laminated siltstone facies, and thus probably represent deposition during storm-wave conditions. Some mud rips-ups 2 cm diameter and load casts of fine sand into siltstone are observed, along with rare micro-scour and fill structures. One unlined backfilled burrow (locality 57) identified by Chamberlain (1989; writt. comm.) as an escape burrow of a clam or snail, is testimony to rapid deposition. Five meters upsection, the sandstone beds show a progressive upward increase in thickness and grain size. At the top of the sequence, siltstone beds become progressively more uncommon and individual hummocky bedded sandstones are amalgamated, representing a shallowing-upward trend.

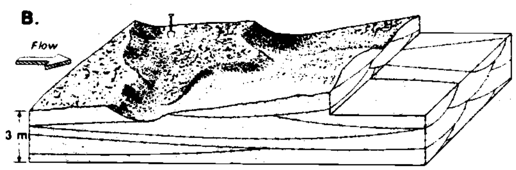
Farr (1989) reported a similar heterolithic facies low in the C & W sandstone consisting of fine-grained arkosic sandsone with abundant mudstone interbeds in his Rocky Point Road section. However, Farr (1989) documented a coal-bearing unit in this facies not present in my field area. This heterolithic facies (termed Lithofacies B; Figure 42) is present in core OM 41A-10 where it is extensively bioturbated, coal-bearing, and also occurs near the base of the C & W sandstone member.

The Fall Creek measured section (Appendix X) is interesting because it contains many depositional features observed in outcrop of the C & W sandstone, and thus was used extensively for constructing the composite measured section (Figure 42). According to measurements made by Farr and myself, approximately 70 m (210 feet) of C & W sandstone is nearly continuously exposed here, along high linked Columbia County mainline roadcuts made by Longview Fibre Company (Plate I; Appendix X). Although the top contact with the Keasey Formation is included in the section, the lower contact with the Hamlet formation is not exposed. These sands display a variety of bed forms - from a massive and horizontally stratified deposit, to one with well-developed hummocky and ripple laminations (Figure 44). Abundant manganese oxide brown crusty layers and carbonaceous matter are present, and in places (i.e., 22 m) the sand shows many 0.34 cm diameter tube shaped and branching burrows (*Thalassinoides* ?).

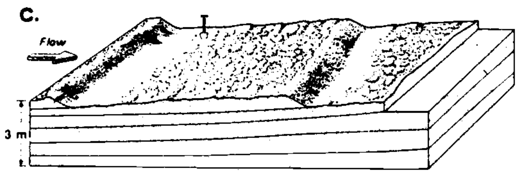
The bottom of the Fall Creek section begins higher in the C & W than the Selder Creek section, and represents the beginning of the second progradational cycle observed in outcrop. The lower portion of the Fall Creek section shows many similarities to the Selder Creek section in that sand/shale ratios are low (3 to 1), with abundant ripple



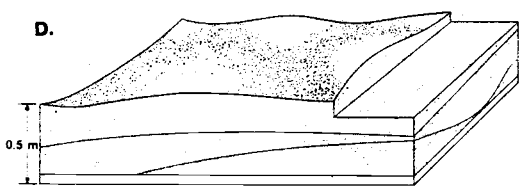
SWASH CROSS STRATIFICATION. Low-angle (2°-10°) cross stratification, subparallel to bases of wedge-shaped sets. Stratification and set boundaries are formed parallel to changing slope of beachface and dip generally seaward.



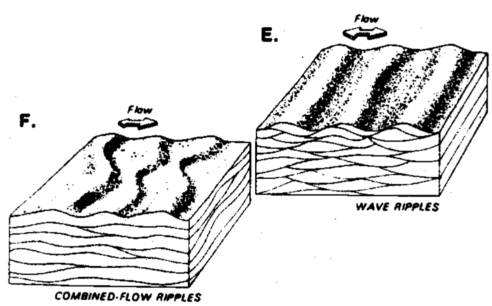
LARGE-SCALE TROUGH CROSS STRATIFICATION formed by subaqueous dunes or "megaripples". High-angle (25°-30°) cross stratification, tangential to bases of trough-shaped sets. Cross strata dip parallel to flow direction.



TABULAR CROSS STRATIFICATION FORMED BY MIGRATING SAND WAVES. High-angle (near 30°) cross stratification in tabular sets. Cross strata are planar and angular to bases of sets where flow is steady but may be tangential under some conditions.



HUMMOCKY CROSS STRATIFICATION. Low-angle (less than 15°) cross stratification, subparallel to smooth, undulatory lower boundaries of sets. Similar appearance in all vertical orientations. Commonly associated with wave ripples.



WAVE RIPPLES. Ripple-trough profiles are symmetrical and rounded, and stratification dips in both directions of oscillatory flow.

COMBINED-FLOW RIPPLES. Formed by superimposed wave and current action or by shoaling waves. Small-scale cross strata are curved and tangential, dipping in direction of dominant flow.

Figure 44. Block diagrams showing common stratification types and associated bedforms in coastal marine sandstones such as C & W sandstone of Cowlitz Formation. D, E and F are most common in C & W. After McCubbin (1982).

laminated silty interbeds in micaceous, friable, laminated sandstone. The similar lithologies and sedimentary structures with the Selder Creek section provides the rational for assigning this part of the Fall Creek section to Lithofacies F (Appendix X). Carbonaceous matter is abundant in the form of intercalated plant macerals. Asymmetrical ripples (Figure 44F) have wavelengths of 10 - 15 cm and crest heights of 1 - 1.5 cm. Orientation data from ripple foresets indicate current propagation in a northwest direction. These sandstones are mildy bioturbated and burrowed, but distinctively devoid of megafossils.

An recessive interval of repetitive sequences of equal thicknesses of dark mudstone and buff sandstone beds approximately 12 cm thick occurs at 11 to 13 m in the section. Sandstone beds show partial grading, sharp lower contacts, and are interpreted to represent shelf turbidites or tempestites, generated in shallow-water by storm-wave setup (Walker, 1984). These laminated beds lacking burrows are interpreted to be deeper water (offshore) shelf deposits equivalent to the storm-generated hummocky beds observed higher in the Cowlitz.

Further upsection in the lower middle portion of the section (30 m), the sands contain some back-filled branching burrows (*Rosselia*) perpendicular to bedding. Small- scale isolated channels are present (Figure 42). These channels are typically 1 to 3 m in thickness, and are interpreted to represent high-energy tractive currents scoured into the inner shelf, possibly associated with storm-waves. Although no fossils were identifiable, rare faint molds of gastropod and pelecypod shells (Moore, 1988; writ. comm.) can be observed as lag deposits in channel bases. The lack of preserved shallow-marine fossils in the C & W may be the result of early diagenetic leaching of calcareous shell material.

Hummocky and micro-hummocky cross-stratification (HCS) characterizes the next facies (Figure 42; Lithofacies H). Hummocky and swaley cross stratification refers to randomly oriented, gently dipping (less than 15 degrees), undulating laminae that reflects deposition on a hummocky sea floor (Figure 45) (Balsley, 1984). Hummocky cross-stratification reflects sand deposition under waning storm-wave conditions and has been attributed to the complex oscillatory motion of storm-waves impinging on the bottom at depths below fair-weather wave base (Walker, 1984). Hydrodynamic conditions necessary for formation of this distinctive sedimentary structure have been debated (Duke, 1985), but it appears that HCS requires combined wave (oscillatory) and unidirectional flow (Swift et al., 1983; Walker, 1984).

Partial HCS sequences characteristic of Lithofacies H can be observed in the C & W sandstone at localities 145, 45, 152, and 138). HCS (Harms et al, 1975) is not the only strata type in this part of the C & W, but is distinctive. It commonly occurs in discrete, tabular sandstone beds 1 m or less in thickness, as well as filling in small, scoured channels (Figure 46). Commonly, antiformal hummocks are not as well preserved as the intervening swales due to amalgamation and erosive deposition (Dott and Bourgeous, 1982). Low-angle cross-bedding is also abundant in these sandstones, in close association with hummocky cross-stratified sequences. Hummocky stratification commonly grades upward to parallel laminations followed by ripple cross-laminations, with bioturbated tops (Figure 45). Many hummocky intervals are capped by convoluted tops which are truncated by the next storm event (Figure 45C). Contorted bedding in HCS deposits represents remobilization of sand and rapid deposition during waning stages of a storm (Dott and Bourgeois, 1982).

About 40-50% of the sandstone beds within this facies (Lithofacies H) do not display hummocky stratification, but instead show either symmetrical ripple cross-lamination (Figure 44E) or more commonly flat, parallel laminations throughout. Massive beds are less common. Wave-formed ripples show well-preserved crest forms

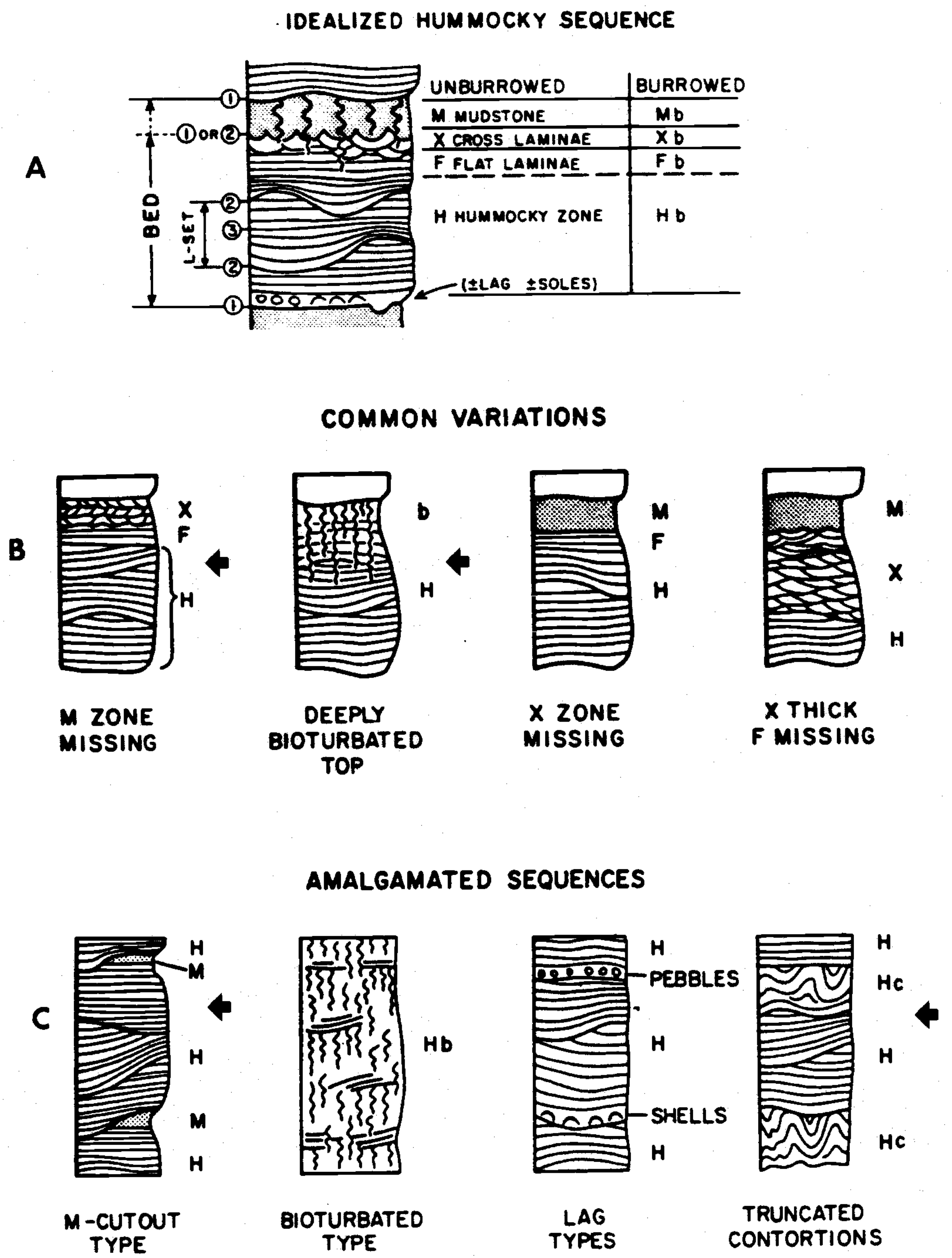


Figure 45. A. Idealized hummocky sequence showing hierarchical order of surfaces (numbers). B. Common variations from hummocky sequences. Two left examples are most abundant in C & W sandstone. C. Several types of amalgamated hummocky beds. M-cutout and truncated contortions are most common types found in C & W sandstone. Compiled from Dott and Bourgeois (1982).

Figure 46. Outcrop exposure of hummocky cross-stratification (see Figure 45B) showing swaley beds overlain by burrowed fairweather top (Rosselia), which is truncated by overlying hummocky beds of next storm event. Locality 132.

draped by mudstone and mudstone flasers. Other ripple forms include asymmetrical and rare interference types.

The Fall Creek section displays many interesting penecontemporaneous deformation features toward the lower middle part of the sequence (16-28 m) not present in the Selder Creek section. These are represented by small offset faults with associated slump folds, convolute and contorted bedding and flame structures in silty sandstones (Figure 47). The contorted cross-bedding in this facies suggests that sediments were deposited rapidly with open packing and subsequently underwent liquefaction, perhaps due to sudden scouring, loading by thicker amalgamated hummocky sandstone beds, or siesmic shock due to earthquakes. The overturned flames and soft sediment deformation features indicate downslope movement of water saturated sediments, suggestive of rapid deposition during storm and flood events on an inclined delta front surface.

Toward the upper part of the unit (Figure 42), the fine-grained C & W sandstone is more sand-rich, micromicaceous, faintly laminated to structureless, and liesegang banded. Calcareous concretionary lenses are commonly concentrated in fractures and bedding planes in exceptionally well sorted, quartzofeldspathic, poorly consolidated sandstone (e.g., locality 32). The outstanding bedform observed here are a few sets of trough cross-beds (Figure 42), with high angle cross-laminae dipping at 20-30 degrees (Figure 48). Trough cross-bedding is common in the shoreface where its formation has been attributed to the migration of lunate megaripples (Balsley, 1984; Reading, 1978). The presence of predominantly higher angle (>10°) trough cross-stratification in this sequence overlying the hummocky deposits suggests a shallowing-upward or progradational trend in the C & W (see Depositional Environment). Trough cross-bedding is common in C & W sandstones, and is well illustrated at localities 35, 187, 118, and 37 (Appendix V). Within the C & W sandstone, sets average about 60 cm or

Figure 47. Large penecontemporaneous soft sediment slump fold in C & W sandstone, indicative of rapid deposition and/or deposition on an inclined depositional surface characteristic of delta front settings. Location: 13 m, Fall Creek measured section (Appendix X).

Figure 48. Exposure of large-scale high-angle trough cross-bedding of the middle to upper shoreface (Lithofacies H) in upper part of C & W sandstone. Trough cross-bedding in the C & W overlies hummocky cross-stratified sandstone and represents coarsening- and shallowing-upward progradational pulses. Locality 35.

less in thickness and range from 8 cm to 1 m. Rare mudstone rip-ups up to 2 cm in diameter and carbonized woody debris are abundant at the base of cross-beds. The trough sets have tangential bases and truncated tops (Figure 44). Burrows are uncommon in this facies and usually are restricted to cylindrical backfilled structures of *Rossellia* (locality 40) (Chamberlain, 1989; writ. comm.). The high sand to shale ratio and trough cross- bedding in the upper part of the Fall Creek section represents shallower deposition and progradation of shoreface sands over inner shelf hummocky cross stratified deposits.

The uppermost part of the C & W sandstone is characterized by 10 - 15 m of massive to faintly horizontally laminated medium-grained arkosic sandstone, containing some thin (1 cm) white tuffaceous mudstone beds (Figure 42). Elsewhere in the thesis area, the top of the C & W unit is marked by concretionary fine-grained sandstone with low-angle cross-bedding (locality 10), or by burrowed fine sandstone containing occasional glauconite pellets (localities 41 and 84) (Figure 42). These glauconitic sandstones locally present near the top of the C & W are not present in the cores from the Mist Gas Field. The unconformably overlying lower Keasey Formation contains glauconitic sandstone and mudstone beds which are interpreted to represent reworked upper Cowlitz sandstones (Figure 42). Perhaps the absence of this slightly glauconitic facies in the core can be attributed to the presence of thick upper Cowlitz mudstone between the Keasey Formation and the C & W sandstone in the subsurface. As mentioned previously, the upper Cowlitz mudstone is very thin or absent in the field area.