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AN ABSTRACT OF THE THESIS OF Leonard Carl Farr, Jr. for the Master of Science in Geology presented November 26, 1989.

Title: Stratigraphy, Diagenesis, and Depositional Environment of the Cowlitz Formation (Eocene), Northwest Oregon.

APPROVED BY MEMBERS OF THE THESIS COMMITTEE:

Robert O. van Atta, Chairman

Curt Peterson

Richard E. Thoms

John Dash

The Upper Eocene Cowlitz Formation is exposed in surface outcrops southwest of the town of Vernonia, in Columbia County, Oregon. The Cowlitz Formation also occurs in the subsurface of the Mist gas field where its Clark and Wilson (C and W) sandstone member (informal) acts as a natural gas reservoir, and its upper Cowlitz mudstone member (informal) acts as a cap rock. Surface exposures and continuous core were studied in order to determine Cowlitz Formation stratigraphy, and

its depositional environment. Fresh core samples were also studied petrographically, and with a scanning electron microscope, in order to determine the effects of diagenesis in the gas producing C and W sandstone member.

The distribution of other Tertiary rock units exposed within a designated field study area, located southwest of Vernonia, were also mapped and briefly described. The stratigraphy of the field study area, in stratigraphic order, consists of the Tillamook Volcanics, the Hamlet formation (informal), the Cowlitz Formation, and the Keasey Formation. Cole Mountain basalts (informal) intrude the Tertiary section near the Cowlitz-Keasey contact. Two major transgressive events are documented by the Tertiary section within the field study area.

The C and W sandstone member represents the shallowest of the deposits composing the younger of the two transgressive sequences. It consists of several minor regressive depositional packages deposited in a strand plain shoreline and/or deltaic setting. Five distinct depositional facies were identified within the C and W sandstone member. The dominant facies is the strand plain/distributary mouth bar facies. Interdistributary bay, distributary channel, and interbedded crevasse splay and interdistributary bay facies were also identified. The fifth facies occurs at the hiatuses separating the minor regressive depositional packages. The overlying upper Cowlitz mudstone member was deposited in an outer shelf to upper slope environment.

The strand plain/distributary mouth bar facies is the most laterally continuous of the five identified depositional facies. Its lateral continuity and consistently high porosity and permeability make it the best reservoir facies in the C and W sandstone.

Diagenesis has produced a slight net decrease in porosity in the C and W sandstone member but has not had a large impact on its reservoir potential. Primary porosity reduction has occurred by compaction, cementation, the precipitation of authigenic minerals, and the alteration of micas. Secondary porosity has been produced in the C and W sandstone member by framework grain dissolution and possibly by decarbonatization of an early calcite cement.

The C and W sandstone is derived from a predominantly plutonic/metamorphic source area during a period of volcanic quiescence. Possible sources include the Northern Cascades and the Idaho Batholith. The sediments may have been transported from the continent interior to the forearc basin by an ancestral Columbia River.

STRATIGRAPHY, DIAGENESIS, AND DEPOSITIONAL ENVIRONMENT
OF THE COWLITZ FORMATION (EOCENE),
NORTHWEST OREGON

by
LEONARD CARL FARR, JR.

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

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in
GEOLOGY

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1989

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INTRODUCTION

The discovery of economic accumulations of natural gas near Mist, in Columbia County, has affirmed the potential for hydrocarbon production in northwestern Oregon. An understanding of the stratigraphy and depositional environment of the reservoir rock is crucial to the further development of the Mist gas field and on going exploration in northwest Oregon and southwest Washington. Such an understanding would make the interpretation of critical factors such as facies geometry and variations in porosity and permeability possible.

The reservoir rock in the Mist gas field is the Clark and Wilson (C and W) sandstone member (informal) of the Cowlitz Formation. The gas producing facies is a fine to very fine-grained, micaceous, arkosic sandstone. It has unusually high porosity and permeability (32% and 1200 md respectively) making it an ideal gas reservoir. The C and W sandstone is overlain by a thick mudstone, the upper Cowlitz mudstone member (informal) of the Cowlitz Formation, that provides the cap rock necessary for petroleum accumulation.

PURPOSE OF INVESTIGATION

The primary purpose of this investigation is to establish a model for the depositional environment of the C and W sandstone member of the Cowlitz Formation. In order to develop a depositional model abundant data concerning the facies architecture and sedimentary structures present within the C and W sandstone had to be obtained.

Previous workers in northwestern Oregon have been limited to working with poorly exposed and thoroughly weathered surface exposures. The recovery of core from the Mist gas field by Oregon Natural Gas Development Corporation has provided a new database from which evidence of depositional environment can be obtained.

Another major objective was to map a 54 square kilometer (21 square mile) field area. The major goal of the mapping phase of the project was to differentiate the Hamlet and Cowlitz formations which have previously been mapped as undifferentiated Cowlitz Formation. Field exposures of the C and W sandstone will also provide additional evidence indicating the depositional environment.

METHODS OF STUDY

Information concerning the depositional environment of the C and W sandstone will be obtained both in a designated field area and from continuous core recovered from the Mist gas field. The type of data obtainable from core differs from that obtainable from surface exposures. Cores provide information on the vertical sequence of facies due to their continuous nature but do not yield information on lateral facies variation and sedimentary structures. Outcrops generally lack vertical continuity but are more laterally continuous than cores and provide more information on lateral facies variation and sedimentary structures. By utilizing data from both sources a larger database from which to make an environmental interpretation is available.

Field Methods

Approximately four months of field work was conducted during the summer of 1987 and the summer of 1988. An additional two weeks was spent in the field during the summer of 1989 in order to check a few problem areas.

Mapping was accomplished using a mylar composite of two U.S. Geological Survey 7.5 minute quadrangles (Clear Creek and Vernonia) as a topographic base. Outcrops were located using both the topographic base and aerial photographs. An outcrop map was constructed by plotting the locations of outcrops on the topographic base. Using the outcrop map, observed contacts, and attitudes measured in the field, a standard geologic map was constructed. The occurrence of sedimentary structures in outcrops was noted and where possible paleocurrent directions were determined. Three stratigraphic sections were measured within the field area and stratigraphic columns were constructed.

Approximately one hundred lithologic samples were collected within the field area for further laboratory analysis. Numerous megafossils were also collected for identification. Basalt samples were sent to Peter Hooper at Washington State University for geochemical analysis. Approximately 20 surface samples were sent out for thin section manufacture. Heavy minerals were separated from five C and W sandstone samples. Eleven samples were disaggregated and picked for foraminifera. Any foraminifera found were sent to ARCO Oil and Gas Corporation for identification.

Core Methods

Core OM12C-3 was selected for detailed analysis. It was logged at a scale of 1"=1' and a stratigraphic column was constructed from the log data. Several samples were then selected for additional laboratory work.

Laboratory methods included: petrography, heavy mineral identification, geochemistry, granulometry, clay mineralogy, and the identification of foraminifera. The core was also sampled for foraminifera by ARCO Oil and Gas Corporation. Porosity and permeability were determined by Core Laboratories of Bakersfield, California.

LOCATION

Field Study Area Location

The field study area, covering 54 square kilometers (21 square miles), is located in southern Columbia County and northern Washington County (Figure 1). Its dimensions are 11.27 kilometers (N-S) by 4.83 kilometers (E-W). This particular field area was selected because it has suitable C and W sandstone exposures.

Most of the field study area is private property belonging to Longview Fibre Company. There are a few small parcels of state forest land and private farm land within the field study area. There are abundant dirt and gravel logging roads providing access throughout most of the field study area. An old state highway, now called Timber Road, parallels the Nehalem River in the western half of the field study area.

Figure 1. Map showing the location of the thesis area and Mist gas field.

Vegetation within the field study area is extremely dense. Most of the land consists of second growth stands of fir and cedar with the exception of the flood plains of the Nehalem River which has been cleared for farm use. Much of the forest land has been recently clearcut. Natural rock exposures are rare and, due to dense vegetation, difficult to find. The great majority of the rock exposures are in road-cuts and are thoroughly weathered.

Core Locations

The cores were recovered from three wells in the depleted Bruer and Flora gas reservoir pools (Figure 2). Their locations and completion data are included below.

OM 41A-10 - Located in the Bruer pool, cored from 80 feet above the C and W sandstone, included 300 feet of C and W sandstone, bottoms in C and W sandstone. Recovery was 85-90%.

OM 12C-3 - Located in the Flora pool, cored from above C and W sandstone, about 300 feet of core from upper contact and extending nearly to the bottom of C and W sandstone. Almost 100% recovery with only one large gap in core section.

IW 33C-3 - Located in the Flora pool, cored from above the C and W sandstone, includes much of the cap rock, bottoms in C and W sandstone, oriented core. The sandstone may be in fault contact with cap rock.

Figure 2. Partial map of the Mist gas field showing the location of the three wells from which core was recovered.

PREVIOUS WORK

The earliest records describing the Tertiary rocks of southwestern Washington and northwestern Oregon are found in the report of James D. Dana (1849) which describes the geology of the Oregon Territory.

The first published geological reconnaissance in northwestern Oregon was conducted by Diller (1896). He described a sequence of Eocene volcanic rocks and Eocene to Miocene sedimentary rocks in Clatsop and Columbia counties. The first large-scale geological investigation in southwestern Washington was published by Weaver (1912). In this report the name Cowlitz Formation was first proposed. Weaver (1916) also published the first reconnaissance geologic map containing some of the Tertiary marine sediments of southwestern Washington and northwestern Oregon. Detailed description of rock units in northwest Oregon began in 1925 when Hertlein and Crickmay described the stratigraphy of Tertiary marine sediments in Washington and Oregon. The Pittsburg Bluff and Keasey formations were formally named two years later by Schenck (1927).

A comprehensive report on the Tertiary stratigraphy of western Washington and northwestern Oregon was published by Weaver (1937). This report included numerous maps, measured sections, and a complete list of Tertiary faunal localities. Warren and others (1945) published the first reconnaissance map of northwestern Oregon to encompass the field study area. Warren and Norbistrath (1946) formalized the Tertiary stratigraphy in the upper Nehalem River basin, naming the Tillamook Volcanics, and establishing the Cowlitz and Keasey stratigraphic nomenclature.

Van Atta (1971a, 1971b) and Newton and Van Atta (1976) described the Tertiary stratigraphy in the upper Nehalem River basin of Columbia County. They distinguished the Tillamook and Goble Volcanics, and the Cowlitz and Keasey formations using the nomenclature of Warren and Norbistrath (1946).

Graduate students (Timmons, 1981; Jackson, 1983; Shaw, 1986) at Portland State University, working under Drs. R.O. Van Atta and R.E. Thoms, have also mapped in Columbia and Washington counties. Graduate students (Olbinski, 1983; Nelson, 1985; Rarey, 1986; Mumford, 1988; Safley, 1989) at Oregon State University, working under Dr. A.R. Niem, have done detailed mapping in neighboring Clatsop and Tillamook counties.

REGIONAL GEOLOGY

The Paleogene stratigraphy of the Coast Ranges of Oregon and Washington includes both accreted volcanic rocks of probable seamount origin and post-accretion volcanic and sedimentary rocks. The oldest rocks exposed in the upper Nehalem River basin, the Tillamook Volcanics, are post-accretion basalts (Heller and others, 1987). The Tillamook Volcanics consist primarily of subaerial flows overlying a base of pillow basalts that erupted in a forearc basin setting.

Overlying the Tillamook Volcanics is a sequence of predominantly marine sedimentary rocks that accumulated in a forearc basin. The sedimentary rock units, in stratigraphic order, are the Hamlet formation (informal), the Cowlitz Formation, and the Keasey Formation.

Correlative volcanic and sedimentary rocks from southwest Washington and Oregon are shown in Figure 3. During accretion of the oceanic crust (approximately 50 Ma) the existing east-dipping trench became clogged causing the subduction zone to jump to the west (Heller and others, 1987). Westward migration of the volcanic arc began between 60 and 55 Ma and ended at about 40 Ma (Heller and others, 1987). Thus, the migration of arc magmatism was apparently not caused by the westward jump of the subduction zone (Heller and others, 1987). During the migration of the volcanic arc there was little local volcanic activity allowing the feldspathic Hamlet and Cowlitz formations to be deposited. Cascade arc volcanism was then initiated, providing the abundant acidic volcanic detritus present in the Keasey Formation.

Uplift and arching of the northern Coast Range has deformed the Tertiary section into a northward plunging anticline (Newton and Van Atta, 1976; Niem and Van Atta, 1973). The anticline is cut by numerous, major north-northwest, and westnorthwest faults related to rotational shear (Wells and Coe, 1985). Vertical and horizontal displacement along these faults varies from tens to hundreds of feet. The wide distribution of these subparallel faults suggests that they may have accommodated nonrigid intraplate deformation that developed in response to oblique subduction of the Kula or Farallon plates beneath North America (Heller and others, 1987). Paleomagnetic studies (Magill, 1982; Duncan, 1982; Wells and Coe, 1985; Heller and others, 1987) have shown that the Oregon and Washington Coast Ranges have been tectonically rotated clockwise. Others have noted that the rotational history of the Coast Ranges of Oregon and Washington differ suggesting that each range

acted as a discrete block. Three models have been proposed to explain the tectonic rotation. The first model calls for rotation to have occurred as rigid oceanic fragments pivoted during collision with North America. In the second model, rotation occurred later during extensional deformation in the Cordillera. In the third model rotation occurred as the continental margin responded to right-lateral shear, possibly driven by oblique subduction.

Figure 3. Correlation diagram of Middle to Upper Eocene strata in Oregon and southwest Washington. Data from: 1. Rarey (1986), and Niem and Niem (1985), 2. Jackson (1983) and Timmons (1981), 3. Bruer and others (1984) fide Berkman (1987), 4. Armentrout and others (1983).

FIELD STUDY AREA ROCK UNITS

Five differentiable rock units occur in the field study area (Figure 4). Two of the units are igneous, and three are sedimentary. They range in age from Mid Eocene to Early Oligocene. The entire thickness of the exposed section is approximately 800 meters. The rock units from oldest to youngest are; Tillamook Volcanics, Hamlet formation, Cowlitz Formation, Cole Mountain basalt, and Keasey Formation, each of which is described in detail below.

TILLAMOOK VOLCANICS

Nomenclature and Distribution

The Tillamook Volcanics were first formally described by Warren and Norbistrath (1946) as Late Eocene basic lavas with abundant interbedded tuff and breccia. Subsequent workers in Columbia County (Van Atta, 1971a, 1971b; Newton and Van Atta, 1976; Timmons, 1981; Jackson, 1983) have followed the nomenclature established by Warren and Norbistrath (1946).

More recently Wells and others (1983) have subdivided the Tillamook Volcanics into an upper subaerial and lower submarine unit. Only the upper subaerial unit, as described by Wells and others (1983), is present within the field study area.

Figure 4. Generalized stratigraphic section showing the approximate thicknesses of the rock units that occur within the field study area.

The Tillamook Volcanics are exposed in two isolated blocks within the field study area. The larger block is located along the western margin of the field study area in sections 15 and 22, T4NR5W (Plate I). The exposure continues to the west and has been mapped by Berkman (in prep.). It was formerly identified as Goble Volcanics by Van Atta (1970) but correctly reinterpreted as Tillamook Volcanics by Jackson (1983). The smaller block is approximately 0.5 kilometers to the southeast of the larger (Plate I). It is exposed only in an abandoned Columbia County quarry where it is lithologically identical to the basalt in the larger exposure at Rocky Point. The Tillamook Volcanics are erosionally resistant and typically form topographic highs. Rocky Point, which is the highest point in the field study area, is composed of Tillamook Volcanics. The separation of the two exposures of Tillamook Volcanics is thought to be caused by the development of a paleosurface with a topographic low between the two highs now represented by the two isolated blocks. A second hypothesis is that the Columbia County quarry is a landslide block shed from the larger Rocky Point block. This hypothesis is considered less likely due to the undisturbed structural attitude of the contact between the Tillamook Volcanics and overlying Roy Creek member (informal) of the Hamlet formation.

Lithology and Petrography

The Tillamook Volcanics contain two distinct lithologies in the field study area. The more common consists of dark gray, phyric, subaerial basalt flows separated by thin (<0.5 meter) soil horizons (Figure 5). The second is interbedded with the basalt flows and

Figure 5. Tillamook Volcanics exposed in a roadcut near Rocky Point (locality 30). Note the thin paleosols between individual flows.

consists of thin debris flow deposits containing angular basalt fragments in a fine-grained, altered basalt matrix.

The subaerial basalt flows vary in thickness from 8-15 meters and appear to be laterally extensive, but due to limited exposure this can not be confirmed over any great distance. Individual flows typically are blocky with vesicular flow tops. The flow tops are locally amygdaloidal with clay, calcite, silica, or zeolite filling. Fractures within the flows are often filled with these same secondary minerals.

All of the flows within the field study area have textures typical of basalt or basaltic andesite. They are aphyric to sparsely phyrlic with augite and smaller plagioclase phenocrysts. Phenocrysts, when present, generally compose less than 5% of the total rock. Rarey (1986)

and Mumford (1988) have reported abundantly phyric (>30% phenocrysts) flows but these were not observed within the field study area. Flow textures are generally absent from the basalts, but crude flow banding was observed at an abandoned quarry south of Rocky Point.

Debris flow deposits were observed at locality 30 within the field study area. They consist of small, highly weathered, basalt fragments within a poorly sorted matrix of clay to pebble sized volcanic material. The basalt clasts are generally less than 5 centimeters in diameter. The thickness of the debris flow deposit is constant throughout the 15-20 meters of exposure but its lateral continuity is unknown beyond the extent of the outcrop.

A single Tillamook Volcanics sample (87-24) was petrographically analyzed. The sample was collected in the Rocky Point block near the top of the blocky zone of a flow within 40 meters of the top of the Tillamook Volcanics. The sample is phyric to glomerophyric with augite and plagioclase phenocrysts up to 2 millimeters in diameter, and smaller opaque phenocrysts. The plagioclase and augite phenocrysts are equally abundant, each composing approximately 2-3% of the sample. The opaque phenocrysts are less abundant composing less than 1% of the rock. The groundmass is pilotaxitic with intergrown plagioclase microlites. The interstices between the plagioclase microlites contain microcrystalline pyroxenes and ferromagnesian granules making the groundmass intergranular. A single clay filled amygdale is present in the thin section. Additional petrographic data is available from Rarey (1986) and Mumford (1988), who conducted detailed petrographic studies of the Tillamook Volcanics.

Geochemistry

Three whole-rock major and trace element analyses were performed on Tillamook Volcanics samples, two from the Rocky Point block (samples 87-24 and 88-63) and one from the Columbia County quarry block (sample 88-2). The analyses were conducted by Peter Hooper's x-ray fluorescence lab at Washington State University. The results of the analyses are shown in Tables I and II. The geochemical data has been plotted in various graphs (Figures 6-9) in order to classify and differentiate the Tillamook Volcanics.

The first plot of total alkalies versus silica is used to differentiate alkaline and subalkaline basalts (Irvine and Baragar, 1971). The Tillamook Volcanics samples plot within the subalkaline field but are very close to the boundary between the alkaline and subalkaline fields (Figure 6). Since the boundary drawn in Figure 6 marks a gradual transition between the two fields, the chemical classification of the three samples should be described as transitional between the alkaline and subalkaline fields.

The subalkaline field can be further subdivided into tholeiitic and calc-alkaline fields (Figure 7). Since the three Tillamook Volcanics samples are transitional between the alkaline and subalkaline fields the subdivision can be made. All three of the Tillamook Volcanics samples plot well within the tholeiitic field.

Geochemistry can also be used to differentiate volcanic rock type. Using the classification of Cox (1979) (Figure 8), two of the analyzed samples, 87-24 and 88-2, classify as basalt while the third, 88-63, is well within the trachyandesite field. The Tillamook Volcanics near

<p>TABLE I</p> <p>MAJOR OXIDE GEOCHEMISTRY OF FIELD AREA VOLCANIC UNITS NORMALIZED WEIGHT PERCENT</p>										
	SiO ₂	Al ₂ O ₃	TiO ₂	FeO	MnO	CaO	MgO	K ₂ O	Na ₂ O	P ₂ O ₅
87-3	53.31	18.02	1.203	8.40	0.135	9.92	5.63	0.34	2.81	0.231
87-8	51.89	18.39	1.262	9.23	0.150	10.77	5.17	0.16	2.76	0.221
87-24	50.82	15.01	3.306	12.48	0.227	8.58	3.99	1.24	3.62	0.728
88-2	49.18	15.03	3.830	13.65	0.194	9.24	3.83	1.12	3.33	0.599
88-7	52.11	18.62	1.256	8.54	0.166	10.51	5.56	0.13	2.86	0.237
88-12	52.95	17.70	1.301	8.75	0.160	10.27	5.30	0.33	2.99	0.259
88-19	53.13	17.48	1.363	8.96	0.188	9.95	5.47	0.28	2.91	0.268
88-63	56.35	15.83	2.029	9.72	0.230	6.00	2.21	2.21	4.60	0.835
88-66	51.70	18.89	1.393	8.56	0.183	10.99	4.83	0.20	2.97	0.284

TABLE II

TRACE ELEMENT GEOCHEMISTRY OF
FIELD AREA VOLCANIC UNITS
IN PARTS PER MILLION

	Ni	Cr	Sc	V	Ba	Rb	Sr	Zr	Y	Nb	Ga	Cu	Zn
87-3	81	86	32	219	119	11	373	139	20	13.0	21	149	84
87-8	58	81	33	214	88	3	370	142	18	12.9	21	152	105
87-24	4	18	27	260	261	21	495	285	41	59.2	24	27	129
88-2	7	13	29	332	230	24	467	255	36	52.0	25	26	125
88-7	66	80	32	221	50	2	379	137	20	12.8	17	123	81
88-12	60	78	29	224	135	10	385	146	21	13.7	20	154	81
88-19	68	80	32	226	97	6	364	153	38	15.4	20	166	81
88-63	0	0	18	97	469	54	450	407	55	79.9	24	15	138
88-66	60	93	30	236	77	1	406	155	36	15.9	19	172	95

Figure 6. SiO_2 versus total alkalis defining the alkaline and subalkaline fields. (After Irvine and Baragar, 1971.)

Figure 7. Ternary diagram defining the tholeiitic and calc-alkaline fields. (After Irvine and Baragar, 1971.)

Figure 8. Classification of field area volcanic rock samples. (After Cox, 1979.)

Green Mountain to the west of the field study area commonly contain andesites with more sodic plagioclase (Safley, 1989) so the composition of sample 88-63 is not uncommon.

Each sample was also plotted in a silica variation diagram (Figure 9) to display the variation in the chemistry of the basalts present within the field study area. The Tillamook Volcanics show considerable variation in geochemistry but the variation appears to occur along a linear trend. As silica content increases, MgO, FeO, TiO₂, and CaO decrease, P₂O₅, K₂O, and Na₂O increase, and Al₂O₃ is constant. The consistent linear trend of the Tillamook Volcanics geochemistry and the small variation in Cole Mountain basalts geochemistry make the two basalts geochemically differentiable.

Contact Relations

The base of the Tillamook Volcanics is not exposed within the field study area. The base of the Tillamook Volcanics has not been reached during drilling in the Mist gas field (Jack Meyer, personal communication, 1988). Thus, the Tillamook Volcanics are considered as "economic basement" in northwestern Oregon.

The Tillamook Volcanics are overlain by the Roy Creek member of the Hamlet formation. The uppermost flows of the Tillamook Volcanics have roughly the same attitude as the overlying Roy Creek member but the contact has been interpreted as unconformable by this author and several others (Warren and Norbistrath, 1946; Jackson, 1983; Rarey, 1986). Criteria that support the interpretation of an unconformable contact include: (1) the absence of interfingering between the basalt and

Figure 9. Silica variation diagram of field area basalts.

overlying sediments, (2) the presence of large boulder sized clasts of Tillamook Volcanics incorporated into the base of the Roy Creek member, and (3) the erosional nature of the contact (Rarey, 1986).

HAMLET FORMATION

Nomenclature and Distribution

The Hamlet formation is an informally designated unit of Late Eocene age proposed by Niem and Niem (1985) that lies between the Tillamook Volcanics and the Cowlitz Formation as restricted by Wells (1981). The Cowlitz Formation was restricted by Wells (1981) so it would conform to the description of the type section defined by Weaver (1937). The sedimentary rocks lying between the Tillamook Volcanics and C and W sandstone member in the Mist gas field, previously described as Yamhill Formation (Bruer and others, 1984), have also been redefined as Hamlet formation (Rarey, 1986). Sedimentary rocks underlying the Tillamook Volcanics have not been redefined and will retain the Yamhill Formation designation (Rarey, 1986).

The Hamlet formation contains three informally defined members. The basal member consists of basalt conglomerate and lithic sandy siltstone and has been designated the Roy Creek member. The middle member is a fine-grained feldspathic litharenite to lithic arkose designated as the Sunset Highway member. The upper member, termed the Sweet Home Creek member, has been described as a turbidite bearing mudstone.

The Hamlet formation is exposed in northern Tillamook, southern Clatsop, southern Columbia, and northern Washington counties in northwest Oregon (Rarey, 1986; Niem and Niem, 1985). It is also found in the subsurface of the Mist gas field where it is referred to as the Yamhill Formation (Bruer and others, 1984; Rarey, 1986). The Sunset Highway member thins and pinches out in central Clatsop County and is replaced by the finer grained Sweet Home Creek member (Rarey, 1986). Within the field study area the Hamlet Formation is exposed in a northwest-southeast trending block and in several small blocks near Rocky Point (Plate I). Exposures are typically extensively weathered road cut outcrops.

ROY CREEK MEMBER

Lithology and Petrography

The Roy Creek member within the field study area consists of 2-4 meters of monomictic, basaltic, boulder to pebble, clast-supported conglomerate at its base overlain by >10 meters of lithic sandy siltstone. The basalt clasts within the conglomerate are texturally identical to the underlying Tillamook Volcanics. The contact between conglomerate and overlying lithic sandstone appears to be gradational.

The character of the conglomerate is highly variable. At an abandoned Columbia County quarry southeast of Rocky Point (locality 76) the Roy Creek member consists of a boulder conglomerate, with clasts up to 2 meters in diameter, grading into a well-sorted, fossiliferous, pebble to cobble conglomerate. The pebble conglomerate is absent from a road cut exposure on the eastern flank of Rocky Point (locality 30). At

locality 30 the boulder conglomerate is overlain by a coarse lithic siltstone (Figure 10). The siltstone is slightly micaceous and moderately fossiliferous, containing dark sand-sized fragments that give the rock a peppered appearance. The only exposure containing the sandy siltstone is extremely weathered and has no apparent bedding.

A single thin section of the sandy siltstone was cut for petrographic analysis. The only monomineralic clasts present in the siltstone are trace quantities of coarse silt-sized plagioclase. The siltstone also contains 30% sand-sized volcanic rock fragments. These are the fragments that give the rock its peppered appearance. The remaining 70% of the rock consists of clay matrix. The rock is generally quite "tight" with only minor secondary porosity produced by the dissolution of volcanic rock fragments.

Figure 10. Basal boulder conglomerate and overlying sandy siltstone of the Roy Creek member exposed at locality 30.

Fossil Content

Megafossils are common in the Roy Creek member. Fossils were collected at both outcrops within the field study area. The pebble conglomerate at locality 76 contains abundant Terebratalia sp. A variety of fossils are present in the sandy siltstone at locality 30. The fossils are, however, extremely weathered and consist only of internal and external molds. Several unidentifiable gastropods and pelecypods were found within the sandy siltstone. Only the pelecypods Nuculanas and Acila sp., scaphopod Dentalium sp., and a Nautilid gen. indet. were identifiable.

Contact Relations

The base of the Roy Creek member of the Hamlet formation is interpreted to be in unconformable contact with the Tillamook Volcanics. The details of the unconformity are discussed on pages 23 and 25.

The upper contact of the Roy Creek member is not exposed within the field study area. The upper contact has been described as conformable by other authors (Mumford, 1988; Safley, 1989).

SUNSET HIGHWAY MEMBER

Lithology and Petrography

The Sunset Highway member consists of approximately 50 meters of dominantly arkosic sandstone with minor interbedded mudstone. The sandstone is friable, well-sorted, and fine-grained. It often contains laminations accentuated by highly micaceous or carbonaceous bedding planes, but may also be massive. Both hummocky and parallel laminae are common. Interbedded mudstones are generally thin (<10 cm) and contain

parallel laminations. The mudstones are typically highly carbonaceous and micaceous. The contacts between mudstone and sandstone are generally sharp, but scour is not evident.

A massive, pebbly basaltic sandstone is also present within the Sunset Highway member. It is >6 meters in thickness. Sparse, short vertical burrows identified as *Skolithos* are present in the basaltic sandstone and constitute the only fossils encountered within the Sunset Highway member. A sample from the basaltic sandstone was picked for foraminifera but none were found. The outcrop in which the basaltic sandstone occurs is faulted so the location of the basaltic sandstone within the Sunset Highway member section is unknown. Safley (1989) found that basaltic sandstones occur more commonly and are thicker in the upper part of the Sunset Highway member.

Three Sunset Highway member samples, two from the friable arkosic sandstone (samples 87-20 and 88-57), and one from the pebbly basaltic sandstone (sample 89-3), were analyzed petrographically. Five hundred points were counted to determine the composition of sample 87-20, and 89-3 (Table III) revealing that sample 87-20 is actually a sandy mudstone containing 52% fine-grained matrix (Figure 11). Much of the matrix, however, may be produced during surface weathering. The sand fraction of the sample is dominated by quartz which constitutes 20% of the rock sample. The feldspars, dominated by potassium feldspar, outnumber rock fragments by a slim margin. Thus, the rock classifies

TABLE III

MODAL ABUNDANCE OF FIELD STUDY AREA
SEDIMENTARY ROCK SAMPLES

Sample Number	87-12	87-17	87-20	87-33	87-36	87-37	87-38	87-39	88-46	88-60
Rock Unit	Tc	Tc	Ths	Tc	Tk	Tc	Tc	Tk	Th	Th
<u>Mineral</u>										
Mono Quartz	17.0	18.1	20.6	16.2	13.2	19.0	20.2	9.8	21.4	23.2
Poly Quartz	1.8	3.4	6.0	1.4	0.6	2.4	3.0	2.8	1.8	2.0
K-Feldspar	13.2	7.4	7.0	9.2	4.0	15.6	10.4	3.8	8.2	11.6
Plagioclase	13.8	4.0	4.2	5.4	14.6	19.8	14.2	8.6	9.6	6.8
Mica	3.2	9.8	0.8	3.2	0.6	10.8	2.2	-	5.2	2.6
Carb. Matter	NC*	NC	NC	NC	NC	NC	1.2	0.2	0.4	0.8
Glauconite	-	-	-	-	-	-	0.8	19.6	-	-
<u>Rock Fragments</u>										
Volcanic	NC	0.4	-	-	34.6	5.2	0.2	2.6	-	NC
Sedimentary	NC	1.2	0.8	0.2	-	-	2.6	2.2	0.6	NC
Plutonic/Met.	NC	4.6	3.4	0.8	-	2.8	0.6	0.2	1.0	NC
Undifferent.	5.2	NC	NC	NC	NC	NC	0.6	NC	-	1.0
Total	5.2	6.2	4.2	1.0	34.6	8.0	4.0	5.0	1.6	1.0
<u>Cements</u>										
Calcite	-	-	-	58.0	-	-	-	-	-	51.1
Quartz	-	-	-	-	-	-	-	-	-	-
Clay Matrix	20.2	44.6	52.0	0.4	23.2	9.6	17.0	29.3	42.5	-
Porosity	18.6	1.4	3.4	-	4.0	14.2	18.0	17.8	-	-
Unknown	7.0	5.2	1.8	3.2	0.6	0.4	6.0	4.4	-	-
* NC = Not Counted

1 mm

Figure 11. Photomicrograph of arkosic Sunset Highway member sample 87-20.

as a lithic arkose (Figure 12). Sample 87-20 contains <1% mica and only minor primary intergranular porosity is present in 87-20.

Due to the extremely friable nature of sample 88-57 a thin section could not be constructed. Its composition was determined using a grain mount. The visually estimated modal composition of sample 88-57 is very similar to the sand fraction of 87-20. Quartz is the dominant framework grain. There are equal concentrations of rock fragments and feldspars, again dominated by potassium feldspar, so the sample falls on the boundary between lithic arkose and feldspathic litharenite.

Figure 12. Plot of field study area sedimentary rocks in a ternary sandstone classification diagram.
(After McBride, 1963.)

The visually estimated modal composition of sample 89-3 is dominated by chloritized rock fragments which compose 40% of the sample (Figure 13). These grains are believed to be predominantly mudstone clasts although some may be extremely altered volcanic rock fragments. Moderately fresh volcanic rock fragments are also abundant composing 20% of the sample. Plagioclase is the only abundant monomineralic grain composing 20% of the rock. Other minor monomineralic grains include quartz (1-2%), augite (<1%), and potassium feldspar (<1%), with the remaining 20% of the rock being fine-grained clay matrix. Very little primary intergranular porosity is present in sample 89-3 but a small quantity of secondary porosity has been produced by the partial dissolution of the chloritized rock fragments and plagioclase.

1 mm

Figure 13. Photomicrograph of basaltic Sunset Highway member sample 89-3.

Contact Relations

The Sunset Highway member is poorly exposed within the field study area and neither its upper or lower contact were encountered. Mumford (1988) and Safley (1989) believed both the upper and lower contacts of the Sunset Highway member to be conformable with the overlying Sweet Home Creek member and underlying Roy Creek member.

SWEET HOME CREEK MEMBER

Lithology and Petrography

The Sweet Home Creek member is the thickest member of the Hamlet formation within the field study area. It consists of approximately 200 meters of micaceous, carbonaceous mudstone with fine-grained arkosic and lesser lithic sandstone interbeds. Sandstone interbeds constitute approximately 5-30% of the Sweet Home Creek member within the field study area.

Massive or bioturbated mudstones are dominant, but thin beds of laminated mudstone also occur. The mudstone is occasionally interlaminated with fine-grained arkosic sandstone. Burrows, identified as Helmenthoida and Chondrites by Rarey (1986), are locally abundant within the mudstone.

Sandstone interbeds within the Sweet Home Creek member are typically massive and range in thickness from a few millimeters to 10's of centimeters. The contact between the sandstone interbeds and host mudstones are generally sharp and some show evidence of scour as well. Calcite concretions are sparsely present within the sandstone interbeds.

Three arkosic sandstone interbeds within the Sweet Home Creek member were petrographically analyzed. Two of the samples were point counted (samples 88-46 and 88-60) while the composition of the third (sample 89-1) was determined by visual estimation. The samples were collected from sandstone interbeds 15 centimeters, 30 centimeters, and 90 centimeters thick, respectively. The interbed from which sample 88-60 was collected was concretionsary.

All three of the samples classify as arkoses (Figure 12) with quartz being the dominant framework grain, followed closely by the feldspars (Figure 14). Potassium feldspar is more abundant than plagioclase in samples 88-60 and 89-1 but not in 88-46. All three of the samples are slightly carbonaceous and their modal abundance of

Figure 14. Photomicrograph of Sweet Home Creek member sample 89-1.

biotite ranges from <1% to >5%. Porosity within the samples is principally in the form of primary intergranular porosity with minor secondary porosity produced by the dissolution of framework grains.

All three of these samples are compositionally and texturally indistinguishable from sandstones from the Cowlitz Formation (Figures 11 and 26). Their occurrence as thin sandstone beds with host mudstones along with their stratigraphic position, however, does distinguish the samples as Sweet Home Creek sandstone interbeds.

Fossil Content

Seven Sweet Home Creek member samples were disaggregated and picked for foraminifera. Five of the samples (87-F7, 87-F12, 87-42, 88-62, 88-64) yielded foraminifera. The foraminifera were examined by Schmidt (1989) of ARCO Oil and Gas Corporation. Fourteen distinct specimens were identified in the five samples (Table IV). With the exception of samples 87-F7 and 87-F12 age diagnostic foraminifera confirm a Narizian age for the samples. Megafossils were found at several localities within the field study area but due to their high degree of weathering their identity could often not be established. Several unidentifiable gastropods and pelecypods were found at locality 24A. A single irregular echinoid was also found at locality 143.

Contact Relations

The basal contact of the Sweet Home Creek member is poorly exposed within the field study area and thus its relationship with the underlying Sunset Highway member is indeterminable. To the west in

TABLE IV

FORAMINIFERA AND OTHER MICROFOSSILS IDENTIFIED IN
FIELD STUDY AREA SAMPLES, BY SCHMIDT (1989).

	Hamlet formation					Keasey Formation	
	F7-F7	87-F12	87-42	88-62	88-64	87-35	88-43
<u>Microfossils</u>							
Sponge Spicules	-	-	-	-	-	P	-
Diatoms, Pyritized	-	-	-	-	-	T	-
Fish Teeth/Remains	-	-	-	-	-	P	-
Radiolaria, Discoidal	-	-	-	-	-	A	-
Radiolaria, Spherical	-	-	T	-	-	P	-
Staloliths Otoliths	-	-	-	-	-	P	-
Cassidulina margareta	-	-	-	-	-	T	-
Chilostomella	-	-	-	-	-	T	-
Florilus applini	-	-	-	-	-	T	-
Globobulimina	-	P	-	C	-	P	T
Lenticulina	T	-	-	-	-	T	P
Pseudoglandulina conica	-	-	-	-	-	T	-
Quinqueloculina	-	-	-	-	-	T	-
Foram Chamber, Internal Casts	-	C	P	C	-	P	C
Guttulina irregularis	-	-	T	-	-	-	-
Ostracod Deep-Median-Sulcus	-	-	T	T	-	-	-
Plectofrondicularia packardii	-	T	-	-	-	-	-
Cibicides haydoni	-	-	-	-	-	-	P
Haplophragmoides, Coarse	-	-	-	-	-	-	P
Bathysiphon eocenica	-	-	-	-	P	-	-
Cyclammina pacifica	-	-	-	-	P	-	-
Eggerella Mist Large	-	-	-	-	C	-	-
Haplophragmoides	-	-	-	-	P	-	-

KEY -> - = Not Present T = 1 Specimen P = 2-5 Specimens C = 5-15 Specimens A = >15 Specimens

Clatsop County several workers have determined that the basal contact of the Sweet Home Creek member is conformable upon and gradational with either the Roy Creek member (Rarey, 1986) or Sunset Highway member (Mumford, 1988; Safley, 1989).

Niem and Niem (1985) consider the Cowlitz Formation to unconformably overlie the Sweet Home Creek member west of the field study area. There is no absolute evidence indicating the presence of an unconformity within the field study area. The two units have similar structural attitudes and are compositionally similar which supports a conformable relationship. Granted, there is a rapid lithofacies change from outer-neritic to mid-bathyal mudstones of the Sweet Home Creek member to the foreshore to inner-neritic sandstones of the Cowlitz Formation. This may, however, simply represent a rapid but conformable regression.

COWLITZ FORMATION

Nomenclature and Distribution

The Cowlitz Formation was first formally described by Weaver (1912) who established a type locality consisting of 61 meters of Late Eocene sediments exposed in the bluffs of the Cowlitz River east of the town of Vader, in southwest Washington. Weaver (1937) later expanded the type locality to include 1310 meters of Eocene strata exposed along Olequah Creek near its confluence with the Cowlitz River in southwestern Washington. Henriksen (1956) expanded the Cowlitz Formation even further including over 1000 meters of shale that underlies the Cowlitz Formation of Weaver (1937). The Cowlitz terminology was first applied

in northwest Oregon by Warren and Norbistrath (1946) to describe a sequence of Tertiary marine sediments in the upper Nehalem River basin. They divided the Cowlitz Formation into four members, a basal conglomerate, a lower shale member, a sandstone member, and an upper shale member. The nomenclature of Warren and Norbistrath (1946) was used in northwestern Oregon until Wells (1981) restricted the Cowlitz Formation to the sandstone member (Clark and Wilson sandstone) and upper shale member (upper Cowlitz mudstone) of Warren and Norbistrath (1946). The restriction of the Cowlitz Formation to a predominantly sandstone unit, as defined by Weaver (1937), made it a more mappable unit as required by the Stratigraphic Code (1983).

The Cowlitz Formation crops out in eastern Clatsop, northern Washington and southern Columbia counties. It also is present in the subsurface of the Mist gas field. The Clark and Wilson (C and W) sandstone member is the reservoir rock, and the upper Cowlitz mudstone member is the cap rock in the Mist field.

Within the field study area the Cowlitz Formation is exposed in several small blocks surrounding Rocky Point (Plate I). The Cowlitz Formation is well-exposed along recently built Longview Fibre Corporation logging roads. The Columbia Mainline (CML), which runs N-S through the field study area from Clear Creek to Fall Creek, has particularly good exposures all along its length. Natural stream cut exposures also occur but are much less common within the field study area.

Lithology

The Cowlitz Formation within the field study area consists almost entirely of the C and W sandstone member and is approximately 135 meters thick (Figure 4). The upper Cowlitz mudstone member occurs in only a single outcrop within the field study area (locality 13). It has a total thickness of approximately three meters and consists of laminated siltstone with thin sandstone interbeds. The contact with the underlying C and W sandstone appears to be gradational.

Two stratigraphic sections, Fall Creek (Figures 15-17) and CML (Figure 18), were measured in the C and W sandstone member along the CML at localities 44 and 16, respectively. A third section, Rocky Point Road, was measured from a stream cut exposure approximately 1.2 kilometers east of Rocky Point (locality 167). Stratigraphic control could be ascertained only in the Fall Creek section.

The Fall Creek section (Figures 15-17) was measured in the uppermost part of the Cowlitz Formation. It is 62 meters thick and begins within 3 meters of the Cowlitz-Keasey contact. The upper Cowlitz mudstone member is absent from the section. The upper part of the C and W sandstone member consists predominantly of massive to faintly cross-laminated, fine-grained, well-sorted, micaceous, carbonaceous, arkosic sandstone. Sparse thin mudstone interbeds and burrowed intervals are also present. Lower in the C and W sandstone member mudstone interbeds increase in both thickness and abundance. Hummocky cross-stratification (Dott and Bourgeois, 1982), planar cross-bedding, ripples, and graded bedding, as well as parallel stratification, all

Lithologic Description

Interpretation

Figure 15. Fall Creek measured section (0-21 meters). Key to symbols is in Appendix B.

Figure 16. Fall Creek measured section (21-42 meters). Key to symbols is in Appendix B.

Figure 17. Fall Creek measured section (42-62 meters). Key to symbols is in Appendix B.

occur in the middle and lower parts of the Fall Creek section. Plant debris and burrows are the only fossils present within the section.

The Columbia Mainline section (Figure 18) is 11 meters thick and begins approximately 20-40 meters below the Cowlitz-Keasey contact. It contains a massive to faintly laminated sandstone at its top. The massive sandstone is underlain by a laminated mudstone containing abundant sandstone channels. The channeled interval does not occur at any stratigraphic level within the Fall Creek section. Underlying the channeled mudstone is an interbedded sandstone and mudstone. The interbeds range in thickness from a few millimeters to 10's of centimeters.

The Rocky Point Road section (Figures 19-20) is 34 meters thick and is near the base of the C and W sandstone member. The upper 21 meters of the section consists of fine-grained arkosic sandstone with sparse, thin, mudstone interbeds. The sandstone is not as well-sorted as the massive sandstone in the two previous measured sections. The increase in silt and clay-sized material in the Rocky Point Road section has produced a more well-indurated, and less porous sandstone. A thin interbedded sandstone, mudstone, and coal bearing unit three meters in thickness is present below the upper sandstone. Both the upper and lower contacts of the unit are erosional. The sandstone interbeds are massive to graded. Sand-filled burrows are present in a mudstone bed at the top of the unit. The coal and interbedded sandstone is also exposed in the bed of the Nehalem River (locality 130) 1.6 kilometers to the southeast of the Rocky Point section. The lateral continuity of the

Figure 18. Columbia Mainline measured section. Key to symbols is in Appendix B.

Figure 19. Rocky Point Road measured section (0-18 meters).
Key to symbols is in Appendix B.

Figure 20. Rocky Point Road measured section (18-34 meters). Key to symbols is in Appendix B.

coal confirms that it was not transported. Sandstone below the coal bearing unit is similar to that above it but contains more abundant mudstone interbeds.

Petrography

Six C and W sandstone samples were petrographically analyzed. Point counts consisting of 500 points were conducted on five of the samples in order to determine their modal composition (Table III). Three of the samples were collected from near the top of the C and W sandstone member (samples 87-12, 87-37, 87-38). One from approximately 50 meters below the top (sample 87-17), and one from a concretionary bed near the middle of the C and W sandstone member (sample 87-33). The sixth sample (which was not point counted) was collected from the distinct coarse-grained sandstone underlying the coal near the base of the C and W sandstone member (sample 88-38). Four of the samples that were point counted classify as lithic arkose while the fifth (sample 87-33) classifies as an arkose (Figure 12).

Quartz and feldspar are the dominant detrital grains in the C and W sandstone member samples with the exception of sample 88-38 (Figure 21). Plagioclase is more abundant than potassium feldspar in the three samples from near the top of the Cowlitz Formation. Potassium feldspar is more abundant than plagioclase in the two samples from near the middle of the Cowlitz Formation. Samples 87-37 and 87-38 which were collected within three meters of the top of the C and W sandstone member also show greater plagioclase dominance than 87-12 which was collected approximately 10-15 meters below the top of the C and W sandstone member. This may indicate a gradual increase in the supply of

Heavy Minerals

Heavy minerals were separated from two C and W sandstone member surface samples (87-14, and 87-9) using the same procedure briefly discussed in the following chapter. The samples were collected from the middle (87-14) and upper (87-9) parts of the Cowlitz Formation. Seventeen heavy mineral species were differentiated in the two samples (Table V).

The composition of the heavy mineral suite from the surface samples is similar to that of the core samples. The only notable difference is the increase in the abundance of amphiboles in surface samples. The average modal concentration of amphiboles in the core samples is only 0.5 percent. The concentration of the amphiboles increases to 12.5 and 6.3 volume percent in samples 87-9 and 87-24.

Fossil Content

The only fossils present in the Cowlitz Formation within the field study area are ichnofossils. Burrows are common in the C and W sandstone member and are generally perpendicular or oblique to bedding. Burrows of identical morphology were found by both Jackson (1983) and Timmons (1981) and identified by C. Kent Chamberlain as Rosselia and/or Cylindrichnus and Thalassinoides. Both are indicative of a nearshore marine environment (Chamberlain, 1978).

Contact Relations

Although the basal contact of the Cowlitz Formation has been described as unconformable by Niem and Niem (1985) there is no unequivocal evidence that it is unconformable within the field study

area. There is a rapid lithologic change at the Hamlet-Cowlitz contact but it may simply represent a rapid regression.

The contact between the Cowlitz and overlying Keasey Formation has been described as unconformable in the subsurface of the Mist gas field. The contact can not be located based on the lithology of well cuttings, so this interpretation is based on both the abrupt change from Narizian to Refugian microfauna between the Cowlitz and Keasey formations and the irregular topography of the paleosurface that has developed at the top of the Cowlitz Formation (Jack Meyer, 1989, personal communication). The Mist gas field, however, is centered on the Nehalem arch. The uplift of the Nehalem arch appears to have caused extensive erosion of the Cowlitz Formation, creating the unconformity present in the Mist field.

The field study area is 12 kilometers south of the Mist gas field and well off the Nehalem arch. The contact relations within the field study area are not as straightforward as in the Mist field. In the field study area the contact between the Cowlitz and Keasey formations can be established based on lithology. The arkosic sandstones at the top of the Cowlitz Formation are easily differentiated from the basaltic and/or glauconitic sandstones at the base of the Keasey Formation. Late Narizian foraminifera are present in the lower parts of the Keasey Formation at localities away from the Nehalem arch (Jack Meyer, 1989, personal communication).

The compositional change between the Cowlitz and Keasey formations appears to be gradational at several localities within the field study area. The gradual increase in plagioclase at the top of the Cowlitz

Formation also provides evidence of a gradational compositional change. Sandstones near the base of the Keasey Formation are often texturally similar to the underlying Cowlitz Formation sandstones. The structural attitudes of the two units are also identical, providing further evidence of a conformable contact. The presence of glauconite at the Cowlitz-Keasey contact, however, is contradictory to a conformable contact. Glauconite is indicative of nondeposition, extensive reworking, or low sedimentation rates which might make the contact slightly disconformable. Therefore, the upper contact of the Cowlitz Formation can be best described as conformable to slightly disconformable based on evidence present within the field study area.

COLE MOUNTAIN BASALT

Nomenclature and Distribution

The Cole Mountain basalt nomenclature was introduced by Niem and Niem (1985) to describe Late Eocene basalt intrusives present in Clatsop County. Subsequent workers in Clatsop County (Rarey, 1986; Mumford, 1988; and Safley, 1989) have adopted the Cole Mountain basalt nomenclature. Cole Mountain basalt is geochemically similar and stratigraphically correlative with the type area Goble Volcanics as defined by Wilkinson and others (1946). Cole Mountain basalt terminology was proposed due to the isolation of Cole Mountain basalt from the type area Goble Volcanics and the Goble Volcanics of southwest Washington (Rarey, 1986).

The aerial extent of the Cole Mountain basalt is limited to southeast Clatsop, southwest Columbia, and northernmost Washington counties (Niem and Niem, 1985).

Cole Mountain basalt is exposed in a large block in the southwestern part of the field study area and in an isolated exposure (locality 6) along Timber Highway in the southern part of the field study area (Plate I). The Cole Mountain basalt exposures within the field study area have been mapped previously as Tillamook Volcanics (Jackson, 1983; Van Atta, 1985). The best Cole Mountain basalt exposure within the field study area is in a small inactive quarry along Kist Creek (locality 11). Cole Mountain basalt road cut exposures are typically extensively weathered, but natural exposures provide several additional fresh outcrops.

Lithology and Petrography

Cole Mountain basalt within the field study area is typically porphyritic, with abundant large (up to 5 mm) plagioclase phenocrysts. Smaller phenocrysts of augite also occur, but are less common. The basalt is vesicular to amygdaloidal with calcite, silica, and zeolites filling both vesicles and fractures. The extent of secondary mineralization is highly variable. Typically, Cole Mountain basalt is massive although radial jointing was observed at locality 11 (Figure 23). Pillow basalts were not observed within the Cole Mountain basalt in the field study area, but a large quarry just outside the western boundary of the field study area contains abundant basalt pillows. The same radial jointing also occurs at this locality.

Pillows have also been reported in Cole Mountain basalt to the west in Clatsop County (Rarey, 1986).

A single Cole Mountain basalt sample (87-3) was petrographically analyzed. The sample contains roughly 25% plagioclase phenocrysts and glomerocrysts (Figure 24). Smaller (<1mm) augite phenocrysts were also observed but compose less than 5% of the basalt. The remaining 70% of the rock consists of a finely crystalline matrix with abundant, randomly oriented plagioclase microlites. Microcrystalline augite and ferromagnesian granules are present in the interstices between the plagioclase microlites. The Cole Mountain basalt sample is easily distinguished from Tillamook Volcanics samples by its felty, intergranular groundmass.

Figure 23. Small inactive quarry in the Cole Mountain basalt at locality 11 displaying radial or fan jointing.

Figure 24. Photomicrograph of Cole Mountain basalt sample 87-3. Shows a plagioclase glomerocryst in a felty, microcrystalline groundmass.

Geochemistry

Six whole-rock geochemical analyses were performed on Cole Mountain basalt samples. Five samples were collected from localities within the large block in the southeast of the field study area (samples 87-3, 87-8, 88-7, 88-12, and 88-19). The sixth sample (88-66) was collected at the isolated exposure along Timber Highway. The results of the geochemical analyses are shown in Tables I and II. The geochemical data has been plotted in several graphs in order to differentiate the Cole Mountain basalt from other field study area volcanic rocks. The graphs are used to classify the Cole Mountain basalt as well.

Using the nomenclature of Irvine and Baragar (1971) the Cole Mountain basalt plots well within the subalkaline field (Figure 6). The subalkaline field can be further subdivided into tholeiitic and calc-alkaline suites. The Cole Mountain basalt samples plot at the boundary between the tholeiitic and calc-alkaline fields (Figure 7) and should therefore be described as transitional between the tholeiitic and calc-alkaline suites.

Using the nomenclature of Cox and others (1979) the Cole Mountain basalt samples classify as basalt to basaltic andesite (Figure 8). Also included in Figure 8 is an average composition of four Cole Mountain basalt samples analyzed by Rarey (1986). As can be seen, the Cole Mountain basalt analyzed by Rarey (1986) is higher in silica and alkalies than the basalts analyzed in this study. Berkman (personal communication, 1989) also reported higher silica content for the Cole Mountain basalt just to the west of the field study area. This is not unexpected because Rarey (1986) noted that the Cole Mountain basalt becomes more silica-rich from east to west. All of Rarey's samples were collected approximately 20 kilometers west of the field study area.

In order to aid in the differentiation of the Cole Mountain basalt samples were also plotted in a silica variation diagram (Figure 9). The Cole Mountain basalt samples form a tight cluster in all of the panels of the silica variation diagram and in no place overlap with the Tillamook Volcanics.

Contact Relations

The Cole Mountain basalt appears to have intruded the Tertiary section at or near the Cowlitz-Keasey contact within the field study area. In several localities Cole Mountain basalt is overlain by lithic sandstones and siltstones of the lower Keasey Formation. Also, in the large quarry just west of the field study area the basalt is overlain by silicified micaceous mudstone of the upper Cowlitz mudstone.

Pillows, soft sediment features, and the irregular basal contact of the Cole Mountain basalt indicates shallow emplacement in wet, unconsolidated sediments (Rarey, 1986). Based on the stratigraphic position and shallow nature of the Cole Mountain basalt its age is interpreted as slightly younger than the sediments of the lowermost Keasey Formation.

KEASEY FORMATION

Nomenclature and Distribution

The Keasey Formation was first described by Diller (1896) who examined outcrops along Rock Creek north of the field study area. The Keasey Formation was formally designated by Schenck (1927) who established a type section along Rock Creek. Warren and Norbistrath (1946) later divided the Keasey Formation into three informal members: a basal dark shale member, a middle massive silty mudstone, and an uppermost stratified tuffaceous sandy mudstone. Van Atta (1971a, 1971b) also described three informal members in the Keasey Formation but disagreed with the placement of the Cowlitz-Keasey contact of Warren and Norbistrath (1946). More recent work in the Keasey Formation has yielded

more informal members including the Jewell member (Olbinski, 1983; Nelson, 1985; Rarey, 1986), and the Vesper Church member (Olbinski, 1983; Nelson, 1985).

In this study the Keasey Formation was not subdivided into members. More detailed mapping may prove that there are several distinct lithologic units composing the Keasey Formation within the field study area. Such detail was not attempted in this study.

The Keasey Formation is exposed at the surface in southeast Clatsop County and throughout much of Columbia, Tillamook, and Washington counties.

Within the field study area the Keasey Formation covers the largest area of any of the exposed rock units (Plate I). In the southern part of the field study area there is minimal logging activity and fresh road cut exposures are not present. As a consequence, the best exposures of the Keasey Formation are in recent road cuts in the northern part of the field study area (Plate I).

Lithology and Petrography

The Keasey Formation consists of thin basaltic and glauconitic sandstones and conglomerates near its base overlain by massive mudstone and siltstone. The thickness of the Keasey Formation within the field study area is difficult to determine due to the lack of measurable stratification within much of the unit. The basal sandstones and conglomerates of the Keasey Formation appear to be approximately 40-80 meters in thickness, while the massive mudstones and siltstones are roughly 200 meters in thickness. The top of the Keasey Formation is not exposed within the field study area.

The base of the Keasey Formation within the field study area generally consists of basaltic and glauconitic sandstones and conglomerates interbedded with siltstones and mudstones. A single large exposure (locality 92) in the southern part of the field study area contains four meters of clast supported conglomerate overlain by eight meters of poorly sorted sandstone. Both the sandstone and conglomerate contain concretions and are well-cemented. Faint parallel stratification is present in the unit and individual sandstone beds vary in thickness from 10's of centimeters to several meters. These are generally massive with both gradational and sharp contacts with interbedded mudstones. Well-sorted sandstones and poorly sorted pebbly sandstones are both common. The lithic and/or glauconitic character of sandstones within the Keasey Formation make them easily distinguishable from Cowlitz Formation sandstones.

Rarey (1986) reported the presence of arkosic sandstone channels and associated clastic dikes within the Keasey Formation in Clatsop County. Although arkosic sandstone channels were not encountered in the field study area, two arkosic clastic dikes were found within the Keasey Formation at locality 7 (Figure 25). Massive mudstones and siltstones overlie the sandstones and conglomerates present near the base of the Keasey Formation. They are generally orange or yellow-brown in color due to surface weathering. Rare, fresh, dark gray outcrops are also present within the field study area. The mudstones are tuffaceous, non-micaceous to slightly micaceous, and commonly contain both microfossils and megafossils.

Figure 25. Clastic dike composed of arkosic sandstone present in the Keasey Formation at locality 7.

Seven Keasey Formation samples were petrographically analyzed. The modal composition of two of the thin sections (samples 87-36 and 87-9) was determined using 500 point counts (Table III). The composition of the remaining five samples (87-5, 88-9, 88-13, 88-15, and 88-16) was estimated visually. All seven of the samples were collected from basaltic and/or glauconitic sandstones and conglomerates near the base of the Keasey Formation.

The two samples that were point counted were both collected within two meters of the base of the Keasey Formation. Sample 87-36 classifies as a feldspathic litharenite and sample 87-39 as a lithic arkose (Figure 12). Volcanic rock fragments in 87-36 and glauconite in 87-39 are the dominant framework grains. The volcanic rock fragments are

typically much larger (up to 1.4 mm) and more rounded than the quartz and feldspar grains in the samples. Glauconite pellets also tend to be slightly larger than quartz and feldspar grains. The dominant monocrystalline grains in the Keasey Formation sandstones are feldspars and quartz. Plagioclase is more abundant than potassium feldspar in both samples. Both samples contain very little porosity due to abundant fine-grained matrix.

The remaining five samples are extremely variable in composition. Sample 87-5 is a glauconitic sandstone consisting of 80% glauconite, minor plagioclase, and a zeolite cement which was identified by its low birefringence and crystal morphology (Figure 26). Sample 88-9 is a litharenite composed almost totally of basaltic (64%) and lesser sedimentary (15%) rock fragments (Figure 27). Minor plagioclase (2%) and trace pyroxene fragments are the only monocrystalline grains present in the sample. It also contains a pervasive zeolite cement. The dominant framework grains in sample 88-13 are extremely altered volcanic rock fragments (35%). Monocrystalline grains, all totaled, are of equal abundance. Quartz and plagioclase are equally abundant (17% and 16% respectively). Potassium feldspar is much less abundant (2%). Unlike most of the volcanic sandstones in the Keasey Formation, sample 88-13 is well-sorted and contains only 10% fine-grained matrix. The high degree of sorting and altered state of the volcanic rock fragments may indicate that the sediments were reworked prior to deposition. Samples 88-15 and 88-16 were collected from locality 92 as mentioned previously. Sample 88-15 came from the sandstone, sample 88-16 from the conglomerate.

Figure 26. Photomicrograph of glauconite sandstone from the Keasey Formation (sample 87-5).

Sample 88-15 is a poorly sorted coarse-grained lithic arkose. Coarse-grained, prismatic plagioclase fragments are the dominant framework grain (30%). Volcanic rock fragments (12%) and glauconite (10%) are also abundant. Minor quantities of sedimentary rock fragments (4%), quartz (2%), and potassium feldspar (1%) are also present. All of these framework grains are floating in a fine-grained matrix that composes approximately 40% of the rock. The proportion of matrix to framework grains is highly variable even at the scale of a thin section. Where matrix material is less abundant, some calcite cement is present.

1 mm

Figure 27. Photomicrograph of basaltic sandstone from the Keasey Formation (sample 88-9). The sample contains a pervasive zeolite cement.

The conglomerate is composed primarily of pebble-sized, rounded, sedimentary (35%) and lesser volcanic (20%) rock fragments. The matrix composes 15% of the conglomerate and contains equal quantities of sand-sized quartz (4%) and plagioclase (4%) and lesser potassium feldspar (1%) and clinopyroxenes (1%). The remaining 5% of the matrix consists of silts and clays. The conglomerate contains as much as 25% calcite cement.

Fossil Content

The Keasey Formation contains abundant microfossils and megafossils. Megafossils were found in nearly every good Keasey

Formation outcrop within the field study area (Table VI). One particularly fossil-rich location (locality 36) yielded 8 identifiable species of gastropods, and 4 identifiable pelecypod species. The gastropods constitute a well known bathyal assemblage (Hickman, 1976, 1980).

Two samples were also picked for foraminifera (Table IV). Sample 88-43 contained a foraminifera assemblage indicative of the Refugian foraminiferal stage. Both samples contain microfossils indicative of an outer-shelf or deeper environment.

TABLE VI
KEASEY FORMATION MEGAFOSSIL CHECKLIST

Gastropods	PelycePods
<i>Bathybembix columbiana</i> *	<i>Acila</i> sp.*
<i>Epitonium keaseyense</i> *	<i>Tellina</i> n. sp.*
<i>Conus weltoni</i> *	<i>Nuculana</i> aff. <i>washingtonensis</i> *
<i>Turricula keaseyensis</i> *	<i>Portlandia</i> (<i>Portlandella</i>) <i>chehalisensis</i> *
<i>Natica weaveri</i> *	<i>Thyasira</i> (<i>Concholele</i>) <i>bisecta</i>
<i>Polinices clementensis</i> *	
<i>Scaphander impunctatus</i> *	Scaphopods
<i>Exilia bentsonae</i>	<i>Dentalium</i> sp.*
* Specimen collected at locality 36	

Contact Relations

The basal contact of the Keasey Formation is conformable to slightly disconformable within the field study area. The basal contact is discussed in detail in the Cowlitz Formation contact relations section.

The upper contact of the Keasey Formation is not exposed within the field study area. The contact between the Keasey and Pittsburgh Bluff formations has been described as disconformable at the type section of the Keasey Formation along Rock Creek (Warren and Norbistrath, 1946).

CORE ANALYSIS

Three cores were recovered from the Mist gas field by Oregon Natural Gas Development Corporation as part of a gas storage project. These cores were made available to me and to Tom Berkman of Oregon State University. Since the three cores constitute a great deal of work it was decided that both Berkman and I would each concentrate our work on a single core. Berkman chose core OM41A-10 and I selected core OM12C-3. Core IW33C-3 was considered less important since it contains only 54.9 meters of sandstone as opposed to 99.1 meters in OM12C-3 and 91.4 meters in OM41A-10.

When made available, the cores were incased in split, 0.9 meter sections of PVC pipe. Many 2.54 centimeter plugs had been removed from the cores by previous workers (Core Laboratories, 1987; D.K. Davies and Associates, 1987; Dan McKeel, 1987a, 1987b). All three cores were cut and mounted and then photographed by Tom Berkman and myself prior to the start of the analytical work.

Core OM12C-3 originated at a depth of 819.9 meters and bottomed at a depth of 919.0 meters. The core had a recovery rate of 83% with two major intervals of core loss; one of 3.5 meters and another of 11.3 meters. In all 82 meters of core was recovered from well OM12C-3. The contact between the upper Cowlitz mudstone and the C and W sandstone occurs at 819.9 meters in OM12C-3. Thus, with the exception of two large, and several small gaps the upper 99.1 meters of the C and W sandstone was recovered.

The core was logged at a scale of 1"=1' and a stratigraphic section constructed. Samples were selected for additional analytical work using the log and stratigraphic section. Samples were collected for thin sections, heavy mineral separation, geochemistry, granulometry, and clay mineralogy. Dan McKeel, a consultant working for ARCO Oil and Gas Corporation, had previously sampled the core for foraminifera.

LITHOLOGY

In core OM12C-3 the C and W sandstone is composed predominantly of fine to very fine-grained, micaceous, carbonaceous, arkosic sandstone and thinly bedded, interstratified mudstone (Figures 28-31).

The sandstone is typically very friable with intermittent small concretions and thin well-cemented beds. It is massive to well-laminated. Laminae are generally roughly parallel but abundant low-angle truncations do occur. The low-angle truncations identify low-angle cross-bedding, some of which may represent hummocky cross-stratification. Thin sets of high-angle cross-laminae and thin bioturbated intervals are also present in the sandstone.

The composition of the sandstone is generally very uniform. One exception to this uniformity is the intervals containing granule to coarse sand-sized scoriaceous basalt fragments. Two such intervals occur in the core. The larger of these zones contains abundant authigenic chlorite giving it a distinct blue-green color. It has been termed the blue-green zone. The blue-green zone also has a distinct electric log signature and has been used extensively as a marker bed in electric log correlation (Jack Meyer, personal communication, 1989).

Figure 28. Core OM12C-3 measured section of depths 820-844 meters. Key to symbols is in Appendix B.

Figure 29. Core OM12C-3 measured section of depths 844-868.5 meters. Key to symbols is in Appendix B.

Figure 30. Core OM12C-3 measured section of depths 868.5-893 meters. Key to symbols is in Appendix B.

Figure 31. Core OM12C-3 measured section of depths 893-919 meters. Key to symbols is in Appendix B.

Two other compositional variables are the abundance of mica and carbonaceous matter. Mica content varies from a few percent to approximately 10%. Both the modal percent of disseminated carbon and the concentration of organic-rich laminae are also variable.

Mudstone occurs as isolated thin beds (<10 cm in thickness) and concentrated in intervals within the sandstone. Intervals with abundant mudstone interbeds are typically 0.6 to 1.2 meters thick and increase in abundance with depth. The sedimentary structures present in the mudstone interbeds include lenticular and parallel lamination, ripples, and biogenic structures. Thin interlaminated sandstone and siltstone are common. Bioturbation is generally moderate in the mudstone. One exception is a thoroughly bioturbated interval 0.6 to 0.9 meters in thickness near the top of the core. Burrows are also sparsely present in the mudstone. The details of variations in the lithology of the C and W sandstone in core OM12C-3 are given in Figures 28-31.

PETROGRAPHY

Eight thin sections of sandstone samples from core OM12C-3 were examined with a petrographic microscope in order to determine their modal composition. Each sample was impregnated with blue epoxy prior to thin section manufacture. Each thin section was stained for potassium feldspar to ease the differentiation of untwinned plagioclase and potassium feldspar. Five hundred points were counted to determine the modal abundances given in Table VII. All of the samples classify as either arkose or lithic arkose (Figure 32).

TABLE VII
MODAL ABUNDANCE OF OM12C-3 SAMPLES

Depth	2705	2736	2767	2806	2884	2926	2956	3001
<u>Mineral</u>								
Mono Quartz	23.5	27.3	28.5	29.4	27.7	24.1	21.6	30.6
Poly Quartz	1.8	1.6	1.0	1.6	0.6	0.4	1.2	3.4
K-Feldspar	16.4	17.9	16.6	12.4	14.8	26.2	17.3	23.7
Plagioclase	5.3	6.5	7.5	8.9	7.4	5.9	6.7	6.8
Alter. Biotite	5.7	2.4	1.7	2.4	0.2	2.5	4.5	0.2
Biotite	3.2	2.8	0.6	1.2	0.2	1.4	1.0	0.0
Muscovite	1.0	5.3	0.8	0.6	0.2	2.0	3.1	0.4
Heavies	0.8	0.6	0.8	1.4	1.0	0.0	1.2	2.4
Carbon. Matter	1.4	2.6	0.2	0.8	0.6	1.2	2.9	0.0
<u>Rock Fragments</u>								
Volcanic	0.0	0.2	0.0	0.6	2.0	0.0	0.0	0.2
Sedimentary	1.0	1.6	4.4	3.9	3.8	3.3	2.2	0.4
Plutonic/Met.	4.6	2.2	2.5	2.8	2.2	0.6	0.6	0.6
Undifferent.	1.2	0.8	0.0	0.8	0.8	0.8	0.0	0.0
Total	6.8	4.8	6.9	8.1	8.8	4.7	2.8	1.2
<u>Cements</u>								
Calcite	0.8	1.2	0.0	0.0	0.0	0.0	7.6	0.0
Quartz	0.0	0.0	0.0	0.0	0.0	0.0	0.0	7.5
Clay Matrix	9.5	4.7	2.0	6.7	24.0	7.0	6.5	9.3
<u>Porosity</u>								
Primary	19.0	20.0	28.9	21.3	10.4	21.1	19.0	13.8
Secondary	4.7	2.0	4.6	5.1	2.4	3.5	4.1	0.6
Total	23.7	22.0	33.5	26.4	12.8	24.6	23.1	14.4

Figure 32. Plot of OM12C-3 C and W sandstone samples in a ternary sandstone classification diagram. (After McBride, 1963.)

The dominant constituents are quartz and feldspar which together account for more than 50% of each sample (Figure 33). Quartz is generally the most abundant followed by potassium feldspar and plagioclase. Other framework grains encountered include mica (both muscovite and biotite), rock fragments (volcanic, sedimentary, plutonic/metamorphic, and undifferentiable), heavy minerals, and carbonaceous matter. Also included in the modal composition are clay matrix, primary and secondary porosity, and authigenic calcite and quartz.

1 mm

Figure 33. Photomicrograph of a typical C and W sandstone sample from core OM12C-3.

Quartz occurs in both unstrained and strained varieties, the latter being dominant. With the exception of sample 3001 polycrystalline quartz is present in only minor quantities (<2%). The higher abundance of polycrystalline quartz in 3001 is attributed to the presence of quartz cement. Although an attempt was made to differentiate quartz cement from detrital polycrystalline quartz, it appears that some quartz cement was counted as polycrystalline quartz. Chert was observed in the core samples but only in very minor quantities (<1%) and was not encountered during point counting.

Potassium feldspar is the dominant feldspar detected. Typically the ratio of potassium feldspar to plagioclase is 2:1 or 3:1. Untwinned potassium feldspar (orthoclase) is more abundant than tartan twinned potassium feldspar (microcline). Plagioclase is dominantly untwinned with lesser albite and rare pericline twinning also present. Plagioclase is frequently clouded by alteration. Both potassium feldspar and plagioclase are commonly partially dissolved.

Mica typically composes 1-10% of each rock sample. Generally biotite is more abundant than muscovite although muscovite is equally abundant in two of the sandstone samples. More than half of the biotite has undergone some alteration. Commonly the micas have been deformed by compaction.

Rock fragments make up only a minor portion of the core samples (1-7%). Undifferentiated plutonic and metamorphic rock fragments and sedimentary rock fragments are equally abundant while volcanic rock fragments are less abundant.

Heavy minerals were counted in order to determine their modal abundance but were not identified in thin section. They compose only 1-2.5 volume percent of each sample. Heavy minerals are discussed in more detail in the following section.

Both disseminated carbonaceous matter and carbon-rich laminae occur in the C and W sandstone core samples being absent only in sample 3001. Generally the particles of carbonaceous matter are two to three times larger than surrounding detrital grains, and exhibit ductile deformation.

Clay matrix is present in all eight of the core samples. It composes between two and ten volume percent of the core samples with the exception of sample 2884, which contains 24% clay matrix. The probable reason for this marked increase in sample 2884 is discussed in detail in the clay mineralogy and geochemistry sections. The identity of the clays was not determined in thin section but is also discussed in the clay mineralogy section. The distinction between detrital and authigenic clay was not quantified during the petrographic analysis, however, data from other sources (x-ray diffraction and electron microscopy, which are discussed later in this report) indicate that a majority of the clay matrix is authigenic. Authigenic clays are the most prevalent cement in the core samples.

Quartz cement was encountered only in sample 3001 where it composes 7.5% of the sample. The quartz cement shows a preference for detrital quartz seed grains, occurring predominantly as overgrowths on detrital quartz.

A well developed calcite cement was also encountered in a single sample. Sample 2956 contains microconcretions of calcite a few millimeters in diameter. Calcite has precipitated authigenically between mica platelets in samples 2705 and 2736 but not in large enough quantities to be considered a cement. Sample 2736 also contains a few intergranular calcite crystals that may be remnants of a more pervasive calcite cement.

The modal abundance of primary and secondary porosity were also determined. Total porosity ranges from 13-33% in the eight samples. Porosity will be discussed in more detail in following sections.

HEAVY MINERALS

Heavy minerals were separated from a 3 to 4.5 phi size fraction of five C and W sandstone samples from core OM12C-3 using 1,1,2,2-tetrabromoethane (specific gravity 2.96 at 25°C). Each sample was weighed prior to mineral separation, and heavy minerals after each separation, in order to determine the weight percent of heavy minerals in each sample (Table VIII). Heavy mineral grains were then mounted on glass slides using Lakeside 70. Three hundred grains were counted for each sample in order to determine the modal abundances which are given in Table V.

Twenty heavy mineral species were differentiated. The most abundant heavy minerals include epidote, opaque minerals, biotite, garnet, sphene, zircon, apatite, and augite. The modal abundance of the remaining 12 minerals is minor (<2.1%).

TABLE VIII
HEAVY MINERAL WEIGHT PERCENT IN C AND W SANDSTONE
CORE SAMPLES

Sample #	Weight of Sample	Weight of Heavies	Weight % Heavies
2715	16.30g	0.463g	2.8
2742	5.39g	0.277g	5.1
2884	24.43g	0.065g	0.3
2806	17.05g	0.052g	0.3
2989	3.21g	0.058g	1.8

Epidote

Epidote is the most common heavy mineral found in the C and W sandstone core samples. It typically occurs as anhedral, colorless to greenish-yellow grains. The more strongly colored grains are often pleochroic. Epidote is a common accessory mineral in igneous rocks and contact and regional metamorphic rocks. It may also be introduced as a result of hydrothermal alteration of a variety of rocks (Nesse, 1985).

Opaque Minerals

Opaque minerals show more variation in modal abundance than any other heavy mineral, ranging from 10 to >50%. The identity of individual heavy mineral species was not determined. Magnetite and ilmenite are typically the most common opaque minerals found in sedimentary rocks. Both are common accessory minerals in most igneous and metamorphic rocks (Nesse, 1985).

Biotite

Red-brown and green varieties of biotite are present in C and W sandstone core samples with the previous being dominant. High titanium gives biotite a reddish brown color while high ferric iron gives it a green color (Deer, Howie, and Zussman, 1985). Biotite is common in a wide variety of igneous and metamorphic rocks.

Garnet

Colorless and reddish-pink varieties of garnet occur in all of the C and W sandstone core samples. Most commonly the garnets occur as anhedral to subhedral crystals with only an occasional euhedral crystal. Garnet is most common in regionally metamorphic rocks but is also found in a variety of igneous rocks.

Sphene

Sphene occurs as anhedral-subhedral colorless grains and less commonly as sugary-brown, pleochroic grains. Sphene is easily recognized by its high dispersion and extreme birefringence. Sphene is common in a wide variety of igneous and metamorphic rocks.

Zircon

Zircon is generally euhedral, prismatic, and colorless in the C and W sandstone core samples. Rare pink zircons are also present as are a few acicular zircons with length to width ratios as high as 6:1. Zircon is very common as a accessory mineral in igneous rocks and is also quite common in a variety of metamorphic rocks (Nesse, 1986). Van Atta (1971) also found zircons with adhering volcanic glass in the Cowlitz Formation indicating a volcanic (pyroclastic) source.

Apatite

Apatite occurs as colorless, euhedral prisms, and as subrounded prisms and occasional broken crystals. Dusky gray apatites are also common and tend to be more rounded. Apatite is an accessory mineral in a wide variety of igneous and metamorphic rocks (Nesse, 1986).

Augite

Augite commonly occurs as pale green stubby prisms. The typical prismatic cleavages of pyroxenes are usually apparent. Augite is most common in alkaline igneous rocks such as basalt alkali granite, and syenite. It occurs in some schists and rarely in alkalic volcanic rocks (Nesse, 1986). Augite is the most abundant nonopaque heavy mineral in the local Tillamook Volcanics and Cole Mountain basalts.

Minor Heavy Minerals

Clinozoisite, orthopyroxenes, tourmaline, rutile, staurolite, zoisite, allanite, amphiboles, monazite, muscovite, kyanite, and glaucophane all occur in minor quantities in the OM12C-3 core samples.

GEOCHEMISTRY

A geochemical study of core OM12C-3 was conducted in order to qualify any geochemical variations within the C and W sandstone. Twelve samples were collected throughout the 99.1 meters of core with a higher sampling density in and around the blue-green zone (from depths of 2880 to 2895) to determine if it could be used as a geochemical marker bed. Geochemical analyses are also useful in determining the provenance of sediments.

Instrumental neutron activation analysis was used to determine the concentrations of major elements sodium (Na), potassium (K), iron (Fe), and 19 trace elements in twelve samples. Approximately 1 gram of each sample was used for the analysis. Samples were irradiated at 250 KW for 1 hour. The activity of each sample was measured twice, using a Ge(Li) detector, in order to obtain both long and short half-life elements. The first count was done 4 days after irradiation and the second 18 days after irradiation.

Results

The elemental concentrations in percent oxide for Na, K, and Fe and in parts per million (ppm) for the 19 trace elements are given in Table IX. Figure 34 displays shale-normalized concentrations of several rare earth elements (REE) determined for each sample.

Three geochemically distinct groups are revealed by this study. The first group is defined by the presence of zirconium (Zr). The samples within this group also contain atypically high values for tantalum (Ta), cerium (Ce), chromium (Cr), europium (Eu), ytterbium (Yb), terbium (Tb), lutetium (Lu), thorium (Th), and hafnium (Hf). There are four samples within this group: 2850, 2900, 2950, and 2981.

The second group is defined by its distinctive major oxide geochemistry (Figure 35), its enrichment in cobalt (Co), Ta, Cs, low La/Sm, and diluted Th relative to lanthanum (La) and scandium (Sc) (Figure 36). The two samples that make up group 2 (2890, and 2893) were collected within the part of the blue-green zone containing abundant scoriaceous basalt fragments.

TABLE IX

GEOCHEMISTRY OF OM12C-3 CORE SAMPLES
Fe, Na, AND K IN PERCENT OXIDE,
TRACE ELEMENTS IN PPM

	Fe	Na	K	La	Sm	Sc	Br	Rb	Cs	Ba	Ce
2735	3.38 + .05	2.39 + .01	5.59 + .19	38.9 + .6	6.05 + .11	8.3 + .4	-	160 + 40	1.15 + .12	1190 + 170	58.3 + 1.6
2785	4.38 + .06	2.64 + .01	5.6 + .2	36.6 + .7	6.99 + .09	10.2 + .6	-	160 + 40	1.46 + .17	1100 + 180	56.4 + 1.9
2850	2.54 + .05	2.93 + .01	4.2 + .3	114.2 + 1.0	16.13 + .12	9.1 + .4	-	110 + 30	.57 + .15	990 + 150	166.0 + 4.0
2870	3.95 + .06	2.62 + .01	6.1 + .2	31.9 + .7	6.22 + .08	10.4 + .5	-	140 + 30	1.07 + .13	1130 + 160	49.1 + 1.5
2878	5.00 + .06	2.31 + .01	6.0 + .2	30.8 + .6	5.80 + .09	9.5 + .5	-	170 + 40	1.15 + .17	1030 + 160	49.1 + 1.8
2890	6.77 + .08	2.13 + .01	4.67 + .17	35.4 + .7	7.45 + .08	11.1 + .5	.45 + .11	130 + 30	.98 + .16	930 + 150	57.5 + 1.7
2893	6.46 + .08	1.63 + .01	3.77 + .14	35.4 + .7	9.53 + .08	11.5 + .5	1.00 + .17	100 + 30	.99 + .13	630 + 170	66.7 + 1.8
2897	2.35 + .04	1.72 + .01	3.26 + .13	60.2 + .7	8.96 + .09	7.2 + .5	.37 + .12	100 + 20	.62 + .10	750 + 110	81.3 + 1.9
2900	2.21 + .04	2.34 + .01	6.9 + .2	88.3 + .9	13.27 + .13	8.2 + .4	-	150 + 40	.74 + .14	1090 + 160	132.0 + 3.0
2950	3.38 + .06	2.09 + .01	5.3 + .3	132.4 + 1.2	18.81 + .13	12.2 + .4	.73 + .16	130 + 30	.76 + .16	1010 + 150	193.0 + 4.0
2981	2.61 + .04	2.25 + .01	4.9 + .2	85.9 + .9	12.2 + .09	8.0 + .3	.41 + .10	130 + 30	.84 + .12	980 + 140	122.0 + 3.0
3010	1.24 + .03	2.30 + .01	4.39 + .19	23.7 + .6	4.25 + .07	4.1 + .4	.55 + .16	100 + 30	.43 + .07	1030 + 130	34.2 + 1.0

TABLE IX
GEOCHEMISTRY OF OM12C-3 CORE SAMPLES
Fe, Na, AND K IN PERCENT OXIDE,
TRACE ELEMENTS IN PPM
(continued)

	Eu	Th	Yb	Lu	Th	Zr	Hf	Ta	Co	Sc	Cr
2735	1.27 + .05	.56 + .09	.32 + .03	.22 + .04	8.5 + .4	-	5.0 + .3	1.3 + .3	9.7 + .3	8.45 + .06	31 + 3
2785	1.27 + .05	.53 + .09	2.2 + .4	.32 + .04	9.0 + .4	-	7.6 + .4	1.5 + .3	11.0 + .4	9.79 + .07	38 + 3
2850	1.94 + .06	1.01 + .11	3.9 + .4	.48 + .05	29.9 + 1.2	900 + 300	22.6 + .9	2.0 + .4	5.7 + .3	9.79 + .07	76 + 3
2870	1.31 + .05	.61 + .10	2.0 + .3	.26 + .04	6.5 + .4	-	6.4 + .3	1.2 + .2	10.4 + .4	10.72 + .08	46 + 3
2878	1.13 + .05	.48 + .09	1.9 + .3	.26 + .04	7.7 + .4	-	6.0 + .3	1.4 + .3	17.2 + .5	9.60 + .07	40 + 3
2890	1.54 + .05	.72 + .12	1.7 + .4	.21 + .05	5.6 + .3	-	6.2 + .4	2.0 + .4	14.9 + .4	11.29 + .08	29 + 3
2893	1.94 + .06	.85 + .12	2.5 + .4	.29 + .05	5.7 + .4	-	6.8 + .4	1.8 + .3	16.2 + .5	11.66 + .08	19 + 3
2897	1.60 + .05	.78 + .10	2.2 + .3	.25 + .03	6.0 + .3	-	5.4 + .3	1.0 + .3	6.3 + .3	7.69 + .06	24 + 3
2900	1.66 + .05	.91 + .10	2.7 + .3	.26 + .04	26.5 + 1.1	800 + 200	12.0 + .6	1.9 + .4	5.5 + .3	8.29 + .07	43 + 3
2950	2.56 + .07	1.22 + .15	4.2 + .5	.46 + .05	28.3 + 1.2	1000 + 400	17.5 + .8	2.9 + .5	7.3 + .3	12.96 + .08	75 + 4
2981	1.89 + .05	.99 + .11	3.4 + .4	.39 + .04	21.2 + .9	800 + 200	12.9 + .6	1.6 + .3	6.6 + .3	8.51 + .06	55 + 3
3010	1.00 + .03	.43 + .06	.95 + .17	.09 + .02	4.7 + .2	-	2.44 + .18	.7 + .16	2.9 + .17	3.95 + .04	13.9 + 1.7

Figure 34. Shale-normalized concentrations of REE in OM12C-3 samples.

Figure 35. Ternary plot (Fe-Na-K) of OM12C-3 samples showing the distinctive major element geochemistry of each of the groups.

Figure 36. Ternary plot (La-Th-Sc) of OM12C-3 samples showing diluted Th of group 2 samples.

The third group is defined by its uniform REE geochemistry (Figure 34). It contains six samples collected from above and below the green zone: 2735, 2785, 2870, 2878, 2897, 3010. The variation in the REE element geochemistry of five of the six samples is small. Sample 3010 has slightly lower REE element concentrations but this difference is attributed to dilution by a calcite cement.

The differences in trace element geochemistry in the C and W sandstone is attributed to two factors; the presence of accessory minerals, and changing provenance. The change in provenance during the depositional history of the cored interval of the C and W sandstone is discussed later.

Accessory Minerals

The modal abundance of accessory minerals such as epidote, zircon, and apatite is generally <2% in C and W sandstone core samples. These and other accessory minerals contain very high concentrations of trace elements relative to the much more abundant (>50%) framework grains of quartz and feldspar. Thus, the abundance of these minerals can have a substantial

effect on the trace element geochemistry of a sample despite their low modal abundance. This effect can be seen in group 1 samples (samples containing Zr). Figure 34 displays the enrichment of the light rare earth elements (LREE) in group 1 samples. The enrichment of LREE is attributed to the presence of accessory minerals such as zircon, which contains the Zr present in group 1 samples, and epidote and/or apatite, which are enriched in LREE (Gromet and Silver, 1983).

Another distinction of group 1 samples is the absence of a Eu anomaly (Figure 34). Both group 2 and 3 samples contain an obvious Eu anomaly. The Eu anomaly in the samples is produced by abundant feldspars, which contain relatively high Eu. The lack of an anomaly in group 1 samples, however, does not indicate a feldspar deficiency. Accessory minerals are not as enriched in Eu as they are in other REE so while the concentrations of other REE's are raised by the presence of accessory minerals Eu is not. This results in a smoothing of the composition diagrams.

GRANULOMETRY

Eleven samples from core OM12C-3 were run through a settling tube in order to determine their grain size distribution. The settling tube system consisted of; a PVC pipe 200 cm in length and 20.32 cm in diameter filled with H₂O, a pan at the bottom of the pipe attached to a strain gauge, and a microcomputer for data processing. Sand was released at the top of the 200 cm column of water and allowed to settle. As the sand accumulated on the pan at the base of the tube it was measured by the attached strain gauge. The raw voltage produced by the tension meter was then sent through an analog digital convertor to the microcomputer. A BASIC program then converted the raw voltage into a data file containing time, cumulative weight percent, phi size, and raw voltage.

The settling tube was calibrated for the density, shape, and rounding characteristics of the Cowlitz Formation, prior to the eleven sample runs. This was done by sieving a randomly selected sample from

core OM12C-3 and running each half phi fraction through the settling tube to determine the average settling time of each half phi fraction. The BASIC program used on the microcomputer could then be "customized" by inserting the equation of the line created by a best fit through the time data plotted against phi size.

The first step in sample preparation was disaggregation. This was done by grinding the rock between the thumb and forefinger. If the rock was too hard to be disaggregated in this manner it was gently ground in a ceramic mortar with a rubber cork. After the disaggregation was complete each sample was wet sieved to remove the finer than 4.5 phi fraction which is too fine-grained for the settling tube system. The <4.5 phi size fraction was set aside for clay mineralogy analysis. Each >4.5 phi sample was then split into 1.0 ± 0.2 gram samples that were ready to be run in the settling tube.

After all of the samples had been run cumulative weight percent curves were constructed using the cumulative weight percent and phi size data from the data file. From these graphs mean, inclusive standard deviation, skewness, and kurtosis were computed using the measures of Folk and Ward (1957) (Table X).

Results

Mean, standard deviation, skewness, and kurtosis are statistical measures used to describe the grain size distribution of sedimentary rocks. The mean is the average grain size of a rock. The range in mean grain size in the eleven samples analyzed is 3.70 to 2.48 phi. This

TABLE X

STATISTICAL MEASURES OF FOLK AND WARD (1957)
FOR OM12C-3 CORE SAMPLES

Sample #	2705	2715	2718	2742	2767	2806	2856	2884	2926	2956	2989
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PHI VALUES

PHI 5	2.26	2.21	2.21	0.85	1.73	2.22	2.09	2.86	1.82	2.34	1.51
PHI 16	2.61	2.57	2.61	1.67	1.94	2.58	2.42	3.24	2.42	2.73	1.77
PHI 25	2.80	2.76	2.81	2.06	2.07	2.79	2.57	3.40	2.69	2.94	1.89
PHI 50	3.16	3.11	3.18	2.45	2.46	3.28	2.86	3.69	3.14	3.36	2.19
PHI 75	3.55	3.54	3.51	2.94	3.00	3.75	3.25	4.01	3.53	3.77	2.64
PHI 84	3.88	3.85	3.71	3.32	3.39	4.00	3.53	4.18	3.75	3.99	3.05
PHI 95	4.45	4.41	4.35	4.22	4.15	4.47	4.20	4.53	4.34	4.41	3.97

STATISTICAL MEASURES

MEAN	3.22	3.18	3.17	2.48	2.60	3.29	2.94	3.70	3.10	3.36	2.34
STANDARD DEV.	0.65	0.65	0.60	0.92	0.73	0.70	0.60	0.49	0.71	0.63	0.69
SKEWNESS	0.16	0.17	0.03	0.05	0.34	0.04	0.24	0.02	-.07	0.01	0.40
KURTOSIS	1.20	1.16	1.25	1.57	1.07	0.96	1.27	1.12	1.23	1.02	1.34

range excludes sample number 2989 which was quartz cemented and not completely disaggregated. This puts all of the samples within the fine to very fine-grained sandstone size range.

The standard deviation of the eleven samples ranges from 0.49 to 0.92 phi. Using the divisions of Folk and Ward (1957) all of the eleven samples are moderately sorted. In the eleven samples analyzed six of the samples have a nearly symmetrical distribution, three are positively skewed, and two are very positively skewed according to the divisions of Folk and Ward (1957). The sample with the largest skewness (2989) can be discounted due to suspected incomplete disaggregation. The final statistical measure, kurtosis, measures the ratio of sorting in the extremes of the distribution relative to sorting in the central portion of the distribution. Using the divisions of Folk and Ward (1957) three of the samples have mesokurtic distributions while the remaining eight samples have leptokurtic distributions.

CLAY MINERALOGY

The clay mineralogy of 7 OM12C-3 core samples was determined using x-ray diffraction. The <4.5 phi (44u) size fraction that was removed from the granulometry samples was used for the clay mineralogy analysis. The only additional sample preparation required was the fractionation of the samples to remove the >2u size fraction. Samples were then mounted on porous ceramic tiles and x-rayed.

An untreated sample was run initially to determine the optimum analytical procedure for each sample. Generally, a magnesium (Mg) saturated and potassium (K) saturated sample were analyzed. The Mg

morphology and are dominantly grain coating (Figure 37). There is a large variety of chlorite species but because of the extensive solid solutions that occur their identification is difficult.

Illite. Illite is the second most abundant clay mineral in the C and W sandstone core samples. It occurs in all samples with the exception of samples from the blue-green zone (2884, and 2893). Its modal abundance ranges from 15 to 20%. It has a high degree of crystallinity with sharp peaks at 10A, 5A, and 3.3A. Illite was observed in thin section as a rare alteration product of muscovite. It was not, however, positively identified using the SEM so its morphology and mode of occurrence is unknown.

10 microns

Figure 37. Electron photomicrograph of core sample 2884 displaying the morphology of authigenic chlorite.

Mixed-layer Clays. Two mixed-layer clays were identified in the OM12C-3 core samples. The most common is an irregularly stratified illite-smectite. It occurs in 6 of the 7 analyzed samples with a modal abundance of up to 25%. The degree of crystallinity can not be determined based on peak sharpness with mixed-layer clays so the degree of crystallinity of both mixed-layer species is unknown. The mixed layer illite-smectite has a d-spacing of between 10.8 and 11.5A. An irregularly stratified mixed-layer chlorite-smectite occurs in 2 of the samples. It produced peaks at 15.5 and 8.3A in a glycerated sample (2742). Neither mixed-layer clay was identified using electron microscopy so their morphology is unknown.

Origin of Clay Minerals

The majority of the clays present in the OM12C-3 core samples are believed to be authigenic. Wilson and Pittman (1977) defined 21 criteria that can be used to distinguish authigenic clays. Six of these criteria were observed in the C and W sandstone samples four of which Wilson and Pittman (1977) consider very reliable indicators of an authigenic origin.

The first of the six criteria is the high degrees of crystallinity of chlorite and illite within the core. Diagenetic clays form slowly at low temperatures and are thus, well crystallized. The honeycombed morphology of the clays is another criteria. The presence of clay mineral "bridges" and delicate needles is the third criteria. Clays with a honeycombed or needle-like morphology are fragile precluding extended transport. Clays commonly partially fill secondary pores created by the dissolution of feldspars, indicating that they

crystallized in place after dissolution. The presence of radially aligned clay minerals (c-axis aligned tangential to grain surface) and the irregular distribution of clays are the fifth and sixth criteria present in the C and W sandstone. They are not considered, by Wilson and Pittman (1977), to be as reliable as the previous four criteria.

The evidence discussed above indicates that at least some of the clays present in the C and W sandstone are authigenic. No evidence is available to indicate the proportion of authigenic and allogenic clays in the C and W sandstone core samples.

BIOSTRATIGRAPHY

Biostratigraphic analysis was conducted on cores OM41A-10 and OM12C-3 for ARCO Oil and Gas Corporation by private consultant Dan McKeel (1987a, 1987b). Twenty-nine samples were examined from OM41A-10 and twenty from OM12C-3.

Two samples from the upper Cowlitz mudstone in OM41A-10 yielded upper and upper middle bathyal assemblages from an open marine environment. They also yielded an age of Upper Narizian. The diagnostic foraminifera include: Cibicides natlandi, Karreriella contorta, and Lenticulina welchi. Two samples from the C and W sandstone in OM41A-10 also contained arenaceous foraminifera. One of the samples contained only unidentifiable foraminifera. The other contained at least one Trochammina sp. which occurs in many water depth habitats. The most likely environment of Trochammina sp. is a marine tidal marsh. A less likely environment, based on fossil data alone, is

a hostile deep water (bathyal) environment with high sedimentation rates. None of the foraminifera found in the C and W sandstone from 41A-10 are age diagnostic.

Only two samples yielded foraminifera in OM12C-3. Both contained only rare Elphidiella sp. Elphidiella sp. occurs today in very shallow, high energy environments such as tidal pools and in the innermost neritic off the coast of Oregon. Elphidiella sp. is not age diagnostic.

Two organic-rich shale interbeds in the C and W sandstone were also examined by Ray A. Christopher for palynomorphs. He found no indication of marine influence in either sample. Thick walled, heavy fern and fungal spores were present in the samples suggesting deposition in close proximity to a terrestrial source.

DEPOSITIONAL ENVIRONMENT

The depositional environment of the Cowlitz Formation can be discussed in detail because of the abundant data collected from both core and surface exposures. By contrast, very little data were obtained on the sedimentary rock units underlying and overlying the Cowlitz Formation so the discussion of their depositional environment is brief. Each unit is discussed in stratigraphic order.

ROY CREEK MEMBER OF THE HAMLET FORMATION

The depositional environment of the Roy Creek member has been described as beach to middle shelf along a high energy, storm-dominated shoreline (Rarey, 1986; Mumford, 1988; Safley, 1989). No new evidence was discovered within the field study area that disputes this interpretation.

The size and shape of the boulders within the boulder conglomerate suggests extremely proximal deposition. Rarey (1986) suggested deposition in a beach or nearshore environment at the base of sea cliffs or sea stacks. The well-sorted pebble to cobble conglomerate present at locality 76 is believed to have been deposited along a high energy shoreline. The presence of the brachiopod *Terebratalia* sp. supports such an environmental interpretation. The sandy siltstone represents deposition in a middle shelf or, less likely, protected embayment. This

fining upward sequence from a thin basal conglomerate to a sandy siltstone depicts a transgression from a beach to middle shelf environment.

SUNSET HIGHWAY MEMBER OF THE HAMLET FORMATION

The depositional environment of the Sunset Highway member of the Hamlet formation has been interpreted as a high energy, shallow marine shelf influenced by storms (Mumford, 1988). Poor exposure of the Sunset Highway member within the field study area affords no evidence contesting this interpretation.

The arkosic sandstone of the Sunset Highway member is generally massive to faintly laminated. Laminae are planar or hummocky. Dott and Bourgeois (1982) interpreted similar hummocky or low-angle cross bedding, in the Middle Eocene Coaledo Formation near Coos Bay, as storm influenced deposition in a zone between outer shelf and nearshore. Mumford (1988) also found rare megafossils indicative of a nearshore depositional environment.

The basaltic sandstone of the Sunset Highway member is poorly sorted and massive. The presence of abundant volcanic detritus and mudstone rip-up clasts combined with poor sorting indicate a high energy environment. Mumford (1988) postulated that the basaltic sandstone was deposited in nearshore environments near volcanic edifices and then mobilized into deeper middle to outer shelf depths. Such an interpretation would account for the mixing of the mudstone clasts which are ripped from the middle shelf environment by resedimentation of the nearshore basaltic sands.

The trace fossil found within the basaltic sandstone were identified as Skolithos. Skolithos is indicative of a shoreface to tidal flat environment. Thalassinoides and Rosselia-Cylindricus trace fossils, which are both indicative of a nearshore marine environment, were also reported by Jackson (1983), Timmons (1981), and Mumford (1988) in the Sunset Highway member.

SWEET HOME CREEK MEMBER OF THE HAMLET FORMATION

The depositional environment of the Sweet Home Creek member has been established as outer neritic to mid-bathyal based primarily on a rich, environmentally diagnostic, Narizian foraminiferal assemblage (Rarey, 1986). Additional environmentally diagnostic foraminifera data from within the field study area agree with this assessment.

Two of the five Sweet Home Creek member samples containing foraminifera contained environmentally diagnostic foraminifera that indicate an upper bathyal or deeper bathymetry. The remaining three samples contain foraminifera that occur in a wide range of depositional environments, from shelf to bathyal.

The lithology of the Sweet Home Creek member also indicates an outer neritic to upper bathyal depositional environment. It consists predominantly of bioturbated and laminated mudstone and siltstone typical of upper slope deposition (Reading, 1986). Localities with an abundance of sandstone interbeds are believed to have been slightly shallower, such as outer neritic. Some of the massive sandstone interbeds within the host mudstones also represent deposition by turbidity currents (Rarey, 1986).

The apparent increase in sandstone at the expense of mudstone in the Sweet Home Creek member within the field study area suggests a slightly shallower environment of deposition than the equivalent strata in Clatsop County to the west of the field study area. This coincides with the pinching out of the Sunset Highway member, which is a shallower water facies than the Sweet Home Creek member, in Clatsop County (Rarey, 1986). The ratio of mudstone to sandstone in the Hamlet formation increases from east to west in northwest Oregon indicating a deepening of its depositional environment.

COWLITZ FORMATION

The small number of cores available, and the lack of good surface exposures within the designated field study area limits the amount of evidence available. The vertical sequence of facies is well documented by the three cores and a few large exposures measured within the field study area. Evidence of the lateral variation, however, is limited. Three cores, separated by 940 and 1040 meters (Figure 2), does not provide substantial evidence pertaining to the degree of lateral facies variation in a depositional system as widespread and complex as the Cowlitz Formation. Information on the lateral variation of facies is also scarce within the field study area, due to poor exposure and the lack of stratigraphic control within the C and W sandstone. Information concerning the geometry of the C and W sandstone is available in the form of geophysical well logs from the Mist gas field but analysis of the well logs was not within the scope of this study. Complex structure within the field study area also precludes the determination of C and W

sandstone geometry within the field study area. The use of fossils to determine the depositional environment of the C and W sandstone is limited by their scarcity. With the exception of burrows and a few foraminifera the C and W sandstone is barren of fossils. Sedimentary structures alone do not absolutely characterize a particular depositional environment, but they can be extremely useful in environmental interpretation.

With the information available the depositional environment of the C and W sandstone has been interpreted as deltaic. The depositional model developed for the Cowlitz Formation contains both delta front and delta plain deposits, with delta front deposits dominating the sequence. The interpretation is based primarily on the sequence of vertical facies and sedimentary structures. Several depositional facies from within the deltaic environment have been identified and are discussed below.

Depositional Facies Analysis

Five distinct depositional facies were identified in surface exposures and subsurface core of the C and W sandstone (Figures 15-20 and 38). Both delta plain and delta front deposits are represented by the five depositional facies. Individual facies range in thickness from 31 meters to <1 meter.

The most abundant facies is the strand plain shoreface/distributary mouth bar facies. Other common facies include the interbedded crevasse splay and interdistributary bay facies, and the interdistributary bay facies. The distributary channel facies is less common occurring only twice in the >200 meters of section and core

Figure 38. Generalized stratigraphic section of core OM12C-3 showing the distribution of depositional facies.

measured. The transgressive facies occurs once within core OM12C-3 and once in the Rocky Point Road measured section. Each of the depositional facies is described below.

Strand Plain Shoreface/Distributary Mouth Bar Facies. The strand plain shoreface/distributary mouth bar facies (Facies A) is the most common of the five depositional facies identified in the C and W sandstone. It occurs in two of the three measured sections, and in all three cores. Facies A is generally between 15 and 25 meters in thickness.

Facies A consists of well-sorted, fine-grained sandstone with only sparse, thin mudstone interbeds. Sedimentary structures present within Facies A include planar cross-bedding, trough cross-bedding, hummocky cross-bedding, planar bedding, and graded bedding. The dominant types of sedimentary structures are planar bedding and low angle planar cross-bedding or hummocky cross-bedding.

The interpretation of Facies A as having been deposited in a distributary mouth bar or strand plain depositional environment is based predominantly on the types of sedimentary structures occurring within it, and to a lesser degree on its stratigraphic position and texture. The types of sedimentary structures reported to occur in a strand plain shoreface or distributary mouth bar settings include low angle cross-bedding, trough cross-bedding, hummocky cross-bedding, plane parallel laminations, distorted laminations, small scale ripple laminations, and graded bedding (Heward, 1981; Balsley, 1986; Coleman and Prior, 1988). Planar bedding and low angle cross-bedding, much like that found in Facies A, is commonly produced during sediment reworking by breaker,

surf and swash zone processes in an upper shoreface setting (Reading, 1986). Some of the low angle truncations in core OM12C-3 may also be hummocky cross-bedding. Hummocky cross-bedding and parallel laminated beds reflect deposition during high energy storm events in a lower shoreface setting (Balsley, 1986). The presence of the rare foraminifera Elphidiella sp. within Facies A in core OM12C-3 also supports an environmental interpretation within a shoreface setting. Elphidiella sp. is known to live today in high energy, very shallow marine environments (Murray, 1973 fide McKeel, 1987).

The distributary mouth bar is the area of shoaling associated with a distributary channel and is the shallowest of the delta front facies. In a shoreface setting sediments of the distributary mouth bar are constantly subjected to reworking by fluvial and wave generated currents producing well-sorted sandstones with characteristic sedimentary structures. In wave dominated deltas wave currents redistribute the distributary mouth bar sands laterally developing large strand plain systems. Thus, in wave dominated deltas, the distributary mouth bar is areally and volumetrically a much smaller depositional setting than the laterally adjacent strand plain shoreface deposits. The shoreline processes occurring along both distributary mouth bar and strand plain coastlines are the same, making sand deposited in the two settings indistinguishable.

Interdistributary Bay. The Interdistributary Bay/Delta Flank Embayment facies (Facies B) occurs in both the Rocky Point Road measured section (Figures 19-20) and in core OM12C-3 (Figures 28-31). The facies ranges in thickness from 1.2 meters in core OM12C-3 to 1.4 meters in the

Rocky Point Road section. Facies B is also present in core OM41A-10 where it is 3 meters in thickness. The two occurrences in the cores are identical and correlative. Facies B in the Rocky Point Road section is lithologically different than in the two cores.

Facies B consists predominantly of extremely bioturbated sandy mudstone in cores OM12C-3 and OM41A-10. The only sedimentary structures that have not been destroyed by bioturbation are a few thin lenticular sandstone beds. The high degree of bioturbation makes it difficult to distinguish individual burrows but it appears that some distinct horizontal burrows do occur. The abundance of fine-grained material and biogenic activity indicates a low-energy depositional setting and a low rate of sedimentation.

Facies B in the Rocky Point Road measured section consists of interbedded coarse-grained sandstone and coal. The sandstone is described in the Cowlitz Formation petrography section within the field study area rock units chapter. The abundance of sedimentary rock fragments within the sandstone may be explained by the destruction and reworking of sediments that have undergone early cementation during a storm. The clasts derived from the sediments may then have been carried into the interdistributary bay by storm waves. The presence of coal in the Facies B occurring in the Rocky Point Road section is indicative of a nearly subaerial environment. The coal probably represents the most landward part of the delta plain present in the C and W sandstone. The coal and interbedded coarse-grained sandstone were also found in the bed of the Nehalem River (locality 130) 1.6 kilometers to the southeast of the Rocky Point measured section, attesting to the lateral continuity of

the coal. The lateral continuity of the coal provides evidence that the coal was deposited "in place" rather than being transported as peat rafts and redeposited in a deeper water environment.

The interpretation of Facies B as having been deposited in an interdistributary bay or delta flank embayment is based primarily upon the sedimentary structures present in the facies, and upon its lithology (Coleman and Prior, 1988). Interdistributary bays and delta flank embayments are areas of open water within the active delta plain. They may be completely surrounded by marsh or distributary levees but are typically open to the sea or connected by tidal channels (Coleman and Prior, 1988). Interdistributary bay deposits are composed primarily of fine-grained sediments that are brought into the bays during periods of high river discharge or during storm events. The most abundant sedimentary structure in interdistributary bays is lenticular laminae. Parallel laminae and bioturbation are also common (Coleman and Prior, 1988). The presence of relatively abundant burrows suggests that the bays were open to normal marine waters (Tillman and Jordan, 1987). Thus, Facies B in the two cores may have been deposited in a delta flank embayment, rather than a delta plain interdistributary bay.

Interbedded Interdistributary Bay and Crevasse Splay Facies. The interbedded interdistributary bay and crevasse splay facies (Facies C) is the second most abundant facies in the measured sections and core (Figures 15-20 and 28-31). It consists of interbedded mudstone and sandstone. The thickness of Facies C ranges from 5-15 meters. Individual sandstone and mudstone beds within Facies C range in thickness from 10's of centimeters to several meters.

The sandstone beds are generally very fine-grained, micaceous, and carbonaceous. Sedimentary structures found within Facies C include planar and lenticular laminae, trough and planar cross-bedding, ripple bedding, and graded bedding. Bioturbation is common in the mudstone beds but rare within sandstone beds. Extremely carbonaceous laminae with small wood and leaf fragments are common within the sandstone beds. The sandstone beds appear to be at least moderately extensive laterally with the exception of some sandstone channel lenses present in the Columbia Mainline section. Sandstone lenses 2.5-3 meters in width and approximately 25 centimeters thick occur within a 2 meter interval in the Columbia Mainline section (Figures 18 and 39). Mudstone rip-ups are present at the base of the channels which are enclosed within a lenticularly laminated mudstone.

The mudstone beds within Facies C contain thin parallel and lenticular laminae of siltstone and sandstone. Some bioturbation and isolated burrows are present but bioturbation is not pervasive. In core OM41A-10 a coal is present at the top of a unit that is correlative with an interval of Facies C in core OM12C-3. The coal contains abundant, predominantly crushed, foraminifera one of which was identified as *Trochammina* sp. (McKeel, 1987). One environmental candidate for the very low diversity delicate walled assemblage present within the coal is a marine tidal marsh (Murray, 1973 fide McKeel, 1987). The coal was also examined for palynomorphs by Ray A. Christopher. The presence of heavy fern and fungal spores in the sample suggests deposition in close proximity to a terrestrial source. There is also no indication of marine influence in the sample (McKeel, 1987).

Figure 39. Sand-filled channel present in Facies C in the Columbia Mainline section.

Facies C is believed to represent deposition in a shallow interdistributary area within the delta plain. The mudstone beds depict normal deposition within the bay during high river discharge or storm events, similar to Facies B. The lack of pervasive bioturbation may indicate a more brackish water environment than in the Facies B occurring in core OM12C-3. The sandstone beds are probably crevasse splay sediments which were deposited within the interdistributary bay during a break in a subaqueous levee. Splay sandstones are characterized by high sandstone content, abundant ripple-bedding, cross-bedding and rip-up clasts (Tillman and Jordan, 1987). The thickness of splay sandstones varies relative to their proximity to the main channel.

They also spread and become more laterally extensive away from the main channel. The channels present in the Columbia Mainline section were probably deposited in close proximity to the main channel. In the subsurface the lateral extent of individual crevasse splay deposits can not be traced with accuracy, so their proximity to the distributary channel is indeterminable.

Distributary Channel Facies. The distributary channel facies (Facies D) occurs once in core OM12C-3 and once in the Columbia Mainline section. Facies D consists of fine-grained, well-sorted sandstone with a few thin mudstone interbeds. The dominant sedimentary structures in Facies D in OM12C-3 is trough cross-bedding while Facies D in the Columbia Mainline section appears to be massive. The basal contact of both Facies D occurrences is sharp and may be scoured into the underlying crevasse splay deposits. Fine-grained carbonaceous matter is abundant in both Facies D occurrences.

The interpretation of Facies D as a distributary channel deposit is based on its stratigraphic position, its sharp basal contact, its lenticular nature, and upon its sedimentary structures. Facies C underlies both occurrences of Facies D. The presence of Facies C, which is deposited in an interdistributary bay, underlying Facies D documents the lateral migration of Facies D into a neighboring interdistributary bay. Such channel migration commonly occurs in the deltaic setting. When channel migration occurs it typically scours into the underlying interdistributary bay sediments creating the sharp basal contact observed in Facies D (Balsley, 1986). In the Columbia Mainline section the underlying Facies C unit contains actively filled crevasse splay

channels that indicate the presence of a proximal distributary channel. Thus, a major shift in the channel is not required. The lenticular nature of Facies D is confirmed by its absence in core OM41A-10. The correlative interval to Facies D in OM12C-3 is interpreted as Facies C in OM41A-10. Trough cross-bedding is typically the dominant sedimentary structure in distributary channel deposits, with subordinate ripple cross lamination, parallel lamination, and wavy parallel lamination (Balsley, 1986; Tillman and Jordan, 1987).

Transgressive Facies. There are two lithologically distinct types of transgressive facies (Facies E) identified in the C and W sandstone. Both occur stratigraphically between delta plain deposits and overlying delta front deposits. Although these distinctive units are thin they are significant because they document delta subsidence or marine transgression.

In core OM12C-3 Facies E consists of medium, to fine grained, massive to planar laminated sandstone with thin carbonaceous and mudstone interbeds. The interpretation of the unit as a transgressive deposit is due to its stratigraphic position and its sharp bounding contacts. Transgressive facies in other deltaic systems typically contain a coarse basal unit (Balsley, 1986). The basal lag deposit is typically composed of sedimentary rock fragments, presumably from sediments that have undergone early cementation. The absence of this basal lag in the transgressive facies of the C and W sandstone may indicate a local lack of hard ground.

In the Rocky Point Road measured section the transgressive facies consists of massive, abundantly burrowed, carbonaceous mudstone. It is also bounded by sharp contacts and lies between an underlying coal and overlying shoreface deposit. Transgressive deposits composed of black carbonaceous siltstone and containing brackish-water fauna have been described in the literature (Balsley, 1986). Such deposits commonly overlie coal beds and are deposited in a more landward deltaic setting than their sandstone counterparts.

The depositional setting of the two transgressive facies is responsible for their difference in lithology. The sandstone deposits develop in high energy environments near the seaward margins of the delta. The carbonaceous mudstone reflects transgression in a more landward setting such as a interdistributary bay or swamp where increasing thickness of the delta plain peat deposits combined with wave attenuation in shoaling water over the subsiding delta plain prevented reworking of the delta front sandstones (Balsley, 1986)

Lateral and Vertical Relationships of Delta Facies

Vertical Facies Relationships. Walther's Law of Facies (1894) states that facies occurring in a conformable vertical sequence were formed in laterally adjacent environments. Thus, facies that are in vertical contact must be the product of geographically neighboring environments (Reading, 1986). By applying Walther's Law to the continuous core and measured sections several regressive sequences documenting delta progradation can be identified.

In core OM12C-3 three regressive facies sequences can be identified. The three sequences are separated by two brief hiatuses at 895, and 855.5 meters. The hiatuses are probably the result of delta lobe abandonment which cut off the local sediment supply. The receiving basin continues to subside under the pressure exerted by the accumulated sediment and since there is no sediment being deposited to keep pace with the subsidence transgression occurs. The most seaward facies present in the C and W sandstone, Facies A, is present above each of the hiatuses. Facies B and C, which are delta plain facies, overlie Facies A in each of the sequences documenting delta progradation. Directly underlying both of the hiatuses are organic-rich mudstones or coal (in OM41A-10) which are deposited in an interdistributary bay or marsh and are the most landward deposits in the C and W sandstone.

Similar regressive sequences, although they are not complete, can be identified in the measured sections within the field study area. In the Fall Creek Section a hiatus is present at 31 meters. Delta plain facies underlie the hiatus and delta front facies overlie the hiatus documenting a minor transgression. Facies A is overlain by Facies C below the hiatus indicating that regression was occurring prior to the hiatus. A hiatus also occurs in the Rocky Point Road section at 22 meters. A delta plain coal underlies the hiatus and delta front sands overlie it. Regression is evident in the facies sequence below the hiatus in the Rocky Point Road section where Facies A deposits are overlain by Facies B deposits. A hiatus is not present in the short Columbia Mainline section. The facies sequence in the Columbia Mainline

section is believed to document lateral migration of a distributary channel into a neighboring interdistributary bay setting.

Lateral Facies Variation. Evidence indicating the lateral variation in facies is not as abundant as is evidence of the vertical variation. The three cores can be correlated to detect lateral facies variation within a small part of the Mist gas field. The three measured sections can not be used to ascertain lateral facies variation due to the lack of stratigraphic control in the Rocky Point Road and Columbia Mainline sections. The large distance between the Mist gas field and the field study area (20 kilometers) makes any attempt at surface to subsurface correlation highly speculative. Thus, this was not undertaken.

Each of the cores was correlated to OM12C-3 using their electric log signature and their lithology (Figure 40). The blue-green zone was used as a datum. In IW33C-3 the Upper Cowlitz mudstone is in fault contact with the C and W sandstone (Jack Meyer, personal communication, 1989). The upper 21.3-27.4 meters of the C and W sandstone appears to be faulted out in IW33C-3 (Figure 40).

There are minor variations in the thickness and lithology of the core facies units but most appear to be laterally continuous within the restricted area represented by the three cores (Figure 40). Facies A, B, C, and E can all be correlated in the three cores. The distributary channel facies (Facies D), however, occurs only in cores OM12C-3 and

Figure 40. Correlation of depositional facies in the three cored Mist gas field wells. The blue-green zone was used as a datum.

IW33C-3. The correlative unit in core OM41A-10 is a bioturbated, predominantly mudstone, interbedded crevasse splay and interdistributary bay deposit (Facies C).

Facies A is laterally extensive within the area represented in the three cores and is consistent in its lithology. Typically the most laterally continuous deltaic deposits are the more marine-type facies (Coleman and Prior, 1988). Facies A is the most marine of the depositional facies interpreted within the C and W sandstone.

Although Facies C and B units as a whole are extensive laterally, recording a specific horizon in the deltaic setting, individual beds within the facies are not. The sandstone beds present in Facies C and B are deposited by isolated local events such as crevasse splay or overbank flooding and thus are not deposited throughout the entire area of a single interdistributary area. The delta plain also consists of many unconnected interdistributary bays that can vary considerably in their depositional history.

The identification of Facies E is difficult due to its lithologic similarity, in the cores, to Facies A which directly overlies it. This makes the determination of its lateral extent difficult. The lateral extent of the hiatus during which Facies E is deposited, however, is easily traceable. The oldest hiatus occurs in all three cores. The younger hiatus occurs in cores OM12C-3 and OM41A-10 but is faulted out in core IW33C-3. Thus, both of the hiatuses appear to be laterally extensive within the area represented by the three cores. The presence

of Facies E at the hiatus is probably dependant upon the presence of reworkable sediment, and the lack of abundant scour in the overlying Facies A deposit.

Grain Size Distribution and Depositional Environment

There have been many attempts to relate grain-size distributions observed in recent sediments directly to depositional environment. There are many environmental factors that influence the grain size of sediments within a single sedimentary environment making it exceedingly difficult to determine the depositional environment of a sedimentary rock based solely on its grain size distribution. Several authors, however, have shown that some generalizations can be made concerning depositional environment (Passega, 1957; Friedman, 1961, 1967).

Friedman (1961), for example, discovered that by plotting skewness versus standard deviation a distinction could be made between beach and river sands. River sands are generally positively skewed and finer grained than beach sands which are generally negatively skewed. Using the scheme of Friedman (1961) the eleven core samples analyzed appear to be river sands (as opposed to beach sands) (Figure 41). This indicates that the river transported sands were not substantially reworked by wave processes.

Figure 41. Skewness versus standard deviation plot of C and W sandstone member core samples. Discriminates river and beach sands. After Friedman (1961).

KEASEY FORMATION

The depositional environment of the Keasey Formation has been interpreted as upper slope, based on microfauna and lithology, by Rarey (1986). Evidence from within the field study area indicates that the depositional environment of the Keasey Formation within the field study area is similar.

Environmentally diagnostic benthic foraminifera were collected from two Keasey Formation mudstone samples from within the field study area. One sample contained an outer shelf to lower bathyal assemblage, the second an upper bathyal to lower bathyal assemblage (Schmidt, 1989). Environmentally diagnostic gastropods were also collected from Keasey Formation mudstones within the field study area. The gastropods have been interpreted as deep-water by Hickman (1976,1980). Fossil data alone is sufficient to indicate an upper slope depositional environment for Keasey Formation mudstones.

Fossils are lacking, however, in the sandstones and conglomerate found near the base of the Keasey Formation making interpretation of their depositional environment based on fossil data alone impossible. Some of the thin volcanic sandstones appear to be turbidite sandstones. The thick sandstone and conglomerate present at locality 92 are believed to have been deposited by a large debris flow. Both of these sandstone lithologies are common in an upper slope environment (Reading, 1986).

DEPOSITIONAL HISTORY

The Tertiary sedimentary rocks exposed in the field study area unconformably overlie subaerial flows of the Tillamook Volcanics. A soil horizon is not present between the Tillamook Volcanics and overlying Roy Creek member of the Hamlet formation, suggesting that the basalts were not subaerially exposed for an extended period prior to deposition of the Roy Creek member. The Roy Creek member was deposited in a nearshore setting calling for a marine transgression to have inundated the underlying, subaerially exposed, Tillamook Volcanics (Figure 42). Conformably overlying the Roy Creek member are the shallow marine shelf sandstones of the Sunset Highway member of the Hamlet formation. The outer neritic to middle bathyal Sweet Home Creek member of the Hamlet Formation conformably overlies the Sunset Highway member documenting continued transgression (Figure 42). Niem and Niem (1985) postulated that the Hamlet formation transgressive sequence spanned a period of approximately 5 million years during the Upper Eocene.

Overlying the deep-water Sweet Home Creek member are the deltaic and shoreline deposits of the C and W sandstone member of the Cowlitz Formation. This calls for a regression between the Hamlet and Cowlitz formations (Figure 43). Several regressive depositional packages separated by minor transgressive hiatuses are present within the C and W sandstone member producing repeated facies associations. The C and W sandstone member is overlain by the outer neritic to upper bathyal upper Cowlitz mudstone member within the Mist gas field. The fining upward Cowlitz formation documents a second transgressive sequence.

Figure 42. Generalized interpretation of paleogeography and depositional environment during Hamlet formation deposition.

The upper bathyal Keasey Formation overlies the Cowlitz Formation. In the Mist gas field the Keasey-Cowlitz contact is unconformable due to the uplift of the Nehalem arch (Jack Meyer, personal communication, 1989). Thus, a large hiatus is present between the Cowlitz and Keasey formations in the Mist gas field. During the hiatus the Cowlitz Formation was uplifted and eroded. Subsidence then occurred prior to the deposition of the upper bathyal Keasey Formation. Such rapid uplift and subsidence indicates tremendous local tectonic activity. Within the field study area a large hiatus is not apparent indicating a much more

Figure 43. Generalized diagrammatic interpretation of paleogeography and depositional environment during deposition of the C and W sandstone member of the Cowlitz Formation.

tectonically stable area. The basaltic and glauconitic sandstones present at the base of the Keasey Formation appear to be conformable to slightly disconformable with the underlying Cowlitz sandstones (Figure 44). The absence of the upper Cowlitz mudstone within the field study area must be explained as lateral variation. Since a large hiatus does not occur in the field study area it could not have been deposited and then eroded.

Additional Tertiary sediments and Columbia River Basalt overlie the Upper Eocene to Oligocene rock units present within the field study area and are exposed in other parts of northwest Oregon.

Figure 44. Generalized diagrammatic interpretation of paleogeography and depositional environment during deposition of the Keasey Formation.

DIAGENESIS OF THE C and W SANDSTONE MEMBER OF THE COWLITZ FORMATION

Nine core samples were examined in detail using both light and electron microscopy in order to detect any effect of diagenesis in the C and W sandstone. Both porosity reducing and porosity increasing diagenetic effects were observed and are described and discussed below.

DIAGENETIC POTENTIAL

In order for a sandstone to be a good petroleum reservoir it must have high porosity and permeability. Even if the original porosity and permeability of a sandstone is high its reservoir potential can be greatly reduced by diagenesis. The original mineralogy and depositional environment of a sandstone are two primary variables that influence the potential for porosity and permeability retention during diagenesis (Blatt and others, 1980).

The feldspathic character of the Cowlitz Formation is favorable for the retention of original porosity and permeability. Feldspars are typically much less susceptible to alteration than volcanic detritus. The alteration of volcanic detritus during diagenesis results in the crystallization of pore clogging clays, reducing primary porosity and permeability.

The depositional environment of the C and W sandstone (discussed in the previous chapter) also has a high potential for porosity and permeability retention. Fragments more susceptible to alteration, such

as sedimentary and volcanic rock fragments, are also more susceptible to destruction during transport. The high-energy depositional setting of the C and W sandstone decreases the diagenetically unstable component of its mineralogy by reworking and breaking down unstable clasts. Thus, the combination of favorable provenance and depositional environment of the C and W sandstone allows for the retention of much of its original porosity making it an excellent petroleum reservoir.

DIAGENETIC EFFECTS DECREASING POROSITY

There are four diagenetic processes that decrease porosity in the C and W sandstone; compaction, cementation, the precipitation of authigenic minerals, and the alteration of micas.

Compaction

Compaction is generally the dominant porosity reducing process in uncemented sandstones. Porosity reduction during compaction occurs by the physical rearrangement of grains, the deformation of ductile grains, and by grain contact dissolution (Burley, 1986). The only obvious evidence of compaction in the C and W sandstone is the presence of deformed framework grains. Both mica and organic material have been deformed in the C and W sandstone (Figure 45). Platey micas are commonly bent or broken. Organic material has been squeezed around and between the grains that surround it. Both mica and organic material are only minor components of the C and W sandstone, and their deformation, therefore, does not significantly reduce porosity. The deformed mica also supplies evidence that grain rearrangement has occurred.

Evidence of grain rearrangement is often not well preserved in compacted sediments, making it difficult to qualify the extent of grain rearrangement (Burley, 1986). In the C and W sandstone fractured and broken grains, and deformed mica provide some evidence of grain rearrangement. Due to the apparent lack of porosity reduction by other mechanisms it can be inferred that the majority of porosity reduction in the C and W sandstone was produced by grain rearrangement.

Contact dissolution of grains also occurs in the C and W sandstone (Figure 46) but is not widespread. Grain contacts in the C and W sandstone are typically point contacts that show little or no contact

0.25 mm

Figure 45. Photomicrograph of OM12C-3 sample 2736. Displays deformed biotite, and fractured muscovite and quartz grains. The biotite is altered with authigenic calcite between its cleavage platelets.

0.25 mm

Figure 46. Photomicrograph of OM12C-3 sample 2705. Shows contact dissolution occurring between two potassium feldspar grains (yellow grains near center). The majority of the grains contacts show no contact dissolution.

dissolution. In cases where the surface area of a grain contact is large, some dissolution has occurred. Due to the rarity of contact dissolution its effect on the porosity of the C and W sandstone is minimal.

Cementation

Generally, the C and W sandstone can be described as an uncemented sandstone, but on a very small scale cementation does occur. The mineral species that occur as cements include quartz, chlorite, and calcite.

1 mm

Figure 47. Photomicrograph of OM12C-3 sample 3001. Shows a locally well-developed quartz cement. "Dust rims" are visible between grain and quartz cement.

A moderately well-developed quartz cement was found in sample 3001 from core OM12C-3 (Figure 47). The cement occurs as a rim cement with a strong preference for a detrital quartz core. Both porosity and permeability have been substantially reduced locally due to the quartz cementation. The quartz cement occurs over a 2 meter interval at a depth of approximately 915 meters in core OM12C-3.

Authigenic chlorite occurs throughout the core but only in small quantities that have a negligible effect on permeability. A more pervasive chlorite rim cement is present in samples 2884 and 2891 in core OM12C-3 (Figure 48). The rim cement occurs in an interval approximately 5 meters thick ranging from a depth of 961 to 966 meters.

0.25 mm

Figure 48. Photomicrograph of OM12C-3 sample 2891. Exhibits a well-developed chlorite rim cement.

Permeability has been reduced by 98% while porosity has remained above average through most of the interval (ONGDC proprietary report, 1988). The reduction in permeability is caused by the crystallization of the authigenic chlorite rim cement in pore throats. The authigenic chlorite does not constitute a large volume percentage of the rock, however, so porosity remains high.

Calcite cement occurs as thin well-cemented beds and as small concretions in the C and W sandstone. Well-cemented beds up to 15 centimeters thick were found in core OM12C-3. Concretions as large as 10 centimeters in diameter were also found in the core. Both the well-cemented beds and the concretions are found throughout the entire length

of the core. Micro-concretions, isolated calcite crystals, and small calcite crystals sandwiched between mica platelets were also observed in thin section. Due to the small scale and wide distribution of the local concentrations of calcite cement their impact on both porosity and permeability is minimal.

However, this may not have been true during the entire diagenetic history of the C and W sandstone. Although not conclusive, there is abundant evidence indicating that early in its diagenetic history the C and W sandstone may have contained an extensive framework-supporting calcite cement. Most decarbonatization porosity closely resembles or exactly mimics primary porosity making its identification difficult (Schmidt and McDonald, 1979). The evidence supporting the presence of a well-developed calcite cement early in the diagenetic history of the C and W sandstone includes corroded and partially dissolved framework grains, inhomogeneous packing, and the presence of authigenic calcite and local calcite cement that may be remnants of a more pervasive calcite cement.

Authigenic Minerals

Another diagenetic effect that decreases porosity in the C and W sandstone is the precipitation of authigenic minerals. The most abundant authigenic mineral in the C and W sandstone is potassium feldspar (Figure 49). It occurs as overgrowths on detrital cores of potassium feldspar, plagioclase, and less commonly quartz. The authigenic potassium feldspar is typically monoclinic and varies in size from a few microns to nearly 100 microns in length. Large overgrowths have been observed to completely enclose their detrital core. The

Figure 49. Electron photomicrograph of sample 2705. Shows a potassium feldspar overgrowth on a detrital core of potassium feldspar.

energy dispersive spectrum of authigenic potassium feldspar indicates that it is chemically pure with no Na, Ca, or Fe within its crystal structure.

Plagioclase also occurs authigenically (Figure 50), but is much less common than potassium feldspar. It is triclinic and rarely exceeds 20 microns in length. Only the pure Na end member of the plagioclase solid-solution series (albite) was observed. Albite is the only type of plagioclase that has been reported to occur authigenically (Kastner and Siever, 1979).

20 microns

Figure 50. Electron photomicrograph of sample 2705. Displays authigenic plagioclase (upper left) and authigenic potassium feldspar (lower right) on a detrital core of plagioclase.

Quartz also occurs diagenetically in the C and W sandstone. It occurs both as isolated overgrowths and locally as a cement as mentioned previously. It is generally less abundant than authigenic potassium feldspar but equally as abundant as plagioclase overgrowths.

Calcite occurs authigenically in two forms. It most commonly occurs as tiny (<.1 mm) crystals sandwiched between biotite cleavage platelets (Figure 51). The surface of biotite platelets attract H^+ ions resulting in an increase in porewater pH in close proximity to the mica surfaces (Boles and Johnson, 1983). This either allows calcite to precipitate, or prevents pore-waters from dissolving calcite from between the biotite platelets. The second mode of occurrence of

50 microns

10 microns

Figure 51. Electron photomicrograph of sample 2705. Shows detrital mica with calcite between its cleavage platelets.

authigenic calcite is isolated euhedral crystals that occur dispersed within sample 2736. These crystals may either be remnants of a more pervasive calcite cement or just isolated authigenic crystals.

As discussed in previous section, x-ray diffraction of samples from the C and W sandstone indicates that both chlorite and illite and/or mixed layer illite-smectite are present in the C and W sandstone. Although some of the clay may be detrital the majority is thought to be authigenic. The C and W sandstone sandstones appear to contain very little fine-grained matrix. The authigenic clays are pore lining and are generally not abundant enough to reduce porosity or permeability.

Sphene is minor authigenic mineral that occurs in the C and W sandstone (Figure 52a). Authigenic sphene is rare but has been reported by other authors (Merino, E., 1975; Helmold and van de Kamp, 1984; Niem, A.R., personal communication, 1989). It was identified by its distinct EDS spectrum (Figure 52b) which contains subequal peaks of Si, Ca, and Ti (Welton, 1984).

Due to the minute size of the authigenic minerals no attempt was made to determine the volume percent of the authigenic minerals quantitatively. The authigenic minerals are more apparent using electron microscopy but a Scanning Electron Microscope (SEM) can not be used effectively to determine volume percent. Due to the small volume and sporadic occurrence of authigenic minerals within the C and W sandstone their impact on porosity is believed to be minor.

Alteration of Micas

Much of the biotite in the C and W sandstone is altered. In seven of the eight core samples examined altered biotite is more abundant than fresh biotite. As biotite alters it expands and its cleavage platelets separate (Figure 53). The volume expansion that occurs during the alteration of biotite decreases porosity. Pores can become clogged as the biotite expands and flares which reduces permeability. As the cleavage platelets separate calcite precipitates between the platelets further reducing porosity.

Muscovite in the C and W sandstone is typically not altered. The few muscovite grains that are altered have not achieved the degree of alteration common for biotite. They have expanded only slightly and their cleavage platelets have not separated. The alteration of mica has

0.1 mm

Figure 53. Photomicrograph of OM12C-3 sample 2736. Altered biotite displaying expanded and separated cleavage platelets with small authigenic calcite crystals between the cleavage platelets.

been interpreted as a major factor controlling the distribution of porosity and permeability in feldspathic sandstones similar to the Cowlitz Formation (Bjorlykke and Brendsdal, 1986). In the C and W sandstone, however, their impact does not appear to be major. Mica content rarely exceeds 10% in the C and W sandstone and only half of the mica is substantially altered. The alteration of biotite is probably responsible for a slight decrease in porosity and permeability but its effect is overshadowed by compaction.

DIAGENETIC EFFECTS INCREASING POROSITY

In thin section, the well developed, open intergranular pore system of the C and W sandstone displays many of the petrographic criteria used by Schmidt and McDonald (1979) to recognize the presence of secondary porosity. Eight criteria have been defined by Schmidt and McDonald and are shown in Figure 54. Many of the criteria are present in the nine core samples analyzed.

Partial Dissolution

Partial dissolution of framework grains is easily identified in thin section. Detrital feldspars are the most common framework grain in the C and W sandstone that is susceptible to partial dissolution, with plagioclase being more susceptible than potassium feldspar. The alteration of biotite may have buffered the porewater with respect to potassium, protecting potassium feldspar in relation to plagioclase (Bjorlykke and Brendsdal, 1986). Both plagioclase and potassium feldspar display small scale pitting and etching to nearly complete dissolution (Figure 55). The remains of a partially dissolved feldspar are often very delicate indicating that the dissolution must have occurred in place. Feldspars account for over 90% of the partially dissolved framework grains in the C and W sandstone.

Other partially dissolved framework grains found in the C and W sandstone include quartz and rock fragments. Quartz is a major component of the C and W sandstone sandstones but is only rarely

(1) Partial dissolution **(5) Elongate pores** **(2) Molds** **(6) Corroded grains** **(3) Inhomogeneity of packing and 'floating' grains** **(7) Honeycombed grains** **(4) Oversized pores** **(8) Fractured grains**

Figure 54. Petrographic criteria used to identify secondary porosity. From Schmidt and McDonald (1979).

0.25 mm

Figure 55. Photomicrograph of OM12C-3 sample 2767. Displays numerous partially dissolved potassium and plagioclase feldspars.

partially dissolved. Rock fragments, on the other hand, are often partially dissolved but are only a very minor component in the C and W sandstone.

Honeycombed Grains

Honeycombed feldspar grains are common in nearly all of the analyzed samples (Figure 56). Again, the delicatenature of the honeycombed feldspars indicates that dissolution occurred in place. Schmidt and McDonald (1979) stated that honeycombed grains are mainly the result of leaching of carbonates which partially replaced detrital

0.1 mm

Figure 56. Photomicrograph of OM12C-3 sample 2767. Shows honeycombed plagioclase feldspar.

feldspars. There is no direct evidence, such as remnant calcite within a feldspar, of partial replacement of feldspars by calcite in the C and W sandstone.

Corroded Grains

Corroded grains differ from partially dissolved grains in that their exterior surface has undergone only slight to moderate etching. Corroded grains are typically common on the margins of solution enlarged pores. Quartz grains which are only rarely partially dissolved are more typically corroded in the C and W sandstone. Mildly corroded grains can be transported without being destroyed and thus the corrosion may not have occurred in place. The corroded quartz grains within the C and W

have occurred in place. The corroded quartz grains within the C and W sandstone are commonly associated with enlarged intergranular pores. Corroded or partially dissolved feldspars are also common along the margins of enlarged pores.

Molds

In the C and W sandstone the dissolution of feldspars creates some secondary porosity in the form of molds. The identification of feldspars as the precursor grains is possible due to feldspar remnants within the molds. The shape of the mold is generally not useful in identifying the precursor grain because all of the compositional varieties of framework grains are identical in shape in the Cowlitz Formation.

Oversized Pores

Oversized pores are extremely common in the open intergranular pore system of the C and W sandstone (Figure 57). Although enlarged pores can at times be produced by sedimentary processes there is abundant evidence in the C and W sandstone that many of the oversized pores are secondary in origin. The presence of remnant grains and etched pore margins supports a secondary origin. The oversized pores are often well-connected as if they formed along porewater flow paths. Isolated oversized pores do occur but only rarely. Such evidence is adequate to conclude that most of the oversized pores are secondary.

Elongate Pores

The open intergranular pore system of the C and W sandstone does not contain abundant elongate pores. Elongate pores generally develop when the grain margins of tightly packed sandstones are dissolved. The absence of elongate pores in the C and W sandstone can be attributed to its typically loose packing.

Inhomogeneous Packing and Floating Grains

In the C and W sandstone the packing of framework grains is typically inhomogeneous. Packing varies from very loose, with abundant floating grains, to moderately packed (Figure 57). The C and W sandstone is never tightly packed.

1.0 mm

Figure 57. Photomicrograph of OM12C-3 sample 2767. Shows enlarged pores and inhomogeneous packing.

Inhomogeneous packing often develops when an inhomogeneous eogenetic cement develops prior to the completion of compaction. Parts of the sandstone in which a cement has developed are supported by the cement preventing further compaction. Parts of the sandstone devoid of cement continue to undergo compaction. This results in the development of inhomogeneous packing.

Another possible mechanism causing the development of inhomogeneous packing is the dissolution of framework grains along porewater flow paths. Only the grains in contact with the circulating porewaters are dissolved while grains isolated from the porewaters remain intact.

Fractured Grains

Fractured and broken quartz and feldspar grains are quite common in the C and W sandstone. Broken and fractured grains are often produced by framework collapse of sandstones in which extensive secondary porosity has developed. An early cement provides support for a sandstone preventing extensive compaction, but if the cement is then dissolved the sandstone becomes unstable and framework collapse occurs.

Fractured grains could also be produced during compaction. Pressure increases with burial depth and the breaking strength of framework grains may be overcome by the rising pressure.

NET EFFECT OF DIAGENESIS ON POROSITY AND PERMEABILITY

In order to determine the overall extent of porosity reduction due to diagenesis in the C and W sandstone the original porosity must be known. Using the scheme of Beard and Weyl (1973) the original porosity

of the C and W sandstone can be approximated as between 40 and 42%. The average porosity of core OM12C-3 is 32.2% (ONGDC proprietary report, 1988). Therefore, diagenesis is responsible for a net decrease in porosity of 8-10% in the C and W sandstone member of the Cowlitz Formation. The majority of this porosity reduction is believed to have occurred by compaction. With an average porosity of >30% and permeability of >1 darcy the C and W sandstone is still an outstanding petroleum reservoir.

DIAGENETIC SEQUENCE

The sequence of diagenetic events in the C and W sandstone is difficult to quantify with the data obtained in this study but some generalizations can be made.

Compaction begins immediately upon the burial of any unconsolidated, water saturated, sediment resulting in a decrease in primary porosity. The inhomogeneity of packing in the C and W sandstone indicates that compaction may have been stopped by the precipitation of an early calcite cement. After the dissolution of such a framework-supporting cement compaction may have proceeded once again in the form of framework collapse. The abundance of broken and fractured grains in the C and W sandstone indicates that framework collapse may have occurred. If an early calcite cement did not precipitate in the C and W sandstone compaction would have continued undisturbed through most of its diagenetic history.

Local and possibly pervasive cementation probably occurred during the early to middle diagenetic history of the C and W sandstone. The quartz cement present in core sample 3001 was preceded by the precipitation of authigenic clays. This is apparent from the "dust rim" present between the detrital grain and the quartz cement. Feldspars in the quartz cemented interval are not as corroded as are feldspars in uncemented parts of the core. This suggests that the quartz cement had developed prior to episodes of dissolution.

The chlorite cemented interval present in core OM12C-3 also is lacking in abundant dissolution features suggesting that the chlorite cement precipitated prior to dissolution. Diagenetic chlorite also occurs within partially dissolved rock fragments and within a few feldspar corrosion pits indicating that there is some overlap in dissolution and the precipitation of authigenic clays.

There are two possible hypotheses for the timing of calcite cementation in the C and W sandstone. The first is that a pervasive calcite cement precipitated early in the diagenetic history of the C and W sandstone. Such a cement may have composed as much as 25% of the C and W sandstone and would have substantially reduced porosity and permeability. The nearly total dissolution of this cement would have occurred later during the diagenetic history of the C and W sandstone since very little calcite cement remains in the C and W sandstone. The second is that a pervasive calcite cement never precipitated in the C and W sandstone. The calcite present in the C and W sandstone would thus represent nothing more than sporadic occurrences of calcite cementation.

0.1 mm

Figure 58. Photomicrograph of OM12C-3 sample 2705. Displays a potassium feldspar overgrowth that is floating due to partial dissolution of its detrital plagioclase core.

The precipitation of authigenic minerals probably occurred during the middle to late diagenetic history of the C and W sandstone. Some authigenic potassium feldspar appears to have precipitated prior to the dissolution of plagioclase. This is apparent in Figure 58 where a potassium feldspar overgrowth is floating due to the partial dissolution of its detrital plagioclase core. Silicate overgrowths generally are not corroded but this can be attributed to the higher stability of the overgrowths in a low temperature environment. The dissolution of a few authigenic overgrowths (Figure 59) attests to the complexity of the

50 microns

Figure 59. Electron photomicrograph of OM12C-3 sample 2989. Shows a partially dissolved potassium feldspar overgrowth.

sequence of diagenetic events in the C and W sandstone. Either there is overlap between the dissolution and authigenic mineral precipitation events or more than one dissolution event occurred.

The alteration of mica probably occurred during much of the diagenetic history of the C and W sandstone. All stages of alteration of biotite are present in the C and W sandstone suggesting that alteration began at different periods in time. Some alteration of biotite had to occur prior to the precipitation of some authigenic calcite since calcite precipitates between the cleavage platelets of altered biotite.

PROVENANCE AND TECTONIC SETTING

PROVENANCE AND TECTONIC SETTING OF THE C AND W SANDSTONE

The provenance of the C and W sandstone has been reported as metamorphic and/or plutonic based on both framework mineralogy (Jackson, 1983, Van Atta, 1971a) and trace element geochemistry (Kadri and others, 1983). The findings of this study also indicate a dominantly metamorphic and plutonic provenance.

Volcanic rock fragments and volcanic accessory minerals typically compose <2% of the sandstone. The major detrital components (quartz, potassium feldspar, plagioclase, and mica) in the sandstone are typically the product of a plutonic/metamorphic source terrane. The heavy mineral suite present in the C and W sandstone also indicates a predominantly plutonic/metamorphic provenance.

Although the dominant source terrain is plutonic/metamorphic, there is a minor volcanic component in C and W sandstone as well. A few volcanic rock fragments are present throughout most of the C and W sandstone. The blue-green zone within the three cores contains atypically high concentrations of volcanic rock fragments. Based on the fragility of the scoriaceous basalt fragments and upon their coarse grain size it is interpreted that they are the product of proximal volcanism. The apparent increase in plagioclase at the top of the C and W sandstone is interpreted as incipient to the influx of volcanic detritus present in the overlying Keasey Formation. The abundant

volcanic detritus in the Keasey Formation was probably produced by increasing volcanic activity in the Cascades volcanic arc.

The trace element geochemistry obtained for geochemical groups 1 and 3 indicates a metamorphic and plutonic provenance. The Th concentrations in group 1 average 25.5 ppm which is much greater than the continental average for Th of 9.6 ppm (Taylor, 1964 fide Kadri and others, 1983). The average Th concentration of group 3 of 7.1 ppm is lower than the continental average indicating that some dilution by a volcanic source has occurred. The average concentration of Th in the blue-green zone (group 2) is 5.6 ppm. This indicates an even greater volcanic input during the time of deposition of the blue-green zone. Other evidences of greater volcanic input are low K/Na ratios, high Fe and Co concentrations (Figure 60), and lower La vs. Sm (Figure 61). The atypically high Th concentration in group 1 is attributed to the presence of accessory minerals such as zircon, or epidote.

One possible local source of the additional volcanic input in group 2 samples is the Tillamook Volcanics. In order to test this hypothesis several plots were constructed comparing the geochemistry of the Tillamook Volcanics with that of the core samples. The geochemical data on the Tillamook Volcanics was obtained from Jackson (1983). A linear data trend was detected with two plots (Figures 35, and 60). The two samples from the blue-green zone plot on a linear trend between Tillamook Volcanics samples and group 1 and 2 samples. This indicates that the underlying Tillamook Volcanics are a possible source of the additional volcanic input in the blue-green zone.

Figure 60. Plot of Co versus Fe for OM12C-3 samples. Displays the high Fe and Co concentrations in blue-green zone samples.

Figure 61. Plot of La versus Sm for OM12C-3 samples. Shows different ratio of La:Sm for blue-green zone samples.

Using the Ternary diagrams of Dickinson and Suczek (1979), which discriminate the tectonic setting of sandstones, four of the C and W sandstone samples, from both core OM12C-3 and surface exposures, plot within the continental block provenance field (Figure 62). The remaining samples plot near the continental block field but are too lithic-rich to plot within it. The majority of the rock fragments that are preventing the remaining samples from plotting within the continental block field are either sedimentary, or plutonic/metamorphic clasts which are commonly derived from continental blocks. Thus, the remaining samples were probably also derived from a predominantly continental block provenance.

The lack of abundant quartz (low maturity) in the Cowlitz sandstones allows the tectonic setting to be placed in the narrower uplifted basement setting. The high relief and rapid erosion typical of uplifted basement terranes (Dickinson and Suczek, 1979) would produce the high sedimentation rates suspected for the Cowlitz Formation.

Potential sources for the material are the North Cascades, the Idaho and Wallowa batholiths, and the Blue Mountains (Heller and others, 1987). Van Atta (1971a) suggested that an ancestral Columbia River may have transported the plutonic and/or metamorphic detritus to the forearc basin in which the Cowlitz Formation accumulated. Longshore currents could then have redistributed the sediment to the north and south of the river mouth. Such a system could explain the increase in amphiboles in field study area samples. The amphiboles may have been transported by longshore currents from the south (where provenance may have been more volcanic) to the north, so that amphibole content increases to the

Figure 62. Plot of field study area C and W sandstone samples and OM12C-3 core samples in a Q-F-L ternary diagram that discriminates tectonic setting. From Dickinson and Suczek (1979).

south. Baker (1988) suggested that the plutonic and/or metamorphic detritus present in the Spencer Formation may have also been derived from an ancestral Columbia River drainage and transported as far south as present day Corvallis by longshore currents.

TECTONIC SETTING OF THE FIELD STUDY AREA BASALTS

Pearce and Cann (1973) devised a scheme for classifying the tectonic setting of volcanic rocks using trace element geochemistry. It consists of several diagrams with fields defining different tectonic settings. The tectonic divisions include ocean floor basalts (diverging plate margin), volcanic arc basalts (converging plate margins), ocean island basalts (within plate oceanic crust), and continental basalts (within plate continental basalts) (Pearce and Cann, 1973).

The geochemistry of the three Tillamook Volcanics samples from within the thesis area were plotted on the ternary diagrams used to differentiate the tectonic setting. In the first ternary diagram (Figure 63) the two Tillamook Volcanics samples that classified as basalts according to Cox (1979) plotted in the "within plate basalt" (continental or ocean island) field while the trachyandesite plotted in the "calc-alkaline, volcanic arc basalt" field. In the second ternary diagram (Figure 64) the basalt samples plot in the "ocean floor basalt" field and the trachyandesite sample is outside the defined fields. Thus, the Tillamook Volcanics appear to contain some of the geochemical characteristics of a divergent margin setting and some of a within plate tectonic setting.

Figure 63. Ternary plot (Ti/100-Zr-Y*3) of field area basalts used to differentiate tectonic setting. From Pearce and Cann (1973).

Figure 64. Ternary plot (Ti/100-Zr-Sr/2) of field area basalts used to differentiate tectonic setting. From Pearce and Cann (1973).

The six Cole Mountain basalt samples were also plotted on the ternary diagrams of Pearce and Cann (1973) to determine their tectonic setting. In the first ternary diagram (Figure 63) three of the samples plot in the "within plate basalt" field and three in the calc-alkaline volcanic arc field. In the second ternary diagram (Figure 64) all six of the samples plot in the calc-alkaline volcanic arc field. This indicates that the Cole Mountain basalt was most likely formed at a converging plate margin.

SUMMARY AND CONCLUSIONS

Seven rock units were identified and mapped within a 54 square kilometer field study area near Rocky Point and southwest of the town of Vernonia in northwest Oregon. The oldest of the rock units identified within the field study area is the Mid to Late Eocene Tillamook Volcanics. They consist predominantly of subaerial basalt and lesser andesite flows and thin interbedded debris flow deposits. Unconformably overlying the Tillamook Volcanics is the Hamlet formation (informal). It consists of three informal members; a basal conglomerate grading to sandy siltstone termed the Roy Creek member, a middle member called the Sunset Highway member that consists of basaltic and arkosic sandstone, and an upper mudstone named the Sweet Home Creek member. The Cowlitz Formation conformably to slightly disconformably overlies the Hamlet formation. It consists almost entirely of the Clark and Wilson (C and W) sandstone member (informal) within the field study area. Conformably to slightly disconformably overlying the Cowlitz Formation is the Keasey Formation. It consists of basaltic and glauconitic sandstone in its lowermost 40-80 meters, overlain by tuffaceous, fossiliferous mudstone. The seventh rock unit identified within the field study area is the Cole Mountain basalt (informal). It intrudes the Tertiary section near the Cowlitz-Keasey contact.

By examining surface exposures and subsurface core from the Mist gas field a depositional model has been developed for the Late Eocene

Cowlitz Formation. The Cowlitz Formation consists of two informal members; the upper Cowlitz mudstone, and underlying Clark and Wilson (C and W) sandstone.

The C and W sandstone member is present in both the subsurface of the Mist gas field, where it acts as a natural gas reservoir, and at the surface in the field study area approximately 15 kilometers south of the Mist field. The depositional environment of the C and W sandstone was interpreted as deltaic utilizing the stratigraphic sequence of depositional facies and sedimentary structures, and to a lesser degree lateral facies relationships and fossil data. Five depositional facies were identified within the C and W sandstone.

The most abundant facies is the strand plain shoreface/distributary mouth bar facies. The dominance of Facies A is believed to indicate that the delta is wave-influenced but not necessarily strongly wave-dominated. Facies A occurs at the base of each of the regressive depositional cycles. If Facies E is present, Facies A directly overlies it.

Facies E consists of two distinct lithologies and has been interpreted as a transgressive facies. It consists of reworked sediments that were deposited during the minor transgressions present in the C and W sandstone.

The interdistributary bay facies (Facies B) is common in both the cores and surface sections. It typically occurs in the middle and upper parts of the regressive sequences. The abundant bioturbation in the

cores is probably due to a high degree of marine influence, perhaps in a delta flank embayment setting. The coal present in the Rocky Point Road section probably developed in a more landward deltaic setting.

Facies C consists of interbedded interdistributary bay mudstones and crevasse splay sandstones. The sandstones are dominant and contain a wide variety of sedimentary structures. The mudstones contain lenticular and planar laminae. Burrows are present within the mudstones but bioturbation is much less common than in Facies B within the core.

The fifth depositional facies identified in the C and W sandstone was a distributary channel sandstone (Facies E). Both occurrences of Facies E overlie Facies C documenting the lateral migration of a distributary channel into an interdistributary area.

The upper Cowlitz mudstone overlies the C and W sandstone in the subsurface of the Mist gas field, but is absent in the field study area. Evidence present within the field study area indicates that the C and W sandstone is in conformable to slightly disconformable contact with the Keasey Formation. Thus, the upper Cowlitz mudstone must pinch out between the Mist gas field and the field study area since it apparently has not been removed by erosion. The depositional environment of the upper Cowlitz mudstone has been interpreted as upper to middle bathyal based predominantly on microfossils. Thus, the Cowlitz Formation as a whole documents a major transgression.

The Cowlitz Formation accumulated in a forearc basin along the western edge of North America. Generally, sediments that accumulate in a forearc setting contain abundant volcanoclastics, but the Cowlitz Formation is arkosic. This is a result of the predominantly plutonic

and/or metamorphic provenance of the Cowlitz Formation. The Cowlitz Formation accumulated during a period of volcanic quiescence. The arkosic detritus it contains was probably derived from the interior of the North American continent and may have been transported by an ancestral Columbia River. The composition of the C and W sandstone correlates with an uplifted basement, continental block provenance.

Although local volcanic activity was greatly reduced during the deposition of the Cowlitz Formation, there is evidence of some minor volcanic activity. A five meter interval, termed the blue-green zone, in core OM12C-3 contains atypically high volcanic detritus. The clasts are coarse sand to granule-sized and scoriaceous. The detritus is believed to be a product of proximal volcanic activity.

Due to the arkosic character of the C and W sandstone diagenesis has not greatly reduced the amount of porosity and permeability in the C and W sandstone. Four porosity reducing diagenetic effects were, however, identified in the C and W sandstone. Compaction is believed to have resulted in the greatest amount of porosity reduction. Minor quartz, calcite and chlorite cementation has also slightly reduced porosity in the C and W sandstone. Authigenic potassium feldspar, plagioclase, quartz, calcite, clays, and sphene have all precipitated in the C and W sandstone, but their effect on porosity is minor. The fourth, and final porosity reducing diagenetic effect identified is the alteration of mica. The expansion and platelet separation that occur during the alteration of micas reduced porosity and permeability slightly in the C and W sandstone.

Some secondary porosity has also developed in the C and W sandstone. Many petrographic criteria that identify the presence of secondary porosity in sandstones are present in the C and W sandstone. The criteria present in the C and W sandstone include; partial dissolution, molds, inhomogeneity of packing, oversized pores, corroded grains, honeycombed grains, and fractured grains. There are two possible hypotheses for the development of secondary porosity in the C and W sandstone. The first is that a pervasive calcite cement developed early in the diagenetic history of the C and W sandstone and later was totally dissolved making the porosity present in the C and W sandstone entirely secondary. The second hypothesis is that the secondary porosity developed simply by the dissolution of framework grains.

The depositional setting, and plutonic and/or metamorphic provenance allowed the accumulation of an arkosic sandstone with both high initial porosity and diagenetically stable composition. Diagenesis has modified the sandstone but not substantially resulting in an excellent natural gas reservoir.

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APPENDIX A

STATION AND SAMPLE LOCALITIES DISCUSSED IN TEXT

Local #	Location	Sample #	Rock Unit
2	NE SW SE ¹ / ₄ sec. 36, T4N, R5W	87-03	Basalt (Tcm)
5	center SW ¹ / ₄ sec. 35, T4N, R5W	87-05	Keasey
6	SW SW SW ¹ / ₄ sec. 35, T4N, R5W	88-66	Basalt (Tcm)
7	SW SW SW ¹ / ₄ sec. 2, T3N, R5W		Keasey
11	NW NE NW ¹ / ₄ sec. 1, T3N, R5W	87-08	Basalt (Tcm)
13	NW SW NW ¹ / ₄ sec. 27, T4N, R5W	87-09	Cowlitz
16	NE NE NW ¹ / ₄ sec. 27, T4N, R5W		Cowlitz
23	NE NE SW ¹ / ₄ sec. 22, T4N, R5W	87-20	Hamlet (Ths)
24A	center W ¹ / ₂ sec. 22, T4N, R5W	87-F7	Hamlet (Th)
29	SE SW SW ¹ / ₄ sec. 15, T4N, R5W	87-24	Basalt (Ttv)
30	SE SE SW ¹ / ₄ sec. 15, T4N, R5W	89-02	Hamlet (Thr)
36	NW SE NW ¹ / ₄ sec. 15, T4N, R5W	87-F11	Keasey
38A	NE SE NE ¹ / ₄ sec. 16, T4N, R5W	87-F12	Hamlet (Thr)
39	NW SW NW ¹ / ₄ sec. 15, T4N, R5W	89-03	Hamlet (Ths)
		88-64	Hamlet (Th)
44	NW SW SW ¹ / ₄ sec. 10, T4N, R5W		Cowlitz
49	center S ¹ / ₂ sec. 3, T4N, R5W	87-35	Keasey
58A	SE SW NE ¹ / ₄ sec. 10, T4N, R5W	87-36	Keasey
66	SE SE SE ¹ / ₄ sec. 10, T4N, R5W	87-38	Cowlitz
		87-39	Keasey
76	SE SE NE ¹ / ₄ sec. 22, T4N, R5W	88-02	Basalt (Ttv)
77	SE SE SE ¹ / ₄ sec. 15, T4N, R5W	87-42	Hamlet (Th)
81	NE NW NW ¹ / ₄ sec. 01, T3N, R5W	88-07	Basalt (Tcm)
82A	NW NE NE ¹ / ₄ sec. 35, T4N, R5W	88-09	Keasey
84	NE NE NE ¹ / ₄ sec. 2, T4N, R5W	88-12	Basalt (Tcm)
87	SW SE SE ¹ / ₄ sec. 35, T4N, R5W	88-13	Keasey
92	NW NW SW ¹ / ₄ sec. 3, T3N, R5W	88-15	Keasey
		88-16	Keasey
97	center SW ¹ / ₄ sec. 36, T4N, R5W	88-19	Basalt (Tcm)

Local #	Location	Sample #	Rock Unit
101	SE SE SE ¹ / ₄ sec 25, T4N, R5W	88-62	Hamlet (Th)
108	center NW ¹ / ₄ sec. 25, T4N, R5W	89-01	Hamlet (Th)
130	SW NW SW ¹ / ₄ sec. 23, T4N, R5W	88-38	Cowlitz
137	SW NW SW ¹ / ₄ sec. 24, T4N, R5W	88-43	Keasey
144	center SE ¹ / ₄ sec. 15, T4N, R5W	88-46	Hamlet (Th)
167	SE NW SE ¹ / ₄ sec. 15, T4N, R5W		Cowlitz
178A	NW SW SW ¹ / ₄ sec. 22, T4N, R5W	88-57	Hamlet (Ths)
180	NW NW NW ¹ / ₄ sec. 26, T4N, R5W	88-60	Hamlet (Th)
182	SW NW NW ¹ / ₄ sec. 22, T4N, R5W	88-63	Basalt (Ttv)

APPENDIX B

KEY TO SYMBOLS USED IN STRATIGRAPHIC SECTIONS

Stratigraphic Section Symbol Key		
Lithology	Fossils	Sedimentary Structures
Sandstone	burrow	parallel bedding
Mudstone	bioturbation	graded bedding
Interbedded Sandstone and Mudstone	plant debris	cross bedding
Not Recovered	Misc.	trough cross bedding
	concretion	no bedding
	carbonaceous	low angle truncation
	mud rip-up	slump structure
	pumiceous	irregular bedding
		ripples
		channel