AN ABSTRACT OF THE THESIS OF

Christina Lynn Robertson for the degree of Master of Science in Geology presented on April 25, 1997. Title: Surface-Subsurface Facies and Distribution of the Eocene Cowlitz and Hamlet Formations, Northwest Oregon.

Abstract approved: Alan R. Niem

Alan R. Niem

Abstract:

Since 1979, over $114 million of natural gas has been produced at the Mist Gas Field, currently the only commercial gas field in the Pacific Northwest. In the Mist Gas Field, the sandstone-dominated Clark and Wilson member of the upper Eocene Cowlitz Formation is the reservoir and the overlying upper mudstone member of the Cowlitz Formation forms the seal. Surface field maps, lithostratigraphic facies and petrographic analyses of a core of the Cowlitz Formation from the gas field, along with isopach maps and correlation of well logs of the Cowlitz and Hamlet formations in and around the gas field were used to constrain the depositional and diagenetic history of the Cowlitz Formation and bounding volcanic and sedimentary units.

The Cowlitz and Hamlet formations were deposited in a volcanically and tectonically active forearc basin during the late Eocene reorganization of the convergent margin of western North America. In outcrops, the Hamlet formation (informal) is a deepening-upwards (transgressive) sequence of a basal rocky coastline basaltic conglomerate, overlying shelfal mollusc-bearing micaceous arkosic sandstone and bathyal mudstone with minor thin turbidite sandstone beds which unconformably overlies "shield"

volcanoes of the middle to upper Eocene Tillamook Volcanics. In the Mist Gas Field subsurface, the mudstone-dominated Hamlet formation thins to the south toward the Tillamook Volcanics paleohigh. The sequence boundary between the Cowlitz and Hamlet formations coincides with a series of basalt flows of Grays River volcanics mapped in the subsurface in the northern part of the gas field. These flows pinch out to the south. The Clark and Wilson member of the Cowlitz Formation onlaps this paleohigh at the Mist Gas Field. In southwest Washington, flows of the Grays River volcanics overlie arkosic sandstone of the Cowlitz Formation.

The basal facies of the Clark and Wilson member at Mist is a bioturbated mudstone-dominated offshore to lower-shoreface transition unit which grades upwards into hummocky-bedded arkosic micaceous reservoir-quality sandstone with minor lignite beds of a storm wave-influenced delta front facies. Both the lower-shoreface facies and the hummocky-bedded facies thin rapidly in the subsurface onto the Grays River Volcanics paleohigh in the north. The uppermost facies of the Clark and Wilson member, the parallel-bedded facies, was reworked by waves into a shore-parallel barrier bar. The northeast-southwest-trending distributary channel axis suggests paleodispersal from the southwest Washington type locality which is dominated by delta plain and estuarine facies.

Following deposition of the Clark and Wilson member, an abrupt transgression (marine flooding surface) occurred and the thick parallel-laminated foraminifera-bearing bioturbated mudstone of the upper member of the Cowlitz Formation was deposited at bathyal water depths. A soft sediment contorted siltstone facies of the upper mudstone member resulted from redeposition of the parallel-laminated mudstone facies of the upper mudstone member. This slumping and redeposition of the late Narizian strata during the early Refugian may be related to normal faulting and horst and graben formation during a regional extensional event that formed the structure at the Mist Gas Field. The Cowlitz Formation is unconformably overlain by the deep marine tuffaceous mudstone and minor graded basaltic conglomerate of the Keasey Formation. This heralded the development of the western Cascade calc-alkaline arc and continuing forearc basaltic (Goble) volcanism.

Surface-Subsurface Facies and Distribution of the Eocene Cowlitz and Hamlet Formations, Northwest Oregon

by

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APPROVED:

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I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

Christina Lynn Robertson

Christina Lynn Robertson, Author

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INTRODUCTION

Hydrocarbon exploration in northwest Oregon dates back to 1910 when a series of exploratory wells were drilled (Warren, Norbisrath and Grivetti, 1945). Each of the four deep wells drilled between 1910 and 1927 encountered shows of natural gas but did not lead to a commercial discovery. Between 1944 and 1947, The Texas Company (now known as Texaco, Inc.) drilled a series of shallow bore holes and two deeper test holes in the Nehalem Basin near the settlements of Mist and Clatskanie, approximately 50 miles northwest of Portland. Although shows of gas were again encountered in each of these wells, a commercial discovery was not made. It was not until 1979 when under the leadership of W.G. ("Wes") Bruer and C. ("Chuck") Newell, commercial quantities of natural gas were discovered near the settlement of Mist in Columbia County, northwest Oregon (Newton, 1979) (Figure 1).

The discovery of commercial natural gas in the Columbia County 1 (CC 1) (Plate 4) redrill well by Reichhold Energy Corporation, in a partnership with Diamond Shamrock Corporation and Northwest Natural Gas, was the first such discovery in the state of Oregon. Over 200 dry holes had been drilled in Oregon prior to the discovery of the Mist Gas Field (Olmstead, 1985). Oregon Natural Gas Development Corporation (a wholly-owned subsidiary of Northwest Natural Gas), Diamond Shamrock Corporation, Reichhold

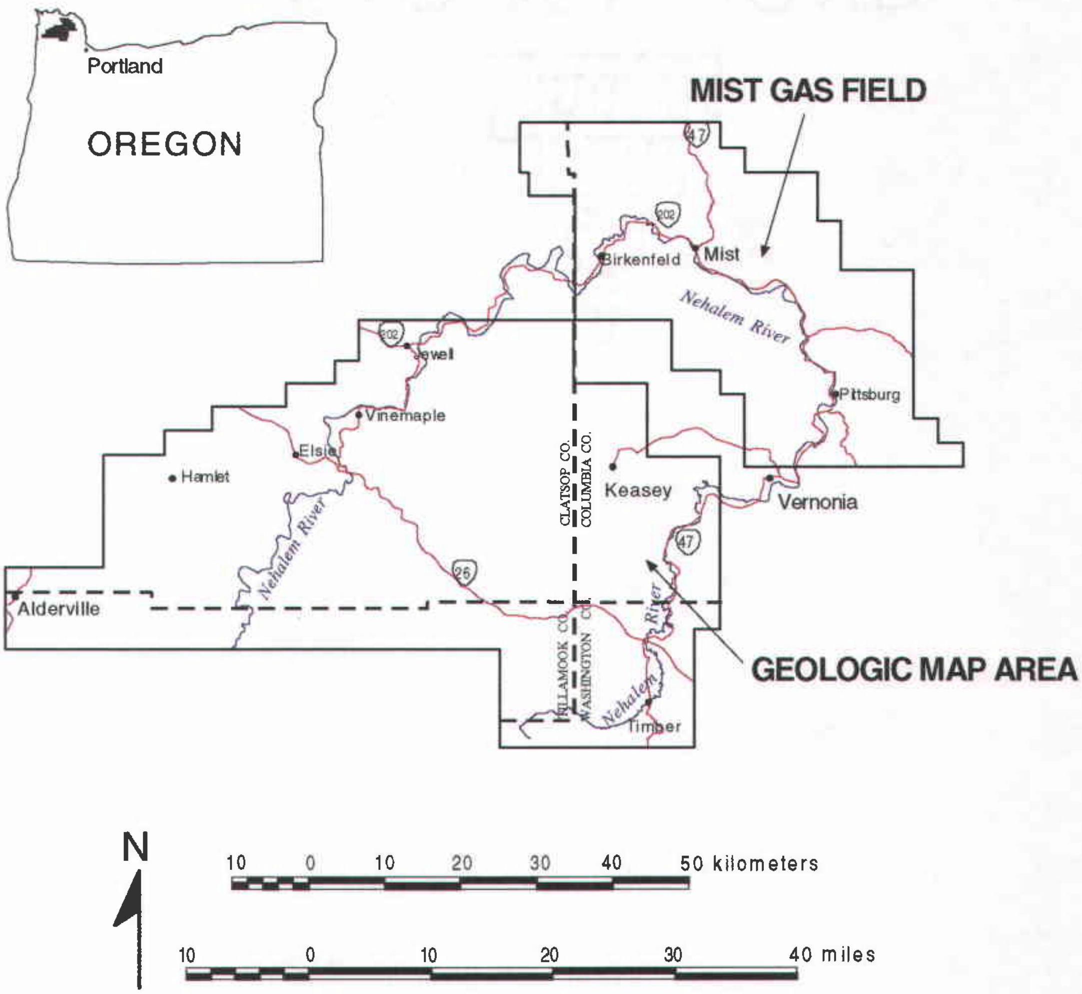


Figure 1. Location of major roads (red) and Nehalem River (blue) relative to the Mist Gas Field (Plate 4) and the geologic map area (Plate 1) where the Cowlitz Formation crops out.

Energy Corporation, the Atlantic Richfield Oil Company (ARCO), Nehama Weagant Oil and Gas Company, and Enerfin, have subsequently explored and developed the Mist Gas Field. As of year-end 1996, cumulative production at the Mist Gas Field was 60,040,296 cubic feet of native natural gas at a value of approximately $114 million (Oregon Department of Geology and Mineral Industries, 1997).

Eighteen wells (Oregon Department of Geology and Mineral Industries, 1997) are currently producing natural gas from the Clark and Wilson (C & W) sandstone member of the upper Eocene Cowlitz Formation at depths ranging from 1000 ft to 2500 ft (Berkman, 1990). Additionally, Northwest Natural Gas, the main supplier of natural gas in the Pacific Northwest, uses the Clark and Wilson member of the Cowlitz Formation as a gas storage reservoir (e.g. Bruer and Flora pools). Current activity at Mist centers on the development of a new underground storage field by Northwest Natural Gas. Exploration for new reserves of natural gas in areas adjacent to the storage pools continues by Enerfin (Jack Meyer, personal communication, 1997).

The Cowlitz Formation crops out several miles southwest of the Mist Gas Field in southern Clatsop and Columbia counties and in northwest Washington County (Plate 1, Figure 1). Since the discovery of natural gas at the Mist Gas Field, the outcrop distribution, facies relationships, mineralogy, diagenesis, textures, micropaleontology and depositional environments of the Cowlitz, Hamlet and Tillamook formations have been the focus of several studies (Newton and Van Atta, 1976; Timmons, 1981; Olbinski, 1983; Jackson, 1983; Nelson, 1985; Niem and Niem, 1985; Armentrout and Suek, 1985; Rarey, 1986; Shaw, 1986; Mumford, 1988; Safley, 1989; Farr, 1989; and Berkman, 1990). Earlier studies by Warren and others (1945), Warren and Norbisrath (1946), Deacon

(1953) and Van Atta (1971a, 1971b) studied the stratigraphy of the Nehalem Basin. Bruer (1980), Bruer and others (1984), Alger (1985), Niem and Niem (1985), Niem and others (1992) and Niem and others (1990) have studied the Cowlitz and Hamlet formations in the subsurface. Additionally, the Cowlitz Formation and the structure at the Mist Gas Field have been the subjects of numerous unpublished internal company reports by petroleum geologists exploring at the Mist Gas Field. Meyer (1986) and Stormberg (1991) discussed the origin of the natural gas at the Mist Gas Field.

Geologic Setting

The Cowlitz Formation and adjacent units were formed in the convergent margin of North America during middle to late Eocene time (Figures 2 and 3). The economic basement of the region is the middle Eocene Tillamook Volcanics (Plate 1). The 10,000 foot thick Tillamook Volcanics are interpreted to be coalescing shield volcanoes that erupted in the marine forearc (Rarey, 1986; Safley, 1989) and built up subaerial edifices. The lower part of the Tillamook Volcanics are submarine basaltic breccias and pillow basalts of tholeitic composition and are differentiated upward to basaltic andesites, andesites and even dacites in the subaerial upper part.

The marine Hamlet and Cowlitz formations were deposited unconformably above the Tillamook Volcanics along a subsiding rocky volcanic coastline (Rarey, 1986). The Cowlitz and Hamlet formations in the study area were initially mapped as a single formation, the Cowlitz Formation by Warren and others (1945). Newton and Van Atta (1976) also included both formations in the Cowlitz Formation in their map of Columbia County. In the subsurface, however, Bruer and others (1984) restricted the Cowlitz

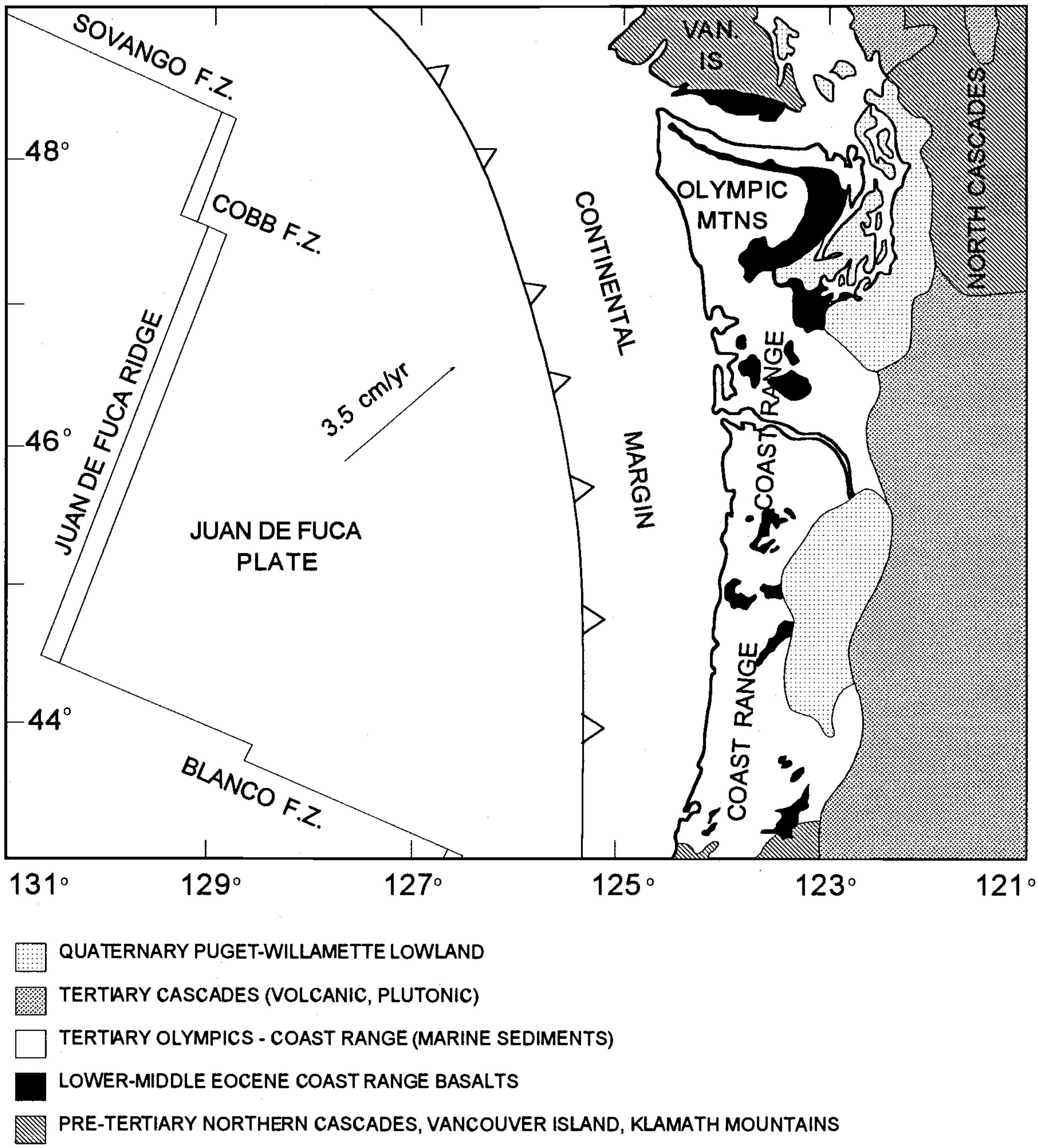


Figure 2. Generalized geologic and tectonic map of western Oregon and Washington (from Niem and others, 1994).

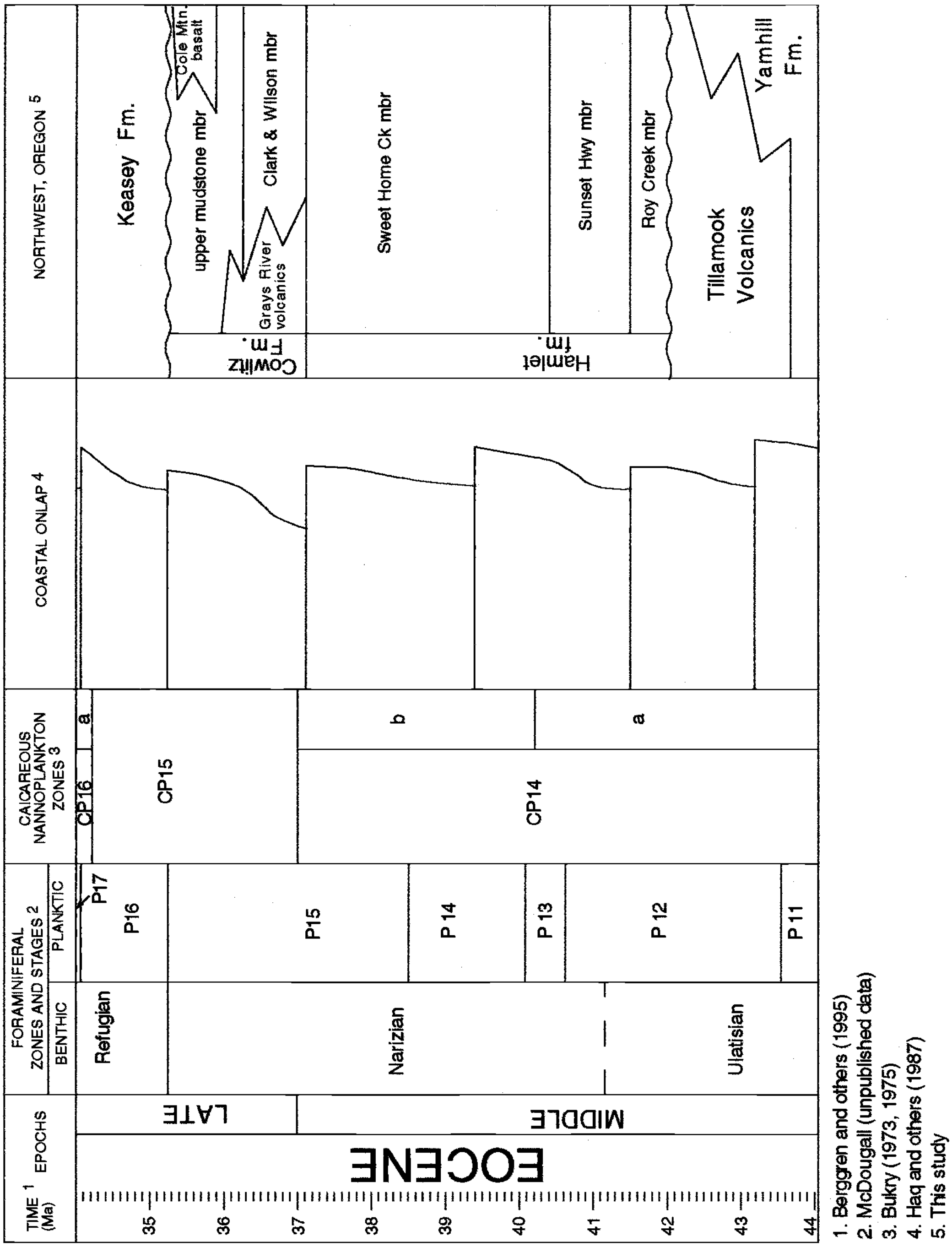


Figure 3. Time-stratigraphic chart of middle and upper Eocene rock units of Columbia County, Oregon with sea-level curves and Foraminifera and coccolith biozones.

Formation to a micaceous arkosic sandstone-dominated unit, the Clark and Wilson member, and an overlying mudstone-dominated unit, the upper mudstone member. Similarly, the type Cowlitz Formation in southwest Washington has also been restricted to an upper Eocene, coal-bearing, micaceous, arkosic, sandstone-dominated unit and overlying mudstone (Wells, 1981; Payne, personal communication, 1997). The mudstone-dominated unit between the Clark and Wilson member of the Cowlitz Formation and the Tillamook Volcanics in the subsurface was tentatively correlated to the middle and upper Eocene Yamhill Formation of the central Oregon Coast Range by Bruer and others (1984). Niem and Niem (1985), Rarey (1986), Mumford (1988) and Safley (1989) informally proposed a new formation name, the Hamlet formation, for this mudstone-dominated unit. The Yamhill Formation is presently mapped beneath and possibly interfingering with the Tillamook Volcanics (Figure 3). This study has also restricted the Cowlitz Formation to the sandstone-dominated unit and locally overlying upper mudstone member (Plate 1 and Figure 3).

The Hamlet formation consists of a basal basaltic conglomerate, a micaceous arkosic sandstone, and a thick overlying mudstone that lie below the Clark and Wilson member of the Cowlitz Formation (Rarey, 1986). By differentiating the mudstone-dominated Hamlet formation, the Cowlitz Formation in the outcrop area is limited to the same or similar lithologic units that are present at the type locality in southwest Washington near Vader (Charles Payne, personal communication, 1997) and in the subsurface at the Mist Gas Field (Niem and others, 1994).

The Cowlitz Formation consists of two members. The basal unit, the Clark and Wilson member, is a 600 ft thick micaceous arkosic sandstone with minor siltstone and lignite interbeds. The overlying unit, the upper mudstone member, is a laminated micaceous mudstone up to 1,000 ft thick.

Some disagreement exists as to the interpretation of the environment of deposition of the Clark and Wilson member. Bruer (1980) suggested that the depositional environment of the Cowlitz Formation in northwest Oregon was deep marine. Others (Van Atta, 1971a; Jackson, 1983; Alger, 1985; Niem and Niem, 1985; Rarey, 1986; Farr, 1989; Berkman, 1990; Niem and Niem, 1992), however, have concluded from surface exposures that the micaceous arkosic sandstone of the Cowlitz Formation in Oregon was deposited as a wave-dominated delta. Arkosic coal-bearing sandstone of the Cowlitz Formation in nearby southwest Washington is dominated by shallow marine to tidal and estuarine deposits (Payne, personal communication, 1997). In an earlier study, Deacon (1953) suggested that the Cowlitz Formation in Oregon is not genetically related to the Cowlitz Formation in Washington based on lithologic differences. He proposed that the Cowlitz nomenclature be dropped for the Oregon strata.

The Cole Mountain basalts are a complex of low TiO_2 and Fe_2O_3 porphyritic basaltic sills, dikes and minor flows that interfinger with the Cowlitz and Hamlet formations (Rarey, 1986, Mumford, 1988, and Niem and Niem, 1985). They have chemical and petrologic affinities to the calc-alkaline Goble Volcanics exposed along the Columbia River near Longview, Washington and Rainier, Oregon. The Cole Mountain basalt may be distal and/or invasive flows of the early western Cascades arc volcanics (Rarey, 1986; Niem and others, 1993). Recently, Steve Kenitz (Portland State University M.S. thesis, in preparation) has identified the Grays River volcanics (Figure 3) interbedded with the Cowlitz Formation in the subsurface at the Mist Gas Field. It crops out near the

Columbia River in northwestern Oregon and southwestern Washington and is chemically and petrologically identical to the Tillamook Volcanics.

The tuffaceous Keasey Formation unconformably overlies the Cowlitz Formation. The tuffaceous mudstone was derived from reworked volcanic ash that was erupted in the developing western Cascade calc-alkaline volcanic arc to the east.

RESEARCH OBJECTIVES

The primary objective of this study is to determine the stratigraphic relationship of the Cowlitz Formation at the Mist Gas Field to the Cowlitz Formation exposed on the surface in northwest Oregon and to describe the surface and subsurface distribution and facies relationships of the Cowlitz and Hamlet formations in northwest Oregon. The surface distribution was compiled from 10 theses and reports (Plate 1). The author spent thirty-five days mapping in the field in northwest Oregon in order to fill in gaps where no mapping existed of Cowlitz and Hamlet formation members and to resolve geologic mapping problems between existing geologic maps. The result of this work is a 1:100,000 scale geologic map (Plate 1) which covers almost all of the outcrop area of the Cowlitz and Hamlet formations in northwest Oregon. A second primary objective was to interpret the depositional environment and reconstruct the paleogeography of the Cowlitz Formation and adjacent units during the late Eocene.

In order to compare lithology and interpret the depositional environment of the Clark and Wilson member to subsurface electric logs, lithology and sedimentary structures from cores of the Clark and Wilson and upper mudstone member of the Cowlitz Formation in one well, IW 22D-10 at the Mist Gas Field were correlated to electric log properties (Plates 2 and 3). Electric logs from 151 wells at and adjacent to the Mist Gas Field were correlated in order to constrain the 3-dimensional geometry of the units of the Cowlitz and Hamlet formations and help in the paleoenvironmental interpretation of the Cowlitz Formation. Several east-west, northwest-southeast, and northeast-southwest stratigraphic cross sections (Plates 5, 6, and 7) through representative wells and isopach maps (Plates 8, 9, 10, 11, 12, and 13) of some of the members of the Cowlitz and Hamlet formations were created using electric logs.

A third primary objective was to do a detailed petrologic analysis of the reservoir and seal at the Mist Gas Field from samples in the cored well IW 22D-10. This objective included analysis of the mineralogy and diagenesis and reconstruction of the burial history of micaceous arkosic sandstones of the Clark and Wilson member of the Cowlitz Formation using X-ray diffraction, scanning electron microscopy, and thin section petrology. The data from this study were compared with earlier core studies of Berkman (1990) and Farr (1989). These data are related to the porosity and permeability of the reservoir units to further help in the exploration for native natural gas and development of gas storage fields.

Control on paleobathymetry and subsurface biostratigraphic ages of units was provided on samples sent to Dr. Kristin McDougall of the U.S. Geological Survey (Appendix II). Additionally, trace fossils were identified by the author with assistance from Dr. C. Kent Chamberlain, consulting geologist.

STRATIGRAPHY, NATURAL GAS OCCURRENCE, AND STRUCTURE OF THE NORTHERN OREGON COAST RANGE

STRATIGRAPHY

Economic basement in the field area consists of the middle to upper Eocene Tillamook Volcanics. The late Eocene Hamlet formation (informal) unconformably overlies the Tillamook Volcanics and is overlain by the Cowlitz Formation (Figure 3). After deposition of the Cowlitz Formation, the northern Oregon Coast Range was faulted to form a basement uplift with the sedimentary strata dipping away from the volcanic high forming a broad anticline. The upper Eocene Keasey Formation unconformably overlies the Cowlitz and Hamlet formations. Many of the faults which cut the underlying Tillamook, Hamlet and Cowlitz formations do not penetrate the Keasey Formation (Plate 1). This indicates that the tectonic event which uplifted the Tillamook Highland and dominates the structure at the Mist Gas Field occurred after the deposition of the Cowlitz Formation and before deposition of the Keasey Formation.

The purpose of the following section is to describe each of the units exposed in the surface geologic map area.

TILLAMOOK VOLCANICS

The oldest rocks in the study area are the middle to upper Eocene Tillamook Volcanics (Plate 1). This volcanic sequence is greater than 3,300 m thick (Snavely and others, 1970; Wells and others, 1983; Magill and others, 1982) in Washington County, forming the rugged mountainous core of the northern Oregon Coast Range uplift. The Tillamook Volcanics appear to thin to the north. In the Clark and Wilson 6-1 well (Plates 4 and 6) at the Mist Gas Field, the Tillamook Volcanics are approximately 430 m thick.

The Tillamook Volcanics consist of a basal unit of pillowed and brecciated tholeitic basalt and an upper unit of subaerial flows of basaltic andesite to dacite (Wells and others, 1983). The units are interpreted as a series of overlapping differentiated shield volcanoes or oceanic islands (Mumford, 1988; Jackson, 1983). Only the upper unit is exposed in the map area. Individual flow tops are vesicular, some with thin red paleosol horizons. Flow bottoms are brecciated. Flow interiors show platy to columnar jointing. Both normal- and reverse-polarity flows are present. Tillamook basalt and andesite in thin section are microphyric to porphyritic containing augite and plagioclase phenocrysts in a pilotaxitic groundmass of plagioclase, ilmenite and titaniferous augite microlites. The pilotaxitic flow texture distinguishes the Tillamook Volcanics from the younger late Eocene Cole Mountain Basalt (equivalent to Goble Volcanics) and intrusions of Grande Ronde Basalt of the middle Miocene Columbia River Basalt Group (Rarey, 1986; Mumford, 1988) exposed in the field area (Plate 1).

Snavely and others (1993) reported a 5 to 20 m thick coccolith-bearing kerogen shale within the lower subaqueous unit of the Tillamook Volcanics. Snavely and others (1993) correlated this discontinuous unit with similar oil shales of the interfingering middle Eocene Yamhill Formation. In the subsurface at the Mist Gas Field there are minor arkosic sandstone and mudstone interbeds in the Tillamook Volcanics which Bruer and others (1984) correlated to the middle Eocene Yamhill Formation. The interfingering relationship of the Tillamook Volcanics with the marine Yamhill Formation and the presence of pillowed lavas and breccias indicate that the lower Tillamook Volcanics were erupted in a marine environment. The base of the Tillamook Volcanics is not exposed in the field area. The Clark and Wilson 6-1 and the Clatskanie 1 wells (Plate 2) at the Mist Gas field penetrate thick mudstone-dominated sequences below the Tillamook Volcanics (Plate 4) which have tentatively been correlated to the Yamhill Formation (Bruer and others, 1984; Kenitz, 1997, personal communication; Meyer, 1997, personal communication).

Whole rock K-Ar dates of the upper subaerial unit of the Tillamook Volcanics in the study area obtained by McElwee (in Safley, 1989; Farr, 1989; Mumford, 1988; and Rarey, 1986) range from 35 to 42 Ma with most samples falling between 36 and 39 Ma. More precise $^{39}Ar/^{40}Ar$ radiometric dating by McElwee (in Berkman, 1990) has yielded consistent age dates of 42 to 43 Ma for the uppermost Tillamook Volcanics. Niem and others, (1992) report a total-fusion $^{39}Ar/^{40}Ar$ radiometric age of 42.4 ± 0.5 Ma for a flow near the top of the Tillamook Volcanics in Clatsop County. Coccoliths collected from the kerogen shale interbedded with the lower subaqueous Tillamook Volcanics are assigned to the *Discoaster bifax* subzone CP14a (Snavely and others, 1993) of Bukry (1973). The biostratigraphic stage conforms best with the total-fusion $^{39}Ar/^{40}Ar$ ages of 42 to 43 Ma. This substantiates the conclusion that the whole rock K-Ar ages are probably in error.

Geochemistry is useful in distinguishing the Tillamook Volcanics from the Cole Mountain basalt (correlative to the Goble Volcanics in southwest Washington) and the Columbia River Basalt Group (Kenitz, 1997, personal communication; Mumford, 1988; Rarey, 1986). The Tillamook Volcanics are higher in total iron, total alkalis, TiO_2, P_2O_5, and MnO and lower in CaO than the Cole Mountain basalt (Niem and Niem, 1985; Rarey, 1986; Kenitz, personal communication). The Tillamook Volcanics are geochemically and petrologically identical to the younger Grays River volcanics (Kenitz, 1997; personal communication) which crop out near the Columbia River in southwest Washington and northwest Oregon, and are present in the subsurface at the northern part of the Mist Gas Field (Plate 6). Stratigraphic position is the most useful method of distinguishing the Tillamook Volcanics from the Grays River volcanics.

HAMLET FORMATION

The nomenclature of the basaltic conglomerate, basaltic sandstone, arkosic sandstone and micaceous siltstone which overlie the Tillamook Volcanics and underlie the arkosic sandstone of the Clark and Wilson member of the Cowlitz Formation has been of some controversy. Many workers (Warren and others, 1945; Warren and Norbisrath, 1946; Van Atta, 1971a; Van Atta, 1971b; Nelson, 1985; Olbinski, 1983; Jackson, 1983) included this sequence with the Cowlitz Formation or undifferentiated upper Eocene strata. Deacon (1953) proposed that this unit be part of the Rocky Point Formation. In the subsurface, Bruer and others (1984) correlated it to the Yamhill Formation. In order to restrict the Cowlitz Formation to the lithologies present at the type locality in southwest Washington, Niem and Niem (1985) first informally proposed the name Hamlet formation for this strata. Rarey (1986) described the units of the Hamlet formation and proposed type localities for each member. This study uses the Hamlet formation nomenclature of Rarey (1986) for both surface exposures and the strata encountered in the subsurface.

The Hamlet formation consists of three mappable members from oldest to youngest: the Roy Creek conglomerate member; the Sunset Highway member, and the Sweet Home Creek member.

Roy Creek Conglomerate

The Roy Creek conglomerate member (informal) is a time-transgressive unit nonconformably overlying the Tillamook Volcanics. Total unit thickness estimates range from less than 1 m to over 125 m (Rarey, 1986). The proposed type locality of this member is located near Roy Creek along the Southern Pacific Railroad (NW ¼, sec. 31, T.3.N, R.9.W.) in northern Tillamook County. The unit is also mappable to the south of the field area and encircles much of the Tillamook highland (Plate 1) (Wells and others, 1994; Niem and Niem, 1985; Snavely and others, 1983).

The Roy Creek member consists of three subunits: a lower basaltic boulder to pebble conglomerate, a middle coarse- to very coarse-grained basaltic sandstone, and an upper fine- to very fine-grained basaltic sandstone to siltstone. The basal conglomerate is very poorly sorted and unstratified to weakly stratified with subangular to rounded clasts up to 2 m in diameter (Figure 4). Rounding of the clasts suggests transportation in fluvial channels and/or later reworking by strong wave action. Some poorly sorted, rounded boulder to pebble conglomerates are interpreted by Safley (1989) to represent debris flow deposits. The basal conglomerate contains fragmented oysters, barnacles and other thick-shelled mollusc fossils attesting to strong wave energy. The subunit is interpreted as pocket beach gravels deposited and reworked on a high energy rocky shoreline of Tillamook Volcanics sea stacks and headlands (Berkman, 1990; Safley, 1989; Mumford,

Figure 4. Poorly sorted, crudely stratified, basaltic conglomerate of the Roy Creek member (informal) of the Hamlet formation.

1988; Rarey 1986). The basal conglomerate grades upward into the middle unit. This middle unit consists of stratified, moderately sorted, coarse- to very coarse-grained basaltic sandstone that may reflect deposition in the surf zone (Mumford, 1988). The uppermost unit of the Roy Creek conglomerate is a fine-grained basaltic, mollusc-bearing, bioturbated, ripple laminated sandstone to siltstone deposited in an inner shelf environment (Berkman, 1990; Mumford, 1988). This fining upward sequence is interpreted to represent a marine transgression.

Basaltic clasts of the Roy Creek conglomerate display pilotaxitic flow texture and are geochemically identical to the underlying Tillamook Volcanics (Rarey, 1986; Mumford, 1988). No age-diagnostic fossils have been collected from the Roy Creek conglomerate, but a late Narizian age is inferred by microfossils from the overlying Sweet Home Creek member (Mumford, 1988; Rarey, 1986; Nelson, 1985).

Locally within the field area, the Roy Creek member is thin (less than 1 m) and rapidly fines upward into a bathyal mudstone. Mumford (1988) suggests this thinning may be caused by local faulting and/or non-deposition. In areas of low relief or where the volcanics were sheltered from wave action, non-deposition may have occurred.

Nelson (1985) observed dikes within the Tillamook Volcanic breccia which are truncated by the Roy Creek conglomerate. This erosional truncation and the absence of interfingering flows of Tillamook Volcanics within the Roy Creek member define the nonconformity between the Hamlet formation and the underlying Tillamook Volcanics observed in surface exposures. The upper contact of the Roy Creek conglomerate with the overlying Sunset Highway member in the eastern Clatsop County and Columbia County, and the Sweet Home Creek member in the central Clatsop County are gradational and conformable.

Sunset Highway Member

The Sunset Highway member of the Hamlet formation (informal) consists of micaceous arkosic sandstones with subordinate siltstone and basaltic sandstone interbeds. The proposed type locality of this unit is located on Sunset Highway (U.S. 26) west of the Quartz Creek bridge (NE ¼, sec. 10, T.4N., R.7W.) in eastern Clatsop County (Mumford, 1988).

Sandstones of the Sunset Highway member consist of predominantly moderately friable, locally mollusc-bearing, micaceous, arkose. The fine-grained sandstone is cemented with iron oxides and secondary clays with local calcareous concretions (Mumford, 1988; Nelson, 1985). Arkosic sandstones are hummocky cross-stratified to parallel laminated to structureless where intensely bioturbated. Bedding orientation is inferred based on the alignment of mica flakes and carbonaceous material. These sedimentary structures suggest a storm wave-dominated inner to middle shelf environment of deposition (Mumford, 1988; Rarey, 1986; Niem and Niem, 1985). Siltstone interbeds commonly form drapes above swaley-bedded sandstones. Siltstone interbeds contain parallel laminations and ripple cross laminations defined by the alignment of mica grains and carbonaceous material. The mudstone drapes probably represent fair-weather deposition on the shelf above storm wave base. Interbeds of coarse- to very coarse-grained basaltic grit; rare very poorly sorted, basaltic sandstone; and rare channels of basalt cobble to boulder conglomerate (Figure 5) become more abundant upward. Basaltic

Figure 5. Basaltic conglomerate channel within laminated sandstone of the Sunset Highway member of the Hamlet formation. Locality is in SE ¼, sec. 33, T.4N., R.7W.

interbeds of the Sunset Highway member are better indurated than the micaceous arkosic sandstones due extensive sparry calcite cement (Mumford, 1988). Basaltic interbeds are interpreted to represent storm events during which basaltic clasts were swept off the exposed Tillamook high and flushed onto the shelf (Safley, 1989; Mumford, 1988; Rarey, 1986).

Presence of both basaltic and arkosic sandstones suggests a mixed sediment source. The micaceous, potassium feldspar-bearing, arkosic sandstone is extra-basinal and was probably transported by an ancestral Columbia River drainage system from the Idaho Batholith or metamorphic core complexes in northeastern Washington. The basaltic clasts were sourced locally from the Tillamook Volcanics (Safley, 1989; Mumford, 1988; Rarey, 1986).

The Sunset Highway member is absent due to stratigraphic pinch-out in Rarey's (1986) study area. Mumford (1988) reports a total unit thickness of 35 m at the proposed type locality along Sunset Highway. Nelson (1985) measured 75 m of section south of the settlement of Jewell. The unit attains a maximum thickness of 410 m in the Clatskanie 1 well at the Mist Gas Field. These observations suggest a basinward thickening to the north and east away from the Tillamook high. The westward and southwest pinch-out of the unit suggests a position of the paleo-shelf edge in eastern Clatsop County (Plate 1).

Both the basal and upper contacts of the Sunset Highway member are conformable. The basal contact of the Sunset Highway member with the Roy Creek member is recognized by the rapid change from a predominantly basaltic sandstone to an arkosic sandstone with only minor basaltic sandstone interbeds. The Sunset Highway member grades upward into thin bedded sandstone and mudstone turbidites of the lower

Sweet Home Creek member. These turbidites are exposed along Sunset Highway (SE ¼, sec. 4, T.4N., R.7W.) and in Wolf Creek south of the Sunset Highway. Where the Sunset Highway member is absent due to stratigraphic pinch out, mudstone and thin bedded turbidites of the Sweet Home Creek member are the time-correlative units (Rarey, 1986; Niem and Niem, 1985).

Sweet Home Creek Turbidites and Mudstone

The uppermost member of the Hamlet formation (informal) is the Sweet Home Creek member (informal). The Sweet Home Creek member, consisting of upper bathyal to outer neritic mudstone and lesser turbidites, occurs throughout the field area (Plate 1). Total thickness estimates for the unit range from 120 m to 400 m (Rarey, 1986). Average thickness at the Mist Gas Field is approximately 300 m (Plate 9). The proposed type locality of this unit is in the bed of Sweet Home Creek south of the settlement of Hamlet (NE ¼, sec. 29, E ½, sec. 20, SE ¼, sec. 17, T.4N., R.8.W.) in Clatsop County (Rarey, 1986).

Sweet Home Creek mudstones are micaceous, locally carbonaceous, generally well laminated with some *Phycosiphon* (also known as *Helminthoida*) burrows (Figure 6). Sandstones of the turbidite facies are thin-bedded, have sharp basal contacts and fine upwards to hemipelagic mudstones. Olbinski (1983) and Mumford (1988) suggest that turbidites observed in their field studies are the time-equivalent deep-water facies to the shallow-marine Sunset Highway member. Berkman (1990) reports a 70 m thick sequence of sandstone, siltstone and mudstone turbidites immediately below the Sweet Home Creek contact with the overlying Clark and Wilson member. These turbidites may represent the

Figure 6. Near-vertical sandstone and mudstone turbidite facies of the Sweet Home Creek Member of the Hamlet formation. Turbidites are exposed in bank of Wolf Creek (NE 1/4, sec. 32, T.4N., R.7W.).

beginning of the shoaling upward trend observed in electric logs at the Mist Gas Field (see chapter Subsurface Correlation and Distribution of Cowlitz and Hamlet Formations, Mist Gas Field, Northwest Oregon).

Paleoenvironmental interpretations based on benthic foraminifera indicate a middle bathyal to outer neritic environment of deposition (McDougall and Rau in Rarey, 1986). McDougall (in Rarey, 1986) assigned samples from the middle of the Sweet Home Creek member in Clatsop County to upper middle bathyal water depths and samples from the base and top of the Sweet Home Creek member to outer neritic to upper bathyal water depths. This suggests a deepening trend followed by a shoaling trend (Rarey, 1986). The onset of shoaling may reflect the beginning of Clark and Wilson sandstone deposition farther to the east.

Foraminiferal data indicate an upper Narizian stage for the Sweet Home Creek member (Rau and McDougall in Rarey, 1986). Coccolith data restrict the age of surface samples to subzone CP-14a (Bukry in Rarey, 1986) and one sample in the subsurface to subzone CP-14b (Bukry in Rarey, 1986). No age or environmentally diagnostic microfossils have been recovered from the turbidites of the Sweet Home Creek member (Mumford, 1988; Rarey, 1986; Nelson, 1985).

The Sweet Home Creek member conformably overlies the Sunset Highway member of the Hamlet formation in eastern Clatsop County and western Columbia County and the Roy Creek member of the Hamlet formation in western Clatsop County (Plate 1). In Columbia County and northeastern Clatsop County, the Clark and Wilson member (informal) of the Cowlitz Formation overlies the Sweet Home Creek member. In the northern part of the Mist Gas Field (Plates 6, 7 and 9), flows of Grays River volcanics overlie the Sweet Home Creek member (see chapter Subsurface Correlation and Distribution of Cowlitz and Hamlet Formations, Mist Gas Field, Northwest Oregon). Niem and Niem (1985) and Bruer and others (1984) report an unconformity at the Sweet Home Creek member contact with the Cowlitz Formation. This author interprets there to be a conformable sequence boundary between the Sweet Home Creek member and the Clark and Wilson member where the Grays River volcanics is not present. The conformable surface between the Sweet Home Creek member and the Cowlitz Formation is time-equivalent to the nonconformity at the top of the Grays River volcanics in the northern part of the Mist Gas Field. Where the Clark and Wilson member (informal) of the Cowlitz Formation is absent in Clatsop County due to stratigraphic pinch-out, the Sweet Home Creek member cannot be distinguished from the upper mudstone member of the Cowlitz Formation (Rarey, 1986; Niem and Niem, 1985). Intrusions and flows of Cole Mountain Basalt occur near the Keasey-Hamlet contact in Clatsop County between the main Tillamook Volcanic high and the Green Mountain outlier (Safley, 1989; Mumford, 1988; Rarey, 1986; Niem and Niem, 1985) (Plate 1).

Cowlitz Formation

The type Cowlitz Formation was originally defined by Weaver (1912) as a 60 m thick Narizian mudstone-dominated unit containing a rich molluscan fossil assemblage exposed in Cowlitz River in southwestern Washington. This section is the famous "Big Bend" fossil collecting locality (Payne, personal communication). In 1937, Weaver amended his original definition of the Cowlitz Formation to include 1,300 m of micaceous arkosic sandstone exposed in Olequa and Stillwater creeks, thus necessitating two type localities for the Cowlitz Formation. Henriksen (1956) defined two members in the Cowlitz Formation; the mudstone-dominated Stillwater Creek member and the overlying coal-bearing, micaceous, arkosic sandstone of the Olequa Creek member. Wells (1981) restricted the definition of the type Cowlitz Formation to the sandstone-dominated Olequa Creek member that Weaver defined in 1937 and assigned the Stillwater Creek member of Henriksen (1956) to the McIntosh Formation.

The usage of the Cowlitz Formation name for upper Eocene strata in northwest Oregon has a long, confusing, and controversial history. Warren and Norbisrath (1946) correlate a 300 m thick sequence of Eocene basaltic conglomerate, basaltic sandstone, micaceous mudstone, and micaceous arkosic sandstone to the type Cowlitz Formation of Washington as amended by Weaver (1937). This designation is based on the similarity of the megafossil assemblage in Oregon to the megafossil assemblage at the type locality in Washington. Deacon (1953) concluded that the Cowlitz Formation of northwest Oregon is not lithologically similar to the mudstone-dominated type Cowlitz Formation defined by Weaver (1912) in southwest Washington. However, he concedes that the Oregon section is lithologically similar to Weaver's (1937) amended Cowlitz Formation exposed in Olequa Creek in southwest Washington. Deacon proposed that the Cowlitz Formation name be dropped for the Oregon strata and instead named these rocks the Rocky Point Formation. Van Atta (1971a and 1971b) concluded, in part, that the Eocene sandstones, siltstones, and mudstones in the upper Nehalem River Basin are more similar than dissimilar to the type Cowlitz Formation of Weaver (1937) and therefore applied the Cowlitz nomenclature to the Oregon strata. Newton and Van Atta (1976) mapped the distribution of the Cowlitz Formation in Columbia County for use in hydrocarbon exploration. In the subsurface at the Mist Gas Field, Bruer and others (1984) restricted the use of the name Cowlitz Formation to a micaceous arkosic sandstone-dominated unit, the Clark and Wilson member, and the overlying mudstone-dominated unit, the upper mudstone member. Similarly, Niem and Niem (1985) and Rarey (1986) defined the Hamlet formation (informal) in order to restrict the Cowlitz Formation exposed at the surface in Oregon to the arkosic sandstone and mudstone present at the amended type locality in Washington.

The Cowlitz Formation of Oregon is interpreted in this study to conformably overlie the Sweet Home Creek member of the Hamlet formation (informal) on the surface and at most of Mist Gas Field and to nonconformably overlie the Grays River volcanics in the northern part of the Mist Gas Field (see Subsurface Correlation and Distribution of Hamlet and Cowlitz Formations, Mist Gas Field, Northwest Oregon chapter). The Clark and Wilson member is the reservoir at the Mist Gas Field and the overlying upper mudstone member is the seal.

Clark and Wilson Member

The Clark and Wilson member (informal) of the Cowlitz Formation is a micaceous arkosic sandstone-dominated unit exposed in the eastern part of the field area (Plate 1). The name Clark and Wilson sandstone was first used in the subsurface for Eocene arkosic sandstone encountered in the Texaco Clark and Wilson 6-1 well. The unit attains a maximum thickness of approximately 320 m in the 21-20-64 well at the Mist Gas Field. The unit pinches out to the west near the Clatsop/Columbia county boundary.

Some controversy exists as to the environment of deposition of the Cowlitz Formation in northwest Oregon. Bruer (1980) suggested that Clark and Wilson member at the Mist Gas Field was deposited in a deep marine environment based on bathyal mudstones overlying and underlying the unit. However, more recent workers (Olbinski, 1983; Niem and Niem, 1985; Alger, 1985; Rarey, 1986, Mumford, 1988; Farr, 1989; Berkman, 1990; Niem and Niem, 1992; this study) have interpreted the environment of deposition of the Clark and Wilson member to range from a wave-dominated delta front to brackish-water swamp. This issue has not previously been resolved to the satisfaction of some subsurface workers (Jack Meyer, personal communication, 1997).

The Clark and Wilson member consists of structureless, planar and hummocky cross-stratified sandstone with lesser bioturbated mudstone interbeds. Sandstones are well sorted, light olive gray (5Y 5/1), micaceous arkoses. The friable nature and lack of basaltic interbeds and mollusc fossils in the Clark and Wilson member help to distinguish it from the Sunset Highway member of the Hamlet formation. The lack of basaltic interbeds within the Clark and Wilson member suggests that the Tillamook Volcanics were buried by the time the Clark and Wilson member was deposited.

Two main subfacies of the Clark and Wilson member are observed on the surface and in the subsurface: a lower heterolithic sandstone and mudstone which coarsens upward to an amalgamated, very-thick bedded, sandstone-dominated facies with rare coal beds (Berkman, 1990; Farr, 1989; Jackson, 1983).

The offshore to lower-shoreface facies is present at the base of the Clark and Wilson member on the surface (Berkman, 1990; Farr, 1989; Jackson, 1983) and in the

Figure 7. Heterolithic sandstone facies of the Clark and Wilson member of the Cowlitz Formation. Note curved lower contacts of sandstone beds, ripple cross laminations in siltstone, parallel laminations in mudstone, and abundant carbonized plant debris.

subsurface (Plates 5, 6 and 7). At the Mist Gas Field, average thickness of the lower-shoreface facies is approximately 65 m (Plate 10). This unit was deposited as the delta prograded seaward.

The heterolithic sandstone facies consists of swaley bedded sandstones and mudstones (Figure 7). Individual sandstone swales have sharp erosive bases and grade upward to ripple cross-laminated siltstone and parallel laminated mudstone. Low-angle cross-laminations, load structures, planar laminations, alignment of mica and carbonaceous plant debris (Olbinski, 1983), and a relatively low sandstone to mudstone ratio (3:1) characterize this unit (Berkman, 1990). The heterolithic facies is locally intensely bioturbated. The unit is interpreted to have been deposited on the lower shoreface. Sandstone swales represent peak storm activity, ripple cross-laminated siltstones represent waning storm conditions, and parallel laminated mudstones represent fair-weather deposition (Dott and Bourgeois, 1982). This unit grades upward to Lithofacies H of Berkman (1990). The bioturbation and parallel-laminated fairweather beds attest to the lower rate of deposition of the heterolithic facies relative to the amalgamated sandstone facies.

The amalgamated sandstone facies attains a maximum thickness of approximately 260 m in wells 21-20, 11-16 and 24-9 in T.6N., R.4W at the Mist Gas Field (Plate 11). Thickness of surface exposures cannot be estimated due to extensive faulting (Berkman, 1990). The amalgamated sandstone facies is the main sandstone facies recovered in the IW 22D-10 core. Additional description of this unit is provided in the Lithofacies of the Cowlitz Formation in Bruer and Flora Gas Storage Pools chapter.

Figure 8. Amalgamated hummocky-bedded sandstone facies of the Clark and Wilson member. Exposure is located on rail-cut along the Southern Pacific rail-line in Washington County (NE ¼, sec 25, T.4N, R.7W.).

The amalgamated sandstone facies (Figure 8) consists of hummocky cross-stratified to parallel-laminated sandstone. Micaceous arkosic sandstones are fine- to very fine-grained with some mudstone drapes. The sandstone to mudstone ratio (6:1) is less than that of the heterolithic sandstone facies (Berkman, 1990). Fairweather beds are often not present in this unit due to the high energy conditions of the middle to upper shoreface. Local load and slump structures attest to rapid sedimentation and liquefaction during storms. Near parasequence tops, rare thin coal beds are preserved (Farr, 1989; Berkman, 1990). Coal beds were deposited in swamps or marshes and reflect lowering of relative sea level.

In surface exposures in Columbia County, the basal contact of the Clark and Wilson member with the Sweet Home Creek member of the Hamlet formation is gradational and interpreted to be conformable. In the subsurface the contact is nonconformable where it onlaps the Grays River volcanics, to conformable where the unit overlies the Sweet Home Creek member. This sequence boundary represents the onset of delta progradation and marine regression. The upper mudstone member of the Cowlitz Formation conformably overlies the Clark and Wilson member at the Mist Gas Field and in some surface exposures in Columbia County (Plate 1). Locally, the angular unconformity at the base of the Keasey Formation cuts into the Clark and Wilson member in Clatsop County, Columbia County, and Washington County (Jackson, 1983; Nelson, 1985; Farr, 1989; Berkman, 1990; this study).

Upper Mudstone Member

The Clark and Wilson member is conformably overlain by the upper mudstone member (informal) of the Cowlitz Formation. This unit consists of laminated siltstone with some thin-bedded turbidites (Berkman, 1990; Niem, unpublished mapping). The upper mudstone member, although widespread in the subsurface, is largely absent on the surface due to erosion by the overlying Keasey Formation (Olbinski, 1983; Niem and Niem, 1985; Nelson, 1985; Farr, 1989; Berkman, 1990).

Surface exposures of the upper mudstone member are poor due to rapid weathering. A complete discussion of the lithology, sedimentary structures, and environmental interpretation of the unit is presented later in this report in the Lithofacies of the Cowlitz Formation in Bruer and Flora Gas Storage Pools chapter.

The basal contact of the upper mudstone member with the Clark and Wilson member is sharp and represents a rapid marine transgression. The upper contact of the upper mudstone member with the Keasey Formation is unconformable. After deposition of the upper mudstone member of the Cowlitz Formation there was a period of regional extensional faulting followed by extensive erosion and deposition of the Keasey Formation. Many of the faults mapped on the surface do not cut the Keasey Formation (Plate 1). This indicates that the faulting event occurred prior to the deposition of the Keasey Formation.

KEASEY FORMATION

The Keasey Formation is a tuffaceous siltstone to sandstone which unconformably overlies the Cowlitz and Hamlet formations. Van Atta (1971a and 1971b) informally defined three members in the Keasey Formation. The base of the Keasey Formation consists of a thin, pebbly, volcanic sandstone. This sandstone is observed in the IW 22D-10 core. The middle unit is a structureless, fossiliferous, tuffaceous siltstone. The uppermost unit consists of interbedded siltstone and sandstone. Rarey (1986) defined a thin glauconitic mudstone member, the Jewell member, which occurs at the base of the Keasey Formation in Clatsop County. The entire Keasey Formation contains thin waterlaid tuff beds. The Keasey Formation is lower Refugian to uppermost Narizian in age. The change in lithology from the micaceous arkosic Cowlitz Formation to the tuffaceous Keasey Formation reflects a change in provenance from a dissected arc to an active volcanic arc (Kadri and others, 1983).

The Keasey Formation overlies the Cole Mountain basalt, upper mudstone member of the Cowlitz Formation, or Clark and Wilson member of the Cowlitz Formation in eastern part of field area and Sweet Home Creek member of the Hamlet formation or Cole Mountain basalt in western part of field area (Plate 1). In Clatsop County the Keasey Formation overlies the Sweet Home Creek member with both units having roughly the same structural attitude (Rarey, 1986). There is no structural evidence of an unconformity between the bathyal Sweet Home Creek member of the Hamlet formation and the bathyal Keasey Formation in Clatsop County. However, the glauconitic mudstone in the basal Keasey Formation described by Rarey (1986) may represent a condensed section or period of slow sedimentation.

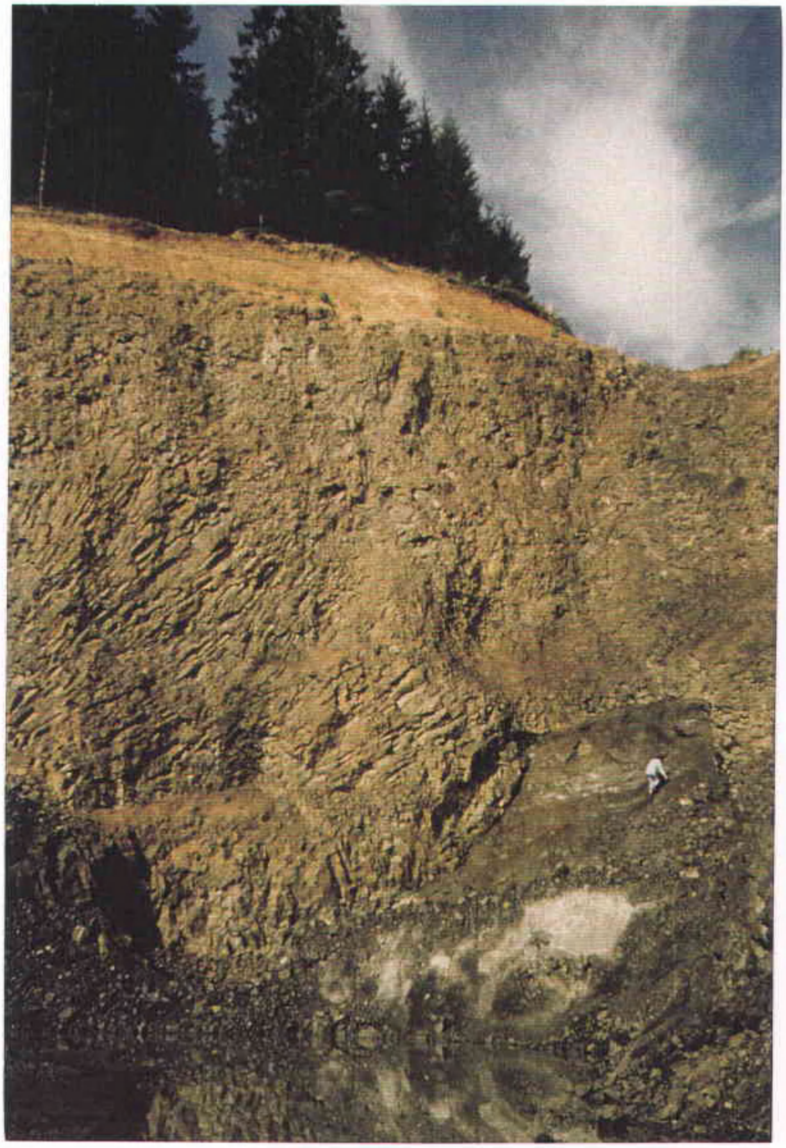


Figure 9. Subaqueous flow of the Cole Mountain Basalt within the Cowlitz Formation. Note radial jointed "Warrior Bonnet" structure of the filled lava tube. Pillowed basalts form a carapace over and between Warrior Bonnets. Arkosic micaceous sandstone of Clark and Wilson member of the Cowlitz Formation is parallel laminated and underlies this flow. Laminated dark gray bathyal mudstone of the upper mudstone member of the Cowlitz Formation overlies this submarine flow. Locality is in SE ¼ of NW ¼, sec. 28, T.4N., R. 5W.

Cole Mountain Basalt

The Cole Mountain Basalt consists of shallow dikes, sills, and subaqueous flows of plagioclase- and clinopyroxene-phyric, glassy vesicular to amygdaloidal, calc-alkaline basalt and basaltic andesite (Niem and Niem, 1985; Rarey, 1986; Safley, 1989; Wells and others, 1994). Thin veins of quartz and pyrite and pods of chert, mudstone, and zeolite are locally present. Thickness estimates for the unit range from <1m to 150 m (Rarey, 1986).

In Clatsop County, intrusions and flows of the Cole Mountain Basalt occur within the Sweet Home Creek member near the contact with the overlying Keasey Formation (Rarey, 1986; Safley, 1989). In Columbia County, flows of the Cole Mountain basalt occur at the contact between the Clark and Wilson member and the upper mudstone member of the Cowlitz Formation (Figure 9) (Berkman, 1990; this study). In Washington County, Oregon intrusions of the Cole Mountain basalt occur within the Sweet Home Creek member of the Hamlet formation (Wells and others, 1994).

A total-fusion ^{39}Ar / ^{40}Ar age date of 34.2 ± 2.1 m.y. is for the Cole Mountain basalt reported by Safley (1989).

Grays River volcanics

The Grays River volcanics consist of a series of basalt flows which are geochemically and petrologically identical to the Tillamook Volcanics. Flows pulses of the Grays River volcanics can be distinguished from each other and the Tillamook Volcanics based only on stratigraphic position (Figure 10) (Kenitz, 1997; personal communication).

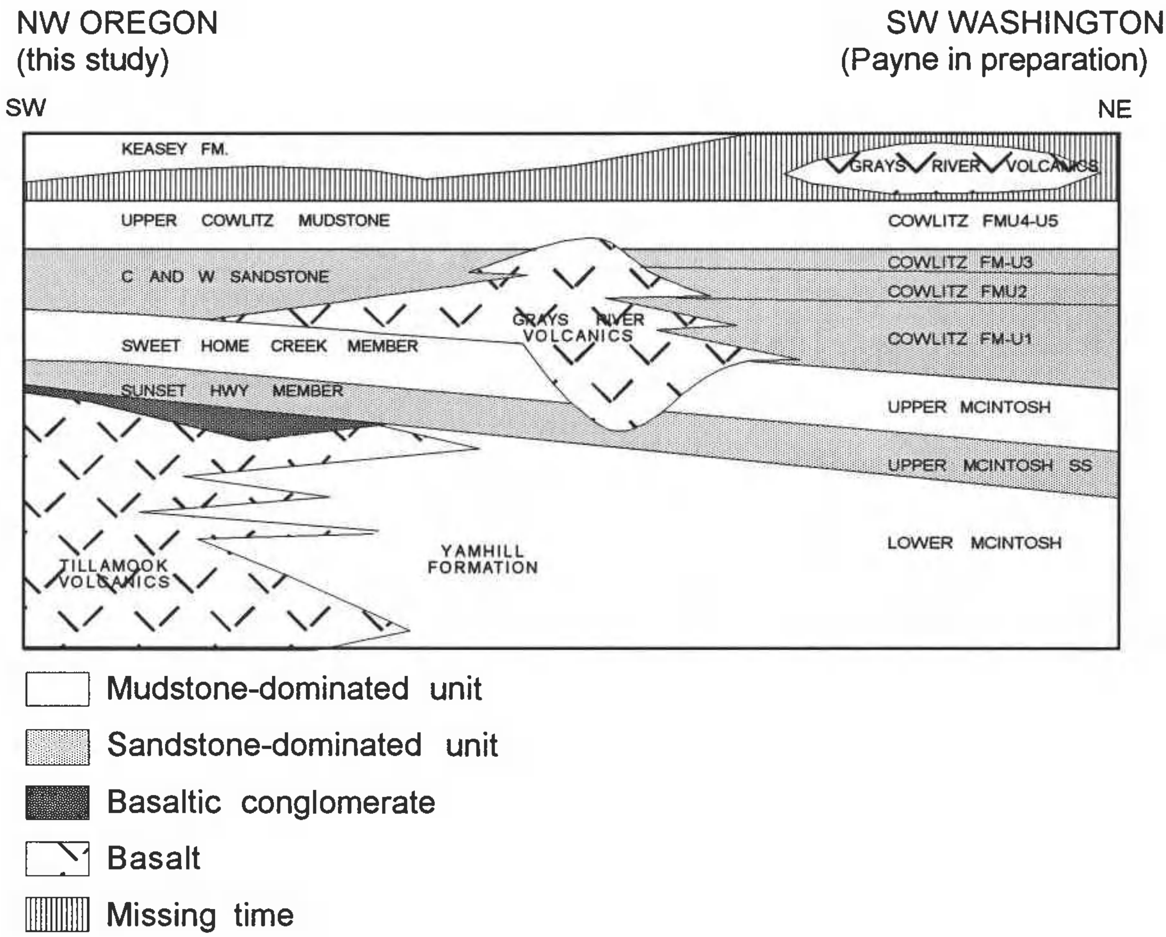


Figure 10. Schematic stratigraphic cross section showing distribution of the Tillamook Volcanics and tongues of the Grays River volcanics relative to sedimentary strata in Oregon and Washington (modified from Payne, Oregon State University M.S., in preparation).

At the Mist Gas Field, a series of flows of the Grays River volcanics underlies and may interfinger with the Clark and Wilson member of the Cowlitz Formation (see Subsurface Correlation and Distribution of Hamlet and Cowlitz Formations, Mist Gas Field, Northwest Oregon chapter). Near the Columbia River in Oregon and Washington, the Grays River volcanics are interbedded with arkosic sandstone of the Cowlitz Formation (Kenitz, 1997, in preparation). At Bebe Mountain in southwestern Washington, the Grays River volcanics overlies the Cowlitz Formation (Payne, 1997; personal communication).

Irving (1996) reports a total-fusion $^{39}Ar/^{40}Ar$ age of 40.2 $\pm$ 0.3 Ma for the Grays River volcanics interbedded with the Cowlitz Formation near the Columbia River in Washington. This Grays River flow sequence may be correlative to the Grays River volcanics interbedded with the Cowlitz Formation at the Mist Gas Field. A radiometric age date of the Grays River volcanics at the Mist Gas Field is needed to confirm this hypothesis. Payne (in preparation) reports age dates of 38.64 $\pm$ 0.40 Ma, 37.44 $\pm$. 0.45 Ma and 36.85 $\pm$ 0.46 Ma by Duncan for Grays River volcanics flows which overlie the Cowlitz Formation. The Tillamook Volcanics have been dated at 42-43 ma. Flows with Tillamook-Grays River chemistry may show a northward progression in age (Payne, 1997; personal communication).

Gas Geochemistry

The most comprehensive academic study of the gas at the Mist Gas Field was conducted by Stormberg (1991). He utilized total organic carbon (TOC), vitrinite reflectance (R_o), rock-eval pyrolysis, visual kerogen, thermal alteration index (TAI), and gas chromatography techniques in an attempt to define the source rocks, characterize the composition of natural gas as the Mist Gas Field, and determine the genetic origin of the gas.

Stormberg found that vitrinite reflectance values for samples from the Cowlitz Formation range from 0.48-0.66%. Stormberg observed the highest vitrinite reflectance value of 0.66% for the Cowlitz Formation in the Crown Zellerbach 32-26-54 (sec. 26, T.5N., R.4W.) well. He attributed this increase in thermal maturity to heat dissipated from upper Eocene flows of Goble Volcanics (correlative to the Cole Mountain basalt) which are intercalated with the Cowlitz Formation in this well. These thermally immature values are well below the 0.9% minimum value where thermogenic gas is thought to form (Tissot and Welte, 1984). Vitrinite reflectance values for samples from the Sweet Home Creek member of the Hamlet formation range from 0.49-1.64%. The highest vitrinite reflectance value in the Hamlet formation is 1.64% in the Exxon G.P.E. #1 well at a depth of 10770 ft.

Isotopic analysis suggests that the natural gas at the Mist Gas Field is a mixture of thermogenic and biogenic methane with a significant nitrogen component (Armentrout and Suek, 1985; Stormberg, 1990). High nitrogen content appears to be associated with a higher content of biogenic methane relative to thermogenic methane. The biogenic gas may have been generated in situ from coals and layers of carbonized plant debris in the Clark and Wilson member of the Cowlitz Formation and/or marine mudstone of the underlying Hamlet formation (Stormberg, 1990). Stormberg suggests that the high nitrogen content may be associated with the late Eocene intrusion or invasive flows of the

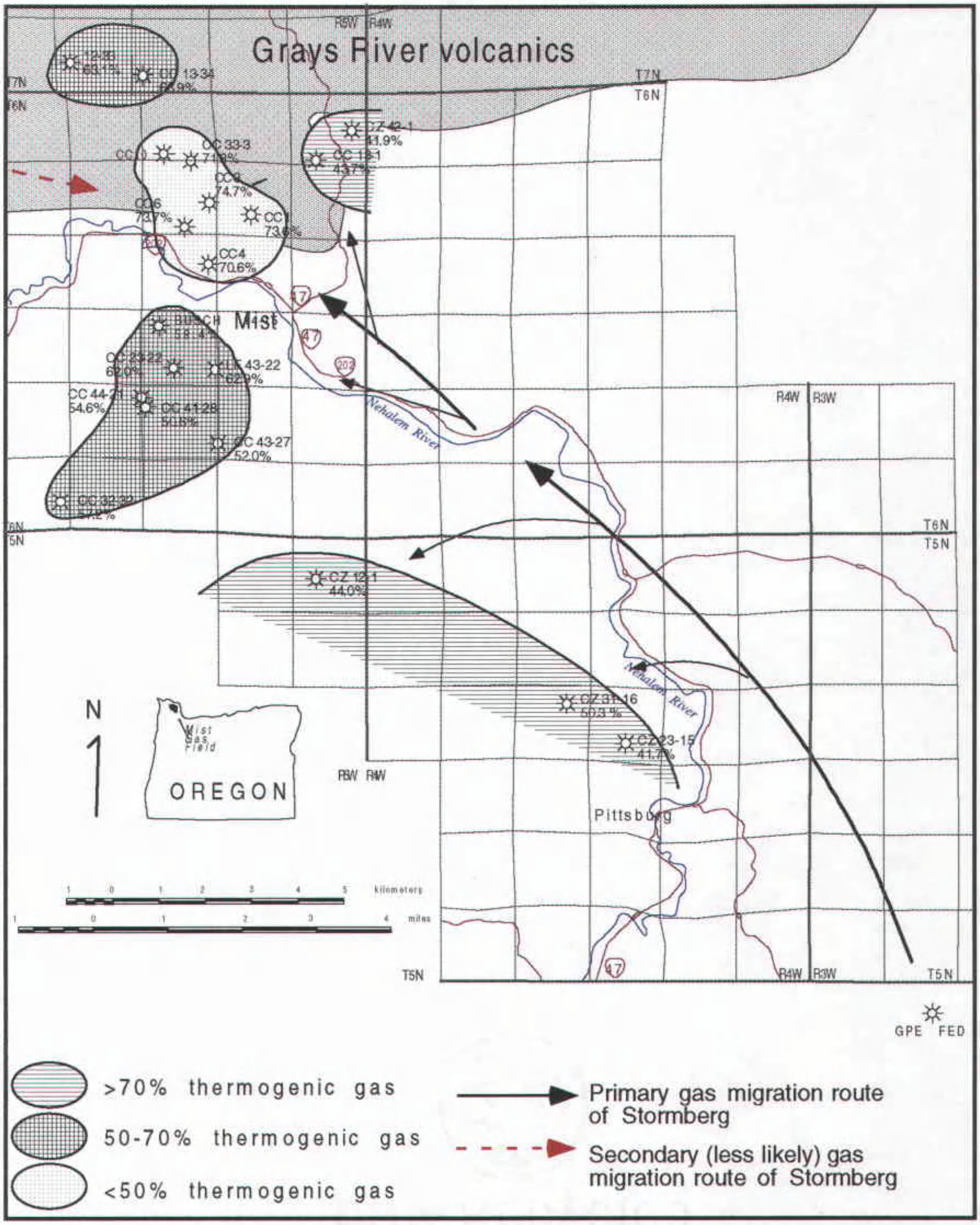


Figure 11. Distribution of gas pools, gas types, and possible gas migration routes. Note correlation between high percentage of thermogenic methane and subsurface distribution of Grays River volcanics. Stormberg hypothesized a primary migration route from near the GPE Federal well in the southeast with a second possible source being the Astoria Basin. Another possibility is that the thermogenic gas was generated *in situ* during eruption of the Grays River volcanics. Modified after Stormberg, 1991.

Goble Volcanics and that the gas migrated updip to its present location (Figure 11). Nitrogen abundance increases in a southwestward direction towards flows of the deeply buried Goble Volcanics in the subsurface.

The presence of thermogenic gas, or dry methane, and areas of mixed biogenic and thermogenic gas at the Mist Gas Field is puzzling in that the probable source rocks within the Cowlitz and Hamlet formations have never been buried deep enough to undergo sufficient maturation to form thermogenic gas (Niem and Niem, 1985). Niem and others (1992) proposed that some thermogenic gas may have been formed in part by "flash heating" of organic-rich deep-marine mudstones of the Hamlet formation by intrusion of late Eocene and early Miocene basaltic dikes and sills. Niem and Niem (1985) observed elevated vitrinite reflectance values, in and above the methane gas generation window, in mudstones up to several hundred feet above the contacts with gabbroic sills of the Miocene Columbia River Basalt Group in the Astoria Basin.

Stormberg (1991) hypothesized that the majority of the thermogenic gas at the Mist Gas Field migrated from the southeast from the deeper buried part of the Nehalem Basin associated with Goble Volcanics flows. Differences in methane and nitrogen abundance in various pools are attributed to differential migration of the gases and to the complex faulting observed at the Mist Gas Field. The limited supply of natural gas may have filled only the top of the anticlinal structure before faulting in the late Eocene; however, Stormberg noted that 54 dry holes and only 4 producing wells have been drilled along his proposed primary migration route (Figure 11). Alternatively, Armentrout and Suek (1985) suggested that gas at the Mist Gas Field was generated by deep-burial maturation of the sedimentary units in the Astoria and Nehalem basins and then migrated updip to the Nehalem arch where the Mist Gas Field is located (Figure 12).

Another possibility that this author suggests is that thermogenic gas formed in conjunction with eruption of the Grays River volcanics, found in the subsurface in the northern part of the Mist Gas Field, during deposition of the Clark and Wilson member. High heat flow associated with the Grays River volcanics may have matured carbonaceous plant debris and coals within the Clark and Wilson member of the Cowlitz Formation and deep marine mudstones of the underlying Hamlet formation. Thermogenic gas is most abundant where the Grays River volcanics is between with the Cowlitz and Hamlet formations.

Structure at the Mist Gas Field

The surface study area is located in a saddle between two gravity highs in the northern Oregon Coast Range (Figure 12). The southern gravity high has a core of middle Eocene Tillamook Volcanics which crops out in the geologic map area and the northern gravity high has a core of late Eocene Grays River volcanics which is mapped in the subsurface and crops out on the surface in southwestern Washington (Wells, 1981). The anticlinal trend formed by these two uplifted volcanic units is termed the Nehalem arch by Armentrout and Suek (1985). On the west of the Nehalem arch is the 10,000 foot thick upper Eocene to middle Miocene sedimentary sequence that fills the Astoria Basin and overlies the Tillamook Volcanics. To the southeast is the 10,000-15,000 foot thick sequence of late Eocene to Middle Miocene sedimentary and volcanic strata that fills the Nehalem Basin.

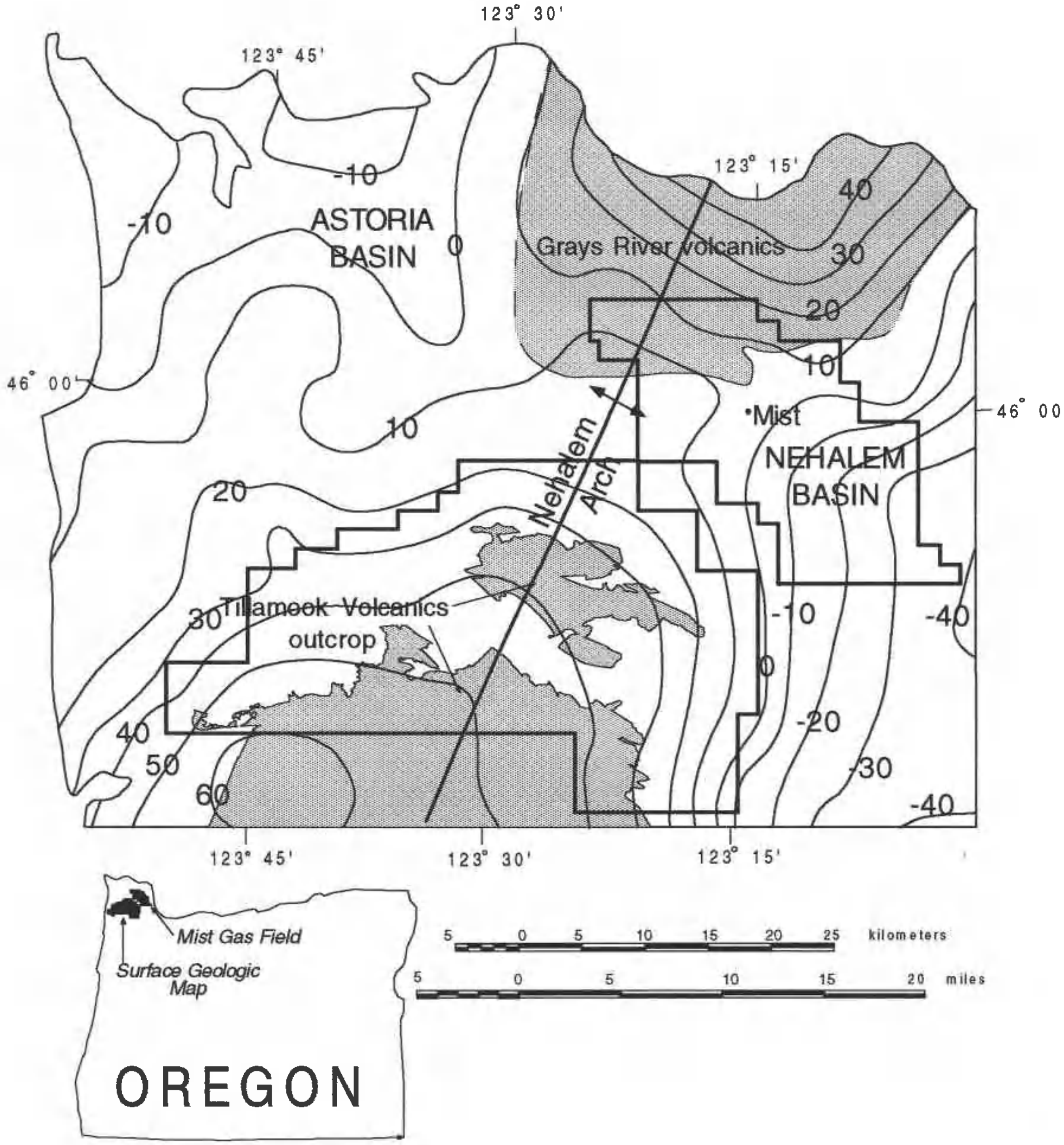


Figure 12. Bouguer gravity map (in milligals) of the northern Oregon Coast Range showing surface distribution of the Tillamook Volcanics and the subsurface distribution of the Grays River volcanics below the Clark and Wilson member of the Cowlitz Formation (Gravity data from Finn and others, 1991).

The Nehalem arch is cut by a series of northwest trending normal faults with smaller antithetic north-south trending normal faults and east-west trending thrust faults (Plate 1). Some northwest-trending normal faults have a right-lateral oblique-slip component (Nelson, 1985; Niem and Niem, 1985). Paleomagnetic evidence suggests that the Tillamook Volcanics have been tectonically rotated up to 45° since the late Eocene (Magill and others, 1981). Using borehole breakouts from wells in northwest Oregon, Werner and others (1991) determined that the modern maximum compression direction in the northern Oregon Coast Range is oriented north-northwest to north-northeast.

The Mist Gas Field is situated high on the east flank of the Nehalem arch. The intricate faulting pattern mapped on the surface (Plate 1) extends through the Mist Gas Field. Seismic reflection records and structure contour maps based on drilling suggest that the Boomer Fault is one of the dominant northwest-trending normal faults in the subsurface (Jack Meyer, personal communication, 1997). The Boomer Fault parallels the Nehalem River in the subsurface near the settlement of Mist. At the Mist Gas Field, the horst and graben style of extensional faulting appears to end prior to deposition of the tuffaceous Keasey Formation. Many normal faults which cut the Tillamook, Hamlet and Cowlitz formations do not appear to offset the Keasey Formation significantly on seismic reflection records (Jack Meyer, personal communication, 1997) (Figure 13). However, Niem has mapped small surface offsets which may be related to the Boomer Fault and synthetic faults (Niem and others, 1992). Niem and others (e.g. Nelson, 1985; Niem and Niem, 1985; Rarey, 1986; Mumford, 1988; Safley, 1989; Berkman, 1990; Niem and others, 1992) have proposed that many of the late Eocene normal faults were reactivated in post-late middle Miocene time (after flows of the Columbia River basalt Group were

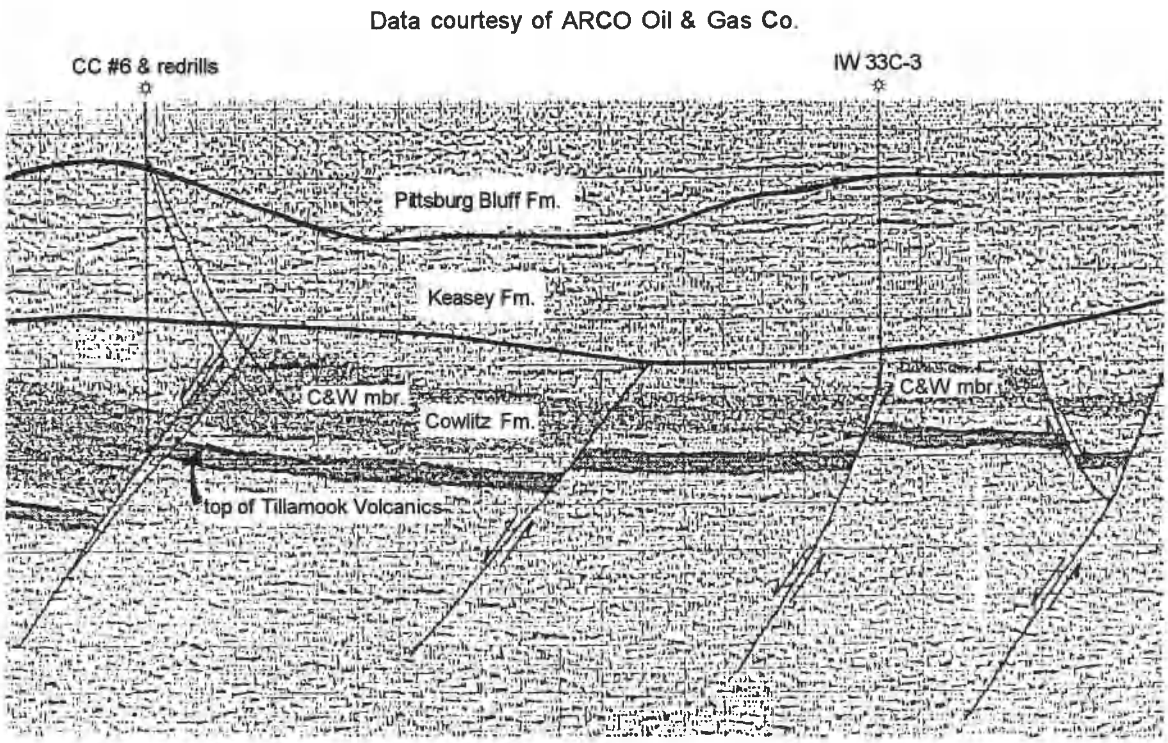


Figure 13. Interpreted seismic reflection profile across the Bruer and Flora pools at the Mist Gas Field (from Jack Meyer in Niem and others, 1994). Note large normal faults, some with horst and graben geometry, and abrupt changes in thickness of the upper mudstone member of the Cowlitz Formation across faults.

emplaced) with dominantly oblique-slip displacement in a wrench tectonic setting (Niem and others, 1992; Alan Niem, personal communication, 1997). The smaller displacement associated with post-late middle Miocene faulting does not readily show up on seismic reflection records (Alan Niem, personal communication, 1997). A structural subsurface analysis is beyond the scope of objectives of this thesis.

Lithofacies of the Cowlitz Formation in Bruer and Flora Gas Storage Pools, Mist Gas Field

INTRODUCTION

As the Mist Gas Field approaches the mature stage of development, attention has shifted from natural gas exploration and production to the development of underground gas storage pools. The Flora and Bruer gas pools were two of the larger gas pools at the Mist Gas Field. As the pools neared depletion, Northwest Natural Gas converted them to underground natural gas storage. Natural gas is transported from Alberta, Canada, and injected during off-peak usage periods. During winter months, when pipeline gas is not always sufficient to meet the Portland area's needs, this stored gas is recovered from withdrawal wells. Approximately 100% of the injected gas is recovered by Northwest Natural Gas (Jack Meyer, 1997, personal communication); however, it is important that the nature of the reservoir and seal are understood to ensure complete recovery. This information is of current relevance as Northwest Natural Gas prepares to develop additional underground storage pools at the Mist Gas Field. The Calvin Creek storage area is located in sections 22 and 23 of T.6N., R.5W (Jack Meyer, personal communication, 1997).

Between 1986 and 1988, Northwest Natural Gas cored four wells (Figure 14) in the Bruer pool vicinity in order to better understand the properties of the reservoir (Clark and Wilson sandstone) and seal (upper mudstone member of Cowlitz Formation) at the

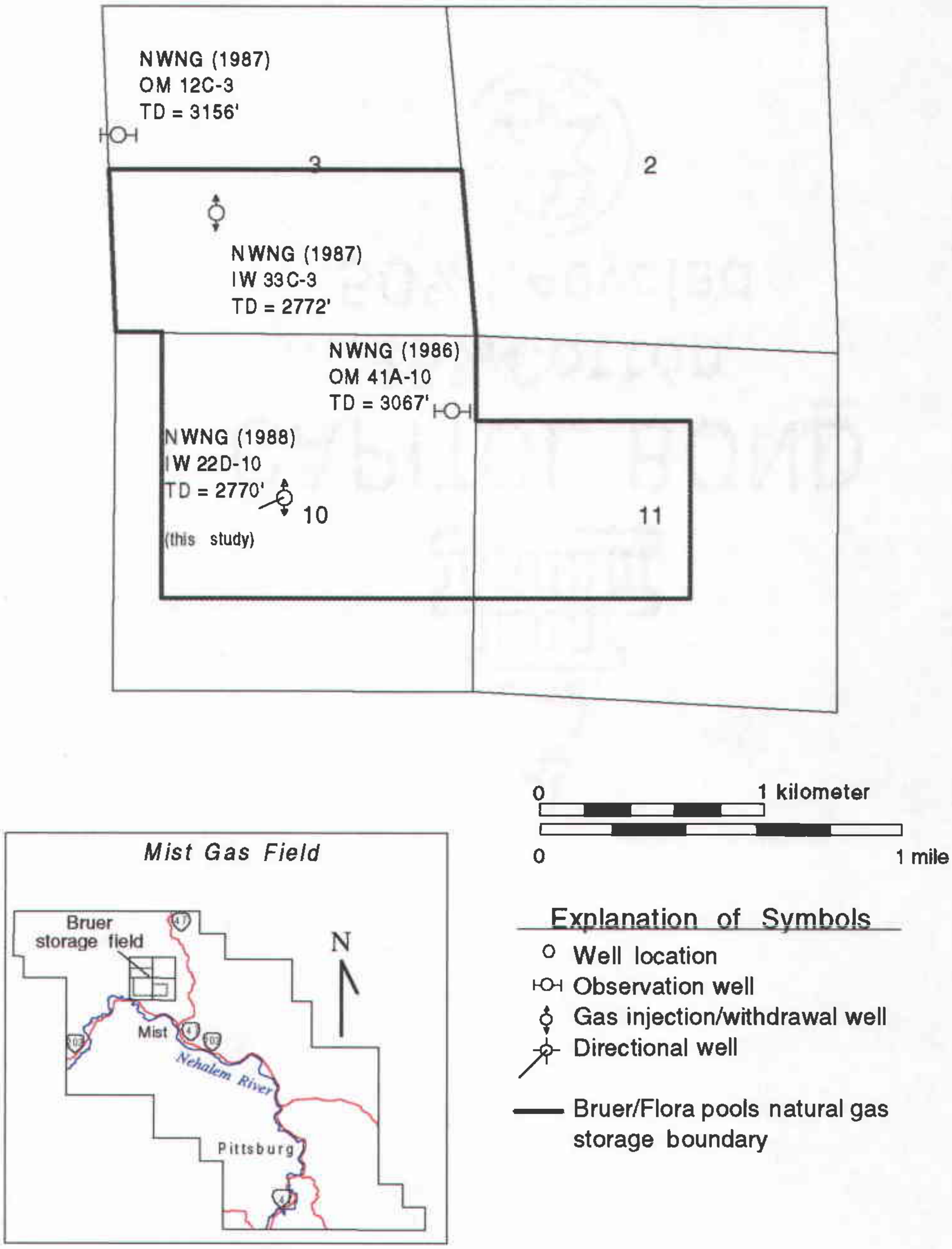


Figure 14. Location of cored wells (IW 22D-10, OM 41A-10, IW 33C-3 and OM 12C-3) at the Mist Gas Field.

Mist Gas Field. These cores were provided to Dr. Alan Niem of Oregon State University and to Dr. Robert Van Atta of Portland State University. All four cores are presently stored at the Oregon State University core repository. Farr (1989) and Berkman (1990) studied three of these cores (IW 33C-3, OM 12C-3, OM 41A-10), and this study considers the fourth well, IW 22D-10, a gas injection well in the Bruer pool. A fence diagram correlating the IW 22D-10, OM 12C-3 and OM 41A-10 wells is presented in Figure 15. The fourth well, IW 33C-3, is not included in the fence diagram because the cored interval is cut by a fault.

The OM 12C-3 core recovered the uppermost 300 ft of the Clark and Wilson member of the Cowlitz Formation. The OM 41A-10 core recovered approximately 80 ft of the upper mudstone member and 300 ft of the Clark and Wilson member. The IW 33C-3 core recovered 150 ft of the upper mudstone member and approximately 150 ft of the Clark and Wilson sandstone member. The contact between the mudstone and sandstone is faulted in this well. The IW 22D-10 core penetrated 321 continuous ft (1997.4 ft - 2318.0 ft) of the Keasey and Cowlitz formations, including the lowermost 6 ft of the Keasey Formation, 110 ft of the upper mudstone member of the Cowlitz Formation and the uppermost 220 ft of the Clark and Wilson member.

The IW 22D-10 core was described and thin section, scanning electron microscope, X-ray diffraction, igneous geochemistry (see Petrologic Analysis of IW 22D-10 Core, Mist Gas Field chapter), and microfossil samples were collected between February and April, 1996. Northwest Natural Gas has provided porosity and permeability data and well logs (Plate 4), which are also considered in this study.

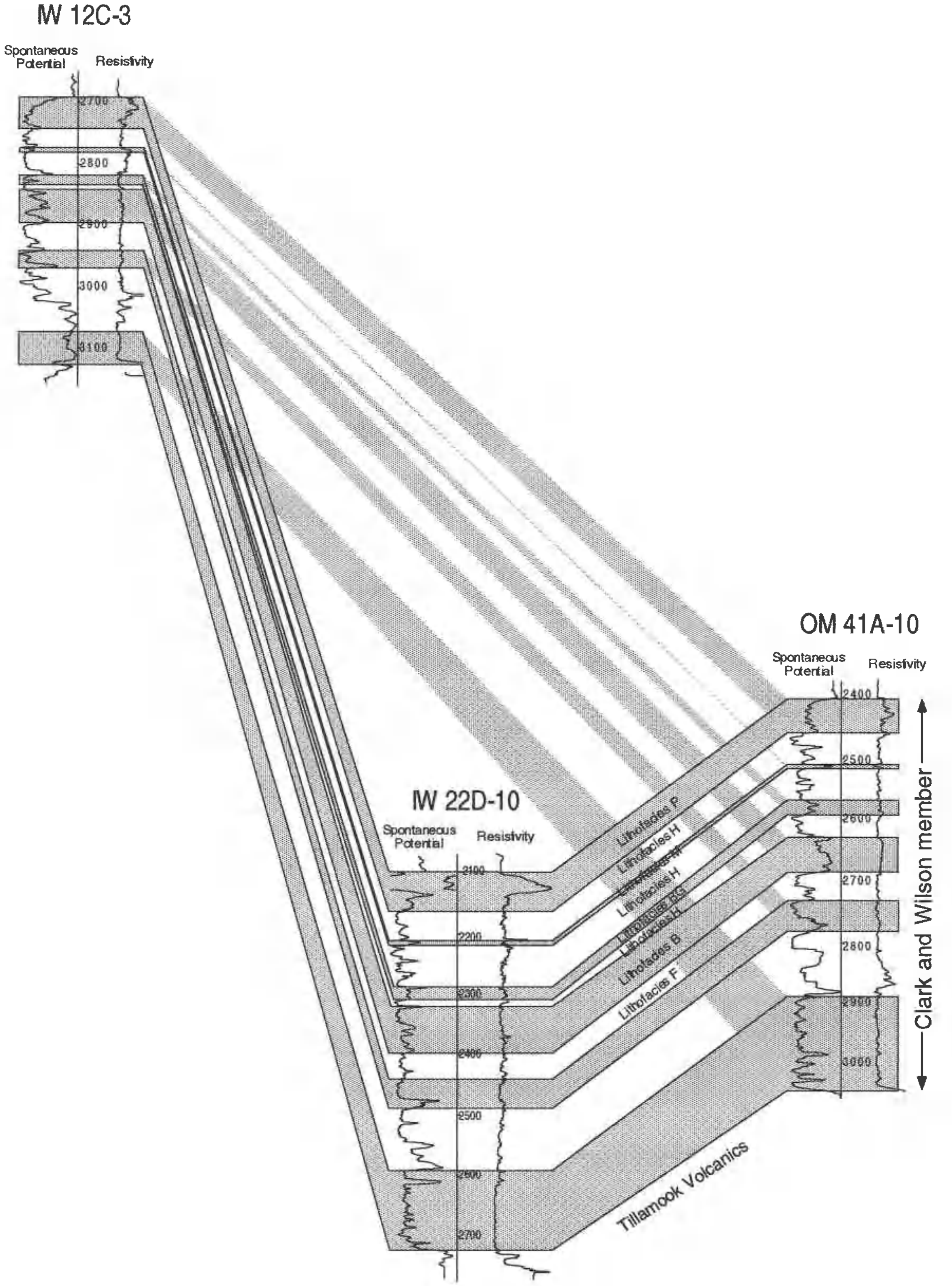


Figure 15. Fence diagram correlating Clark and Wilson member of the Cowlitz Formation in wells OM 41A-10, IW 12C-3, and IW 22D-10. Note rapid thinning of the Clark and Wilson sandstone to the north. See Figure 14 for well locations and spacing.

The oldest unit in the IW 22D-10 core is the Clark and Wilson sandstone. The stratal patterns and sedimentary structures in the core suggest that the sandstone was deposited by a wave-dominated delta in a middle to upper shoreface environment. Thin lignite beds may represent marginal marine deposition. After deposition of the Clark and Wilson member an abrupt regional marine transgression occurred. This deepening is represented by the upper mudstone member of the Cowlitz Formation. After deposition of the upper mudstone member of the Cowlitz Formation, there was a period of extensional faulting. The contorted siltstone facies of the upper mudstone member of the Cowlitz Formation contains redeposited Narizian foraminifera within a Refugian microfossil assemblage (Kristin McDougall, written and personal communication, 1997). Redeposition of the Narizian strata may have been caused by slumping related to earthquakes. Tuffaceous basalt conglomerate and siltstone of the Keasey Formation sharply overlie the upper mudstone member of the Cowlitz Formation. Although this contact is clearly erosive, there is no evidence of missing time. A detailed lithofacies description of the IW 22D-10 core is presented in Plate 2. The core description, porosity and permeability data, electric logs, and lithofacies designations are correlated in Plate 3.

Berkman (1990) studied two cores (IW 33C-3 and OM 41A-10) from the Mist Gas Field (Figure 14). He subdivided the Clark and Wilson sandstone into several lithofacies which are designated lithofacies F, B, H, BG, M and P. The following section describes each of the sandstone lithofacies encountered in IW 22D-10 using the terminology of Berkman. Additionally this study characterizes the lithology and sedimentary structures of the upper mudstone member (informal) of the Cowlitz Formation and the base of the Keasey Formation in the IW 22D-10 core.

Unless otherwise noted, all core and log depths are reported in feet (English system instead of metric system) to maintain consistency with core depths, depths in well reports, and for the convenience of other subsurface workers. Note approximately 6 foot discordance between core depths and wireline log depths due to stretch in the wireline logging tool. The core description and electric logs were aligned using lignite and mudstone horizons as datum. The following section describes each of the lithofacies observed in core from the bottom of the core up.

CLARK AND WILSON MEMBER

The Clark and Wilson sandstone is 628 ft thick in the IW 22D-10 well. However, the core only preserves the uppermost 208 ft of the unit. This study divides the Clark and Wilson sandstone into three lithofacies assemblages: the lowermost offshore to lower shoreface facies, the middle hummocky-bedded facies (lithofacies H, BG, B, M), and the uppermost parallel-bedded facies (lithofacies Pa and Pb) (Figure 16). The lower shoreface facies was not cored in any of these wells.

Lithofacies F

Berkman (1990) observed and described lithofacies F, a sequence of friable flaser bedded sandstone with lesser siltstone, in the OM 41A-10 well. The IW 22D-10 core did not go deep enough to penetrate this lithofacies; however, lithofacies F in OM 41A-10 may correlate to the interval between 2340 ft and 2395 ft in IW 22D-10.

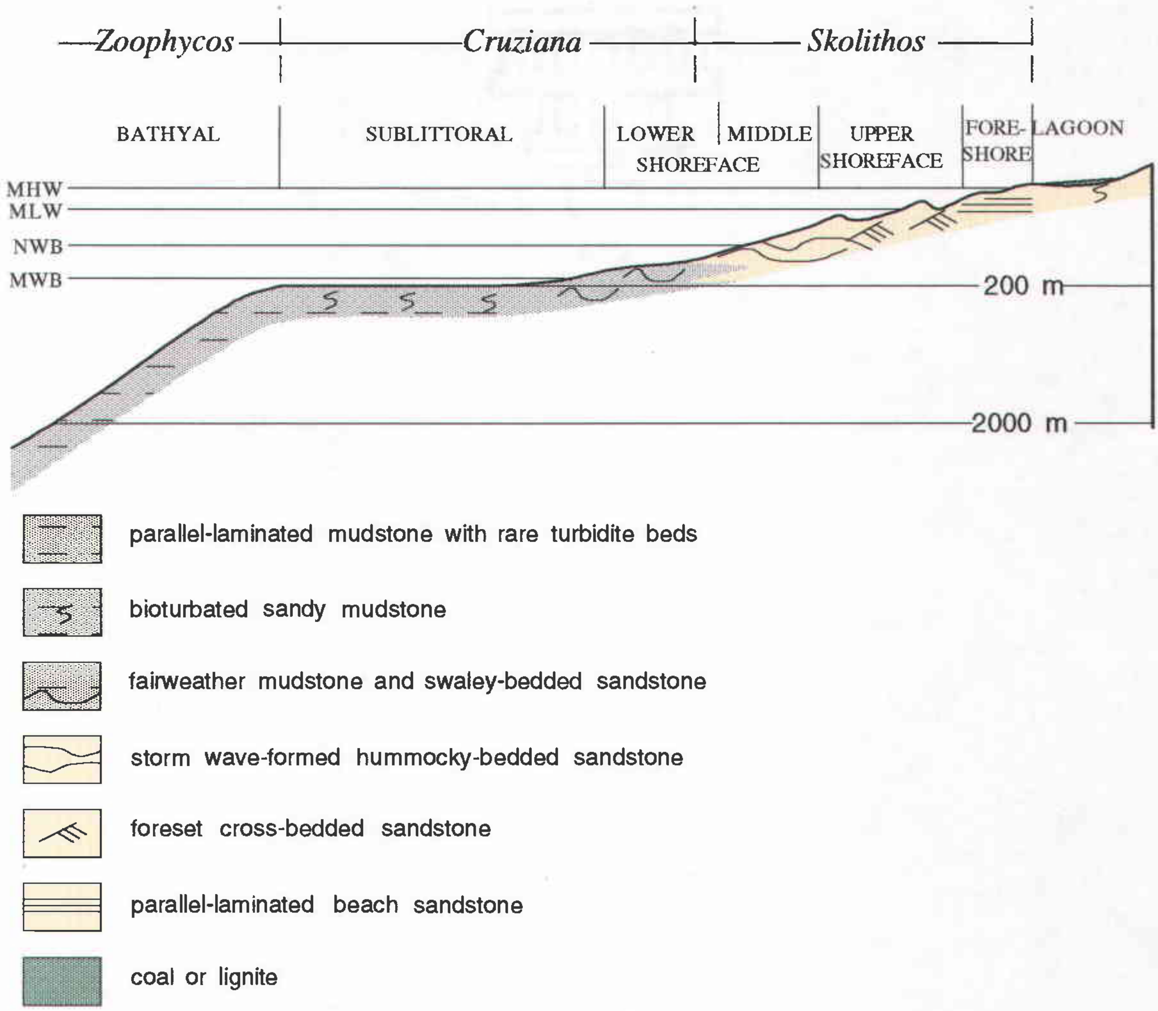


Figure 16. Schematic cross section of depositional environments, ichnofacies and substrate types observed in IW 22D-10 core. Not to scale. (MHW - Mean High Water, MLW - Mean Low Water, NWB - Normal Wave Base, MWB- Maximum Wave Base). Modified after Pemberton, Van Wagoner and Wach (1992) and Pemberton, MacEachern and Frey (1992).

Berkman described lithofacies F as a coarsening upwards sequence of moderately- to well sorted, fine-grained, micaceous, arkosic sandstone with siltstone and mudstone drapes. Individual siltstone and mudstone beds have gently curved bounding surfaces. These lithologies become less common up-section. Mixed unidirectional to oscillatory wave and current ripple laminations, contorted bedding, flame structures, and mudstone rip-ups are common in lithofacies F of the OM 41A-10 core. Fecal pellet-lined *Ophiomorpha* burrows are locally present. A high sedimentation rate, rapid loading, and perhaps effects of earthquake-shaking liquefaction are evidenced by soft sediment deformation and fluid escape structures.

Berkman (1990) interpreted the depositional environment of Lithofacies F to be a distributary mouth bar or tidal channel. This interpretation is based on the tidally-formed flaser bedding with mud drapes, oscillatory to unidirectional current ripples and shallow marine to estuarine *Ophiomorpha* burrows. Because this interval is not present in the IW 22D-10 core, no evidence is supplied by this study to dispute Berkman's interpretation.

Berkman (1990) reports average an porosity in the OM 41A-10 core of 33% for lithofacies F with values ranging from 30-36%. Average horizontal permeability is 721 md with values ranging from 331-1104 md.

Lithofacies B

Lithofacies B is a sequence of interbedded sandstone and siltstone with capping coal or lignite beds. The OM 41A-10 core studied by Berkman (1990) recovered the entire 57 foot thick sequence of lithofacies B. The base of the IW 22D-10 core is very near the top of lithofacies B. Only 1.4 ft of lithofacies B (2316.6 ft - 2318.0 ft) was recovered by the IW 22D-10 core. Because only the uppermost 1.4 ft of this lithofacies was recovered in the IW 22D-10 core, the following summarizes Berkman's (1990) findings.

Berkman (1990) described lithofacies B as a sequence of wavy-bedded bioturbated siltstone and very fine-grained sandstone with a few streaks of rippled very fine-grained sandstone or silty sandstone. The base of this unit consists of highly carbonaceous, wavy-laminated sandstone which grades upward into an intensely bioturbated mixture of siltstone and sandstone. Many of the primary sedimentary structures in lithofacies B are completely obliterated by bioturbation. Chamberlain (in Berkman, 1990, p. 205) identified *Thalassinoides* and *Schaubcylindirchnus* (also known as *Terebellina*) burrows in the bioturbated mudstone interval. A thin, brownish-black (5YR 2/1), organic-rich layer (lignite) overlies the sandstone and bioturbated siltstone dominated interval. The lignite is absent in well IW33C-3 (Berkman, 1990) and well OM 12C-3 (Farr, 1989), and is approximately 3 ft thick in well OM 41A-10 (Berkman, 1990). The organic-rich siltstone, or "coaly" lignite, is 1.4 ft thick in IW 22D-10 (Figure 17). The variability in thickness of the lignite in this small area indicates that deposition and/or preservation of these organic-rich beds was very discontinuous due to erosion (see sharp contact with overlying sandstone in Figure 17). Although ARCO used lignites extensively as regional marker horizons, the erosive nature of the contact and rapid changes in thickness as observed in this study, suggest that individual lignites can be correlated only locally.

Sandstones and siltstones of lithofacies B were interpreted by Berkman (1990) to have been deposited in an open marine bay with crevasse splays. The capping coals were interpreted to represent a coastal marsh which formed as the distributary bay began to fill.

Figure 17. Dark ("coaly") lignitic mudstone of lithofacies B of the Clark and Wilson member of the Cowlitz Formation in IW 22D-10 core at depth 2316.5 ft. Note sharp upper contact with light gray, faintly laminated, fine-grained arkosic sandstone of lithofacies H. Core is 7 cm wide.

Because of limited recovery of lithofacies B in the IW 22D-10 core, no new evidence is presented to modify this interpretation.

Berkman (1990) reported average porosity of 25% with values ranging from 4-31% for lithofacies B in OM 41A-10. Average horizontal permeability is 31 md with values ranging from 0.01-222 md. The permeability of lithofacies B is less than that of other lithofacies. This is perhaps due to bioturbation which mixed detrital clay with sandstone, clogging pores in the fine-grained sandstone. There are no porosity and permeability data available for lithofacies B in the IW 22D-10 core.

Lithofacies H

Hummocky-bedded fine-grained sandstone with lesser fairweather mudstone interbeds of lithofacies H is the dominant facies observed in cores of the hummocky-bedded facies of the Clark and Wilson sandstone in the Mist Gas Field. The IW 22D-10 core penetrated lithofacies H facies at the following depths: 2152.0 ft-2204.0 ft, 2207.0 ft-2277.9 ft, and 2308.5 ft-2316.6 ft (Plates 2 and 3).

Lithofacies H mainly consists of hummocky cross-stratified sandstone (Figure 18) which locally fines upward to siltstone (Figure 19). A sandstone to siltstone ratio of 6:1 is higher than that of the other lithofacies (Berkman, 1990). Fine- to very fine-grained, well sorted light olive gray (5Y 6/1), micaceous, carbonaceous, arkosic sandstone locally grades upward to medium olive gray (5Y 5/1) siltstone interbeds. Sandstone is parallel-laminated to low-angle cross-stratified. Dark, fine-grained laminations in lithofacies H are defined by concentration and alignment of dark gray carbonaceous plant debris with fewer large flakes of muscovite and biotite. Low-angle cross-stratification is interpreted to represent storm wave-formed hummocky cross-stratification (Dott and Bourgeois, 1982). Sedimentary structures include mudstone rip-up clasts, load structures, fluid escape structures, and calcareous nodules. Teredo-bored carbonized wood is locally present. The lack of bioturbation, and the presence of fluid escape and load structures indicate a high sedimentation rate. Berkman (1990) reported burrows from the *Skolithos* ichnofacies (e.g. middle shoreface, Figure 16) within lithofacies H of the OM 41A-10 core; however no bioturbation was observed in the IW 22D-10 core.

Lithofacies H was interpreted by Berkman (1990) to represent deposition and later reworking on the lower to upper shoreface (Figure 16). The presence of storm wave-generated hummocky and swaley cross-stratification supports the interpretation that lithofacies H was deposited above storm wave base. The locally present siltstone drapes and gradational lower contact with the hummocky-bedded sandstone represent waning storm conditions and intervening fairweather deposition of mudstone and siltstone from suspended load between storms (Dott and Bourgeois, 1982). These intervening siltstones are commonly scoured out by the next storm event as evidenced by the sharp basal contacts of sandstone with the underlying siltstone. The swaley-bedded sandstone and siltstone subfacies and the sandstone-dominated hummocky-bedded subfacies are gradational and represent shoaling from lower shoreface (swaley bedded sandstone and fairweather siltstone) to upper shoreface (amalgamated hummocky-bedded sandstone). Similar facies interpretations have been published in Dott and Bourgeois (1982) and Chan and Dott (1986) for the late Eocene Coaledo Formation delta-front sandstone of southwest Oregon.

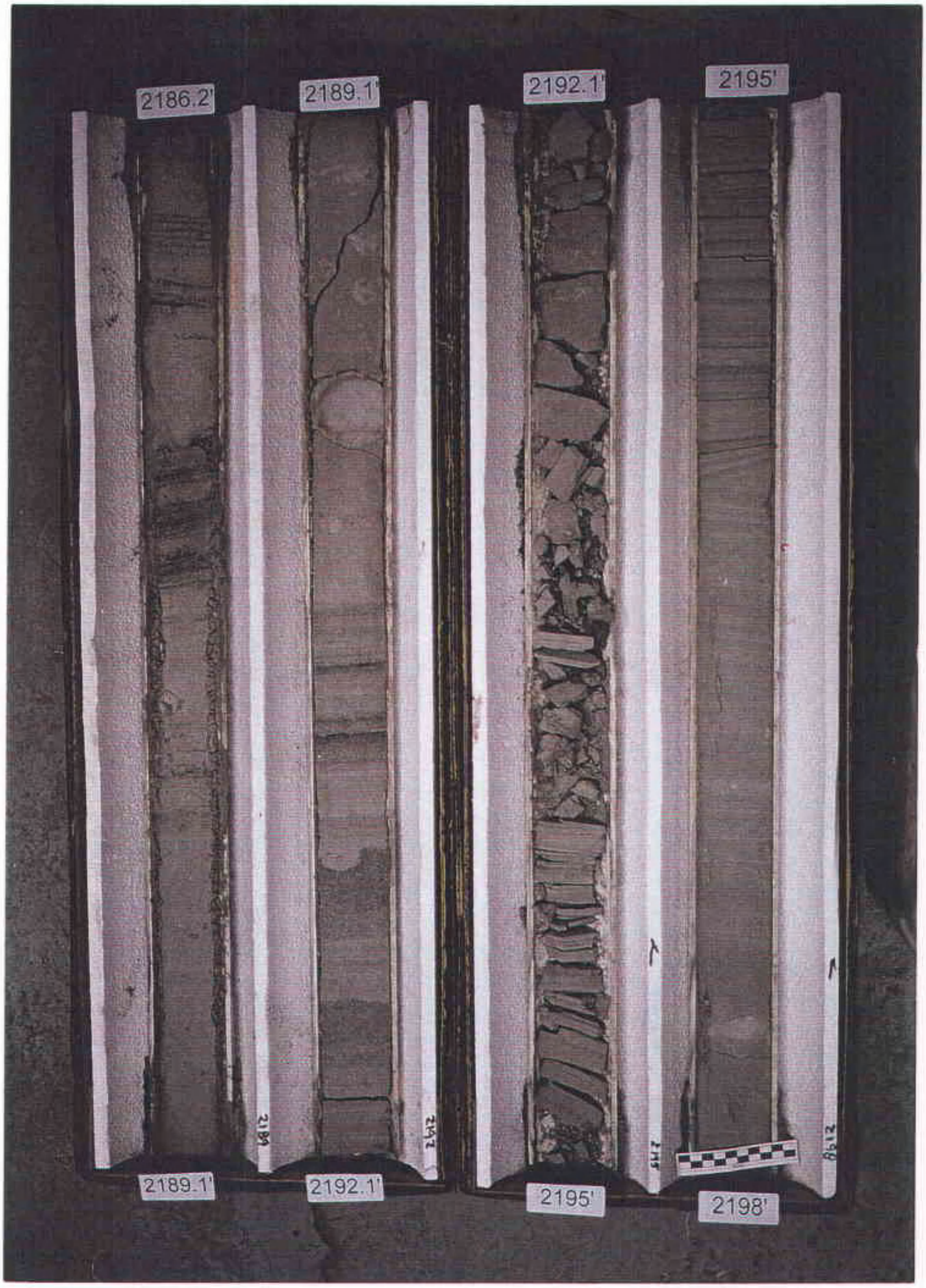


Figure 18. Storm wave-formed hummocky cross-stratified sandstone of lithofacies H. Note scour and fill structure (2191.1 ft), low-angle cross laminations (2192.2 ft), and calcareous nodules (2189.3 ft, 2189.5 ft, 2189.7 ft, 2190.1 ft, 2197.6 ft). Laminations are composed of concentrated carbonaceous material with lesser amount mica (2187.4 ft). Scale at bottom right is 10 cm.

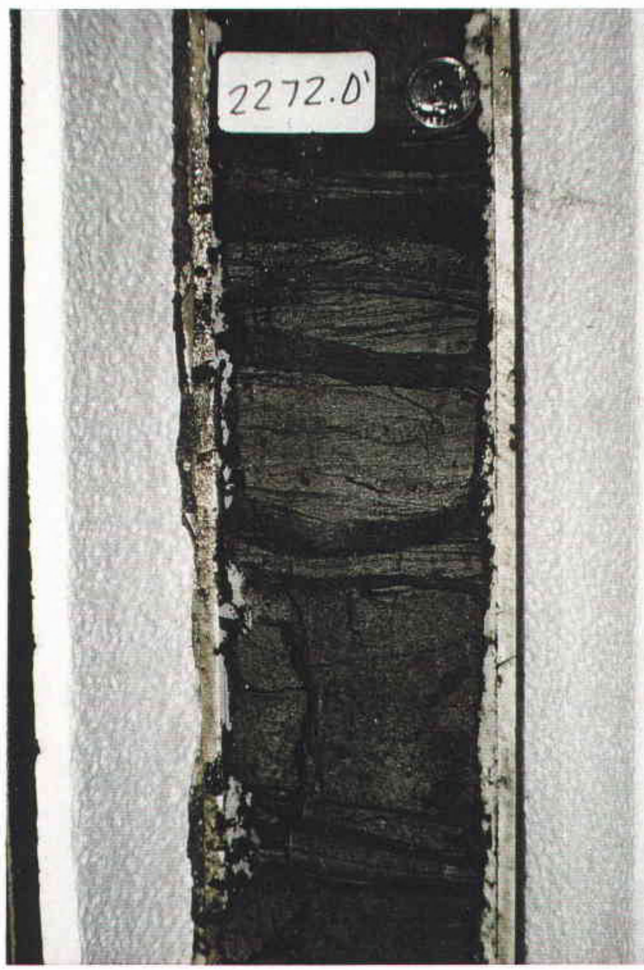


Figure 19. Micro cross-laminated sandstone and dark siltstone of lithofacies H at 2272.0 ft in IW 22D-10 core. Note curved bottom contacts and rippled micro cross-lamination of very fine-grained sandstone and parallel laminations in siltstone. U.S. dime for scale.

Storm wave-formed lithofacies H is the best reservoir facies within the Clark and Wilson sandstone. Average porosity of this unit in the IW 22D-10 core is 31.2% with values ranging from 2.1-41.6% (Plate 4). Average horizontal permeability is 894.9 md with values ranging from 0-3040 md. Berkman (1990) reported similar average porosity and horizontal permeability values for lithofacies H in the OM 41A-10 core. The sample with very low porosity (2.1%) and permeability (0 md) is a calcareous concretion. Calcite cement is not pervasive in lithofacies H and this sample is not representative of lithofacies H of the Clark and Wilson sandstone. The high porosity and permeability of this sandstone-dominated facies probably reflects strong wave energy which winnowed out pore-clogging mudstones and sorted the sandstones. The intervening lower energy fairweather siltstone and mudstone interbeds and some of the thicker carbonaceous and micaceous laminae in the sandstone could act as partial permeability barriers to vertical flow of fluids. Because of its lack of siltstone interbeds good sorting, the upper shoreface amalgamated hummocky-bedded sandstone of lithofacies H would probably make the best reservoir within the Clark and Wilson member.

Lithofacies BG

Lithofacies BG is a diagenetically-altered, chlorite-rich, blue-green sandstone which is bounded by hummocky-bedded sandstone of lithofacies H. This 17.9 ft thick interval occurs between 2290.6 ft and 2308.5 ft in the IW 22D-10 core (Plates 3 and 4).

Berkman (1990) described lithofacies BG as an 18.0 ft thick sequence of chlorite-altered, laminated, scoriaceous, fine-grained basaltic sandstone which he observed in the OM 41A-10 core. Lithofacies BG in OM 41A-10 contains abundant poorly sorted scoriaceous clasts throughout the entire interval. However, the IW 22D-10 core contains only one 0.1 ft thick band of pebble-sized scoriaceous clasts at the base of the BG zone (2308.4 ft) (Figure 20) within a calcite-cemented concretion. In the IW 22D-10 core, lithofacies BG consists of chlorite-altered, light olive gray (5Y 6/1), fine- to very fine-grained, well sorted lithic arkosic sandstone with carbonaceous and micaceous laminations and a few calcareous concretions. This interval fines upward to siltstone. Lithofacies BG is identified by its distinctive color and a slightly lower spontaneous potential log response than other sandstones of the Clark and Wilson member.

The observation of volcanic clasts in the BG interval is important because it indicates that subaerial volcanism was occurring within the basin during deposition of the Clark and Wilson member (Berkman, 1990; Steve Kenitz, personal communication, 1997). The mafic Grays River volcanics, which underlie and are interbedded with the Clark and Wilson sandstone in the northern part of the Mist Gas Field (Plates 6 and 7; see Subsurface Correlation and Distribution of Cowlitz and Hamlet Formations, Mist Gas Field, Northwest Oregon chapter), are a likely source of the volcanic lithic fragments (Kenitz, personal communication, 1997). The thinning of scoriaceous pebble clasts from north to south suggests a northward source. Subsurface workers with Northwest Natural Gas use the BG zone extensively as a time-synchronous marker horizon within the Clark and Wilson sandstone at the Bruer and Flora storage pools (sec. 3, 10 and 11, T.6N., R.5W.) at the Mist Gas Field. However, the BG zone cannot be correlated beyond the gas storage area (Meyer, 1995, personal communication).

The porosity and permeability of lithofacies BG is reduced by early, authigenic, grain-rimming, pore-clogging chlorite cement (Plate 3, see Petrologic Analysis of IW

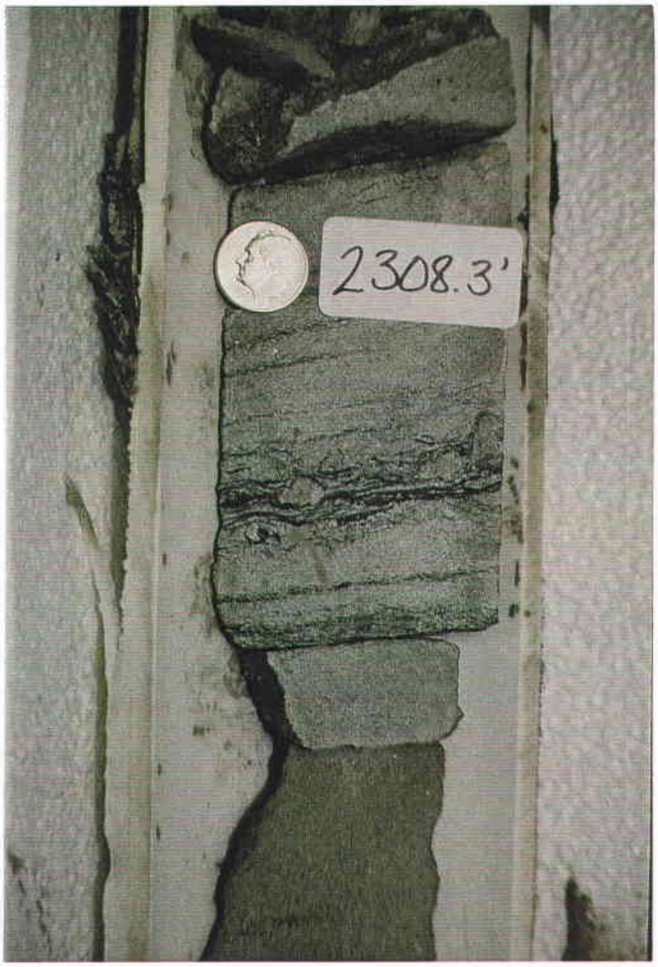


Figure 20. Thin scoriaceous basalt pebble conglomerate bed within carbonate-cemented sandstone of lithofacies BG in IW 22D-10 core. Note contorted carbonaceous laminations surrounding scoriaceous basalt clasts. U.S. dime for scale.

22D-10 Core, Mist Gas Field chapter). Average porosity of lithofacies BG in IW 22D-10 is 32.2% with values ranging from 27.3-38.1%. Average horizontal permeability is 574.8 md with values ranging from 3-2045 md. Berkman (1990) reported a greater reduction in permeability (average horizontal permeability of 6 md) in the OM 41A-10 core than is observed in IW 22D-10 core. The observed rapid lithologic change from altered volcaniclastic to arkosic sandstone which occurs in the Bruer pool emphasizes the lateral heterogeneity of the deposit.

Lithofacies M

Berkman (1990) described lithofacies M as an 8.0 ft thick interval of highly carbonaceous sandy mudstone in the OM 41A-10 core. This lithofacies was not observed in the IW 22D-10 core. There are at least three explanations for the absence in IW 22D-10: the unit was not deposited, it was scoured out by the overlying arkosic sandstone, and/or lithofacies M is represented by the interval of non-recovery between 2204.0 ft and 2207.0 ft in the IW 22D-10 core. Deflection of the spontaneous potential log curve towards the shale line suggests that the missing interval may be composed of siltstone.

Lithofacies M in the OM 41A-10 core consists of structureless dark gray to black carbonaceous mudstone with abundant subangular to subrounded volcanic rock fragments up to 2 cm in diameter (Berkman, 1990). Berkman interpreted lithofacies M to represent a volcanic debris flow that flowed into a tidal marsh or estuary of carbonaceous mud from a nearby Grays River volcanic high.

The average porosity of lithofacies M in the OM 41A-10 core is 31% and the average horizontal permeability is 2 md (Berkman, 1990). These low values reflect the fine grain size of this subfacies.

Lithofacies P

The uppermost unit of the Clark and Wilson sandstone in the IW 22D-10 core is the 41.4 ft thick parallel-laminated to cross-bedded arkosic sandstone and siltstone of lithofacies P (Plates 2 and 3). This interval occurs in the IW 22D-10 core between 2110.6 ft and 2152.0 ft. Lithofacies P coarsens upward from a sandy bioturbated siltstone, lithofacies Pb, to a blocky, parallel-laminated, fine-grained, well sorted, micaceous, arkosic sandstone, lithofacies Pa. These two subunits of lithofacies P are described separately below.

The lower part of lithofacies P, lithofacies Pb, is a laminated to intensely bioturbated siltstone. This siltstone horizon is laterally continuous and can be correlated through much of the Mist Gas Field. Lithofacies Pb occurs at the base of the parallel-bedded facies (Plates 5, 6, and 7). The IW 22D-10 core penetrated lithofacies Pb between 2137.7 ft and 2152.0 ft.

The siltstone interval is a micaceous, medium olive gray (5Y 5/1) sandy siltstone with wispy local micro cross-laminated sandstone laminae. This mottled unit in IW 22D-10 is intensely bioturbated (Figure 21), with *Thalassinoides* and possibly *Phycosiphon* (also known as *Helminthoida*) burrows preserved (Chamberlain, 1996, personal communication). Berkman (1990) also reported the presence of *Schaubcylindirchnus* burrows. *Thalassinoides* is a dwelling burrow of a thalassinid shrimp (Pemberton and

Figure 21. Large vertical *Thalassinoides* burrow in lithofacies Pb of the Clark and Wilson member of the Cowlitz Formation at 2146.3 ft - 2145.0 ft in the IW 22D-10 core.

Wach, 1992) and is associated with the *Cruziana* ichnofacies (Figure 21) (Chamberlain, 1996, personal communication). However, *Thalassinoides* can also occur in low-diversity brackish water environments (Pemberton and Wach, 1992). *Phycosiphon* is a grazing trace of a worm-like organism and is common in the lower *Cruziana* ichnofacies (Pemberton and Wach, 1992). *Schaubcylindirchnus* is a communal dwelling trace of suspension feeders found mainly in shoreface settings. *Schaubcylindirchnus* has not been reported in brackish water settings (Pemberton and Wach, 1992).

The bracketing of this unit between shoreface sandstones, lack of root structures, presence of shallow marine burrows from the Cruziana ichnofacies and interbedded unidirectional ripples in siltstone support the interpretation that lithofacies Pb was deposited on the lower shoreface (Figure 16) below normal wave base. Oscillatory ripples are common on the continental shelf of Oregon (Komar, 1975). Microfossil samples from this unit were submitted to Dr. Kristin McDougall of the United States Geological Survey and found to be barren of foraminifera (Kris McDougall, written communication, 1997).

Average porosity in the IW 22D-10 core is 29.4% with values ranging from 20.9-39.1%. Average horizontal permeability is 43.7 md with values ranging from 5-322 md. The porosity and permeability of lithofacies Pb is relatively low due to the fine-grain size of the siltstone. This laterally continuous siltstone interval may be a significant vertical permeability barrier between the overlying arkosic sandstone of lithofacies Pa and the underlying blocky arkosic sandstone of lithofacies H of the Clark and Wilson member of the Cowlitz Formation.

Figure 22. Parallel-laminated, arkosic, micaceous sandstone of lithofacies Pa in Clark and Wilson member of the Cowlitz Formation in IW 22D-10. White splotches between 2117.0 ft and 2113.0 ft are discolored by hydrochloric acid. Scale at bottom right is 10 cm.

The uppermost unit of the Clark and Wilson sandstone is lithofacies Pa. This unit consists of light olive gray (5Y 4/1), fine- to very-fine grained, well sorted, micaceous, arkosic sandstone (Figure 22). The moderately-indurated sandstone is structureless to parallel-laminated with several hard calcareous nodules or concretions. No siltstone interbeds are observed in the channel-fill sequence. Laminations are defined by concentrations of coarse grains of muscovite and biotite alternating with fine-grained light gray, slightly thicker laminae of quartz and feldspar. Berkman (1990) reports a coarse-grained, crudely-stratified zone of volcanic clasts 10 cm thick in the OM 41A-10 core. One important distinction between lithofacies Pb and lithofacies H is that laminations in lithofacies P are predominantly micaceous whereas laminations in lithofacies H are mainly carbonaceous plant debris with lesser coarse-grained mica flakes. Additionally, laminations in lithofacies P are mostly parallel whereas lamination in lithofacies H are mainly low angle hummocky cross-laminations.

Berkman (1990) interpreted the depositional environment of lithofacies Pa to be a distributary channel. Parallel laminated sandstone of lithofacies Pb displays little evidence of post-depositional reworking by storm waves and longshore current, such as oscillatory ripples or hummocky cross-stratification. Nor is there evidence, such as the presence of root structures, that this sandstone sequence was deposited as a beach. The interpretation that this is a stacked distributary channel and reworked barrier bar complex is partially based on the three-dimensional geometry of this unit (lithofacies Pa and Pb) in the subsurface (see Subsurface Correlation and Distribution of Hamlet and Cowlitz Formations, Mist Gas Field, Northwest Oregon chapter).

Lithofacies Pa in the IW 22D-10 core has an average porosity of 31.4% with values ranging from 21.2-35.4%. Average horizontal permeability is 293 md with values ranging from 36-1011 md. These values are similar to those for the OM 41A-10 core reported by Berkman (1990). Sandstone of lithofacies Pa is significantly less permeable than sandstone of lithofacies H. This may be attributed to the higher mica content of lithofacies Pa (see Petrologic Analysis of IW 22D-10 Core, Mist Gas Field chapter).

UPPER MUDSTONE MEMBER

The IW 22D-10 core provides the unique opportunity to study the upper mudstone member of the Cowlitz Formation. This unit is mainly absent in the field (Plate 1) due to truncation by an erosional unconformity at the base of the Keasey Formation. Additionally, field exposures of this unit are generally very poor due to the susceptibility of the mudstone to weathering. Thickness of the upper mudstone member in the subsurface is extremely variable due to the unconformity with the overlying Keasey Formation (Farr, 1989; Berkman, 1990; this study). A significant stratigraphic section of the upper mudstone member has been removed by the Keasey unconformity (Figure 23) and only the base of the member is preserved in the IW 22D-10 core. The core recovered approximately 110 ft of the upper mudstone member between 1999.85-2110.6 ft. The upper mudstone member is divided into two subunits: the basal parallel-laminated mudstone facies and the upper contorted siltstone facies. An intraformational unconformity, or tectonically forced sequence boundary, separates these two facies of the upper mudstone member (Plate 3, Figure 26).

Figure 23. Keasey-Cowlitz contact in IW 22D-10 core. Note sharp erosive contact of Keasey Formation (1999.85) with underlying Cowlitz Formation, poorly sorted graded, altered, white to red basaltic conglomerate beds with tuffaceous mudstone interbeds, and contorted yellow orange to medium gray siltstone of upper mudstone member of Cowlitz Formation. Scale at bottom right is 10 cm.

The upper mudstone member (informal) abruptly overlies the Clark and Wilson member (informal) of the Cowlitz Formation. The contact between the two units is sharp with a thin discontinuous volcanic pebble horizon at the base of the micaceous mudstone (Figure 24). The top of the Clark and Wilson sandstone (lithofacies Pa) is carbonate-cemented and displays *Phycosiphon* burrows. The thin pebble layer and sharp contact between the deep-water mudstone and the shallow marine sandstone suggests that this is an erosive flooding surface (Van Wagoner and others, 1990). This reflects wave reworking of sandstone and concentration of pebbles followed by a rapid transgression and deepening of the sequence to bathyal water depths (Figure 16).

McKeel (1983) defined the Keasey-Cowlitz contact at the Mist Gas Field wells based on the first downhole occurrence of the planktic Foraminifera *Turborotalia insolita*. This index fossil does not occur in the overlying Refugian Keasey Formation. It is important to note that this biostratigraphic contact does not coincide with the lithologic contact between the Keasey and Cowlitz formations. Other useful, but less abundant, planktic Foraminifera marker species in the upper mudstone member include *Globigerinatheka index* and *Pseudohastigerina micra*. McKeel (1983) interpreted the environment of deposition of the upper mudstone member to be outer neritic to middle bathyal based on these foraminifera. A maximum transgression is identified by maximum abundance of *Uvigerina sp.* and the highest occurrence of *Uvigerina churchi* (McKeel, 1983).

Dr. Kristin McDougall (personal and written communication, 1997) of the U.S. Geological Survey recently completed analysis of 11 samples from the Keasey and Cowlitz formations in the IW 22D-10 core. A list of foraminifera identified by McDougall is

	1998.7 ft	2000.2 ft	2014.0 ft	2017.0 ft	2030.2 ft	2040.0 ft	2050.5 ft	2070.0 ft	2081.0 ft	2089.0 ft	2100.1 ft
Alabamina kernensis	x				x			x			
Allomorpina trigona	x							x	x	x	x
Ammodiscus incertus									x	x	
Anomalina spp.										x	
Bathysiphon eocenica			x	x					x	x	x
Boivina pisciformis		x									
Boivina spp.											x
Boldia hodgei				x							
Bolivina kleinpelli	x	x		x			x				
Bolivina pisciformis	x										
Bolivina scabrata		x									
Bulimina cf.		x	x	x							
Bulimina microcostata		x	x	x							
Bulimina sculptilis			x			x	x	x			
Caucasina schencki		x					x				
Chilostomella oolina		x									
Cibicides fortunatus			x								
Cibicides lobatulus		x									
Cibicides mcmastersi	x	x									
Cibicides natlandi						x			x	x	x
Cyclammina pacifica					x		x		x	x	x
Dentalina cf.			x								
Dentalina communis									x		
Dentalina consobrina				x					x	x	x
Dentalina soluta									x		
Eggerella subconica			x								
Eponides mexicanus						x	x	x	x	x	x
Fursenkoina bramletti		x									
Globobulimina pacifica	x	x		x	x	x		x	x	x	x
Globocassidulina globosa		x	x	x							
Globulina gibba							x	x		x	x
Guttulina problema		x									
Gyroidina condoni	x	x	x	x			x				x
Gyroidina ococamerata	x										
Gyroidina spp.						x		x			
Haplophragmoides deflata	x		x	x	x	x		x	x	x	x
Haplophragmoides spp.					x	x		x	x	x	x
Karreriella elongata										x	
Lagena becki		x					x	x			
Lagena costata		x									
Lagena hexagona		x									
Lagena spp.						x					
Lenticulina inonata		x									
Lenticulina spp.	x	x	x	x	x	x	x	x	x	x	x
Lenticulina welchi			x	x		x	x	x	x		x
Marginulina exima									x	x	x
Marginulina spp.				x							
Marginulina subbullata			x							x	
Nodosaria longiscata			x	x							
Nodosaria pyrula				x						x	
Nodosaria spp.		x	x								
Nonion halkyardi	x	x		x							
Nonionellina applini	x	x						x	x	x	x
Planularia tolmani			x					x	x	x	x
Plectofrondicularia minuta				x							
Plectofrondicularia oregonensis		x									
Plectofrondicularia packardi		x	x	x	x	x		x			
Pseudonodosaria inflata		x							x		
Quinqueloculina goodspeedi							x				x
Quinqueloculina imperialis		x						x	x	x	
Robertina washingtonensis		x									
Saracenaria schencki								x		x	x
Spiroloculina texana		x	x	x							
Stilostomella advena			x	x							
Stilostomella lepidula				x						x	x
Triafarina hannai	x	x									
Trochammina globigeriniformis					x	x	x	x	x	x	x
Uvigerina cocoaensis	x	x									
Uvigerina garzaensis		x	x								
Vaginulinopsis saundersi									x	x	x
Valvulineria cf. V. tumeyensis				x							
Valvulineria jacksonensis welcomensis		x	x	x							

Table 1. List of foraminifera identified in Keasey and Cowlitz formation samples from IW 22D-10 core by Dr. Kristin McDougall of the U.S. Geological Survey.

Figure 24. Sharp, slightly erosive contact of the dark gray upper mudstone member and the light gray Clark and Wilson member (Cowlitz Formation) in IW 22D-10. Note *Phycosiphon* burrows in sandstone and fine scoriaceous (?) pebble horizon at base of mudstone.

supplied in Table 1. McDougall defines the Refugian Narizian boundary based upon the first downhole occurrence of *Bulimina microcostata* and *Bulimina* cf. *B. instabilis*. These species are restricted to the Narizian and do not occur in the Refugian Keasey Formation. The Keasey Formation contains foraminifera which are restricted to the Refugian, including *Uvigerina cocoaensis* (Kristin McDougall, personal and written communication, 1997).

Parallel laminated mudstone facies

The lower parallel laminated mudstone facies of the upper mudstone member of the Cowlitz Formation consists of laminated, medium olive gray (5Y 5/1), micaceous to micro-micaceous mudstone with some siltstone and fine-grained sandstone interbeds. Individual thin-bedded, very fine-grained, arkosic, micaceous sandstone interbeds are parallel-laminated to ripple cross-laminated and grade upwards to siltstone, suggesting deposition by turbidity currents. Similar turbidites are observed in field exposures of the upper mudstone member of the Cowlitz Formation (Alan Niem, personal communication, 1996). Sandstone interbeds become less common up section. The basal contact of the sandstone beds is sharp with some load structures. Pyrite nodules, thin-shelled molluscan fossil fragments, calcite veins, calcareous nodules or concretions, carbonaceous stringers of plant debris, and trace fossils are present in the unit.

In the IW 22D-10 well, the mudstone between 2110 ft and 2018 ft was deposited in upper bathyal water depths (150-500 m). The deepest paleo-water depth (maximum transgression) occurs near 2018 ft. The 10 ft thick mudstone interval between 2018 ft and

Figure 25. Tiny, dark gray, hook-shaped *Phycosiphon* (*Helminthoida*) burrows in fine-grained arkosic sandstone of the upper mudstone member of the Cowlitz Formation in IW 22D-10 core.

2008 ft was deposited in upper middle bathyal water depths (500-1500 m) (Kristin McDougall, written communication, 1997).

Asterosoma, Phycosiphon (also known as *Helminthoida*), and *Planolites* burrows are present (C. Kent Chamberlain, 1996, personal communication) in the parallel-laminated facies of the mudstone member of the IW 22D-10 core (Figure 25). Both *Asterosoma* and *Phycosiphon* are feeding burrows of worm-like organisms. *Asterosoma* is generally found in upper shoreface deposits of the *Cruziana* ichnofacies. *Phycosiphon* is common in the distal *Cruziana* ichnofacies and the proximal *Zoophycos* ichnofacies (Pemberton and Wach, 1992). *Phycosiphon* is relatively tolerant of low oxygen levels; however, the relatively large size of the *Phycosiphon* burrows in the IW 22D-10 core implies locally moderate to good oxygenation of the substrate (Chamberlain, 1996, personal communication). *Planolites*, the dwelling trace of a deposit feeder, is found in most marine environments. This assemblage of ichnofossils belongs to the *Cruziana* ichnofacies (Figure 16). Other non- burrowed, parallel-laminated, dark gray mudstone facies suggest either rapid deposition or non-oxidizing conditions that prevented much burrowing by organisms. No trace fossils are observed in the upper middle bathyal mudstone of the parallel-laminated mudstone facies. This may be a result of the lower oxygen level in the deeper water.

A 0.3 ft thick horizon of pale green, very fine-grained, altered, vitric tuff is observed between 2076.0 ft and 2076.3 ft in IW 22D-10 core. The bottom and top contacts of the tuff are bioturbated. Dr. Paul Hammond of Portland State University performed an X-ray fluorescence chemical analysis of this sample (Appendix 1).

The chemistry of the tuff is that of a calc-alkaline silicic andesite with unusually high trace element content of Zr, Y, and Nb and a moderately high Al content. Although this sample is altered, the chemistry indicates either a mid-continental or a mid-oceanic source, and not arc-volcanism (Hammond, 1996, written communication). The Grays River volcanics is a possible source of this tuff. The moderate TiO_2 content of 0.54% of the tuff is lower than the >2% TiO_2 content of most Grays River-Tillamook Volcanic samples. Another possible source is the Goble Volcanics of the western Cascades which erupted toward the end of Cowlitz time and the beginning of Keasey time (Rarey, 1986). Steve Kenitz of Portland State University is presently completing a M.S. thesis on the geochemistry of volcanic samples from the Hamlet, Cowlitz and Keasey formations at the Mist Gas Field. Kenitz (personal communication, 1997) believes that most volcanic samples within the Cowlitz Formation at the Mist Gas Field were derived from the Grays River volcanics.

Contorted siltstone facies

The uppermost 12 ft (1999.85-2012.0 ft) of the upper mudstone member in the IW 22D-10 core consists of medium olive gray (5Y 5/1) to moderate yellowish brown (10YR 5/4) highly contorted siltstone (Figure 23). This interval was diagenetically altered (see Petrologic Analysis of IW 22D-10 Core, Mist Gas Field chapter) and redeposited prior to deposition of the basal basaltic conglomerate and tuffaceous mudstone of the Keasey Formation.

Analysis of foraminifera from the contorted siltstone facies of the upper mudstone member by McDougall has found that there are foraminifera which are restricted to both

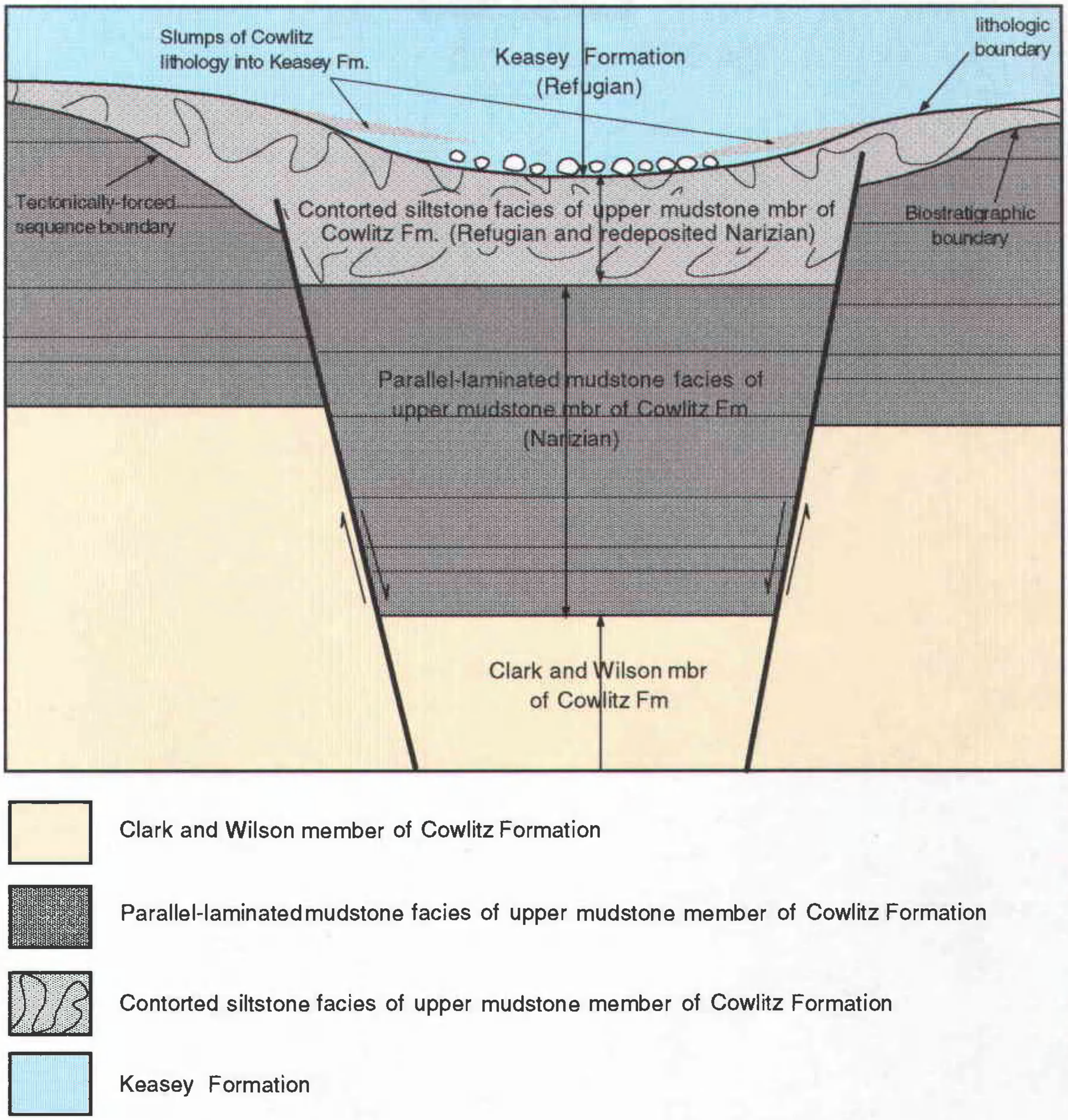


Figure 26. Schematic cross section through Keasey and Cowlitz formations illustrating extensional faulting, redeposition of the contorted siltstone facies of the Cowlitz Formation, and the erosional unconformity at the base of the Keasey Formation.

the Narizian and the Refugian in sample IW 22D-10 2000.2 ft (Table 1). The Narizian fauna were originally deposited at upper middle bathyal (500-1500 m) water depths and then redeposited during the early Refugian at upper bathyal (150-500 m) water depths (McDougall, written and personal communication, 1997).

The Narizian strata may have been uplifted by normal faults related to a regional extensional faulting event which occurred near the beginning of the Refugian or end of the Narizian (Figure 26). Soft sediment deformation and liquefaction related to shaking by earthquakes may have caused this strata to slump downslope and be redeposited. The biostratigraphic boundary is interpreted to be a tectonically forced sequence boundary as defined by Ryu (1995). This intraformational unconformity has not been reported previously.

McDougall (written communication, 1997) has reported abundant glauconite in the IW 22D-10 2000.0 ft sample. This may indicate that there was a period of slow deposition or nondeposition prior to deposition of the tuffaceous Keasey Formation.

KEASEY FORMATION

The IW 22D-10 core recovered the lower 3 ft (1997.0-1999.85 ft) of the tuffaceous, nonmicaceous Keasey Formation (Figure 23). The basal contact of the Keasey Formation with the micaceous upper mudstone member of the Cowlitz Formation is sharp and erosive. The Keasey Formation in the core consists of several 0.1-0.8 ft thick layers of coarse grained basaltic sandstone to pebbly basaltic conglomerate which are overlain by laminated tuffaceous mudstone. The scoriaceous basaltic pebbles are subrounded, poorly sorted and alter to white clays and zeolites. Tuffaceous siltstone locally forms drapes over clasts in the conglomerate. Molluscan fossil shell fragments, suggesting a marine environment of deposition, are observed within conglomerate.

The poor sorting, lack of grading and sharp bottom and top contacts suggest these conglomerates were emplaced as grain or debris flows into the deepwater environment of the Keasey Formation. Pilotaxitic flow texture in basaltic clasts suggest that the basalt was derived from either the Tillamook Volcanics or the Grays River volcanics. Berkman (1990) and Niem (personal communication, 1997) found similar graded volcanic conglomerate in the tuffaceous Keasey in outcrops along the Nehalem River several miles south of the Mist Gas Field.

Analysis of foraminifera by McDougall (personal communication, 1997) suggests that the base of the Refugian Keasey Formation was deposited in upper bathyal water depths.

PETROLOGIC ANALYSIS OF IW 22D-10 CORE, MIST GAS FIELD

INTRODUCTION AND SAMPLE PREPARATION

A petrologic study of the IW 22D-10 core was conducted in order to better understand the provenance and diagenetic history of the Cowlitz and Keasey formation sandstones and mudstones. These data are critical for understanding the reservoir and seal properties at the Mist Gas Field. Thin section petrography was conducted to determine the composition of framework grains and distribution of matrix and cements. X-ray diffraction (XRD) analyses were performed to identify the composition of the clay-sized minerals. Scanning electron microscopy (SEM) analyses were performed to understand the morphology of the clay-sized minerals and interpret the sequence of diagenetic events.

A total of seventeen thin section samples from the IW 22D-10 core were point-counted (Plate 3). One volcanic sandstone sample from the base of the Keasey Formation, two mudstone samples and one tuff sample from the upper mudstone member of the Cowlitz Formation were analyzed. Eleven sandstone samples from the Clark and Wilson member of the Cowlitz Formation, one mudstone interbed from the Clark and Wilson member, and one lignite interbed from the Clark and Wilson member. Samples were commercially impregnated with blue epoxy prior to thin section preparation. After thin section preparation, half of each sample was etched with hydrofluoric acid and potassium feldspar grains were stained yellow with sodium cobaltinitrite. Three hundred points were counted on each thin section using a mechanical stage.

X-ray diffraction analysis (XRD) of clay-sized minerals was performed on 26 samples from the IW 22D-10 core including each thin section sample (with the exception of the calcite-cemented 'bone bed' at 2308.0 ft). X-ray diffraction analyses were performed using a Phillips 3100 Automated XRD unit maintained by Dr. J.R. Glasmann of the Department of Geosciences at Oregon State University.

Sandstone and mudstone samples for X-ray diffraction analysis were prepared using the procedure of Glasmann and Simonson (1985). Each sample was disaggregated and separated into silt- (2-15 μm) and clay- (<2 μm) sized fractions by use of a centrifuge. An oriented silt film on a glass side was made with the silt-sized fraction and allowed to air-dry. The clay-sized fraction was magnesium-saturated with 0.5 *M* $MgCl_2$ solution and washed three times with distilled water. A magnesium-saturated clay film was prepared on a glass slide and then placed in a hydrator at 54% relative humidity and allowed to equilibrate for 12 hours. After initial XRD analysis of the magnesium-saturated clay sample, the sample was placed in a hydrator with magnesium-glycol and the hydrator was placed in a 65°C oven for three hours. The glycolated sample was allowed to equilibrate for 12 hours prior to XRD analysis. After preparation of the magnesium-saturated slide, the remaining clay-sized sample was potassium-saturated with 1 *M* KCl solution and washed three times with distilled water. An oriented clay film was prepared on a glass slide with the with the potassium-saturated clay-sized fraction. The slide was placed in a hydrator at 54% relative humidity and allowed to equilibrate for 12 hours prior to X-ray diffraction analysis. After initial XRD analysis, the potassium-saturated sample was placed in a 110°C oven for 2 hours. The oven-dried sample was analyzed immediately after being removed from the oven. X-ray pattern interpretation was done by comparing the 2θ peak position and intensity with the diffraction patterns of known minerals. Identification of clay minerals was done using the computer program Jade. X-ray diffraction patterns of the magnesium-glycolated and 54% relative humidity magnesium-saturated clay treatments are presented in this chapter.

Nine samples from the Cowlitz and Keasey formations were analyzed using scanning electron microscopy (SEM). Samples were mounted on aluminum stubs, unnecessary surfaces were painted with a graphite compound to avoid charging problems between the sample and the electron beam, and sputter-coated with a gold-palladium compound. SEM analysis was performed with Dr. J.R. Glasmann using an AMR 1000 SEM equipped with a KEVEX elemental analyzer maintained by Mr. Al Soeldner in the Botany Department at Oregon State University.

COWLITZ FORMATION

Clark and Wilson Sandstone

Sandstones of the Clark and Wilson member of the Cowlitz Formation are classified as arkoses and lithic arkoses (classification of Folk, 1974; Figure 27). All but one sample from lithofacies H and P classify as arkosic sandstones. Both samples from lithofacies H-BG are lithic arkoses.

Arkosic sandstones of lithofacies H and P are petrologically similar and will be treated together in this discussion. Sandstone samples contain approximately subequal proportions of quartz and feldspar (Figure 27 and 28). The quartz is dominantly

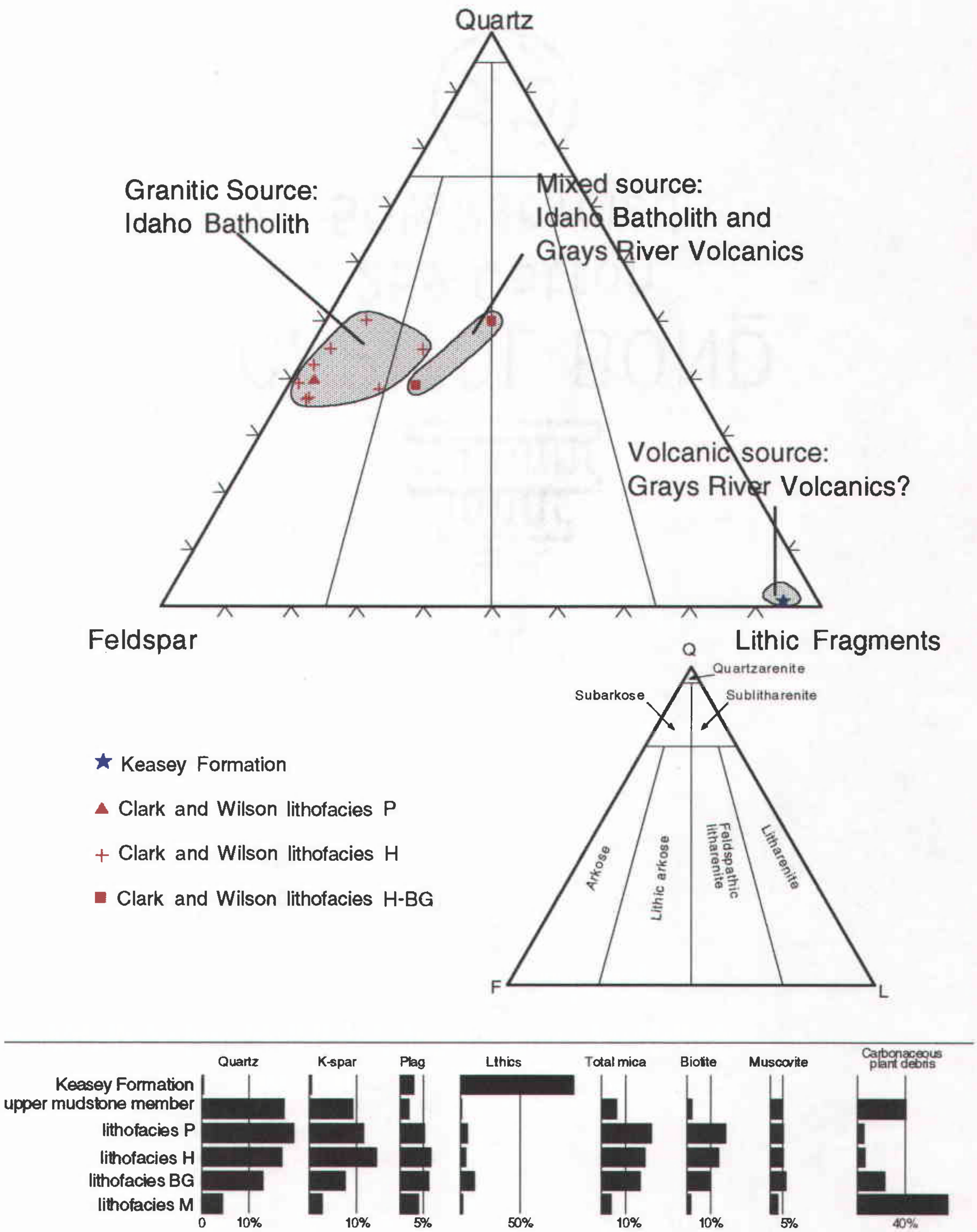


Figure 27. QFL classification diagram (after Folk, 1974) of sandstone samples (upper diagram) and framework grain composition (lower diagram) of Cowlitz and Keasey samples from IW 22D-10 core.

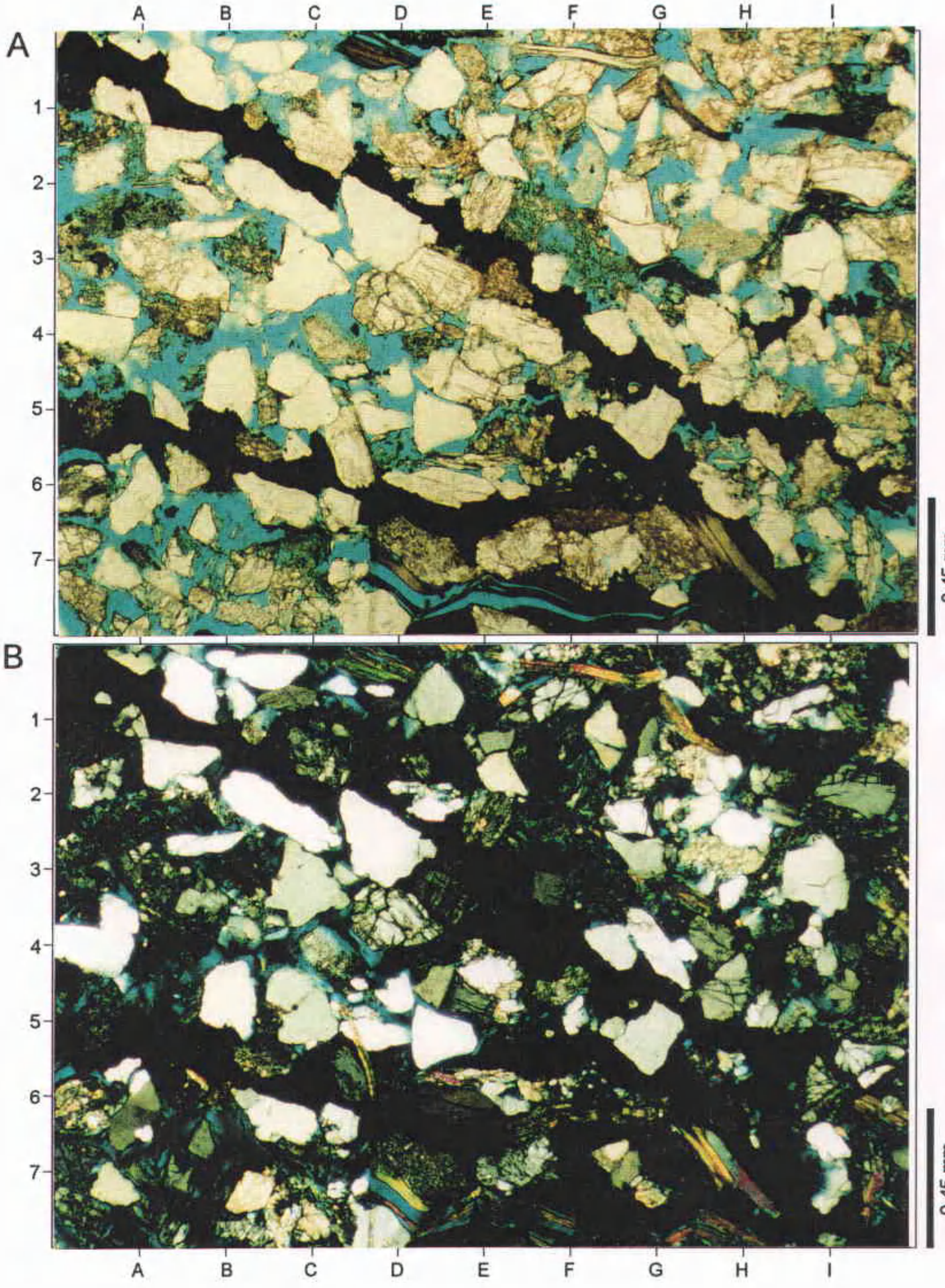


Figure 28. Photomicrographs of micaceous arkosic sandstone of lithofacies H (sample 22D-10 2189.0 ft) of Clark and Wilson member. Note abundant angular to subangular quartz and feldspar grains, bent mica flake (7E), feldspar overgrowth (D3), and opaque carbonaceous plant debris defining bedding. Porosity (blue dye) is dominantly intergranular. (A. Plane-polarized light, B. Crossed nichols).

monocrystalline although a few grains of polycrystalline quartz are present. The ratio of potassium feldspar to albite-twinned plagioclase feldspar is roughly 2:1. Untwinned orthoclase feldspar is more abundant than gridiron twinned microcline. Lithic fragments in arkoses are dominantly basaltic, although few granitic plutonic clasts also occur.

Cowlitz sandstone samples are very micaceous, containing slightly more biotite than muscovite. Samples from lithofacies H and P contain an average of 12% mica. Sample IW 22D-10 2116.0 ft from lithofacies P contains 20% mica. Carbonized plant debris in thin section is slightly more common in lithofacies H than in lithofacies P. These observations correspond with the observation that laminations in lithofacies P tend to be more micaceous than the laminations in lithofacies H which are mostly carbonaceous (see Lithofacies of the Cowlitz and Hamlet Formations in Bruer and Flora Gas Storage Pools, Mist Gas Field chapter) Additionally, mica in lithofacies P is finer-grained than mica in lithofacies H.

Grain contacts are commonly tangential indicating that the sandstone has not undergone much burial compaction by loading. Both carbonaceous plant debris and mica bend ductily between rigid quartz and feldspar grains as a result of burial compaction. Visual estimates of porosity average 18% with values ranging from 1-31% (Appendix II). Porosity is dominantly primary or intergranular with minor secondary porosity formed by partial dissolution of plagioclase feldspar grains. Primary or depositional porosity is open and shows good interconnection. Pore throats are wide and are not clogged by diagenetic clay minerals. Vertical permeability is, however, affected by long impermeable aligned lamina of carbonized plant debris. The dissolution of feldspar occurred relatively late in the diagenetic history of the Cowlitz Formation. The sample with 1% porosity is a sparry calcite-cemented “bone bed”. This sample is discussed separately below.

Chlorite and illite are the dominant clay-sized components of arkosic sandstone samples (Figures 29 and 30). However, scanning electron microscope analysis discovered no grain-rimming authigenic chlorite or illite. Clay-sized chlorite is interpreted to be largely a diagenetic or predepositional alteration product of detrital biotite flakes. Clay-sized illite is largely a diagenetic or predepositional alteration product of detrital muscovite flakes. Sample IW 22D-10 2116.0 (Figure 30) from lithofacies P contains a minor amount of authigenic clay-sized smectite cement. Some of these clay minerals may be acting as thin grain-rimming cements (Niem, personal communication, 1997). However, other than in sample IW 22D-10 2116.0 ft, no authigenic grain-rimming cements were observed in arkosic sandstone samples from lithofacies H and P.

One calcite-cemented sandstone from lithofacies H was analyzed (Figure 31). Framework-grain composition of this sample is similar to that of other Clark and Wilson sandstones. However, some of the plagioclase feldspar grains have been partially replaced by sparry calcite. Muscovite and chloritized biotite flakes in this sample are straight and framework grains appear to float in the sparry calcite cement. These observations indicate that sparry calcite cement formed before compaction of the mica flakes by overlying strata could occur. Perhaps some of the concretionary calcite cement occurred at or near the sediment-water interface. This sample contains minor late-stage secondary porosity where plagioclase feldspar grains have been partially dissolved.

Two samples from the volcanic-rich, blue-green colored, lithofacies BG were analyzed in thin section. These samples show an enrichment in mafic volcanic rock

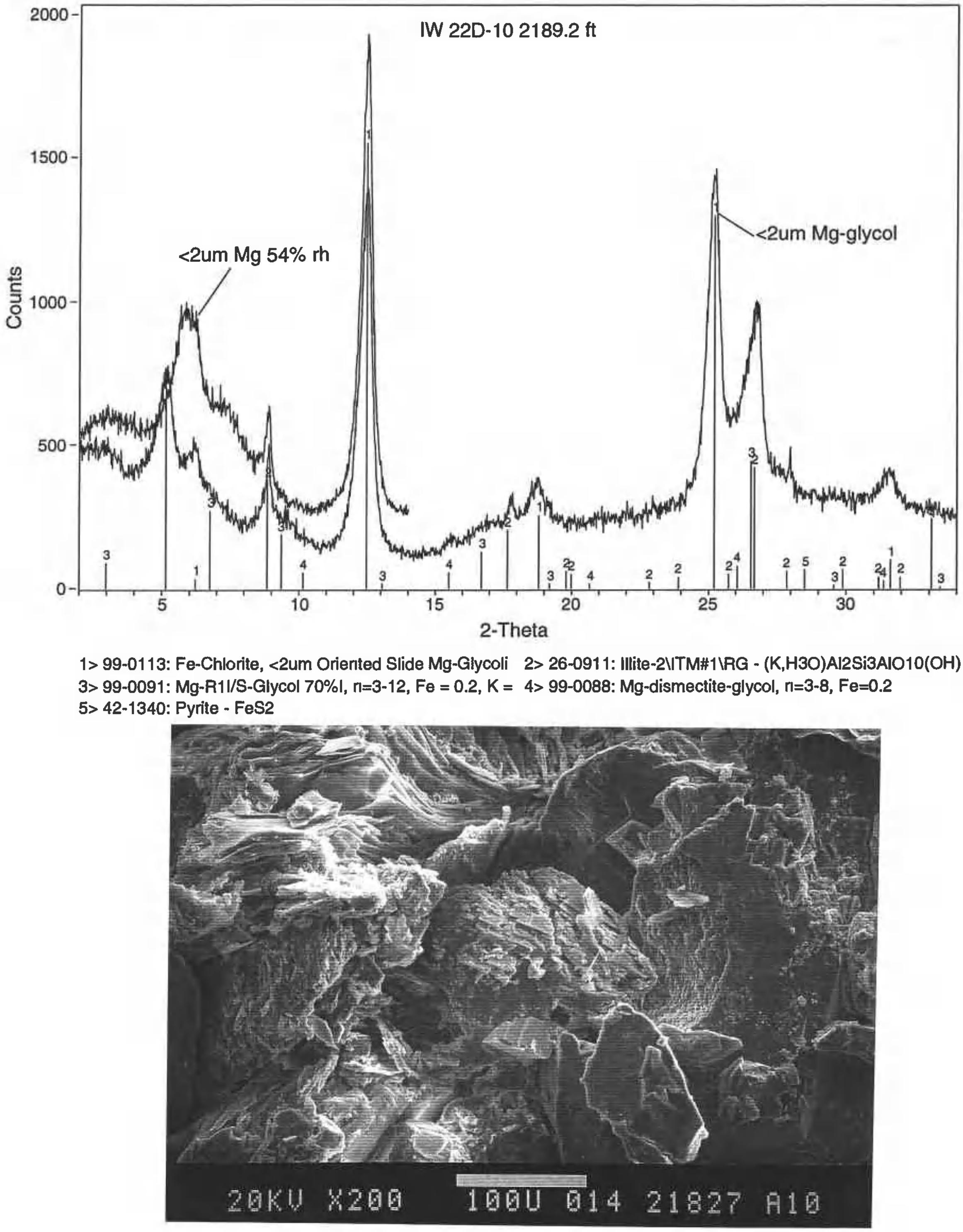
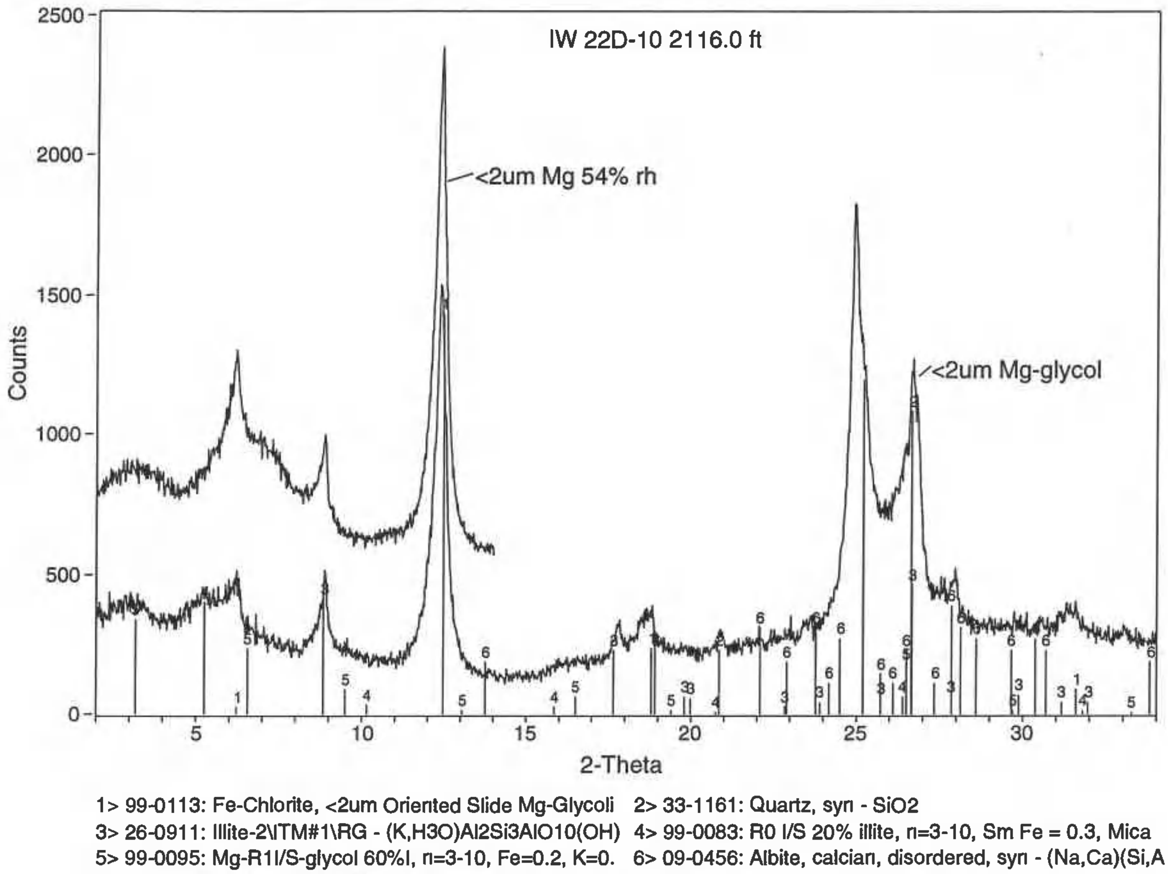


Figure 29. X-ray diffraction pattern (sample IW 22D-10 2189.2 ft) and SEM photograph (sample IW 22D-10 2182.7 ft) of arkosic sandstone from hummocky-bedded lithofacies H of Clark and Wilson member of the Cowlitz Formation. Note bent mica flake and etched feldspar grain. Authigenic clay minerals are not observed in this sample.



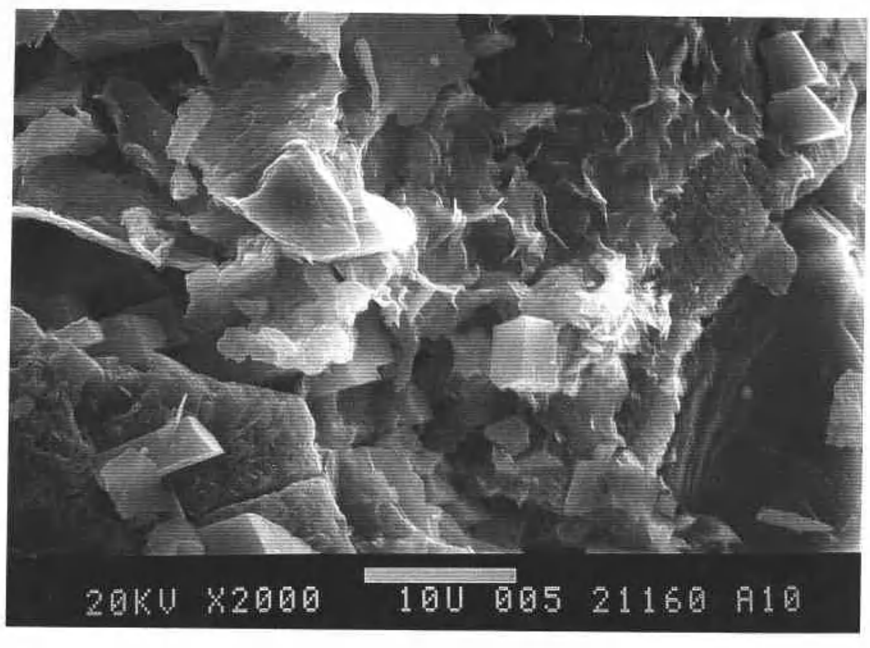


Figure 30. X-ray diffraction pattern and SEM photograph of sample IW 22D-10 2116.0 ft from parallel-bedded sandstone of lithofacies P of Clark and Wilson member. Note wispy, authigenic, grain-rimming smectite cement and crystals of authigenic potassium feldspar overgrowths. Scale at bottom of SEM photo is 100 microns.

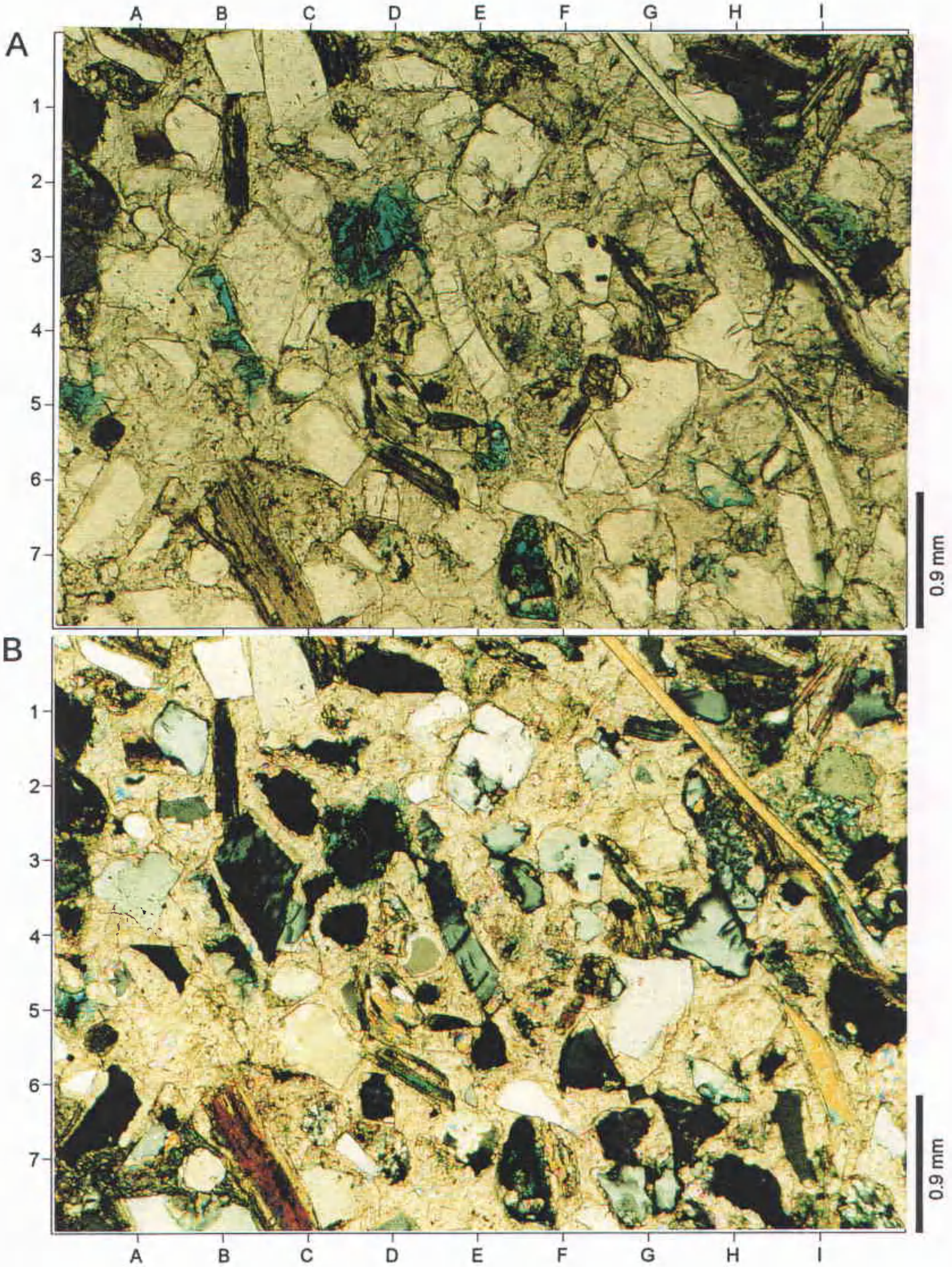


Figure 31. Photomicrographs of sparry calcite-cemented sandstone (sample IW 22D-10 2200.0 ft) from wave-dominated lithofacies H of Clark and Wilson member. Note angularity of quartz and feldspar grains, straight muscovite grain (G1), partial calcite replacement of feldspar grains (D6), and minor secondary porosity (blue dye in plane-polarized light) developed in partially dissolved plagioclase feldspar grain (B4) (A. Plane-polarized light, B. Crossed nichols).

fragments (Figures 27 and 32). One calcite-cemented sample from the BG zone contains flattened altered "scoria" clasts (Figure 32). The presence of delicate scoria indicates that explosive basaltic volcanism (e.g. cinder cone at top of flows) was occurring in the basin during deposition of the Clark and Wilson member. Authigenic grain-rimming chlorite cement (Figure 33) is pervasive in samples from lithofacies BG which are not calcite-cemented. The explosive basaltic volcanic event which produced the scoria fragments may have also produced fine-grained glassy ash which was altered and remobilized to form the authigenic pore-filling chlorite cement. Berkman (1990) and Farr (1989) also found abundant scoriaceous fragments and grain-rimming pore-clogging chlorite cement.

In the calcite-cemented, scoria-bearing lithic arkose (sample IW 22D-10 2308.3 ft) no authigenic grain-rimming chlorite cement is observed. Therefore, calcite cement is interpreted to have occurred earlier in the diagenetic history of the BG zone than chloritization. Potassium feldspar overgrowths are present in the lithic arkose sandstones, however, they are not as common in the BG zone as they are in arkosic sandstones of lithofacies H and P. Partial dissolution of plagioclase feldspar is not as common in the BG zone as it is in lithofacies H and P. Grain-rimming chlorite cement formation in the BG zone may be an early diagenetic stage which reduced the porosity of the zone and protected plagioclase grains from later alteration by corrosive pore fluids. Porosity of chlorite and calcite-cemented lithic arkoses is greatly reduced compared to other sandstones of the Clark and Wilson member of the Cowlitz Formation (Plate 3, Appendix 3). The BG zone may act as a significant permeability barrier to the vertical flow of fluids in the reservoir.

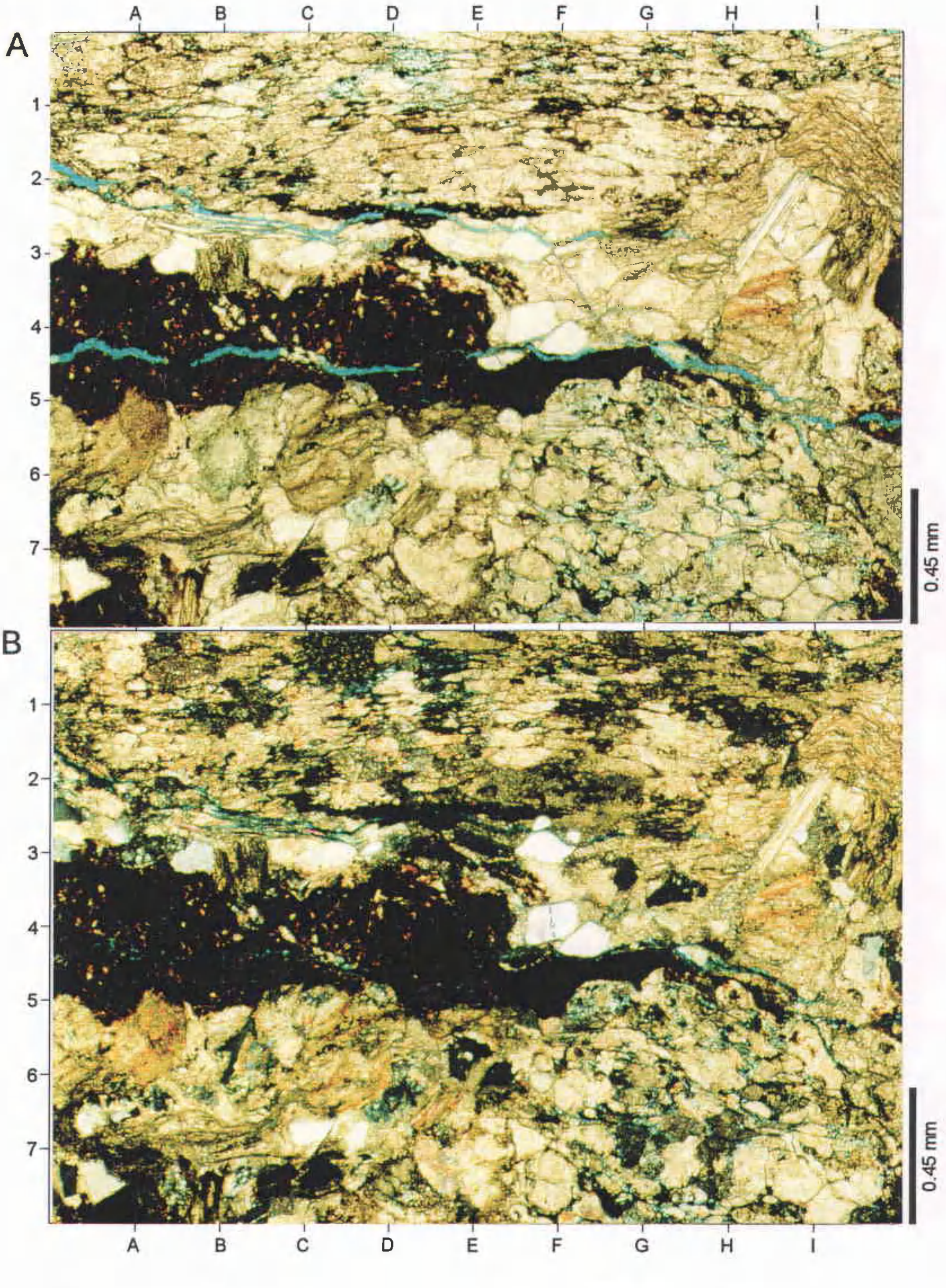
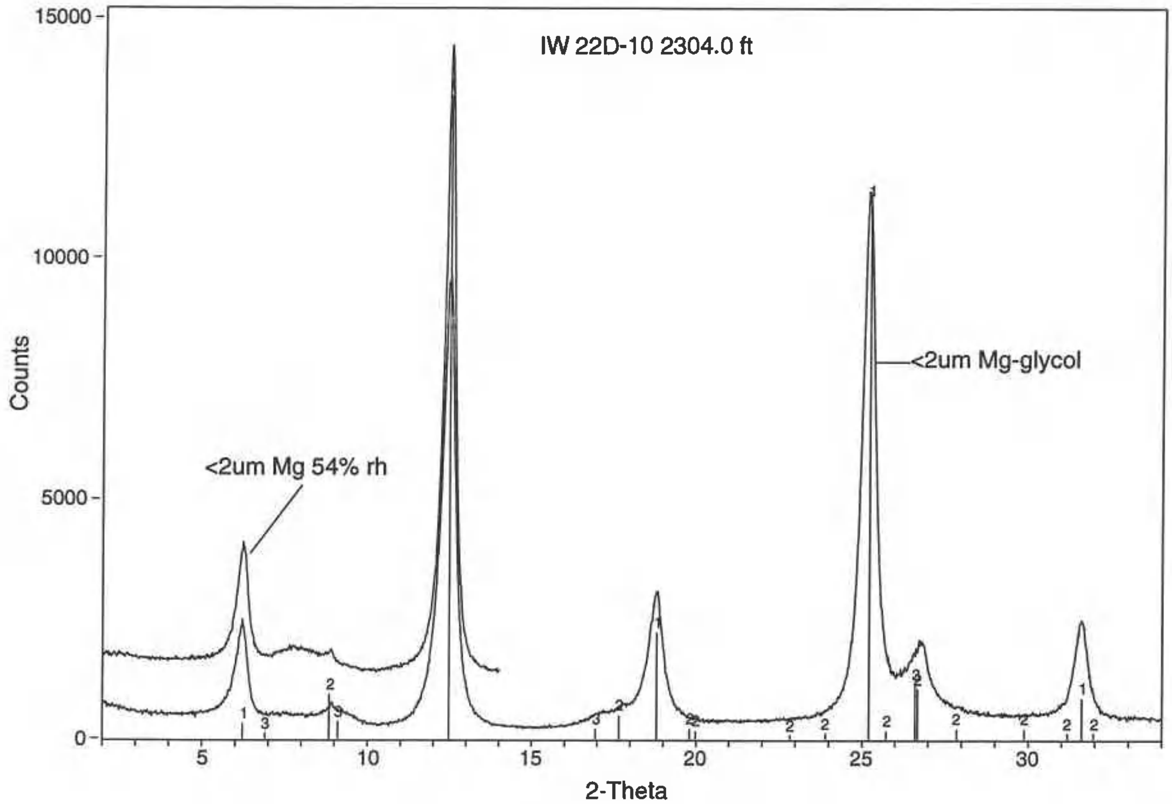


Figure 32. Sparry calcite-cemented sandstone (sample IW 22D-10 2308.3 ft) from base of volcanic lithic arkosic sandstone of lithofacies BG of the Clark and Wilson member of the Cowlitz Formation. Note compacted altered "scoria" pebble at top of photomicrograph (A1-H1), abundant contorted and compacted opaque carbonized plant fragments and calcite replacement of plagioclase grain (I2). (A. Plane-polarized light, B. Crossed nichols).



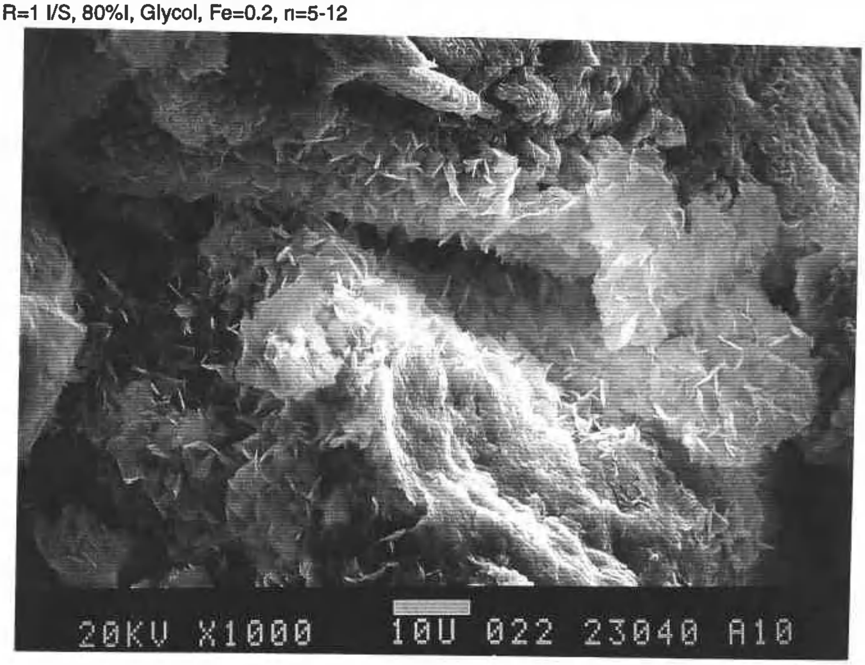


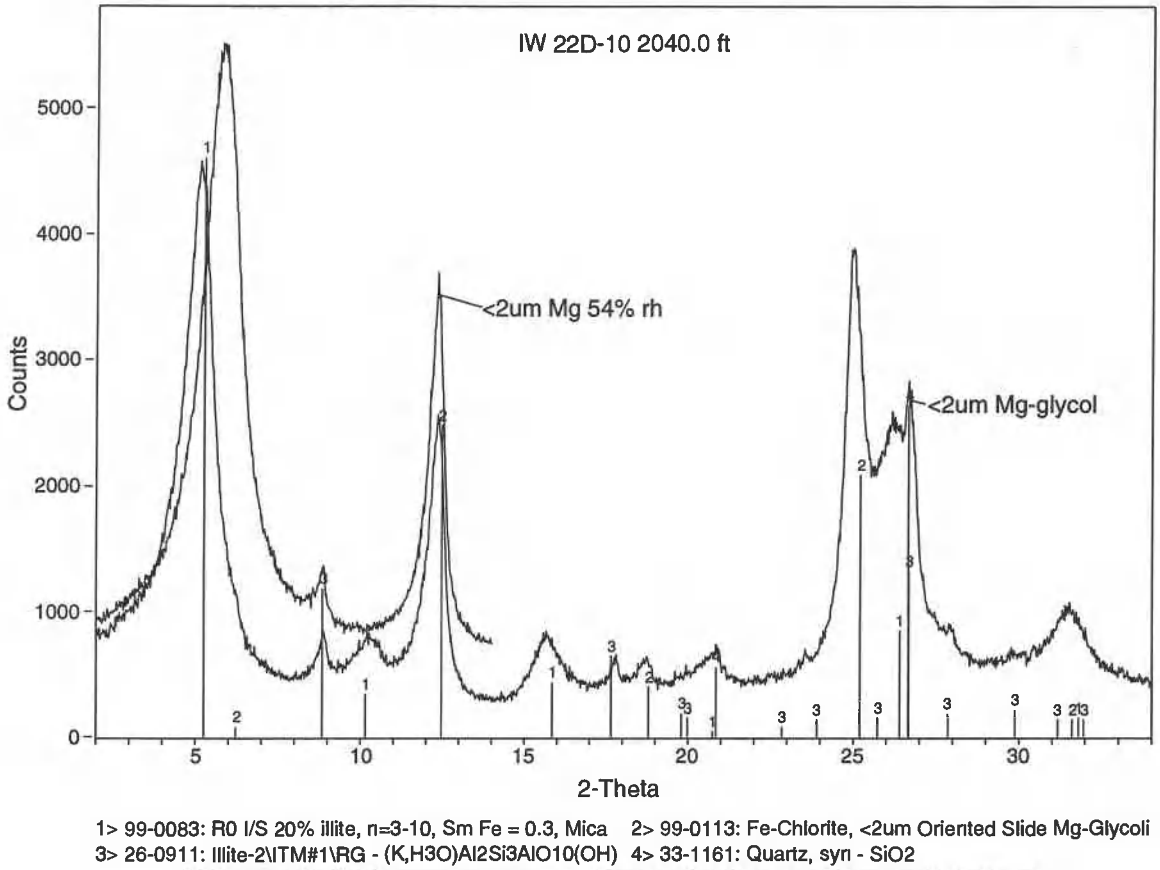
Figure 33. X-ray diffraction pattern and SEM photograph of altered volcanic lithic arkose sandstone (sample IW 22D-10 2304.0 ft) from lithofacies BG. Note widespread permeability-reducing, grain-coating, pore-clogging authigenic chlorite rosettes that form extensive cement. Bar scale of SEM photo is 10 microns.

The lignite interbed in the Clark and Wilson member is the most carbonaceous interval studied (Figure 27). Abundant volcanic lithic fragments and cubic pyrite were observed in this interval. The presence of authigenic pyrite indicates that this sample was altered in a reducing environment.

Upper mudstone member

Three samples from the upper mudstone member of the Cowlitz Formation were point-counted and examined using the scanning electron microscope. Ten samples were analyzed using X-ray diffraction. All samples analyzed from the upper mudstone member contain abundant silt-sized particles. Silt-sized grains are predominantly angular quartz and feldspar with minor amounts of muscovite and chloritized biotite flakes. Siltstone samples contain slightly more muscovite than biotite. The clay mineral assemblage of samples from the upper mudstone member (Figures 34 and 35) is similar to that of samples from the Clark and Wilson member (Figures 29 and 30) of the Cowlitz Formation. Smectite, chlorite and illite are the dominate clay-sized minerals. However, the upper mudstone member contains more randomly interstratified illite-smectite than the Clark and Wilson member of the Cowlitz Formation.

The redeposited contorted siltstone facies at the top of the upper mudstone member was studied in order to determine the nature of the boundary between the contorted siltstone facies and the parallel-laminated mudstone facies of the upper mudstone member of the Cowlitz Formation. Samples from the contorted zone and those from the laminated dark mudstone zone are petrologically similar. Analysis of Foraminifera from the contorted siltstone facies by McDougall (written and personal



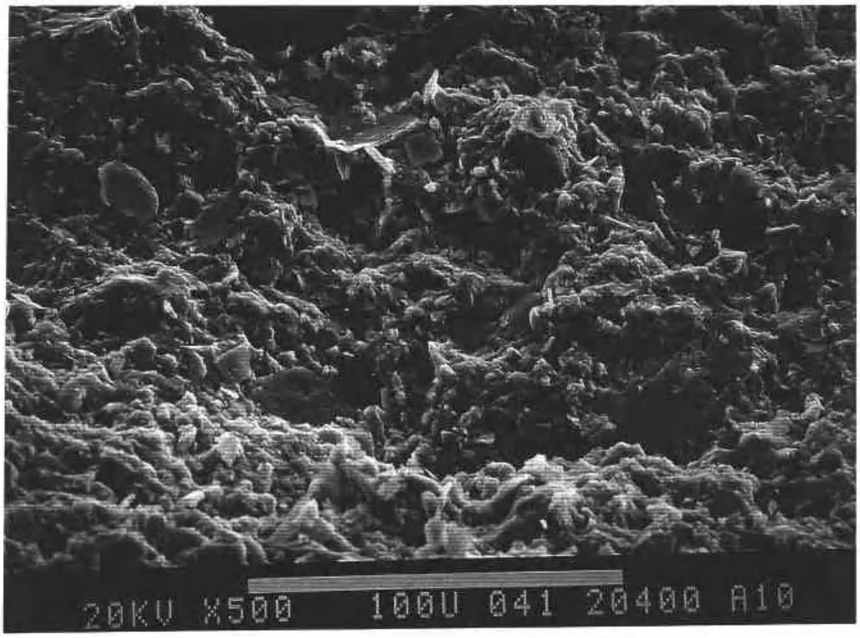


Figure 34. X-ray diffraction pattern and SEM photograph of the laminated mudstone facies (sample IW 22D-10 2040.0 ft) of upper member of the Cowlitz Formation. Note silt-sized quartz grain and mica flakes. Scale at bottom of SEM photo is 100 microns.

communication, 1997) suggests that the contorted siltstone was redeposited in the early Refugian (see Lithofacies of the Cowlitz Formation in Bruer and Flora Gas Storage Pools, Mist Gas Field chapter).

The thin (0.3 ft) pea-green tuffaceous mudstone interval near the base (2076.0 ft - 2076.4 ft) of the upper mudstone member (Plate 2) was analyzed to determine the nature of the clay. The pea-green mudstone consists of almost pure iron-rich smectite (Figure 36). The honeycomb texture of smectite indicates an authigenic origin. Smectite is a common weathering product of mafic volcanic ash. Star-shaped authigenic goethite crystals are observed in thin section and under the scanning electron microscope (Figure 36). Glasmann and Simonson (1985) reported similar goethite crystals in highly weathered basalts of western Oregon.

Trace and major oxide analysis of the reworked tuff was conducted using X-ray fluorescence by Dr. Paul Hammond of Portland State University (Appendix II). The composition of this ash fall tuff is that of a calc-alkaline silicic andesite (see Lithofacies of the Cowlitz Formation in Bruer and Flora Gas Storage Pools, Mist Gas Field chapter). X-ray fluorescence results should be considered with caution due to the intense alteration of the sample as observed through scanning electron microscope and X-ray diffraction analyses.

KEASEY FORMATION

A graded basaltic sandstone sample (Plate 2) from the Keasey Formation in the IW 22D-10 core was point-counted and analyzed using X-ray diffraction and scanning

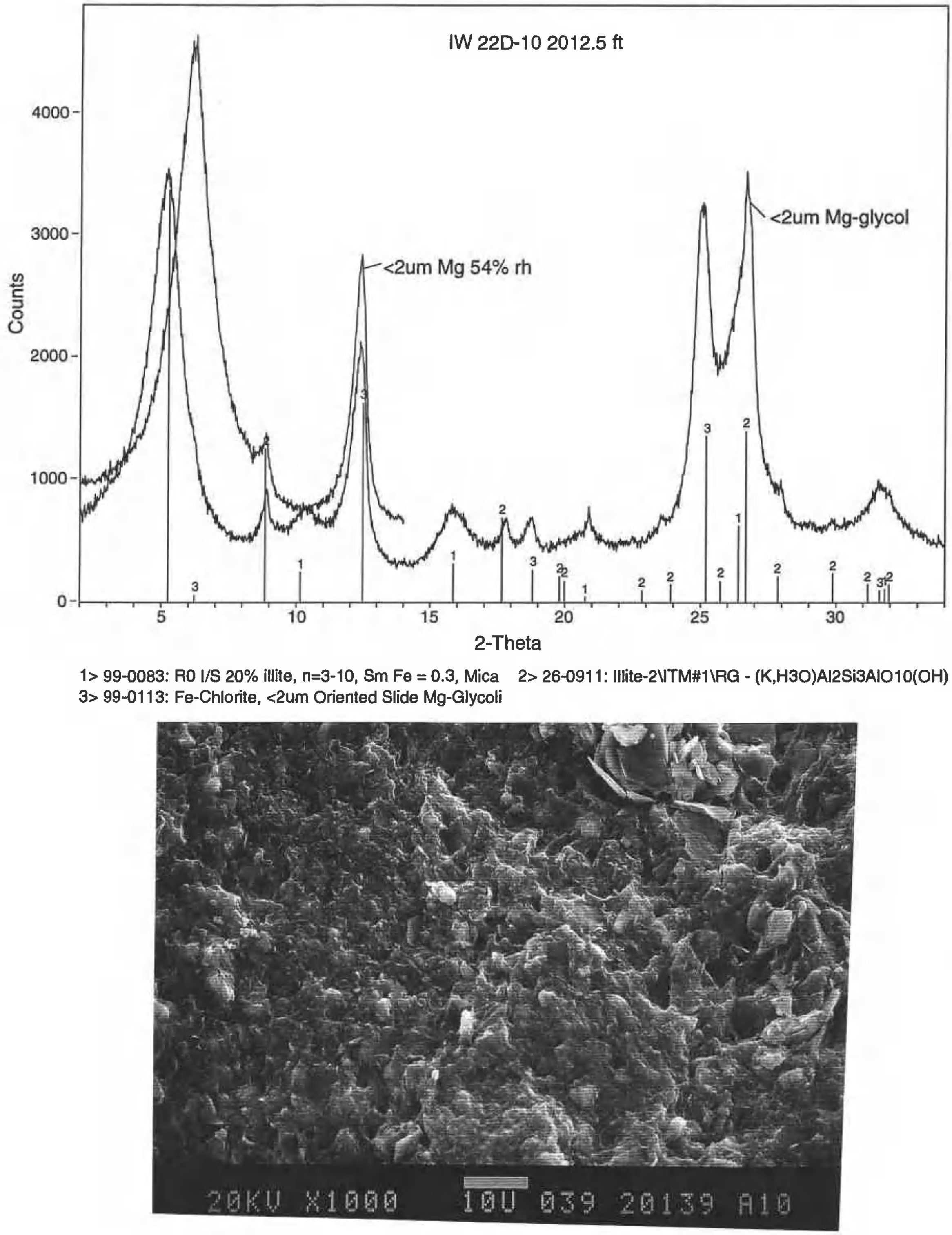
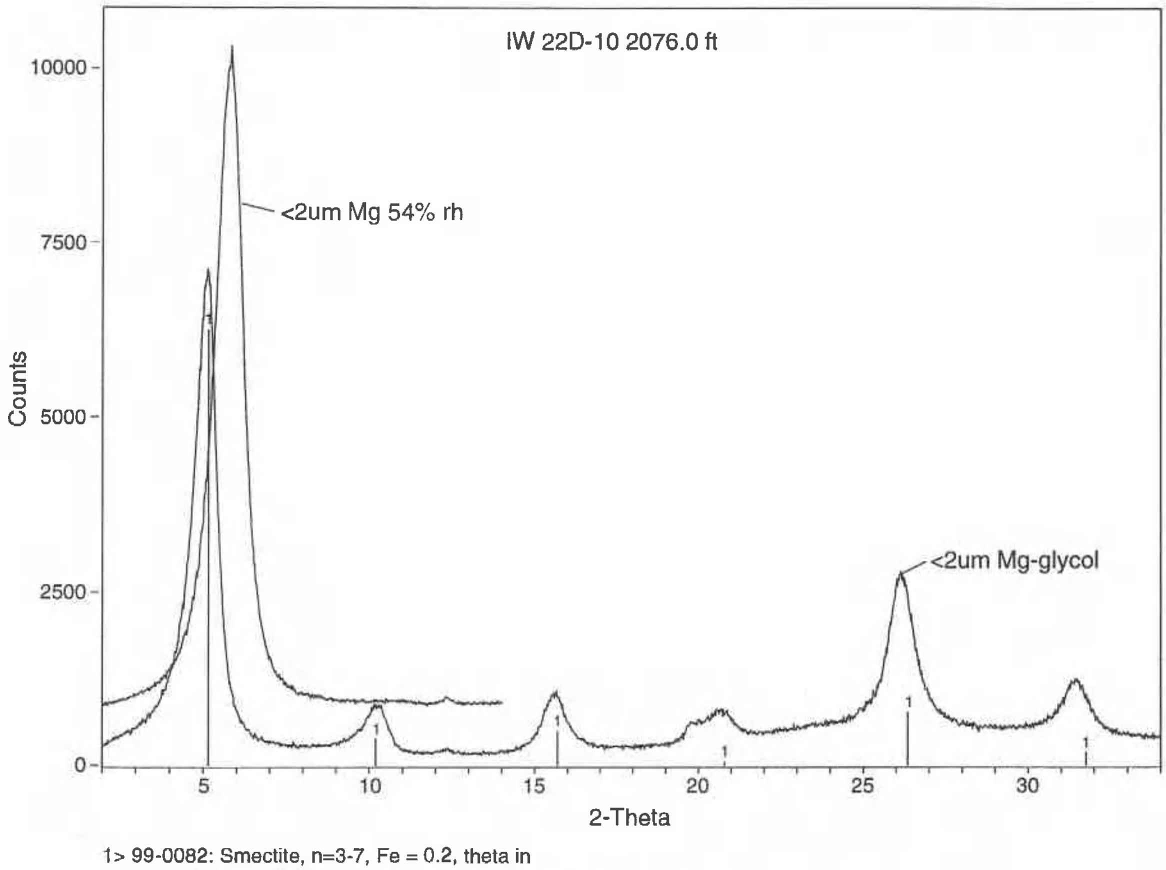


Figure 35. X-ray diffraction pattern (sample IW 22D-10 2012.5 ft) and scanning electron microscope (SEM) photograph (sample IW 22D-10 2013.9 ft) of siltstone from the redeposited contorted siltstone facies of the upper mudstone member of the Cowlitz Formation. Scale at bottom of SEM is 10 microns.



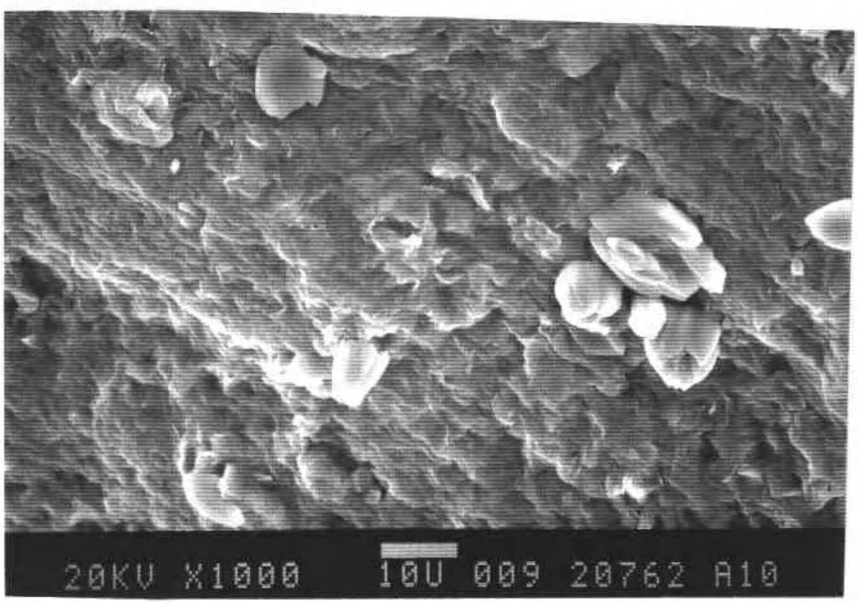


Figure 36. X-ray diffraction pattern and scanning electron microscope photograph of altered tuff (sample IW 22D-10 2076.0 ft) in upper mudstone member of the Cowlitz Formation. Note star-shaped authigenic crystals of goethite and honeycomb texture of authigenic iron-rich smectite. Scale at bottom of SEM picture is 10 microns.

electron microscopy. Additionally, one mudstone sample from the Keasey Formation in the IW 22D-10 core was analyzed using X-ray diffraction.

The sandstone sample is a poorly sorted, coarse-grained, pebbly, basaltic arenite (Figure 37). This sample classifies as a litharenite according to Folk's (1974) classification scheme (Figure 27). Foraminifera, indicative of a marine environment of deposition, occur in thin section. Lithic clasts consist of fresh to very weathered basalt clasts and a few chert grains. Keasey Formation sandstone contains more plagioclase feldspar than orthoclase (Figure 27, Appendix II). Some volcanic plagioclase grains are oscillatory zoned. No muscovite or biotite was seen in the Keasey Formation thin section samples; however, traces of illite are present in X-ray diffraction analyses (Figure 38). No monocrystalline quartz is observed in the Keasey sandstone samples from the IW 22D-10 core. The lack of mica and quartz, abundance of volcanic rock fragments, and presence of zoned plagioclase reflect the mafic volcanic origin of the Keasey sandstone.

Plagioclase microlites in pebble-sized basalt clasts are commonly flow-aligned. Pilotaxitic flow texture and opaque grains of ilmenite are characteristic of basalts of the Tillamook Volcanics and Grays River volcanics (Rarey, 1986; Berkman, 1990). Many sand-sized grains in the Keasey Formation resemble green glauconite; however, several of these grains contain aligned angular plagioclase laths and are probably celadonite, and alteration product of volcanic glass. Therefore these grains were classified as altered volcanic rock fragments. The range in alteration stages of the basaltic lava clasts may represent a mixing of weathered and fresh lava sources. Alternatively, the more intensely altered grains may represent the weathered rind of a fresh basalt flow.

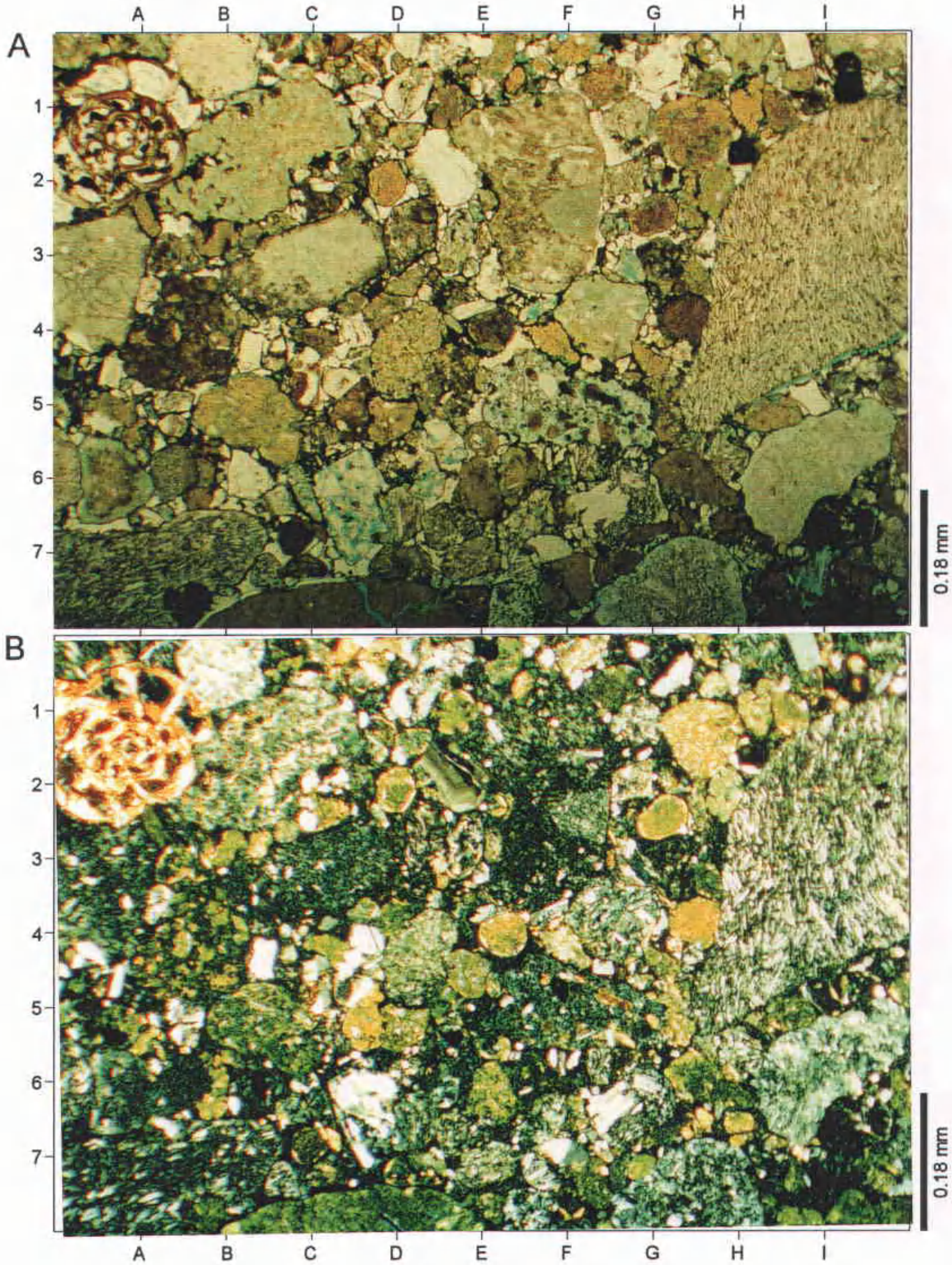


Figure 37. Photomicrographs of poorly sorted basaltic sandstone (sample IW 22D-10 1997.4 ft) of the Keasey Formation. Note pilotaxitic flow texture of the celadonite-altered basaltic clasts, oscillatory zoned volcanic plagioclase feldspar grain (E2), and large Foraminifera (A1). Pervasive heulandite, a high relief zeolite mineral, cement has filled most primary intergranular porosity including the internal structure of the Foraminifera (A1).

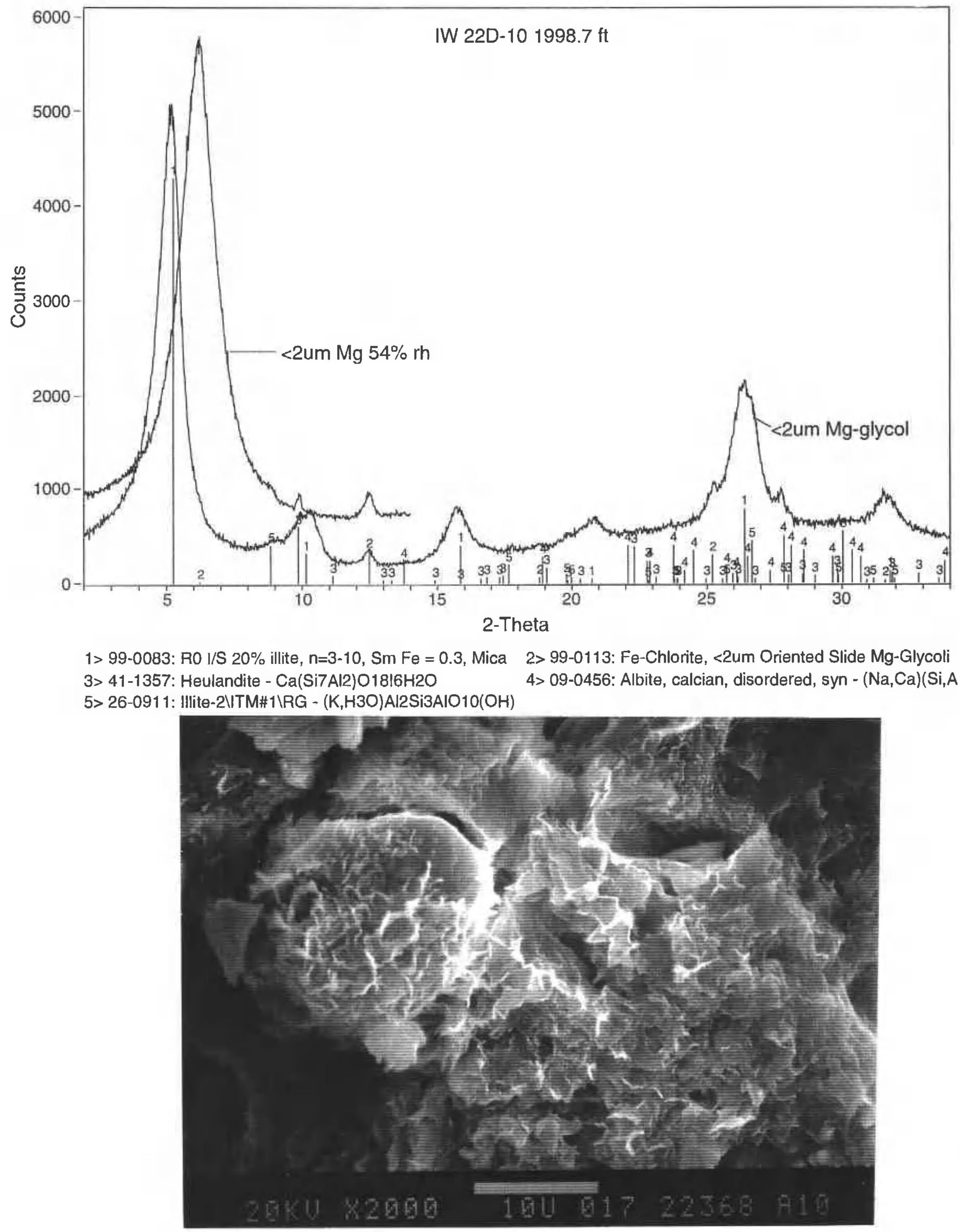


Figure 38. X-ray diffraction pattern and scanning electron microscope (SEM) photograph of altered basaltic sandstone (sample IW 22D-10 1998.7 ft) of Keasey Formation. Note abundant pore-clogging smectite coating grains in photograph. Scale at bottom of SEM photograph is 10 microns.

Heulandite, a high-relief zeolite mineral, cement is pervasive throughout the sandstone sample (Figures 37 and 38) and reduces visual porosity to less than 1%. Authigenic pore-clogging smectite (Figure 38) and framboidal pyrite are observed with the scanning electron microscope, and in the X-ray diffraction patterns of the Keasey Formation.

Conclusions

A general paragenetic sequence of diagenesis can be described for the Clark and Wilson member of the Cowlitz Formation based on observations of the IW 22D-10 core. The earliest diagenetic effect is local, scattered sparry calcite cement. Some sparry calcite cement replaces plagioclase feldspar framework grains. In lithofacies BG, authigenic chlorite was an extensive early alteration product of glassy volcanic ash which greatly reduced primary porosity and protected these volcanic lithic arkose sandstones from further diagenesis. With increasing burial, compaction of ductile muscovite, biotite and carbonized plant debris occurred in the arkosic sandstones, further reducing porosity. Some volcanic scoria fragments are flattened; however, mechanical compaction of quartz and feldspar grains is not observed. Most framework grain contacts of are tangential, suggesting only minor compaction effects by burial of up to 5000 ft by of overlying strata. Minor development of euhedral potassium feldspar overgrowths on feldspar framework grains is a late diagenetic stage followed by late stage partial dissolution of plagioclase feldspar grains creating minor secondary porosity. Scanning electron microscope analysis of Cowlitz samples found no authigenic chlorite, other than in the BG horizon, or authigenic illite. Clay-sized chlorite and illite in X-ray diffraction patterns are interpreted

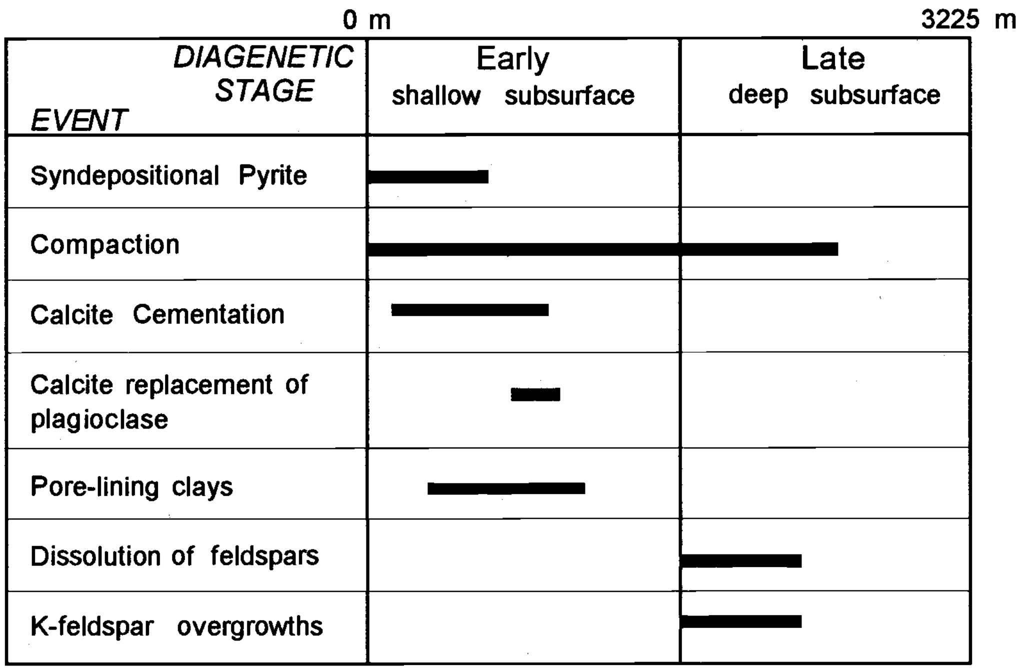


Figure 39. Paragenetic sequence of cements and diagenetic effects observed in the IW 22D-10 core. Depth of burial increases to the right. Modified after Berkman (1990).

to be a product of the weathering and alteration of biotite and muscovite. The timing of this alteration cannot be constrained. Minor calcite and clay cements may loosely consolidate the friable arkosic sandstone of the Clark and Wilson member of the Cowlitz Formation. The diagenetic sequence described above is similar to that observed by Berkman (1990) in the nearby OM 41A-10 core.

Petrographic and X-ray techniques are useful in characterizing the Keasey-Cowlitz contact. Thin section analysis shows that the Clark and Wilson member of the Cowlitz Formation is rich in monocrystalline quartz, potassium feldspar, plagioclase feldspar, muscovite and chloritized biotite. Mudstones from the upper mudstone member contain silt-sized grains of similar mineralogy. The Keasey sandstone contains predominantly mafic volcanic lithic fragments and volcanic plagioclase feldspar grains. Results of X-ray diffraction analyses reflect this change in lithology. The micaceous mudstones and sandstones of the Cowlitz Formation contain mostly clay-sized randomly interstratified illite/smectite, chlorite and illite whereas the Keasey Formation samples contain abundant interstratified illite/smectite and heulandite with only trace amounts of other clays.

Kadri (1982), Kadri and others (1983), and Lira (1990), using neutron activation analysis for whole rock geochemistry, also found that the Cowlitz Formation is enriched in potassium relative to the Keasey Formation. This enrichment is due to the abundant potassium feldspar and muscovite in the Cowlitz Formation. The increase in potassium-rich detrital muscovite at the Keasey Cowlitz contact causes a sharp increase in gamma ray log. This characteristic can be used to define the contact in the subsurface at the Mist Gas Field (Lira, 1990; Jack Meyer, personal communication, 1997). Niem and others (1985) also observed an abrupt increase in gamma ray activity at the Keasey-Hamlet contact in Clatsop County which they attributed to the presence of glauconite at the contact.

A change in provenance accompanied the structural and erosional event (unconformity) which occurred near the end of deposition of the upper micaceous mudstone member of the Cowlitz Formation and before deposition of the Keasey Formation. The Cowlitz Formation sediment was transported from a dissected arc (the Idaho Batholith) via an ancestral Columbia River fluvial system. The provenance of the tuffaceous Keasey Formation is that of an active arc (Cascade Range) and volcanic forearc (Grays River volcanics).

SUBSURFACE CORRELATION AND DISTRIBUTION OF COWLITZ AND HAMLET FORMATIONS, MIST GAS FIELD, NORTHWEST OREGON

Electric logs from Mist Gas Field exploration and production wells were studied in order to determine the three-dimensional distribution of the subunits of the Cowlitz and Hamlet formations. Electric log interpretation allows for more accurate and numerous measurements of unit thickness than surface exposures. Isopach maps, which show the 3-dimensional geometry of individual units, can provide important information as to the environment of deposition and basin geometry of the units being investigated. The following section discusses the log criteria used for unit identification and geometries of the members of the Cowlitz and Hamlet formations.

The two primary correlation logs used in this study are the spontaneous potential (SP) log and the resistivity (R) log (Figures 40 and 41). The spontaneous potential logging tool measures the difference in DC voltage potential between a moveable electrode in the wellbore relative to an electrode at the surface (Asquith and Gibson, 1983). This logging technique is used to identify permeable beds in the wellbore. In general, permeable sandstones have higher SP log response than less permeable mudstones do. The resistivity logging tool measures the resistance of rocks in the wellbore to flow of electric current (Asquith and Gibson, 1983). Resistivity logs are used to identify formation fluid (e.g. saline water, fresh water) and to detect the presence of natural gas or petroleum. At the Mist Gas Field, the resistivity log is especially useful in identifying strongly resistive basaltic units. The gamma ray logging tool, which measures natural gamma radiation given off by rocks in the wellbore, is useful in identifying the boundary between the Keasey and Cowlitz formations (Niem and others, 1985; Lira, 1990; Jack Meyer, personal communication, 1997). However, this log was not run in most of the exploration wells at the Mist Gas Field and is, therefore, not used extensively in this study. Dipmeter logs are used to determine the structural orientation of strata in the wellbore. Driller's logs and proprietary micropaleontological reports were also consulted to help identify lithologies and formation boundaries. Jack Meyer of Northwest Natural Gas freely gave advice and helped the author with interpretations.

Two wells were chosen to typify the spontaneous potential and resistivity log response of the Cowlitz and Hamlet formations at the Mist Gas Field. The 32-10-65 well (Figure 40) was chosen for the northern part of the Mist Gas Field because it contains an unfaulted stratigraphic sequence through the Cowlitz and Hamlet formations down to the Tillamook Volcanics. This is one of the few wells in the northern part of the Mist Gas Field which drilled completely through the Grays River volcanics to penetrate the Hamlet formation. In the southern part of the Mist Gas Field, the 32-26-54 well (Figure 41) was chosen as a type well. This well contains a complete, unfaulted stratigraphic sequence from the Clark and Wilson member of the Cowlitz Formation through the Sunset Highway member of the Hamlet formation. Both of these wells provide a good standard log response that allowed for correlation to surrounding wells.

All wells at the Mist Gas Field were studied, and 151 of these wells are used in this study. The wells that are not used in isopachs and/or correlation diagrams are either not deep enough to penetrate the entire thickness of the unit of study, are faulted, or do not

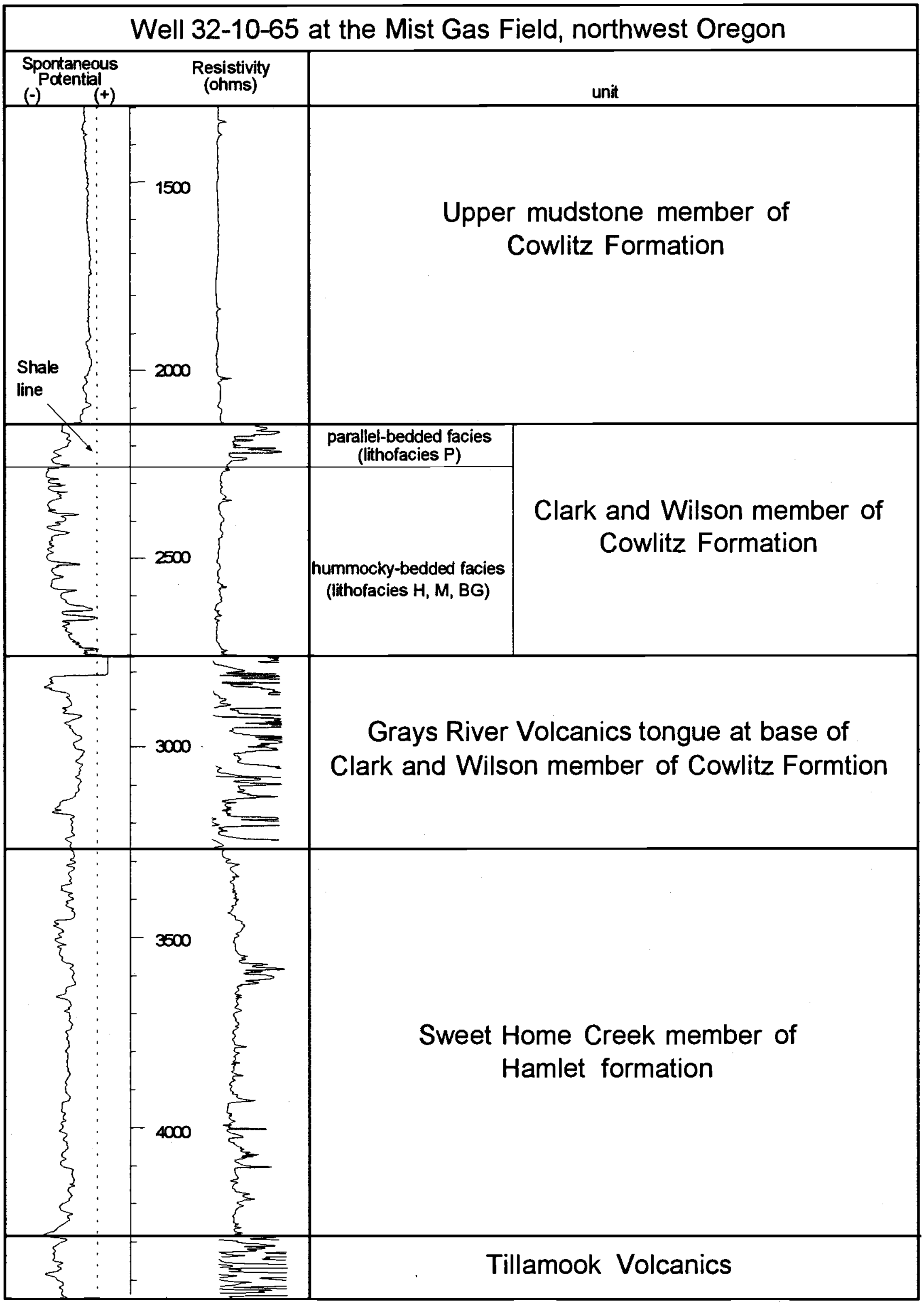


Figure 40. SP and resistivity log curves from well 32-10-65 (sec. 10, T.6N., R.5W.), Mist Gas Field, Northwest Oregon.

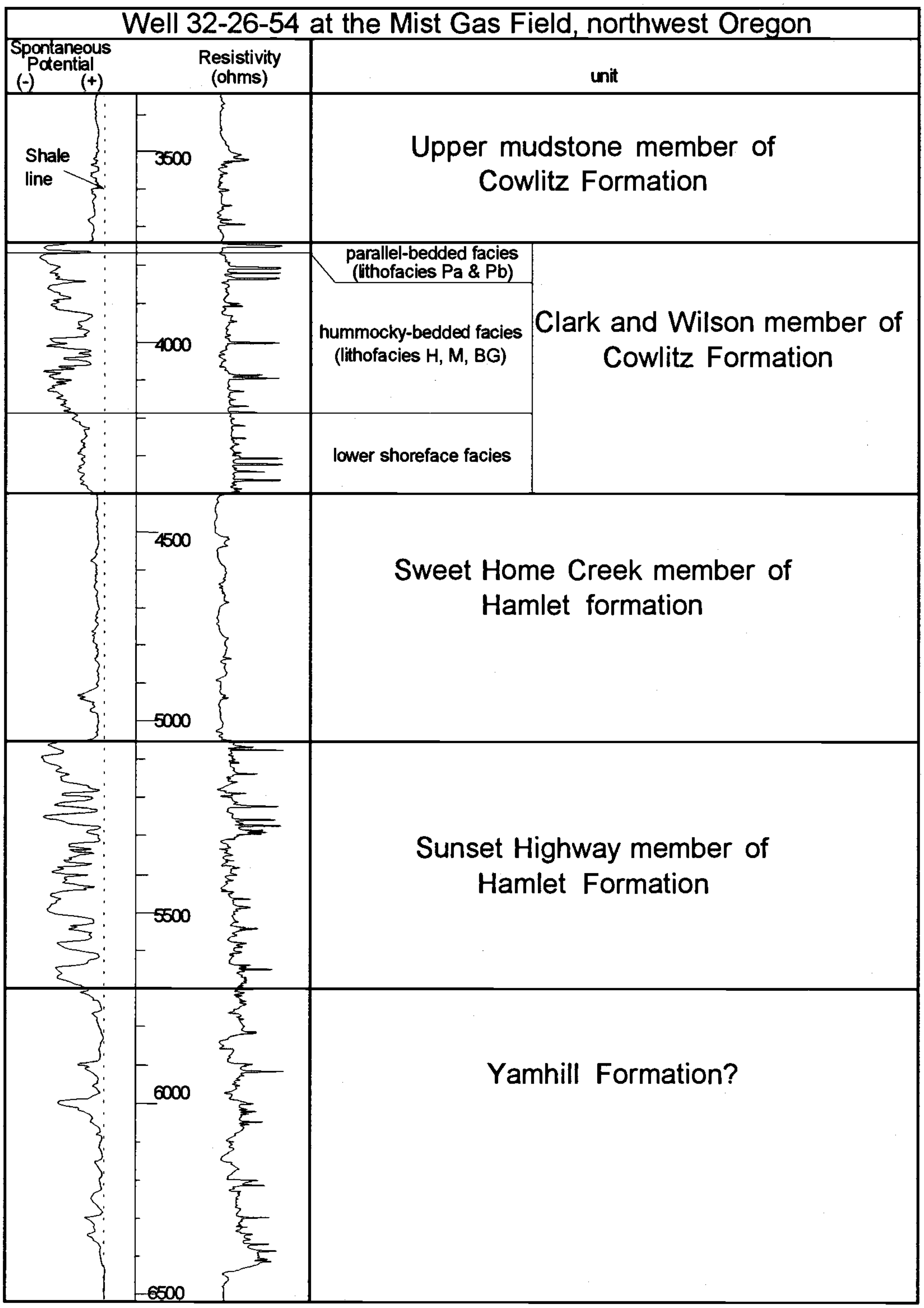


Figure 41. SP and Resistivity log curves from well 32-26-54 (sec. 26, T.5N., R.4W.), Mist Gas Field, northwest Oregon.

correlate well with surrounding wells. Criteria for each unit pick is described separately in the following sections.

After unit tops were identified in each well, unit thickness calculations were made correcting for structural dip where possible. Average structural dip, calculated using dipmeter logs from 82 wells, is 12° at the Mist Gas Field. Because, in most cases, the structural dip at the Mist Gas Field is relatively low, correction for structural dip does not change the thickness values significantly (i.e. $<3\%$). However, thickness values which are uncorrected for structural dip must be regarded with caution because they represent maximum thickness values. Deviated wellbores are another example where the apparent thickness of a unit is greater than the true stratigraphic thickness of the unit. Because thickness values that have not been corrected for wellbore deviation and/or structural dip represent maximum thickness values, they are plotted in green on the isopach maps and used with less confidence than the values, plotted in black, which have been corrected for structural dip. After thickness values were calculated and plotted, lines representing equal thickness were drawn. These isopach maps are discussed separately below.

Tillamook Volcanics

Tillamook Volcanics cuttings are medium grayish black aphanitic to vesicular basalt chips with common zeolites and calcite (Niem and Niem, 1985). Major oxide chemical analysis shows that the cuttings typically contain high percentage of TiO_2 and Fe_2O_3. These cuttings display a pilotaxitic flow structure of aligned plagioclase microlites with abundant ilmenite and titaniferous augite (Alan Niem, personal communication, 1997).

There are a few thin arkosic and basaltic sandstone and minor mudstone interbeds in the Tillamook Volcanics in the subsurface at the Mist Gas Field which Bruer and others (1984) correlated to the Yamhill Formation. Niem and others (1985) showed an upper tongue of the Tillamook Volcanics interbedded with the Hamlet formation in the southeastern part of the Mist Gas Field. Kentiz (Portland State University M.S. thesis, in preparation) correlates some of the arkosic interbeds at the top of the Tillamook Volcanics with the Sunset Highway member of the Hamlet formation. Surface workers (Jackson, 1983; Rarey, 1986; Mumford, 1988; Safley, 1989; Berkman, 1990; Wells and others, 1994) have not found arkosic sandstone between flows of the Tillamook Volcanics. However, oxidized paleosols and basaltic conglomerate have been observed. Kenitz has expanded the definition of the Hamlet formation in the subsurface to include arkosic sandstones interbedded with the Tillamook Volcanics. This interpretation suggests that Tillamook volcanism continued in the vicinity of the Mist Gas Field during deposition of the arkosic sandstones of the Sunset Highway member of the Hamlet formation.

The Tillamook Volcanics in wells at the Mist Gas Field display the following log characteristics: high (commonly off scale) resistivity log response (Figure 40); negative spontaneous potential (SP) deflection from the shale line; and lower gamma ray (GR) response than the more radioactive mica-rich and potassium feldspar-rich sandstones and mudstones of the overlying Cowlitz and Hamlet formations (Niem and Niem, 1985). The log response of the Tillamook Volcanics is similar to that of the Grays River volcanics. Kenitz (Portland State University M.S. thesis, in preparation) has found that these two basalt sequences are geochemically identical and that they can be distinguished only by stratigraphic position. The Tillamook Volcanics underlie the Hamlet formation. The Grays

River volcanics at the Mist Gas Field underlie and are interbedded with the Cowlitz Formation (Kenitz, personal communication, 1995, 1996, 1997) (Figure 40). In southwest Washington the Grays River volcanics overlie the Cowlitz Formation (Charles Payné, personal communication, 1997).

In outcrop the Tillamook Volcanics consist of over 10,000 ft of tholeitic basaltic breccia and pillow lavas overlain by differentiated alkalic subaerial flows of basaltic andesite and a few dacites (Rarey, 1986; Mumford, 1988). In the southeast part of the Mist Gas Field (Figure 41), the Tillamook Volcanics may either pinch out or interfinger with deepwater mudstone of the Yamhill Formation (Plate 6) (Niem and others, 1992). In the Clark and Wilson 6-1 well (Plate 4) in the northern part of the Mist Gas Field, Tillamook Volcanics are only 800 ft thick. This thin stratigraphic section of the Tillamook Volcanics may represent the distal flank of a submarine volcano. Alternatively, this well may penetrate a normal fault. Unfortunately this is the deepest well at the Mist Gas Field and there are no other wells to with which to compare this well.

HAMLET FORMATION

Roy Creek member

Cuttings of the Roy Creek member of the Hamlet formation in the subsurface in Clatsop County are a mixture of angular aphyric basalt fragments with rounded small pebbles of basaltic sandstone and scattered molluscan fossil shell fragments (Niem and others, 1985). In the Mist Gas Field, it is difficult to distinguish this well-lithified impermeable unit from the underlying Tillamook Volcanics lava flows based on electric log response. Resistivity log response of the unit is high and commonly off scale due to the well-indurated, calcite-cemented nature of the reworked volcaniclastic unit. Spontaneous potential log response of the Roy Creek member is variable; and GR activity is lower than that of the overlying mudstones and sandstones of the Cowlitz and Hamlet formations (Niem and others, 1985).

Sunset Highway member

Cuttings of the Sunset Highway member of the Hamlet formation consist of fine-grained micaceous arkosic and basaltic sandstone (Niem and others, 1985). Spontaneous potential log response of the Sunset Highway member is higher than that of the overlying mudstones of the Sweet Home Creek member and similar to that of the Clark and Wilson member (Figures 40 and 41). Resistivity log response of the Sunset Highway member is higher than that of the overlying Sweet Home Creek member.

The Sunset Highway member is approximately 650 ft thick in the 32-26-54 well (sec. 26, T.5N., R.4W.) in the southeastern part, 800 ft thick in the 25-33-65 well (sec. 25, T.6N., R.5W.) in the central part, and 1200 ft thick in the Clatskanie 1 well (sec. 36, T.7N., R.4W.) in the northeastern part of the Mist Gas Field of the Mist Gas Field. Surface exposures of the Sunset Highway member of the Hamlet formation in Clatsop County also thicken to the north away from the Tillamook Highlands (Nelson, 1985; Rarey, 1986; Mumford, 1988).

No isopach was created for this member because there are very few wells in the Mist Gas Field and adjacent area which penetrate the entire thickness. In the 32-10-65 (sec. 10, T.6N., R.5W.) and Clark and Wilson 6-1 (sec. 19, T.6N., R.4W.) wells, the Sunset Highway member is not present above the Tillamook Volcanics. Minor arkosic sandstone interbeds within the top of the Tillamook Volcanics in these wells may be correlative to the Sunset Highway member (Kenitz, 1997, personal communication) (Plates 5, 6, and 7). Alternatively, these volcanic units interpreted as lava flows may be reworked basaltic sandstone and/or debris flows containing clasts from the Tillamook Volcanics within the Sunset Highway member. Log response of well-indurated basaltic sandstones is similar to that of basalt flows. Well-indurated volcanic debris flows crop out within arkosic sandstone in the type section along Highway 26 (Mumford, 1988; Safley, 1989; Niem and others, 1994) an in a logging road cut in the Wolf Creek drainage (this study).

Sweet Home Creek member

Well cuttings of the Sweet Home Creek member of the Hamlet formation are commonly micaceous, laminated, and carbonaceous. The top of the Sweet Home Creek member of the Hamlet formation is identified by a slight decrease in resistivity relative to the lower shoreface facies of the Clark and Wilson member of the Cowlitz Formation. The spontaneous potential log response of the Sweet Home Creek member is lower than that of the overlying Clark and Wilson member of the Cowlitz Formation (Figure 41; Plates 5, 6, and 7). In the 32-10-65 (sec. 10, T.6N., R.5W.) and the Clark and Wilson 6-1 (sec. 19, T.6N., R.5W.) wells, the Sweet Home Creek member underlies the Grays River volcanics and is identified by a sharp decrease in resistivity (Plates 6 and 7).

An isopach map of the Sweet Home Creek member was created based on the 12 wells which penetrate the entire unit (Plate 8). The limited number of wells which penetrate the Sweet Home Creek member makes correlation difficult within the unit. The Sweet Home Creek member maintains an average thickness of approximately 975 ft in the northern part of the Mist Gas Field (T.6N., R.4.W.; T.6N., R.5.W.; T.6N., R.6.W.) and thins to 643 ft towards the southeast (T.5N., R.4.W.). The thinning of this unit to the south may be due to effects of the Tillamook Volcanic high on the depositional pattern of these deep-marine mudstones.

Previous workers (Bruer and others, 1984; Niem and Niem, 1985) reported an unconformity due to the apparently abrupt lithologic change in logs and in outcrop between these two formations. However, this study has found no evidence of channelization of the Clark and Wilson sandstone into the Sweet Home Creek member at the Mist Gas Field. This study interprets the contact between the Sweet Home Creek member and the Clark and Wilson member of the Cowlitz Formation to be, in part, gradational and conformable (see discussion of Clark and Wilson member of Cowlitz Formation).

GRAYS RIVER VOLCANICS

Cuttings of the Grays River volcanics are medium grayish black porphyritic to vesicular and amygdaloidal basalt chips with common zeolites and calcite. Resistivity log response of the Grays River volcanics is high and commonly off scale (Figure 40, Plate 7). Spontaneous potential log response commonly shows a negative deflection from the shale line. These characteristics are similar to the Tillamook Volcanics.

Kenitz (Portland State University M.S. thesis, in preparation) unsuccessfully attempted to geochemically differentiate the Grays River volcanics from the Tillamook Volcanics using major oxides, trace elements and rare elements. However, his analyses showed that the two volcanic units are geochemically identical and can be distinguished only on the basis of stratigraphic position and source. There are at least 17 distinct basalt flows in the subsurface at the Mist Gas Field which have Tillamook/Grays River chemistry (Kenitz, personal communication, 1997). The northward-thinning "flows" in the lower part of the Hamlet formation are assigned to the Tillamook Volcanics. The flows in the upper part of the Hamlet formation and in the Cowlitz Formation which thin to the south are assigned to the Grays River volcanics. The Champlin well next to the Columbia River, north of the Mist Gas Field encountered several thousand feet of the basalt which crops out in southwestern Washington. A gravity high a few miles to the north of the Mist Gas Field may reflect this volcanic center (Figure 5).

There is one major series or group of flows which occurs at the sequence boundary between the Cowlitz and Hamlet formations. This tongue of the Grays River basalt at the base of the Cowlitz Formation is approximately 470 ft thick in the Clatskanie 1 well (sec. 36, T.7N., R4W.) and 520 ft thick in the 32-10-65 well (sec. 10, T.6N., R.5W.) (Figure 40) at the Mist Gas Field. Fifty-eight wells in the northern part of the Mist Gas Field (secs. 1-12, T.6N., R.5W.; sec. 11, T.6N., R.6W.; T.7N., R.5W.; T.7N., R.4W.) penetrated this tongue of the Grays River basalt at the base of the Clark and Wilson member of the Cowlitz Formation. An additional 45 wells in the southern part of the Mist Gas Field were drilled deep enough to encounter the Grays River volcanics, if the volcanic unit was present. However, these wells encountered the Sweet Home member of the

Hamlet formation and not basalt. This observation suggests that the volcanic unit thins to the south. A subsurface lithofacies map (Plate 9) showing the distribution and inferred southern edge of this flow series of the Grays River volcanics was created based on these well data.

The thick tongue of the grays River Volcanics directly below the Clark and Wilson member of the Cowlitz Formation had a strong influence on the deposition of the lower shoreface facies and the hummocky-bedded facies of the Clark and Wilson sandstone member of the Cowlitz Formation (Plates 10, 11, and 12). There are minor flows of the Grays River volcanics in the upper mudstone member of the Cowlitz Formation (see well 44-8-64 on Plate 6). Kenitz (personal communication, 1997) has observed flows of the Grays River volcanics interbedded with arkosic sandstones of the Clark and Wilson member of the Cowlitz Formation.

The inverted bell-shaped curve in the lower-shoreface facies at the base of the Clark and Wilson member of the Cowlitz Formation and just above the Sweet Home Creek member of the Hamlet formation, reflects an increasing number of sandstone beds and fewer mudstone beds upwards in the section. This coarsening-upwards pattern reflects the conformable progradation of the Cowlitz delta-front/lower-shoreface facies over the Hamlet formation. The basal contact is unconformable where a nonconformity occurs between the Clark and Wilson sandstone and the Grays River volcanics in the northern part of the Mist Gas Field (Figure 40, Plate 7). The Clark and Wilson sandstone units appear to unconformably onlap the Grays River volcanics. This unconformable to conformable contact fits the definition of a sequence boundary of Van Wagoner and others (1993).

COWLITZ FORMATION

Clark and Wilson sandstone

In the Mist Gas Field, cuttings of the Clark and Wilson sandstone consist of fine-grained, micaceous, arkosic sandstone mixed with minor laminated dark gray siltstone and lignite chips. The top contact of the Clark and Wilson member with the overlying upper mudstone member of the Cowlitz Formation is identified by a sharp positive deflection of spontaneous potential log response. The gradational base of the Clark and Wilson member is picked at the base of a funnel-shaped log sequence. At the base of this coarsening-upwards sequence there is a gradual decrease in spontaneous potential (negative deflection from the shale line) and a slight decrease in resistivity.

At the Mist Gas Field, three facies of the Clark and Wilson sandstone have been identified and correlated: the lower shoreface facies, the hummocky-bedded facies (lithofacies H, BG, M, B), and the parallel-bedded facies (lithofacies Pa and Pb). These three lithofacies assemblages have similar electric log responses and distinctive 3-dimensional geometries defined by isopach maps. Data presented in the chapter on Lithofacies of the Cowlitz Formation in Bruer and Flora Gas Storage Pools, Mist Gas Field (Plate 3) and in Berkman's 1990 core study are used to relate lithology and environmental interpretation to electric log character.

The lower shoreface facies is a gradual coarsening- and thickening-upwards sequence. This unit consists of mainly siltstone beds at the base and mainly sandstone beds at the top (Figure 40; Plates 5, 6, and 7). There is a slight decrease in resistivity at the base of this unit which defines the contact between the Clark and Wilson member of the Cowlitz Formation and the underlying mudstones Hamlet formation. The upper contact of this unit is identified on the spontaneous potential log where sandstone begins to dominate over siltstone.

The lower shoreface facies abruptly pinches out against the Grays River volcanics (Plates 7 and 10) and is an average of 180 ft thick where the thick tongue of Grays River volcanics pinches out to the south.

The hummocky-bedded facies (lithofacies H, M, BG, B) of the Clark and Wilson member consists of hummocky-bedded sandstone with minor coastal marsh lignite and laminated siltstone beds (See Lithofacies of the Cowlitz Formation in Bruer and Flora Gas Storage pools, Mist Gas Field chapter). This middle to upper shoreface unit overlies the lower shoreface facies and the log top of this unit is picked at the base of a laterally continuous siltstone, or marine flooding surface (lithofacies Pa), that shows an abrupt positive spontaneous potential log increase (Figures 40 and 41; Plates 5, 6, and 7). Individual sandstone-dominated units in this facies show a blocky to thinning-upwards to coarsening-upwards spontaneous potential log response.

An isopach map of this lithofacies assemblage suggests a broad lobate geometry (Plate 12) which thins rapidly onto the Eocene Grays River volcanic paleohigh. This unit also appears to thin to the south. This southward thinning may reflect increased distance from the source of the sediment (i.e. southwest Washington). The smooth, broad, sheet-like geometry of this unit is interpreted to reflect intense reworking and lateral spreading of a distributary mouth bar to delta-front shoreface sandstone by storm waves and longshore currents (Figure 42). Minor shelter from wave action may have been provided by the Grays River volcanics.

The uppermost subunit of the Clark and Wilson sandstone is the parallel-bedded facies. This facies overlies a thin, but laterally continuous, bioturbated siltstone interval or marine flooding surface (lithofacies Pb; see Core description and lithofacies of IW 22D-10 core), and underlies the upper mudstone member (Figures 40 and 41; Plates 5, 6, and 7). In the IW 22D-10 core, the parallel-bedded facies consists of parallel-bedded micaceous arkosic sandstone (lithofacies Pa) which overlies a laterally continuous siltstone interval (lithofacies Pb). Lithofacies Pa has a blocky-shaped spontaneous potential log response. There is a sharp deflection towards the shale line in lithofacies Pb (Figures 40 and 41). Significant stratigraphic changes occur in this unit of the Clark and Wilson member. In the 44-8-64 well (sec. 8, T.6N., R.4W.) electric and driller's logs suggest that this interval contains abundant siltstone. The siltstone may represent flood plain or coastal lagoon overbank deposits. In the main distributary channel, a coarse-grained facies may be present. Northwest Natural Gas is preparing to core the parallel-bedded facies in several wells in the Calvin Creek Storage area (secs. 22 and 23, T.6N., R.5W.) in Summer, 1997 (Jack Meyer, personal communication, 1997). Study of these cores may provide additional insight into the lithologic changes which occur in the parallel-bedded sandstone facies of the Clark and Wilson member.

The isopach map of the parallel-bedded facies (Figure 42, Plate 13) has a 3-dimensional morphology similar to other ancient (San Miguel and Dunvegan Formations) and modern (Senegal River delta) wave-dominated deltas (Bhattacharya and Walker, 1992). Isopach map of this unit (Plate 13) shows that there is a thick, shore-parallel

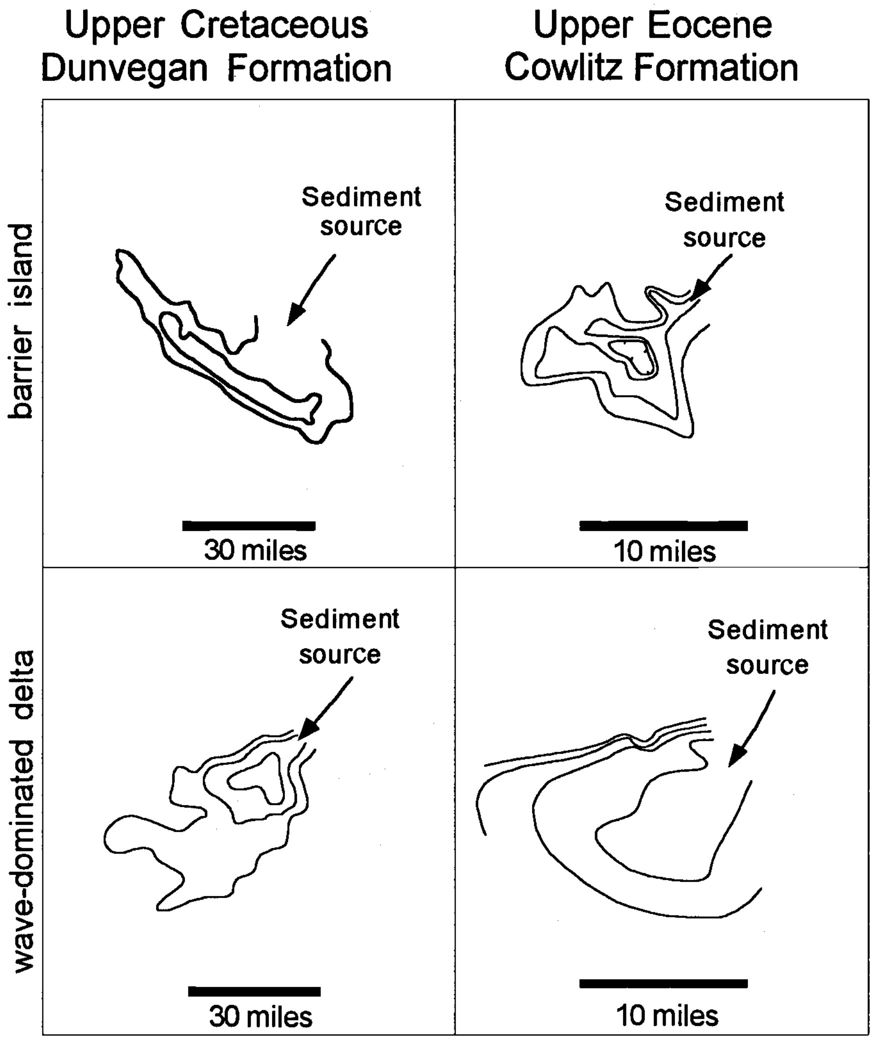


Figure 42. Schematic comparison of isopach maps of the upper Cretaceous Dunvegan Formation (after Bhattacharya and Walker, 1992) and upper Eocene Cowlitz Formation delta morphologies. Note lobate geometry of wave-dominated deltas (hummocky-bedded facies) and reworked shore-parallel sandstone bars created by more intense reworking of sediment (parallel-bedded facies).

sandstone bar which is oriented perpendicular to the distributary channel of this unit. This sandstone bar is interpreted to be a barrier bar which was formed by intense reworking of the sediment by storm waves and longshore current. The Grays River volcanic high, which provided some shelter to the hummocky-bedded facies was probably covered with sediment by the time the parallel-bedded facies was deposited. Thus, sediment of the parallel-bedded facies was not protected from storm waves. The study of more numerous and widely spaced cores is necessary in order to gain more insight into the depositional setting of this unit.

An important observation from the isopach map of the parallel-bedded facies is that the distributary channel is oriented northeast-southwest. This suggests that arkosic sandstone was transported from southwest Washington. This isopach map is the first direct evidence that shows a genetic relationship between the Cowlitz Formation in Oregon and the type Cowlitz Formation that crops out in southwest Washington. Charles Payne (Oregon State University M.S. thesis, in preparation) noted that thick fluvial and estuarine sandstone facies dominate the 3000 ft thick Cowlitz Formation type locality in southwest Washington (Charles Payne, personal communication, 1997). Bidirectional paleocurrent indicators in the estuarine facies of the Cowlitz Formation indicate northeast-southwest flow. The greater thickness of sediment and shallower paleo water depths in southwest Washington suggest that the Washington strata was more proximal to the source of sediment.

Upper mudstone member

Cuttings of the upper mudstone member of the Cowlitz Formation consist of dark gray micaceous mudstone and some laminated mudstone chips. The resistivity and spontaneous potential log response of the upper mudstone member form a straight railroad-track signal compared to the sandstone of the Clark and Wilson member. The contorted siltstone facies has similar log response to the parallel laminated sandstone facies of the upper mudstone member. Resistivity and spontaneous potential log response of this unit is similar to that of the Keasey Formation (Figures 40 and 41; and Plates 5, 6 and 7). The contact between the Cowlitz and Keasey formations can be identified by an abrupt increase in gamma ray log activity at the unconformable base of the Keasey Formation (see well 33-9-65 on Plate 7). Lira (1990) interpreted this increase in GR activity to reflect the increase in abundance of mica in the Cowlitz Formation. X-ray diffraction analyses of the upper mudstone member of the Cowlitz Formation and tuffaceous siltstone at the base of the Keasey Formation confirm this abrupt change in mineralogy (see Petrologic analysis of IW 22D-10 Core, Mist Gas Field chapter). Radioactive glauconite occurs at the boundary between the Hamlet and Keasey formations in Clatsop County where a similar increase in gamma ray activity is observed by Niem and others (1985). The gamma ray log is a very useful tool in identifying the top of the Cowlitz Formation; however, this log was not run in most of the exploration wells at the Mist Gas Field.

At the Mist Gas Field, McKeel (1983) identified the Keasey-Cowlitz boundary using the biostratigraphic boundary between the Narizian and Refugian Foraminiferal stages. However more recent work (Lira, 1991; this study) has demonstrated that the lithologic boundary between the Keasey and Cowlitz formations does not correspond to the Narizian-Refugian boundary (see Core description and lithofacies of IW 22D-10 core, Mist Gas Field chapter).

The thickness of the upper mudstone member is highly variable due to erosion and redeposition, possibly related to extensional or normal faulting and the unconformity at the base of the overlying Keasey Formation. This unconformity appears to be strongly influenced by the tectonic event which occurred at the end of the Narizian, prior to deposition of the tuffaceous marine Keasey Formation (Figure 26) (Niem and others, 1994; Jack Meyer, personal communication, 1997). These northwest-, north- and northeast-trending faults, observed on seismic reflection profiles and structure contour maps, do not appear to significantly offset the overlying Keasey and younger strata above the unconformity. Minor oblique-slip and strike-slip reactivation of some of these faults has occurred based upon surface mapping by Niem (in Niem and others, 1994; Niem unpublished data).

Near the top of the upper mudstone member, there is a 160 ft thick glauconitic, micaceous, arkosic sandstone which is present in only a few wells at the Mist Gas Field. Bruer and others (1984) refer to this sandstone as the Crown sandstone, presumably after the Crown Zellerbach #4 well (sec. 36, T.5N., R.4W.), which first penetrated the sandstone. The sandstone is thought to be preserved in this well because it was faulted down into a graben and protected from erosion (Jack Meyer, personal communication, 1997). Another possibility is that the sandstone is redeposited Clark and Wilson sandstone which was eroded and transported due to the extensional faulting that occurred near the end of the Narizian. Berkman (1990) also described a several foot-thick glauconitic arkosic sandstone near the base of the Keasey Formation. In outcrop, this glauconitic sandstone directly overlies the arkosic sandstone of the Clark and Wilson member of the Cowlitz Formation. At this locality the entire upper mudstone member is missing and has presumably been removed by the erosional event which reworked the glauconite. McDougall (written and personal communication, 1997) has reported glauconite residue (sample IW 22D-10 2000.2 ft) in the redeposited contorted siltstone facies of the upper mudstone member of the Cowlitz Formation.

An isopach map of the upper mudstone member of the Cowlitz Formation was not created for several reasons. The Keasey Cowlitz lithologic boundary cannot be identified in most of the wells where the gamma ray log was not run. The Narizian-Refugian boundary, which has previously been used by subsurface workers (McKeel, 1983) to define the formational boundary does not correspond to the lithologic boundary between the tuffaceous mudstone of the Keasey Formation and micaceous mudstone of the Cowlitz Formation. Additionally, the thickness of the mudstone member is intimately linked to the structural development of the Coast Range. This problem should be addressed as part of a subsurface structural study of the Mist Gas Field and not in this stratigraphic study.

GEOLOGIC HISTORY AND CONCLUSIONS

Conclusions

Analysis of surface exposures, well core and electric logs provide new insights into the depositional setting of the Cowlitz Formation. This study reinterprets the nature of the contact between the Cowlitz and Hamlet formations, establishes a genetic link between the Cowlitz Formation in northwest Oregon and outcrops of the Cowlitz Formation in Washington, illustrates changes in sand deposition and distribution within the Cowlitz Formation, and relates 3-dimensoinal distribution of the Clark and Wilson member of the Cowlitz Formation to intrabasinal volcanic units.

Bruer and others (1984) and Niem and Niem (1985) interpreted a unconformity at the base of the Clark and Wilson sandstone. These previous interpretations of an unconformity were based on the absence of the Hamlet formation between the Clark and Wilson member of the Cowlitz Formation and basalt flows in the northern part of the Mist Gas Field (Bruer and others, 1984; Niem and others, 1985; Niem and others, 1992). At the time these basalt flows were thought to be the Tillamook Volcanics; however, they are now known to be Grays River volcanics. More recent work (Kenitz, Portland State University M.S. thesis, in preparation; this study) and drilling at the Mist Gas Field has established that the Tillamook Volcanics underlie the Hamlet formation and that the Grays River Volcanics in Oregon underlie and are locally intercalated with the Cowlitz Formation. Wells in the northern part of the Mist Gas Field did not penetrate the Hamlet formation because they were not drilled deep enough.

Evidence of a conformable contact between the Hamlet formation and the Cowlitz Formation is provided by an isopach map of the Sweet Home Creek member of the Hamlet formation. The bathyal mudstone of the Sweet Home Creek member maintains a constant thickness in the central and northern parts of the Mist Gas Field both beneath the Cowlitz Formation and beneath flows of the Grays River volcanics. There is no evidence of channelization of the Clark and Wilson member of the Cowlitz Formation into the mudstone-dominated Sweet Home Creek member of the Hamlet formation. The contact between the Sweet Home Creek member and the lower shoreface facies of the Clark and Wilson sandstone is gradational as indicated by a funnel-shaped spontaneous potential log response. This trend reflects a thickening- and coarsening-upward sequence from mudstone to sandstone. The electric log response of this offshore to shoreface transition is similar to those observed in other deltaic systems that are interpreted to be conformable (Brown and Richards, 1989). In the future, coring of the lower shoreface facies of the Cowlitz Formation could provide further insight as to the nature of the contact between the Cowlitz and Hamlet formations.

The mudstone-dominated Hamlet formation onlaps the Tillamook Volcanics in the southern part of the study area. The Tillamook paleohigh was submerged by the time the Cowlitz Formation was deposited and does not influence the three-dimensional distribution of the sandstone-dominated Clark and Wilson member of the Cowlitz Formation. The Cowlitz Formation onlaps a different volcanic paleohigh, the Grays River volcanics. These observations illustrate a change in basin geometry at the sequence boundary between the two units.

The environment of deposition of the Cowlitz Formation has been debated for over 28 years. Previous studies (Timmons, 1981; Jackson, 1983; Olbinski, 1983; Farr, 1989; Berkman, 1990) of surface exposures of the Cowlitz Formation in Oregon interpreted the unit to represent a prograding storm wave-dominated shelf. No new evidence is presented to dispute this interpretation. The 3000 ft thick Cowlitz Formation in southwest Washington is interpreted to have been deposited in a subtidal to tidal deltaic coastal plain (Payne, personal communication, 1997). Bruer (1980) interpreted the Cowlitz Formation in the subsurface at the Mist Gas Field to have been deposited as a submarine fan in a deep marine strait between the two shallow marine facies that crop out to the north and the south. Berkman (1990) and Farr (1989) studied three closely spaced cores of the Clark and Wilson member of the Cowlitz Formation from the Mist Gas Field and determined that much of the sandstone-dominated Clark and Wilson member at the Mist Gas Field was deposited in a shallow-marine deltaic environment. However, this problem has not been resolved to the satisfaction of subsurface workers (Jack Meyer, personal communication, 1995, 1996, 1997).

Two subunits of the Clark and Wilson member were identified: the lower hummocky-bedded facies and the upper parallel-bedded facies. The lower facies, the hummocky bedded facies, was deposited on a storm wave-influenced shelf and thins rapidly onto the Grays River volcanics. This subunit may have been sheltered by the Grays River volcanics paleohigh. Three-dimensional geometry of the uppermost unit, the parallel-bedded facies, indicates that the sediment was reworked by storm waves and longshore current to form a shore-parallel bar or barrier bar. The parallel-bedded facies of the Clark and Wilson member is bracketed by mudstones which contain trace fossils from the Cruziana ichnofacies. The geometry of this sandstone facies and the trace fossils assemblage are strong evidence that this unit was deposited on a high-energy continental shelf.

The orientation of the distributary channel indicates that micaceous arkosic sand was being transported from the northeast. Paleocurrent indicators in the southwest Washington type locality of the Cowlitz Formation suggest that the sand was dispersed to the southwest (Payne, personal communication, 1997). This is the first evidence that the Cowlitz Formation in northwest Oregon is related to the Cowlitz Formation in southwest Washington.

Previous paleoeographic reconstructions of the upper Eocene of western Oregon and Washington (Dott, 1964; Armentrout and Suek, 1985) suggested that the Cowlitz Formation in Oregon was fed by a different river system than the type Cowlitz Formation in southwest Washington. However, the orientation of the distributary channel mapped in this subsurface study is a strong indication that the Oregon and Washington strata are actually part of the same depositional system (Figure 43). The thicker (975 m) shallow- to marginal-marine sandstone of southwest Washington was more proximal to the main point of fluvial discharge than the thinner (275 m) predominantly shelf sandstone of the Clark and Wilson member in northwest Oregon.

The abundance of potassium feldspar, muscovite, biotite and monocrystalline quartz in most Clark and Wilson sandstone samples suggests an extra-basinal provenance, i.e. the Idaho Batholith, via an ancestral Columbia River drainage system. Chlorite-altered scoreaceous basaltic sandstone interbed (lithofacies BG) that thickens and coarsens to the north within the micaceous arkosic sandstone of the Clark and Wilson member testifies to the continuing active volcanism of the Grays River volcanics during deposition of the Cowlitz Formation. This volcanism may have had an effect on the maturation of lignites and carbonaceous mudstones to form thermogenic gas. Pervasive authigenic chlorite in lithic arkoses of lithofacies BG, local calcite cement in arkoses of lithofacies H and Pa, and the laterally continuous siltstone of lithofacies Pb may represent porosity and permeability barriers which have led to the compartmentalization of porosity and permeability zones in the generally highly-friable, porous, and permeable Clark and Wilson sandstone. Minor compaction of micas and carbonaceous plant debris and potassium feldspar overgrowths have had a minor effect on the reduction of porosity and permeability of the reservoir. Minor secondary porosity is developed by partial dissolution of plagioclase feldspar grains.

GEOLOGIC HISTORY

The Narizian Hamlet formation (informal) unconformably overlies the middle Eocene Tillamook Volcanics. This deepening upwards sequence of basaltic conglomerate, arkosic sandstone with minor basaltic sandstone interbeds and bathyal mudstone represents a marine transgression. In the Mist Gas Field subsurface and in surface exposures, the mudstone-dominated Hamlet formation thins to the south toward the Tillamook Volcanics paleohigh.

Micropaleontological data from the Sweet Home Creek member of the Hamlet formation in the Clark and Wilson 6-1 well (sec. 19, T.6N., R.4W.) indicate that the unit was deposited in an open-marine environment (McKeel, 1983; Nelson, 1985; Rarey, 1986; Safley, 1989). Following onset of Grays River volcanism north of the Mist Gas Field, open circulation between northwest Oregon and southwest Washington was restricted. The tide-dominated nearshore deposits of the type Cowlitz Formation in southwest

Washington may have been, in part, protected from wave action by flows of the Grays River volcanics (Charles Payne, Oregon State University M.S. thesis, in preparation). In the Mist Gas Field, the hummocky-bedded facies of the Clark and Wilson member of the Cowlitz Formation laps onto the paleohigh formed by these lavas.

There is a sequence boundary between the Cowlitz and Hamlet formations; however, there is no evidence of a time gap or missing strata where the Cowlitz Formation overlies the Hamlet formation. The Cowlitz Formation nonconformably overlies the Grays River Volcanics. This partially conformable and partially unconformable contact is a sequence boundary.

Subsurface analysis (isopach maps and cross sections) of the Cowlitz Formation at the Mist Gas Field, using lithologic description of core, microfossil analysis, trace fossil analysis and electric logs, indicates that the Cowlitz Formation was deposited largely as reworked delta front sheet-like sandstones on a storm dominated shelf with fewer lower shoreface and marginal-marine marsh deposits.

The lowermost facies of the Clark and Wilson member is the lower shoreface mudstone-dominated facies. This unit grades upwards from mudstone-dominated offshore to lower shoreface to a wave-dominated shoreface sandstone. Both the lower shoreface facies and the hummocky-bedded facies thin rapidly onto the Grays River volcanics paleohigh. Sedimentary structures in the hummocky-bedded facies of the Clark and Wilson member at the Mist Gas Field suggest significant reworking of the delta front sands by storm waves and longshore current.

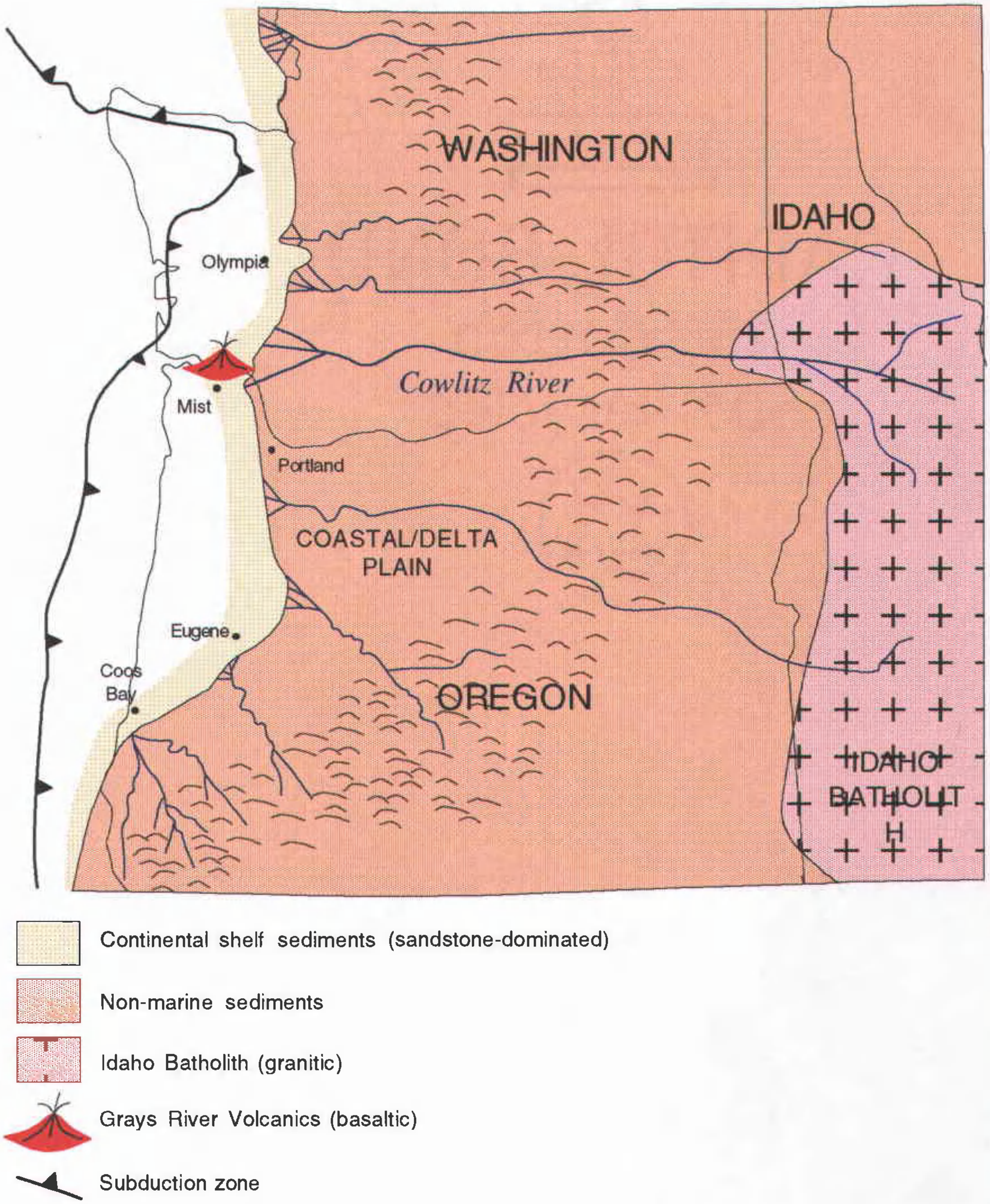


Figure 43. Paleogeographic reconstruction of the late Eocene shoreline of Oregon and Washington. Modified after Dott (1964) and Armentrout and Suek (1985). Location of subduction zone and Idaho Batholith are from Christiansen and Yeats (1992).

During deposition of the Clark and Wilson sandstone, much of the Grays River volcanic high was buried and a change in sand distribution occurred. At the transition from the hummocky-bedded facies (lithofacies H, M, BG, and B) to the parallel-bedded facies (lithofacies Pa and Pb), wave action increased. The increase in wave action may be related to the submergence of the Grays River volcanics paleohigh.

A rapid marine transgression followed the deposition of the Clark and Wilson sandstone. In northwest Oregon a basal mudstone conglomerate lag at the sharp contact of the shallow-marine parallel-bedded facies and the bathyal upper mudstone member reflects a significant marine flooding event, perhaps related to a eustatic sea level rise or local tectonics. The deepest water fossil assemblage observed in this study is middle bathyal (McDougall, personal communication, 1997). At or near the Refugian/Narizian boundary there was a regional tectonic event. In the IW 22D-10 core at the Mist Gas Field, the slump-folded, contorted facies at the top of the upper mudstone member of the Cowlitz Formation contains redeposited middle bathyal Narizian microfossils within a upper bathyal Refugian microfossil assemblage (McDougall, personal communication, 1997). Lithologically, this unit is similar to the Cowlitz Formation, although it contains benthic foraminifera, which are correlative to the Keasey Formation. The soft sediment slumping which recycled the Narizian microfossils took place at or near the beginning of the Refugian, prior to deposition of tuffaceous siltstone of the Keasey Formation. This intraformational unconformity, or tectonically-forced sequence boundary, may be related to the development of the western Cascade calcalkaline volcanic arc to the east.

Deposition of the tuffaceous Keasey Formation marks the onset of extensive western Cascade volcanism. Between the Keasey and Cowlitz formations there is a pronounced unconformity which may be strongly influenced by the complex horst and graben regional fault pattern.

This study establishes the regional stratigraphic correlation of upper Eocene strata on the surface and in the subsurface of northwest Oregon. This foundation can be utilized in further studies that interpret the tectonic evolution of the Coast Range and the Mist Gas Field. Additionally, isopach maps and sandstone petrography of the Cowlitz Formation can be used as a predictive tool in the subsurface when evaluating a prospect for natural gas storage and/or natural gas potential in the northern Oregon Coast Range.

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APPENDICES

APPENDIX I

FORAMINIFERA ANALYSIS OF CORE SAMPLES BY DR. KRISTIN MCDOUGALL OF THE U.S. GEOLOGICAL SURVEY

U.S. DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

REPORT ON REFERRED FOSSILS

Stratigraphic Range late Eocene	**Shipment Number** WNGM-97-2
General Locality (state, country, ocean, etc.) Oregon	**Number of Samples** 18
Quadrangle or Area Cedar Creek 15' Quadrangle and Marshland 7.5' Quadrangle	**Region (county, province, sea, etc.)** Columbia and Washington County
Fossil Type(s) Foraminifers	**Referred By** Christina Robertson
Formation Keasey and Cowlitz Formations	**Report By** Kristin McDougall
Latitude **Longitude**	**Report Date** March 19, 1997

Project: Pacific Northwest Urban Corridor Project

Mf8912 (Field number R1-96) Sample was collected from SE1/4, NW1/4, Sec. 28, T4N, R5W.
Sample is believed to be in upper Cowlitz or basal Keasey Formation.

Benthic foraminifers
- *Bolivina pisciformis* Galloway and Morrey
- *Fursenkoina bramletti* (Galloway and Morrey)
- *Globobulimina pacifica* Beck
- *Globocassidulina globosa* (Hantken)
- *Plectofrondicularia oregonensis* Cushman, Stewart and Stewart

Planktic foraminifers
Diatoms
Radiolarians (Spumullaria)

AGE: late Eocene, late Narizian Stage
Although no age diagnostic species are present, this assemblage is probably correlative with the late Eocene, late Narizian interval in the Mist Field well 22D-10 samples Mf2924 to Mf8927.

ECOLOGY: upper bathyal (150-500 m)

REPORT NOT TO BE QUOTED OR PARAPHRASED IN PUBLICATION WITHOUT A FINAL RECHECK BY THE PALEONTOLOGIST

Mf8913 (Field Number R6-96) Sample was collected from SW1/4, SE1/4, sec. 5, T3N, R5W. Sample is from the Sweet Home Creek member of the Hamlet formation (informal names) or the upper Cowlitz Formation.

Sample is barren of microfossils.

COMMENTS: Sample is too weathered.

Mf8916 (Field Number 22D-10 at 1998.7feet) Well samples are from injection well 22D-10 which is 285 feet N and 2516 feet E of southwest corner of Sec. 10, T16N, R5W.

Benthic foraminifers

Alabamina kernensis Smith [=*A. dissonata* (Cushman and Renz)]
Allomorphina trigonia Reuss
Bolivina kleinpelli Beck
Bolivina pisciformis Galloway and Morrey
Cibicides mcmastersi Beck
Globobulimina pacifica Beck
Gyroidina condoni (Cushman and Schenck)
Gyroidina octocamerata Cushman and Hanna
Haplophragmoides deflata Sullivan
Lenticulina spp.
Nonion halkyardi Cushman
Nonionellina applini (Howe and Wallace)
Trifarina hannai (Beck)
Uvigerina cocoaensis Cushman

Diatoms
Radiolarians (Spumullaria)
Megafossil shell fragments
Sponge spicules
Fish debris

AGE: late Eocene, Refugian Stage coeval with planktic foraminiferal zones P16-P17. This age interpretation based primarily on the first appearance of *Uvigerina cocoaensis* (early Refugian, P16) and the last appearance of *Alabamina kernensis* (= *A. dissonata*, range P6a-P17).

ECOLOGY: upper bathyal (150-500 m)

Mf8917 (Field Number 22D-10 at 2000.2 feet)

Benthic foraminifers

Bolivina kleinpelli Beck
Bolivina pisciformis Galloway and Morrey
Bolivina scabrata Cushman and Bermudez
Bulimina cf. *B. instabilis* Cushman and Parker
Bulimina microcostata Cushman and Parker
Caucasina schencki (Beck)
Chilostomella oolina Schwager

Cibicides lobatulus (Walker and Jacob)
Cibicides mcmastersi Beck
Fursenkoina bramletti (Galloway and Morrey)
Globobulimina pacifica Beck
Globocassidulina globosa (Hantken)
Guttulina problema d'Orbigny
Gyroidina condoni (Cushman and Schenck)
Lagena becki Sullivan
Lagena costata (Williamson)
Lagena hexagona (Williamson)
Lenticulina inornata (d'Orbigny)
Lenticulina spp.
Nodosaria spp.
Nonion halkyardi Cushman
Nonionellina applini (Howe and Wallace)
Plectofrondicularia oregonensis Cushman, Stewart and Stewart
Plectofrondicularia packardi Cushman and Schenck
Pseudonodosaria inflata (Costa)
Quinqueloculina imperialis Hanna and Hanna
Robertina washingtonensis Beck
Spiroloculina texana Cushman and Elllisor
Trifarina hannai (Beck)
Uvigerina cocoaensis Cushman
Uvigerina garzaensis Cushman and Siegfus
Valvulineria jacksonensis welcomensis Mallory

Diatoms (pyrite)
Radiolarians (Spumullaria)
Megafossil shell fragments
Echinoid spines

AGE: late Eocene, near the Narizian/Refugian Stage boundary coeval with the boundary between planktic foraminiferal zones P15/P16.
This age interpretation is based on the presence of species restricted to the Narizian (*Bulimina microcostata, B.* cf. *B. instabilis*) or to the Refugian (*Uvigerina cocoaensis*).

ECOLOGY: upper middle bathyal (500-1500 m) and upper bathyal (150-500 m).
The assemblage is mixed; upper middle bathyal species compose approximately 50% of the fauna and include the species restricted to the Narizian, whereas the upper bathyal species which are less abundant, include species restricted to the Refugian. This faunal mixture suggests initial deposition at upper middle bathyal depths during the Narizian. Reworking and redeposition occurred in the early Refugian at upper bathyal depths following a decrease in sea level (sea level curve drop near P15/P16 boundary).

Mf8918 (Field Number 22D-10 at 2010.4 feet)

Benthic foraminifers

Bathysiphon eocenica Cushman and Hanna
Bulimina cf. *B. instabilis* Cushman and Parker

Bulimina microcostata Cushman and Parker
Bulimina sculptilis Cushman
Cibicides fortunatus Martin
Dentalina communis (d'Orbigny)
Dentalina cf. *D. dusenburyi* Beck (small)
Eggerella subconica Parr
Globocassidulina globosa (Hantken)
Gyroidina condoni (Cushman and Schenck)
Haplophragmoides deflata Sullivan
Lenticulina spp.
Lenticulina welchi (Church)
Marginulina subbullata Hantken
Nodosaria longiscata d'Orbigny
Nodosaria spp.
Planularia tolmani Cushman and Simonson
Plectofrondicularia packardi Cushman and Schenck
Quinqueloculina goodspeedi Hanna and Hanna
Spiroloculina texana Cushman and Ellisor
Stilostomella advena (Cushman and Laiming)
Uvigerina garzaensis Cushman and Siegfus
Valvulineria jacksonensis welcomensis Mallory

Planktic foraminifers
Megafossil shell fragments
Echinoid spines
Fish debris

AGE: late Eocene, Narizian Stage coeval with planktic foraminiferal zone P15

This age interpretation is based on the range of *Plectofrondicularia packardi* (late Narizian to early Oligocene), and *Valvulineria jacksonensis welcomensis* (early Narizian to Refugian) and the last appearance of *Bulimina microcostata* (late Narizian), *B.* cf. *B. instabilis* (late Narizian), and *Lenticulina welchi* (late Narizian).

ECOLOGY: upper middle bathyal (500-1500 m)

Mf8919 (Field Number 22D-10 at 2017.0 feet)

Benthic foraminifers

Bathysiphon eocenica Cushman and Hanna
Boldia hodgei (Cushman and Schenck)
Bolivina kleinpelli Beck
Bulimina cf. *B. instabilis* Cushman and Parker
Bulimina microcostata Cushman and Parker
Dentalina consobrina d'Orbigny
Globobulimina pacifica Beck
Globocassidulina globosa (Hantken)
Gyroidina condoni (Cushman and Schenck)
Haplophragmoides deflata Sullivan
Lenticulina spp.

Lenticulina welchi (Church)
Marginulina spp.
Nodosaria longiscata d'Orbigny
Nodosaria pyrula d'Orbigny
Nonion halkyardi Cushman
Plectofrondicularia minuta Sullivan
Plectofrondicularia packardi Cushman and Schenck
Spiroloculina texana Cushman and Ellisor
Stilostomella advena (Cushman and Laiming)
Stilostomella lepidula (Schwager)
Valvulineria jacksonensis welcomensis Mallory
Valvulineria cf. *V. tumeyensis* Cushman and Simonson

Planktic foraminifers
Radiolarians (Spumullaria)
Megafossil shell fragments
Fish debris

AGE: late Eocene, Narizian Stage coeval with planktic foraminiferal zone P15
This age interpretation is based on the range of *Plectofrondicularia packardi* (late Narizian to early Oligocene), *Valvulineria jacksonensis welcomensis* (early Narizian to Refugian) and *V. tumeyensis* (P12-P17); and the last appearance of *Bulimina microcostata* (late Narizian), *B.* cf. *B. instabilis* (late Narizian), and *Lenticulina welchi* (late Narizian).

ECOLOGY: upper middle bathyal (500-1500 m)

Mf8920 (Field Number 22D-10 at 2030.2 feet)
Benthic foraminifers
Ammodiscus incertus d'Orbigny
Cyclammina pacifica Beck
Globobulimina pacifica Beck
Haplophragmoides deflata Sullivan
Haplophragmoides spp.
Lenticulina spp.
Plectofrondicularia packardi Cushman and Schenck
Trochammina globigeriniformis (Parker and Jones)

Megafossil shell fragments
Sponge spicules
Fish debris

AGE: probably late Eocene, Narizian Stage coeval with planktic foraminiferal zone P15
The age is based on the stratigraphic position (sample under lies late Narizian samples) and the range of the range of *Plectofrondicularia packardi* (late Narizian to early Oligocene).

ECOLOGY: upper bathyal depths (150-500 m)

Mf8921 (Field Number 22D-10 at 2040.0 feet)
Benthic foraminifers

Bulimina sculptilis Cushman
Cibicides natlandi Beck
Eponides mexicanus (Cushman)
Globobulimina pacifica Beck
Gyroidina spp.
Haplophragmoides deflata Sullivan
Haplophragmoides spp.
Lagena spp.
Lenticulina spp.
Lenticulina welchi (Church)
Plectofrondicularia packardi Cushman and Schenck
Trochammina globigeriniformis (Parker and Jones)

Echinoid spines
Plant fragments

AGE: late Eocene, Narizian Stage coeval with planktic foraminiferal zone P15
This age interpretation is based on the range of *Bulimina sculptilis* (late middle to late Eocene), *Cibicides natlandi* (Narizian), and *Plectofrondicularia packardi* (late Narizian to early Oligocene), and the last appearance of *Lenticulina welchi* (late Narizian).

ECOLOGY: upper bathyal depths (150-500 m)

Mf8922 (Field Number 22D-10 at 2050.5 feet)

COMMENTS: Sample contains rare fish debris, and rare to few arenaceous blobs and fragments which were probably once foraminifers.

Mf8923 (Field Number 22D-10 at 2060.0 feet)

Benthic foraminifers
Bolivina kleinpelli Beck
Bulimina sculptilis Cushman
Caucasina schencki (Beck)
Cyclammina pacifica Beck
Eponides mexicanus (Cushman)
Globulina gibba d'Orbigny
Gyroidina condoni (Cushman and Schenck)
? *Karreriella* spp.
Lagena becki Sullivan
Lenticulina spp.
Lenticulina welchi (Church)
Quinqueloculina goodspeedi Hanna and Hanna
Trochammina globigeriniformis (Parker and Jones)

Planktic foraminifers
Megafossil shell fragments (very worn)
Echinoid spines

AGE: late Eocene, Narizian Stage coeval with planktic foraminiferal zone P15

This age interpretation is based on the range of *Bulimina sculptilis* (late middle to late Narizian) and *Caucasina schencki* (late Eocene) and the last appearance of *Lenticulina welchi* (late Narizian).

ECOLOGY: upper bathyal depths (150-500 m)
Most of the fauna is transported from the outer shelf.

Mf8924 (Field Number 22D-10 at 2070.0 feet)
Benthic foraminifers
Alabamina kernensis Smith [=*A. dissonata* (Cushman and Renz)]
Allomorphina trigonia Reuss
Bulimina sculptilis Cushman
Eponides mexicanus (Cushman)
Globobulimina pacifica Beck
Globulina gibba d'Orbigny
Gyroidina spp.
Haplophragmoides deflata Sullivan
Haplophragmoides spp.
Lagena becki Sullivan
Lenticulina spp.
Lenticulina welchi (Church)
Nonionellina applini (Howe and Wallace)
Planularia tolmani Cushman and Simonson
Plectofrondicularia packardi Cushman and Schenck
Quinqueloculina imperialis Hanna and Hanna
Saracenaria schencki Cushman and Hobson
Trochammina globigeriniformis (Parker and Jones)
Diatoms
Radiolarians (Spumullaria)
Ostracod
Planktic foraminifers
Echinoid spines
Fish debris

AGE: late Eocene, Narizian Stage coeval with planktic foraminiferal zone P15
This age interpretation is based on the range of *Bulimina sculptilis* (late middle to late Eocene), *Plectofrondicularia packardi* (late Narizian to early Oligocene), and *Saracenaria schencki* (Narizian to Refugian); and the last appearance of *Alabamina kernensis* (= *A. dissonata*, P17), and *Lenticulina welchi* (late Narizian).

ECOLOGY: upper bathyal depths (150-500 m)

Mf8925 (Field Number 22D-10 at 2081.0 feet)
Benthic foraminifers
Allomorphina trigonia Reuss
Ammodiscus incertus d'Orbigny
Bathysiphon eocenica Cushman and Hanna

Cibicides natlandi Beck
Cyclammina pacifica Beck
Dentalina communis (d'Orbigny)
Dentalina consobrina d'Orbigny
Dentalina soluta Reuss
Eponides mexicanus (Cushman)
Globobulimina pacifica Beck
Haplophragmoides deflata Sullivan
Haplophragmoides spp.
Lenticulina spp.
Lenticulina welchi (Church)
Marginulina exima Neugeboren
Nonionellina applini (Howe and Wallace)
Planularia tolmani Cushman and Simonson
Pseudonodosaria inflata (Costa)
Quinqueloculina imperialis Hanna and Hanna
Trochammina globigeriniformis (Parker and Jones)
Vaginulinopsis saundersi (Hanna and Hanna) of Beck (1943)

Planktic foraminifers
Diatoms
Ostracods

AGE: late Eocene, Narizian Stage coeval with planktic foraminiferal zone P14 to P15
This age interpretation is based on the range of *Cibicides natlandi* (Narizian), and the last appearance of *Lenticulina welchi* (late Narizian) and *Vaginulinopsis saundersi* of Beck (1943). Although I've followed Pacific Northwest terminology, *Vaginulinopsis saundersi* is probably not correctly identified as this is an early Eocene, Penutian species. The specimens in this section are probably *V. asperuliformis* which occurs in the middle Eocene (P6b-P14).

ECOLOGY: upper bathyal depths (150-500 m)

COMMENTS: Specimens preserved primarily as siliceous molds.

Mf8926 (Field Number 22D-10 at 2089.0 feet)
Benthic foraminifers
Allomorphina trigonia Reuss
Ammodiscus incertus (d'Orbigny)
Anomalina spp.
Bathysiphon eocenica Cushman and Hanna
Cibicides natlandi Beck
Cyclammina pacifica Beck
Dentalina consobrina d'Orbigny
Eponides mexicanus (Cushman)
Globobulimina pacifica Beck
Globulina gibba d'Orbigny
Haplophragmoides deflata Sullivan

Haplophragmoides spp.
Karreriella elongata Mallory
Lenticulina spp.
Marginulina exima Neugeboren
Marginulina subbullata Hantken
Nodosaria pyrula d'Orbigny
Nonionellina applini (Howe and Wallace)
Planularia tolmani Cushman and Simonson
Quinqueloculina imperialis Hanna and Hanna
Saracenaria schencki Cushman and Hobson
Stilostomella lepidula (Schwager)
Trochammina globigeriniformis (Parker and Jones)
Vaginulinopsis saundersi (Hanna and Hanna)

Planktic foraminifers
Diatoms
Micro-mollusks
Fish debris

AGE: late Eocene, Narizian Stage coeval with planktic foraminiferal zone P14 to P15
This age interpretation is based on the range of *Cibicides natlandi* (Narizian), and the last appearance of *Karreriella elongata* (P8-P17) and *Vaginulinopsis saundersi* of Beck (1943) (P6b-P14). See notes on *Vaginulinopsis saundersi* (sample Mf8925).

ECOLOGY: upper bathyal depths (150-500 m)

Mf8927 (Field Number 22D-10 at 2100.1 feet)
Benthic foraminifers

Allomorphina trigonia Reuss
Bathysiphon eocenica Cushman and Hanna
Bolivina spp.
Cibicides natlandi Beck
Cyclammina pacifica Beck
Dentalina consobrina d'Orbigny
Eponides mexicanus (Cushman)
Globobulimina pacifica Beck
Globulina gibba d'Orbigny
Gyroidina condoni (Cushman and Schenck)
Haplophragmoides deflata Sullivan
Haplophragmoides spp.
Lenticulina spp.
Lenticulina welchi (Church)
Marginulina exima Neugeboren
Nonionellina applini (Howe and Wallace)
Planularia tolmani Cushman and Simonson
Quinqueloculina goodspeedi Hanna and Hanna
Saracenaria schencki Cushman and Hobson
Stilostomella lepidula (Schwager)

Trochammina globigeriniformis (Parker and Jones)
Vaginulinopsis saundersi (Hanna and Hanna) of Beck (1943)

Diatoms (pyrite)
Micro-mollusks
Megafossil shell fragments
Echinoid spines

AGE: late Eocene, Narizian Stage coeval with planktic foraminiferal zone P14 to P15
This age interpretation is based on the range of *Cibicides natlandi* (Narizian), and the last appearance of *Lenticulina welchi* (late Narizian) and *Vaginulinopsis saundersi* of Beck (1943) (P6b-P14).

ECOLOGY: upper bathyal depths (150-500 m)

Mf8915 (Field Number 22D-10 at 2225.3 feet)
Sample is barren of microfossils.

Mf8914 (Field Number 22D-10 at 2271.6 feet)
Sample is barren of microfossils

Mf8928 (Field Number 22D-10 at 2274.4 feet)
Sample is barren of microfossils.

Mf8929 (Field Number 22D-10 at 2293.8 feet)
Sample is barren of microfossils.

SUMMARY:

The microfossiliferous portion of the Mist Gas Field Well 22D-10 analyzed in this report was deposited in the late Eocene, Narizian and Refugian benthic foraminiferal stages coeval with planktic foraminiferal zones P15 and P16. The lower samples Mf8925 to Mf8927 may be as old as zone P14. This age interpretation is based on age diagnostic species (see included figures and discussion above).

Deposition of the fossiliferous interval occurred at upper bathyal and upper middle bathyal depths. The oldest assemblages (Mf8927 to Mf8924) overlying the basal barren samples indicate deposition occurred at upper bathyal depths (150-500 m) in a water mass with lower oxygen conditions based on the abundance of globobuliminids, mica, silica replacement, and siliceous organisms. Similar abundances have been found in modern sediments off California near the lower boundary of the oxygen minimum zone (Mullins et. al., 1985, Geology, v. 13, p. 491-494; Vercoutere et. al., 1986, Jour. Sed. Pet., v. 57, p. 709-722).

Deposition continues at upper bathyal depths through sample Mf8920, however the water depth increases in this interval. Evidence of increased depths is the rare appearance of species with upper depth limits in the upper middle bathyal biofacies. The rapidly fluctuating abundance of shelf species and their poor preservation indicates considerable transport from the shelf, particularly the outer shelf. The abundance of arenaceous species in this interval is believed to be an artifact of down slope transport moving the calcareous species to greater depths and *in situ* dissolution.

Samples Mf8919 and Mf8918 suggest deposition occurred at upper middle bathyal depths (500-1500 m) and below the oxygen minimum zone. Uvigerinids and buliminds which have upper depth limits in the upper middle bathyal biofacies dominate. Transported shelf species are common.

Although upper middle bathyal species dominate the assemblage in sample Mf8917, this assemblage is mixed and suggests deposition occurred at upper bathyal depths (150-500 m) above an unconformity (nonconformity or disconformity). The assemblage is composed of species which last appear in the late Narizian and have upper depth limits in the upper middle bathyal biofacies, and species which first appear in the early Refugian and have upper depth limits in the upper bathyal biofacies. This mixture implies deposition of the late Narizian species at upper middle bathyal depths, a period of nondeposition or erosion during which sea level dropped, and finally reworking of the late Narizian species and deposition of the early Refugian species at upper bathyal depths. Glauconite which is abundant in the residue, also indicates deposition in the upper bathyal biofacies above the oxygen minimum zone (see glauconite distribution in the Mullins et. al. and Vercoutere et. al.). Sample Mf8916 was also deposited in the upper bathyal biofacies. Late Narizian species are not present in this assemblage.

APPENDIX II

X-RAY FLUORESCENCE ANALYSIS OF TUFF BED IN THE UPPER MUDSTONE MEMBER OF THE COWLITZ FORMATION BY DR. PAUL HAMMOND OF PORTLAND STATE UNIVERSITY

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June 17, 1996

Christina Robertson
1516 La Granada Drive
Thousand Oaks, CA 91362

Dear Christina:

I enclose a copy of the analysis of your sample, 22D-10, -2076.2 ft, of pale green clayey tuff. It corresponds to my sample number PHA 96009, the first one listed on the page.

It looks like a good calc-alkaline silicic andesite in composition. Notable is its moderately high alumina content, moderate titania and phosphorus, and strikingly high trace element content in Zr, Y, and Nb. The latter two elements possibly indicate that the tuff is a product of mid-continental or mid-oceanic volcanism, not arc volcanism. The alumina content suggests that alteration/diagenesis has enriched the clay content of the tuff at the expense of alkalis and silica, but how much is not known. The titania content is not indicative of strong alteration. And there are reasonable amounts of magnesia, and alkalis. The content of Zr, Y, and Nb is more than 2x the amount, commonly more than 5x the amount, in most tuffs interbedded in the Cowlitz Fm. I can not find another tuff like it in my database. Could the tuff have been erupted from the Tillamook highlands? Possibly it's an altered basaltic tuff from the Tillamook or Grays River formations?

This is about all I can say at the present. If I see another tuff of unusual trace element content such as this one during the summer, I'll let you know.

Please let me know of the correctness of the tuff sample location. Thank you.

Have a good summer and best regards,

Paul

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Unnormalized results (weight %)

SiO2	57.07
Al2O3	20.77
TiO2	0.504
FeO	5.53
MnO	0.005
CaO	1.41
MgO	3.24
K2O	0.69
Na2O	3.43
P2O5	0.062
Total	92.71

Normalized results (weight %)

SiO2	61.56
Al2O3	22.4
TiO2	0.544
FeO	5.96
MnO	0.005
CaO	1.52
MgO	3.49
K2O	0.74
Na2O	3.7
P2O5	0.067

Trace elements (ppm)

Ni	21
Cr	10
Sc	9
V	17
Ba	13
Rb	17
Sr	140
Zr	1112
Y	90
Nb	67
Ga	39
Cu	14
Zn	133
Pb	0
Th	21

APPENDIX III

POINT COUNT DATA OF SANDSTONE AND MUDSTONE SAMPLES FROM THE COWLITZ AND HAMLET FORMATIONS IN THE IW 22D-10 CORE

sample ID	mono quartz	poly quartz	k-spar	plag	plut RF	volc RF	sandstone	shale	chert	musc	biotite	other	glauconite	carb frags	forams	laminar shale	dispersed shale	clay	calcite cement	pyrite	feldspar cement	pores	secondary porosity	fractures	total grains counted
1997.4	1		1	14		247									3		32	1		1					300
2040.0	9		3							1				34	1	252									300
2076.0																289			2		6			3	300
2104.1	15		9	2						2	1			2		217			4	14	13			21	300
2116.0	61		66	20				4		7	52			5					23	6	12	44			300
2145.0	52	13	19	14		12				8	10	2		9			153			8					300
2177.0	73	9	97	8		4			3	4	15							4	3	4	8	61	7		300
2182.7	39	7	50	20		1				5	29			81				1	7	3		50	7		300
2189.2	76	2	55	38		3		1		13	26							6	4	2		71	3		300
2200.2	60	2	69	15		1			2	7	36							1	58	11	3	29	6		300
2207.1	73		41	20		27			1	12	19			2				2	1	3	5	81	13		300
2236.1	53	3	32	17		6				7	26			5				20	20	4	54	25	28		300
2244.5	63	4	50	62		8				17	31			1				6	3	7		41	7		300
2279.7	60	2	43	35		21			1	15	39	2		9				7		3	1	58	4		300
2304.0	73	4	49	33		36			1	10	19	2		5				12	2	4		50			300
2308.3	16		4	4					8	7	4			65					192						300