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ONSHORE-OFFSHORE GEOLOGIC CROSS SECTION, NORTHERN OREGON COAST RANGE TO CONTINENTAL SLOPE

1992

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Special Paper 26

Onshore-Offshore Geologic Cross Section,
Northern Oregon Coast Range to Continental Slope

By A.R. Niem and others

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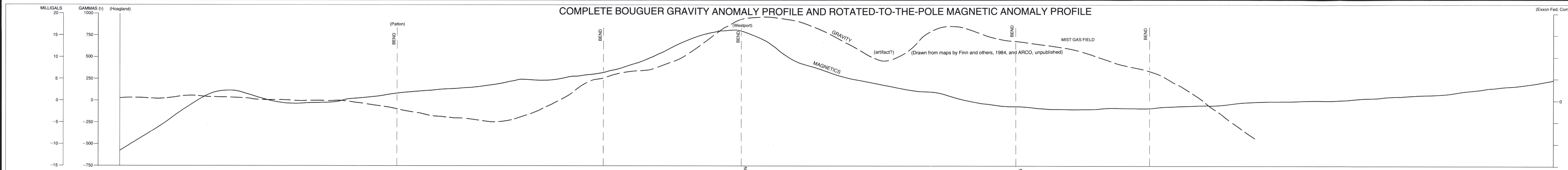
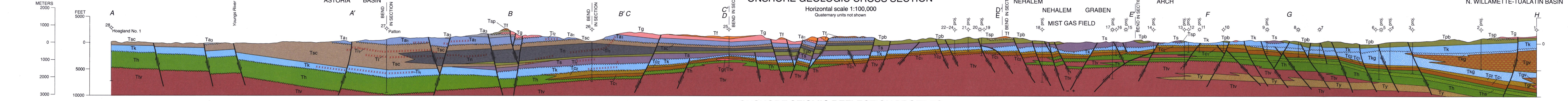
COMPLETE BOUGUER GRAVITY ANOMALY PROFILE AND ROTATED-TO-THE-POLE MAGNETIC ANOMALY PROFILE

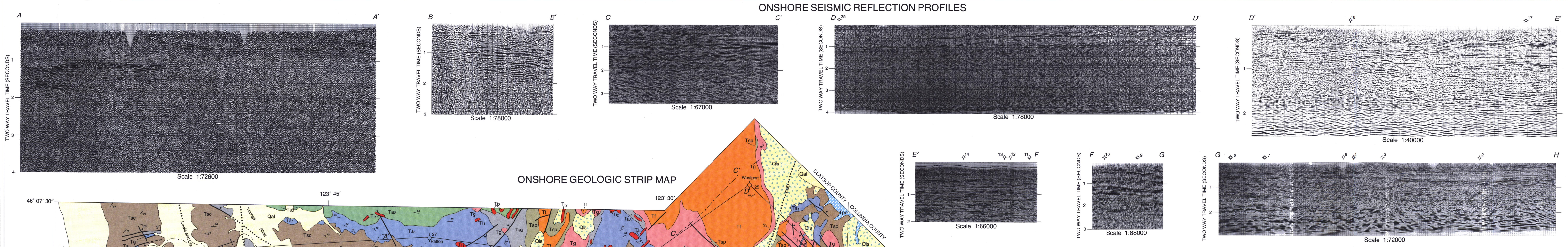


ONSHORE GEOLOGIC CROSS SECTION

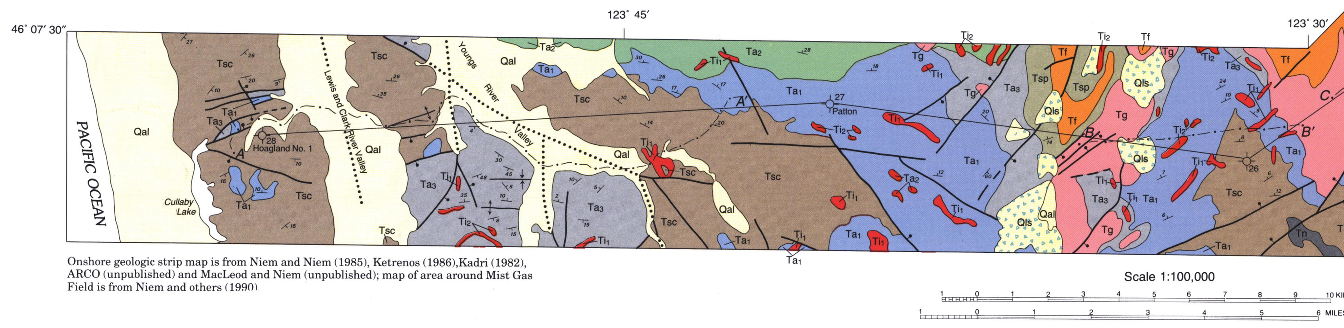
Horizontal scale 1:100,000

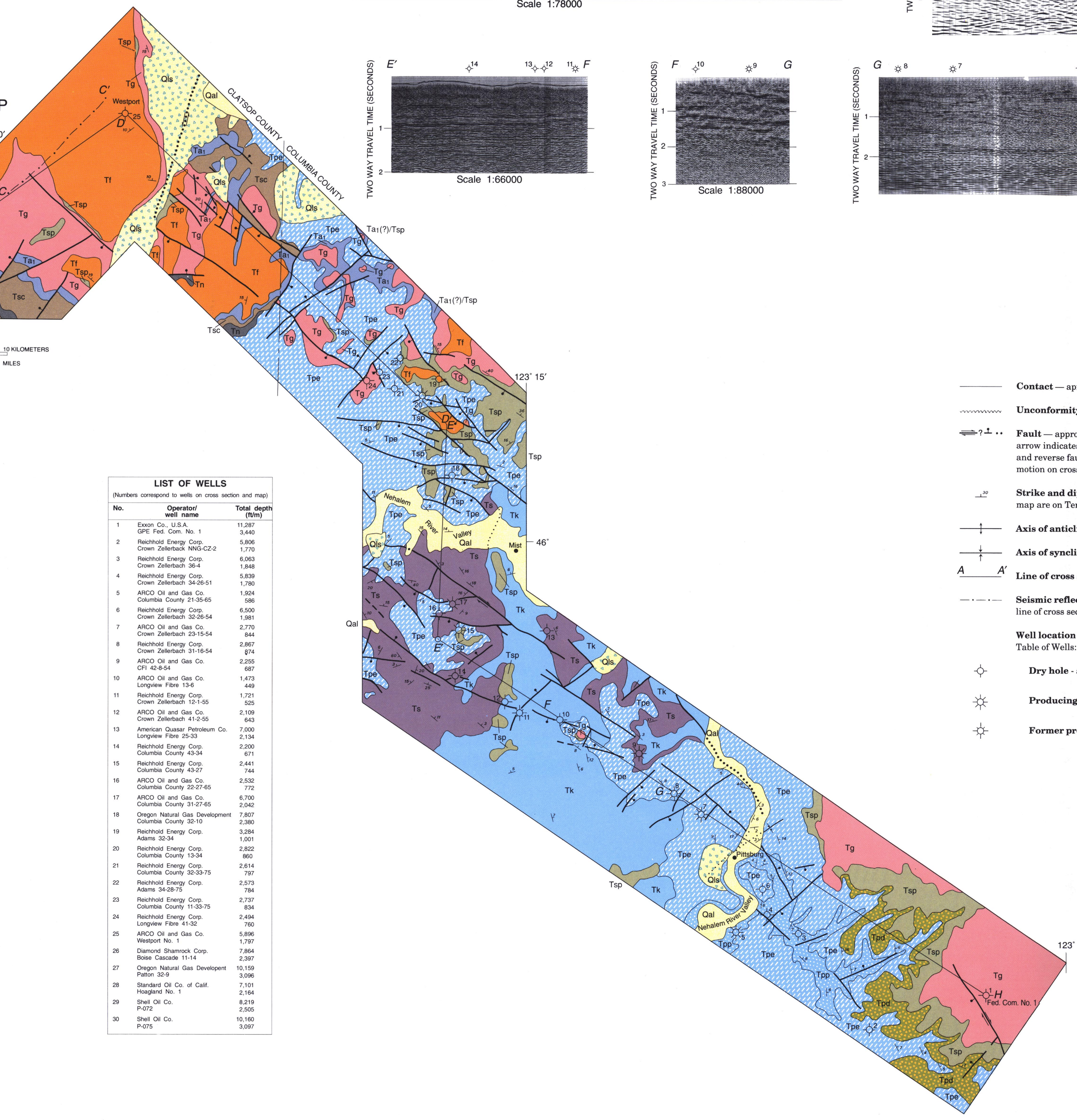


ONSHORE SEISMIC REFLECTION PROFILES



ONSHORE GEOLOGIC STRIP MAP





Onshore geologic strip map is from Niem and Niem (1985), Kelmore (1986), Kadri (1982), ARCO (unpublished) and MacLeod and Niem (unpublished); map of area around Mist Gas Field is from Niem and others (1990)

Scale 1:100,000

LIST OF WELLS

(Numbers correspond to wells on cross section and map)

No.	Operator/ well name	Total depth (ft/m)
1	Exxon Co., U.S.A. GPE Fed. Com. No. 1	11,287 / 3,440
2	Reichhold Energy Corp. Crown Zellerback NNG-CZ-2	5,806 / 1,770
3	Reichhold Energy Corp. Crown Zellerbach 36-4	6,063 / 1,848
4	Reichhold Energy Corp. Crown Zellerbach 34-26-51	5,839 / 1,780
5	ARCO Oil and Gas Co. Columbia County 21-35-65	1,924 / 586
6	Reichhold Energy Corp. Crown Zellerbach 32-26-54	6,500 / 1,981
7	ARCO Oil and Gas Co. Crown Zellerbach 23-15-54	2,770 / 844
8	Reichhold Energy Corp. Crown Zellerbach 31-16-54	2,867 / 874
9	ARCO Oil and Gas Co. CFI 42-8-54	2,255 / 687
10	ARCO Oil and Gas Co. Longview Fibre 13-6	1,473 / 449
11	Reichhold Energy Corp. Crown Zellerbach 12-1-55	1,721 / 525
12	ARCO Oil and Gas Co. Crown Zellerbach 41-2-55	2,109 / 643
13	American Quasar Petroleum Co. Longview Fibre 25-33	7,000 / 2,134
14	Reichhold Energy Corp. Columbia County 43-34	2,200 / 671
15	Reichhold Energy Corp. Columbia County 43-27	2,441 / 744
16	ARCO Oil and Gas Co. Columbia County 22-27-65	2,532 / 772
17	ARCO Oil and Gas Co. Columbia County 31-27-65	6,700 / 2,042
18	Oregon Natural Gas Development Columbia County 32-10	7,807 / 2,380
19	Reichhold Energy Corp. Adams 32-34	3,284 / 1,001
20	Reichhold Energy Corp. Columbia County 13-34	2,822 / 860
21	Reichhold Energy Corp. Columbia County 32-33-75	2,614 / 797
22	Reichhold Energy Corp. Adams 34-28-75	2,573 / 784
23	Reichhold Energy Corp. Columbia County 11-33-75	2,737 / 834
24	Reichhold Energy Corp. Longview Fibre 41-32	2,494 / 760
25	ARCO Oil and Gas Co. Westport No. 1	5,896 / 1,797
26	Diamond Shamrock Corp. Boise Cascade 11-14	7,864 / 2,397
27	Oregon Natural Gas Developent Patton 32-9	10,159 / 3,096
28	Standard Oil Co. of Calif. Hoagland No. 1	7,101 / 2,164
29	Shell Oil Co. P-072	8,219 / 2,505
30	Shell Oil Co. P-075	10,160 / 3,097

MAP SYMBOLS

Contact — aproximately located

Unconformity — (cross section only)

Fault — approximately located; dotted where concealed; ball and bar on downthrown side; arrow indicates relative offset of faults with transcurrent movement on map and of normal and reverse faults in cross section; + equals toward-, - equals away-sense of transcurrent motion on cross section

Strike and dip of bedding — attitudes in areas mapped as Quaternary deposits on geologic map are on Tertiary bedrock in exposures too small to show on map

Axis of anticline

Axis of syncline

Line of cross section

Seismic reflection line — approximately located; shown only where relatively distant from line of cross section

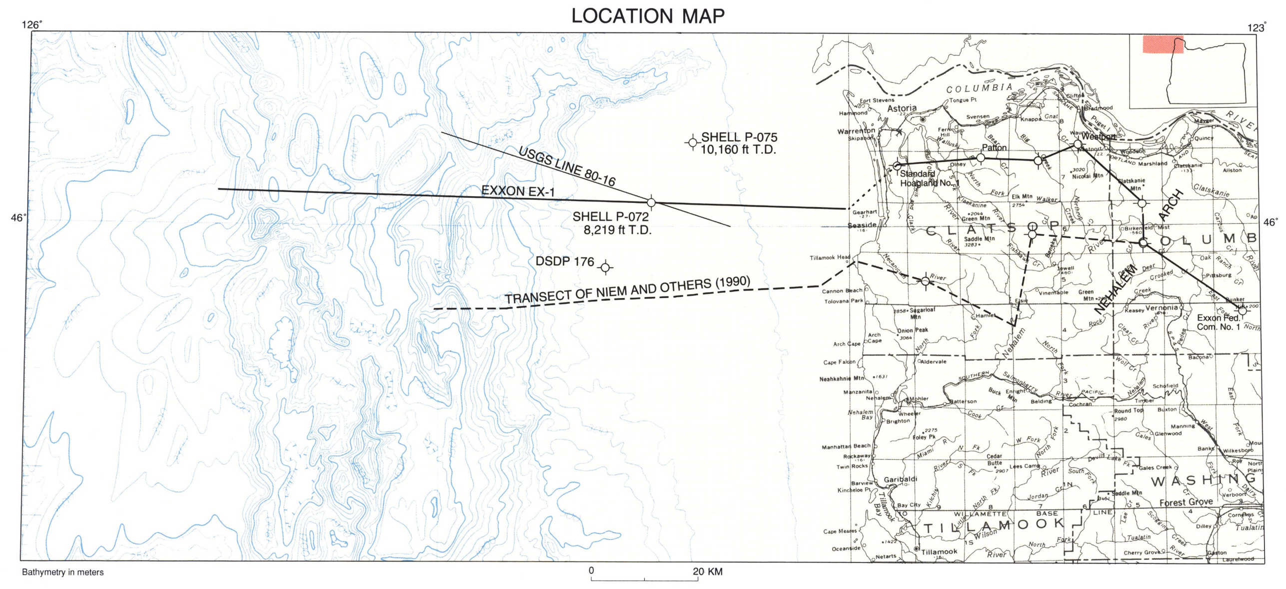
Well location — numbers identify wells on cross section and geologic map and are keyed to Table of Wells:

Dry hole - abandoned

Producing gas or capable of production

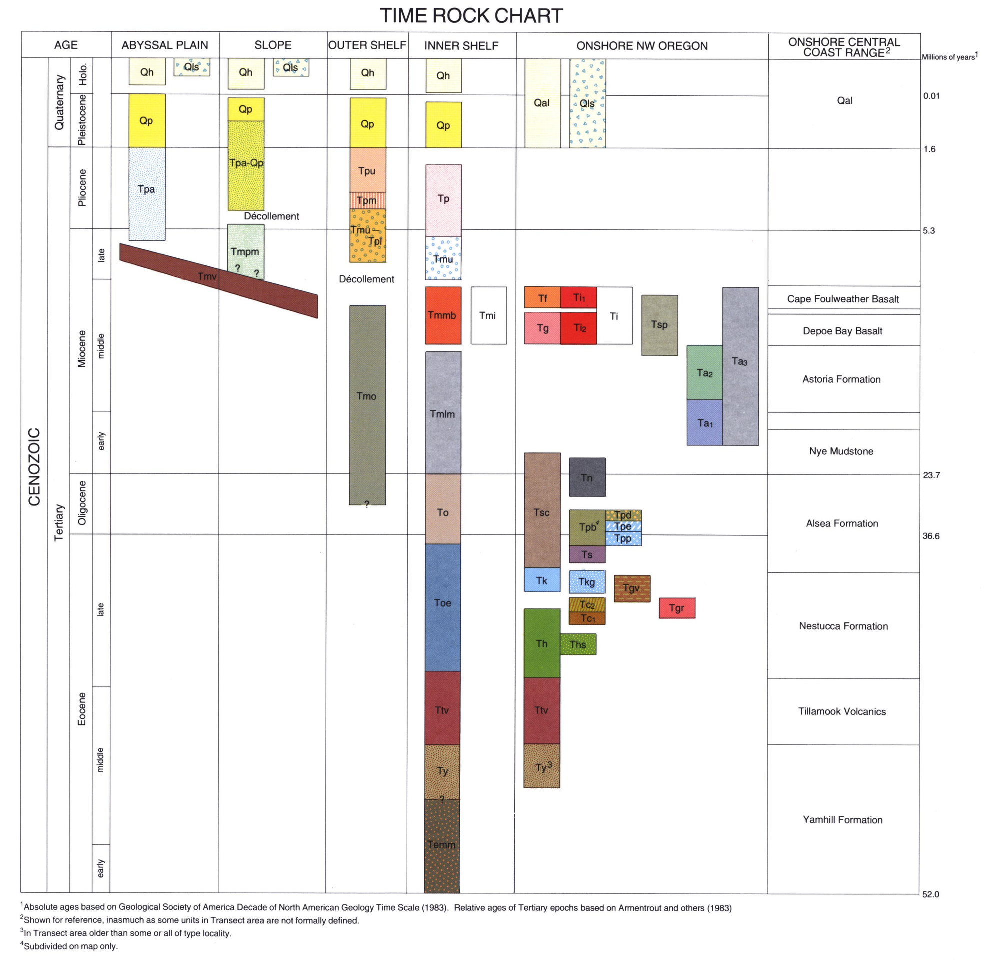
Former producer - abandoned

LOCATION MAP

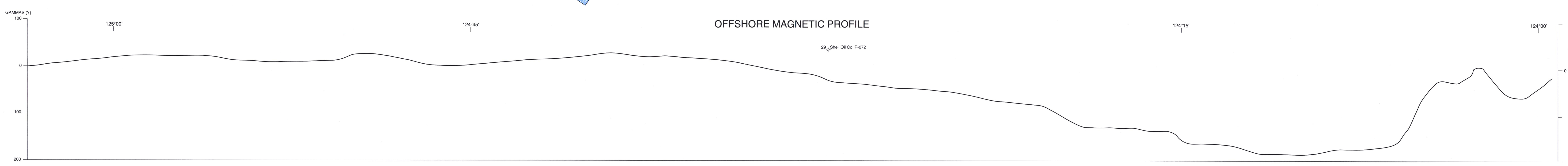


Index map showing location of this cross section (solid line) and transect of Niem, Snavely, and others, 1990 (dashed line). The two sections coincide along the short north-south line north of Mist.

TIME ROCK CHART

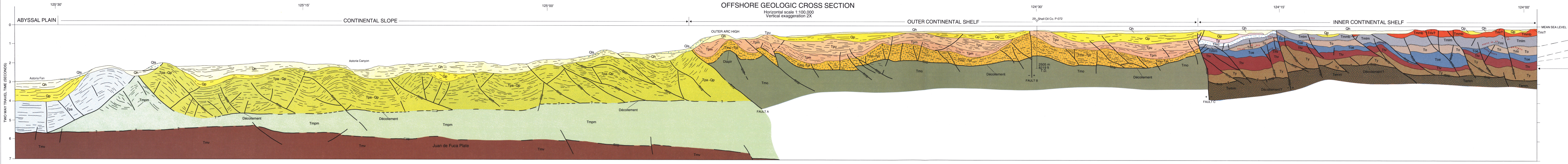


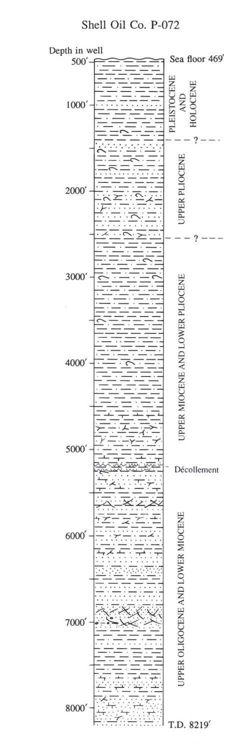
OFFSHORE MAGNETIC PROFILE



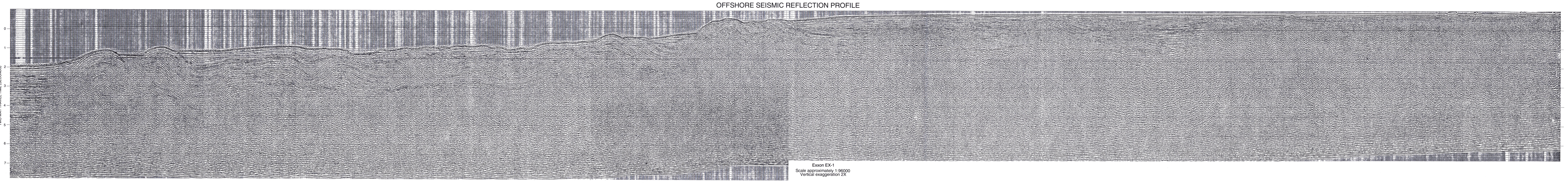
OFFSHORE GEOLOGIC CROSS SECTION

Horizontal scale 1:100,000
Vertical exaggeration 2X





OFFSHORE SEISMIC REFLECTION PROFILE



Exxon EX-1
Scale approximately 1:96000
Vertical exaggeration 2X

EXPLANATION

ONSHORE

(Modified from Niem, Snavely, and others, 1990)

Qal — **Quaternary alluvium (Holocene and Pleistocene)** — Unconsolidated gravel, sand, silt, and clay in and along stream beds; locally includes sand and gravel of low-lying stream and coastal terraces, estuarine mud and silt, and beach sand and gravel

Qls — **Landslide deposits (Holocene and Pleistocene)** — Unconsolidated chaotic deposits of Tertiary sedimentary and volcanic rocks formed as a result of bedrock failure; only larger deposits are shown

Columbia River Basalt Group

Tf — **Wanapum Basalt, Frenchman Springs Member (middle Miocene)** — Subaerial sparsely porphyritic basalt flows, pillow lava, breccia, and tuff. Locally includes interbedded sandstone and siltstone. Correlates with Cape Foulweather Basalt of Snavely, MacLeod, and others (1973)

Tg — **Grande Ronde Basalt (middle Miocene)** — Subaerial aphyric basalt flows, pillow lava, breccia, and tuff. Locally contains interbedded sandstone and siltstone. Correlates with Depoe Bay Basalt of Snavely, MacLeod, and others (1973)

Ti1, Ti2, Ti — **Intrusions (middle Miocene)** — Sills, inclined sheets, and dikes of basalt related to Wanapum Basalt (unit **Ti2**), Grande Ronde Basalt (unit **Ti1**), and undifferentiated basalt (unit **Ti**). Interpreted to result from invasion of surface flows downward into sedimentary sequence (Niem and Niem, 1985). Intrusions are abundant only where surface flows are dominantly submarine. Cross section shows only thicker sills or sills intersected in wells

Tsp — **Scappoose Formation of Van Atta and Kelty (1985) (middle Miocene)** — Weakly indurated fluvial cross-bedded micaceous arkosic sandstone, basalt conglomerate, and lacustrine mud and peat; locally interbedded with and underlying Columbia River Basalt Group; conglomerate is reported by Van Atta and Kelty (1985) to contain clasts from Columbia River Basalt Group; probably mostly younger than the Scappoose Formation of Warren and Norbisrath (1946) and Wickiup Mountain member (unit **Ta1**) of the Astoria Formation; however, may locally include Oligocene fossiliferous arkosic sandstone and mudstone; occurs in eastern half of transect, but distribution is questionable owing to poor exposures in some areas; equivalent sedimentary rocks are locally included in Columbia River Basalt Group (units **Tg** and **Tf**). In Wickiup Mountain area, Tsp includes deep-marine mudstone, minor cross-bedded basaltic sandstone, glauconitic sandstone, and basalt conglomerate (unit Tac3 of Niem and Niem, 1985)

UNCONFORMITY

Ta1, Ta2, Ta3 — **Astoria Formation (middle and lower Miocene)** — Massive to well-bedded micaceous mudstone, siltstone, and arkosic sandstone. In transect, area consists of shallow-water deposits of the Wickiup Mountain member (informal) (unit **Ta1**), channelized friable arkosic sandstone of the Youngs Bay member (informal) (unit **Ta2**), and bathyal mudstone and sandstone of the Cannon Beach member (informal) (unit **Ta3**) of Niem and Niem (1985). Absent in eastern part of area. Contains foraminiferal assemblages assigned to the Saucesian Stage of Kleinpell (1938)

UNCONFORMITY

Tsc — **Smuggler Cove formation of Niem and Niem (1985) (informal) (lower Miocene to upper Eocene)** — Thick-bedded bioturbated tuffaceous claystone and siltstone with minor thin-bedded turbidite sandstone, glauconite, and tuff beds. Contains foraminiferal assemblages assigned to the Saucesian to Refugian Stages of Kleinpell (1938)

Tn — **Northrup Creek formation of Niem and Niem (1985) (informal) (lower Miocene and Oligocene?)** — Well-bedded carbonaceous micaceous mudstone and minor fine-grained micaceous feldspathic turbidite sandstone. A channelized facies that correlates with upper part of Smuggler Cove formation (unit Tsc) of Niem and Niem (1985)

Tpb, Tpd, Tpe, Tpp — **Pittsburg Bluff Formation (Oligocene and upper Eocene)** (subdivided on map only) — Thick-bedded well-indurated tuffaceous to arkosic shallow-marine sandstone and subordinate tuffaceous siltstone-claystone, glauconitic sandstone, and pebbly mudstone. In eastern part of map area, unit is informally subdivided into units **Tpd** (Divide member), **Tpe** (East Fork and Scaponia members), and **Tpp** (Pebble Creek member), based on unpublished mapping by ARCO and Niem and MacLeod. Unit **Tpd** is formed of friable, cross-bedded, medium-grained arkosic to quartzose sandstone with minor pebble lenses and local coal beds. The underlying unit **Tpe** is formed of thick sequences of shallow-marine bioturbated fossiliferous well-indurated arkosic tuffaceous fine-grained sandstone and less common laminated siltstone (East Fork member) overlain by tuffaceous thin-bedded mudstone, siltstone, sandstone, and a distinctive pebbly mudstone or debris flow (McKnight and Niem, 1991) (Scaponia member). Basal member **Tpp** is formed of fine- to coarse-grained, cross-bedded arkosic fluvial sandstone with some pebble conglomerate, mudstone, and claystone. Pittsburg Bluff Formation correlates with the lower to middle part of the Smuggler Cove formation of Niem and Niem (1985) (unit **Tsc**). Contains foraminiferal assemblages assigned to the Refugian and Zemorrian Stages of Kleinpell (1938) (Moore, 1963)

Ts — **Sager Creek formation of Niem and Niem (1985) (informal) (upper Eocene)** — Laminated deep-marine mudstone rhythmically interbedded with thin micaceous and carbonaceous graded feldspathic sandstone; locally forms nested turbidite channel deposits. Sager Creek formation is channelized into Keasey Formation. Correlates with lower part of Smuggler Cove formation (unit **Tsc**). Contains foraminiferal assemblages assigned to Refugian Stage of Kleinpell (1938)

Tk — **Keasey Formation (upper Eocene)** — Thin- to thick-bedded tuffaceous outer-shelf to bathyal bioturbated mudstone with a few arkosic sandstone lenses, sandstone dikes, and tuff beds; locally glauconitic at base. Together with upper mudstone member of the Cowlitz Formation forms seal in the Mist Gas Field. Contains foraminiferal assemblages assigned to lower Refugian Stage of Kleinpell (1938) and uppermost Narizian Stage of Mallory (1959)

UNCONFORMITY

Tkg — **Unnamed strata (upper Eocene)** (shown only on cross section) — Tuffaceous mudstone, siltstone, and minor sandstone in subsurface of eastern part of transect. Consists of a basinward-thickening (eastward-thickening) wedge that pinches out or is cut out against overlying unconformity. Partly interfingers with Goble Volcanics (unit **Tgv**) and may be partly equivalent to Keasey Formation (unit **Tk**)

Tgv — **Goble Volcanics (upper Eocene)** (shown only on cross section) — Flows and breccia of porphyritic basalt and basaltic andesite with interbedded sandstone and siltstone. Occurs only in subsurface (east end of cross section) and may include sills and dikes. Volcanic rocks from EXXON GPE Fed. Com. No. 1 well show low-titanium chemical compositions similar to those of the subaerial and submarine flows of the Goble Volcanics near Goble, Oregon, and in southwestern Washington (Bruer and others, 1984; Phillips and others, 1989; Berkman, 1990; Niem, Snavely, and others, 1990)

Tgr — **Grays River Volcanics (upper Eocene)** (shown only on cross section) — Subaerial aphyric to pyroxene- and plagioclase-phyric tholeiitic basalt flows. Flows display columnar and platy jointing. Flow tops are weathered; basal flow breccias are oxidized red. Flows are interbedded with sandstone of the Cowlitz Formation. Grays River Volcanics are chemically, mineralogically, and texturally similar to the Tillamook Volcanics which are slightly older (Phillips and others, 1989)

Tc1, Tc2 — **Cowlitz Formation (upper Eocene)** (shown only on cross section) — Friable thick-bedded to cross-bedded shallow-marine shoreface to wave-dominated deltaic micaceous arkosic sandstone (Clark and Wilson reservoir in Mist Gas Field) (unit **Tc1**) with local coal. Sandstone is overlain by thick micaceous mudstone and minor arkosic sandstone (upper mudstone member of the Cowlitz Formation) (unit **Tc2**) that forms seal in the Mist Gas Field (Bruer and others, 1984; Niem, Snavely, and others, 1990; Berkman, 1990). Contains foraminiferal assemblages assigned to the Narizian Stage of Mallory (1959)

Th, Ths — **Hamlet formation of Niem and Niem (1985) (informal) (upper Eocene)** — Carbonaceous micaceous deep-marine mudstone with a few thin turbidite beds of graded arkosic micaceous sandstone and basaltic sandstone. Occurs only in subsurface in transect area (see Niem and Niem, 1985; Niem, Snavely, and others, 1990). Includes Clatskanie sand of Bruer and others (1984) (unit **Ths**) in subsurface (Deacon, personal communication, 1985; Niem, Snavely, and others, 1990). Lower part of unit contains basal basalt conglomerate and sandstone and overlying shallow-marine arkosic lithic sandstone (Rarey, 1986; Niem, Snavely, and others, 1990). May correlate with the Yamhill mudstone of Bruer and others (1984) but is renamed Hamlet formation based on recent mapping by Rarey (1986), Mumford (1989), and Berkman (1990). Interfingers with Tillamook Volcanics (unit **Ttv**) in some wells, but contact is unconformable at surface (Niem and Niem, 1985; Rarey, 1986; Berkman, 1990). Contains foraminiferal assemblages assigned to the Narizian Stage of Mallory (1959)

UNCONFORMITY

Ttv — **Tillamook Volcanics (upper and middle Eocene)** — Subaerial aphyric to abundantly plagioclase- and pyroxene-phyric high-titanium basalt and basaltic andesite flows. Upper part of 3,000-m-thick unit includes minor volcanic mudflow breccia, fluvial basalt conglomerate, scoriaceous tuff, and andesite and dacite flows; minor basaltic and arkosic sandstone and siltstone found within unit in subsurface near Mist. Unit includes normal and reversed polarity flows. Lower part of unit south of transect area contains submarine breccia and pillow lavas (Wells, Niem, and others, 1983). A thin unit of volcanic rocks interfingered with strata of the Hamlet formation and Cowlitz Formation and younger than the Tillamook Volcanics at the base of the well may be an extension of the Grays River Volcanics (unit **Tgr**) of southwest Washington (Wells, 1981; Phillips, 1987). Probable economic basement

Ty — **Yamhill Formation (upper and middle Eocene)** — Mudstone, siltstone, and sandstone. Occurs only in subsurface in eastern part of area. May interfinger with lower part of Tillamook Volcanics (unit **Ttv**). Formation is used here as restricted by Wells, Niem, and others (1983); Bruer and others (1984) included the lower part of the Hamlet formation of Niem and Niem (1985), which overlies the Tillamook Volcanics, within the Yamhill Formation

CONTINENTAL MARGIN

[Descriptions and ages of acoustic units are based mostly on regional correlations with units penetrated in exploratory wells and are modified from Snavely and McClellan (1987) and Niem, Snavely, and others (1990)]

Qh — **Holocene deposits** — Clayey silt; contains some interbedded turbidite sands on abyssal plain

Qls — **Landslide deposits (Holocene)** — Acoustically chaotic deposits adjacent to relatively steep slopes

Qp — **Pleistocene deposits** — Clayey silt

Tpa — **Upper Miocene(?), Pliocene, and lower Pleistocene strata** — Thin-bedded silty clay, silt, and fine sand; contains interbedded turbidite sands on abyssal plain

Tp — **Pliocene strata** — Silty clay, silt, and sand

Tpu — **Upper Pliocene strata** — Silt and fine sand on outer continental shelf

Tpm — **Pliocene strata** — Silt and clay on outer continental shelf

Tpl — **Lower Pliocene strata** — Silt and clay on outer continental shelf

Tmu — **Upper Miocene strata** — Silt and clay on continental shelf

Tmpm — **Miocene and Pliocene strata** — Fine-grained deep-water sedimentary rocks that are interpreted to form melange beneath décollement on continental slope

Tmlm — **Middle and lower Miocene strata** — Silty claystone on inner continental shelf; probably correlates with the Astoria Formation (Cooper, 1981; Niem and Niem, 1985)

Tmv — **Miocene basalt** — Submarine tholeiitic basalt of the abyssal plain; was produced at the Juan de Fuca Ridge and has spread eastward toward and beneath continental margin. Unit is older and progressively deeper toward east. Assigned to magnetic anomaly 5

Tmmb — **Middle Miocene basalt** — Basalt flows, pillow basalt, sills, and tuff; correlates with Grande Ronde (unit **Tg**) and Wanapum Basalt (unit **Tf**) onshore

Tmi — **Middle Miocene basalt intrusions** — Basalt sills and inclined sheets on inner continental shelf that produce strong reflectors. Queried unit at and near sea floor is a strong acoustic reflector that may be either sills or flows, pillows, and breccia of unit **Tmmb**. Niem, Snavely, and others (1990) have subdivided intrusions in nearby cross section according to correlative units of the Columbia River Basalt Group

Tmo — **Middle Miocene to upper Oligocene strata** — Indurated sandstone with siltstone interbeds; sheared and fractured. Interpreted as melange and broken formation; may correlate with Hoh melange and broken formation along west coast of Olympic Peninsula, Washington (Rau, 1975, 1979; Snavely and Kvenvolden, 1989)

To — **Oligocene strata** — Siltstone and mudstone. Correlates with upper part of the Smuggler Cove formation of Niem and Niem (1985) (unit **Tsc**) onshore

Toe — **Eocene and Oligocene strata** — Siltstone and mudstone on inner continental shelf; probably correlate with Hamlet formation (unit **Th**), Keasey Formation (unit **Tk**), and Smuggler Cove formation (unit **Tsc**) onshore

Ttv — **Eocene volcanic rocks** — Basaltic volcanic rocks that probably correlate with Tillamook Volcanics onshore. May also include flows or intrusions that correlate with the Cole Mountain basalt of Niem and Niem (1985)

Ty — **Eocene strata** — Siltstone and sandstone that probably correlate with Yamhill Formation (unit **Ty**) onshore

Temm — **Eocene(?) strata** — Sandstone and siltstone melange and broken formation(?). Acoustic unit below inner continental shelf décollement is interpreted to correlate with Ozette melange and broken formation of Snavely and Kvenvolden (1989) of west side of Olympic Peninsula

References cited on this sheet are listed in bibliography in accompanying text

Cartography by Paul E. Staub

Onshore-Offshore Geologic Cross Section, Northern Oregon Coast Range to Continental Slope

By Alan R. Niem[1]; Norman S. MacLeod[2]; Parke D. Snavely, Jr.[3]; David Huggins[4]; J. Daniel Fortier[5]; H. Jack Meyer[6]; Alan Seeling[7]; and Wendy A. Niem[1]

INTRODUCTION

This geologic cross section was constructed as an aid in evaluating the oil and gas potential of the Oregon continental margin. It results from cooperative efforts by geologists with several affiliations, guided by the Oregon Department of Geology and Mineral Industries and funded by the U.S. Department of the Interior, Minerals Management Service.

The cross section is one of two that go through the Mist Gas Field, Oregon, the site of the only producing gas field in the Pacific Northwest. The first section (Niem, Snavely, and others, 1990) extends across the continental margin to Mist and is mostly south of the present cross section (see index map on accompanying map sheet). Other cross sections of the continental margin of Oregon and Washington are described by Snavely and Wagner (1981, 1982); Snavely, Wagner, and others (1980, 1985); and Snavely, von Huene, and others (1986).

The geologic and geophysical data used to construct this cross section came from several sources. For the onshore parts of the cross section, subsurface data (drillers' logs, electric and gamma ray logs, synthetic seismograms, paleontologic reports, and K-Ar ages) and seismic-reflection profiles were generously provided by ARCO Oil and Gas Co., Oregon Natural Gas Development Corp., Wexpro, EXXON Co. U.S.A., and Diamond Shamrock Corp. (now Maxus Exploration Co.). The uninterpreted seismic sections from which the onland cross section was constructed are shown at reduced scale. The western part of the geologic strip map, in Clatsop County, is from the geologic map of Niem and Niem (1985), which is partly based on earlier studies (Coryell, 1978; Nelson, 1978; Murphy, 1981; Goalen, 1988). The east end of the geologic strip map, in Columbia County, is modified from geologic mapping by ARCO Oil and Gas Co. (unpublished data), Niem and McKnight (unpublished mapping), and Kadri (1982) for areas east of the Mist Gas Field and reconnaissance mapping by N.S. MacLeod and A.R. Niem (unpublished data) and Ketrenos (1986) northwest of the Mist Field. The cross section of the Mist Gas Field is from Niem, Snavely, and others (1990) (but reversed, so that north is on left). Geologic mapping of the Mist area is by A.R. Niem (unpublished data).

The offshore continental shelf and slope part of the cross section is an interpretation by P.D. Snavely, Jr., for a multichannel seismic-reflection profile kindly provided by EXXON Co., U.S.A. That profile is shown at reduced scale. Subsurface data from the Shell Oil Co. well P-072 and a multichannel seismic-reflection profile of nearby areas by the U.S. Geological Survey (S.P. Lee cruise 11-80, line 16, Snavely and Wagner, 1983) provided supplementary data.

Onshore industry seismic lines were collected primarily by using dynamite and less commonly (western end) Vibroseis energy sources and varying arrays of digital recorders. Seismic processing included deconvolution, CDP stacking, and migration. Reflectors on the seismic lines were correlated with lithologic units in several wells on the basis of synthetic seismograms provided by ARCO Oil and Gas Co. The offshore EXXON Co., U.S.A., EX-1 seismic-reflection profile is a time section. The magnetic and gravity profiles are from geophysical maps by Finn and others (1984), U.S. Geological Survey (1984), and ARCO Oil and Gas Co. (unpublished data).

LOCATION OF CROSS SECTION

The cross section was located to coincide with the maximum amount of available geologic and geophysical data. The offshore part of the cross section is along the EXXON Co., U.S.A., multichannel seismic-reflection line EX-1. It begins at the abyssal plain and extends about 75 mi (120 km) across the continental slope and shelf through the Shell Oil Co. well P-072 to near the Oregon coast (see index map). Onshore, the cross section passes through or near many wells (see list of wells) and near industry seismic-reflection lines. It extends for 51 mi (82 km) from the Standard Oil Co. Hoagland No. 1 well eastward through several deep wells to the Mist Gas Field and then to the EXXON GPE Fed. Com. No. 1 well.

A 6-mi-long gap in seismic data (dotted on index map on accompanying map sheet) lies between the end of the EXXON EX-1 offshore seismic-reflection profile and the onshore Standard Oil Co. Hoagland No. 1 well. The geology of this segment can be tentatively extrapolated from adjacent onland areas. However, in the cross section, the offshore part is a time section and has not been velocity migrated, whereas the onshore part is a depth section. Therefore, we have not directly connected the two cross sections except to show correlation of some units. The onshore-offshore relationships of units not far to the south are shown on a continuous onshore-offshore cross section drawn by Niem, Snavely, and others (1990) for which offshore seismic data were converted to a depth section.

STRATIGRAPHY

The following sections describe the stratigraphy and structure starting at the west end of the transect and progressing eastward. The offshore and onshore descriptions necessarily differ in detail owing to the greater availability of onshore lithologic data obtained from geologic mapping, numerous exploration wells, and seismic lines (particularly in Columbia County around Mist).

The west end of the transect crosses a filled trench at the base of the continental slope. The trench marks the convergent margin between the Juan de Fuca and North American Plates, which are separated by an east-dipping subduction zone (see Figure 1).

The stratigraphy of the continental margin along the seismic-reflection profile line EX-1 is discussed in a chronostratigraphic sense because onshore formations exposed in the northern part of the Coast Range can be only tentatively correlated with offshore acoustical units. Also, some onshore formations change their lithologic characteristics seaward due to facies changes that reflect deeper water depositional environments. However, provisional correlations have been made between offshore chronostratigraphic units and onshore formations in the Oregon Coast Range (see time rock chart). The ages assigned to acoustical units along profile EX-1 are subject to change when new subsurface data are acquired.

The only stratigraphic controls for the sedimentary units along seismic-reflection profile EX-1 are lithologic descriptions and ages of strata penetrated in Shell Oil Co. well

[1]Oregon State University
[2]Consultant
[3]U.S. Geological Survey
[4]Nehama and Weagant Energy Co.
[5]ARCO Oil and Gas Company
[6]Oregon Natural Gas Development Corp.
[7]Maxus Exploration Co.

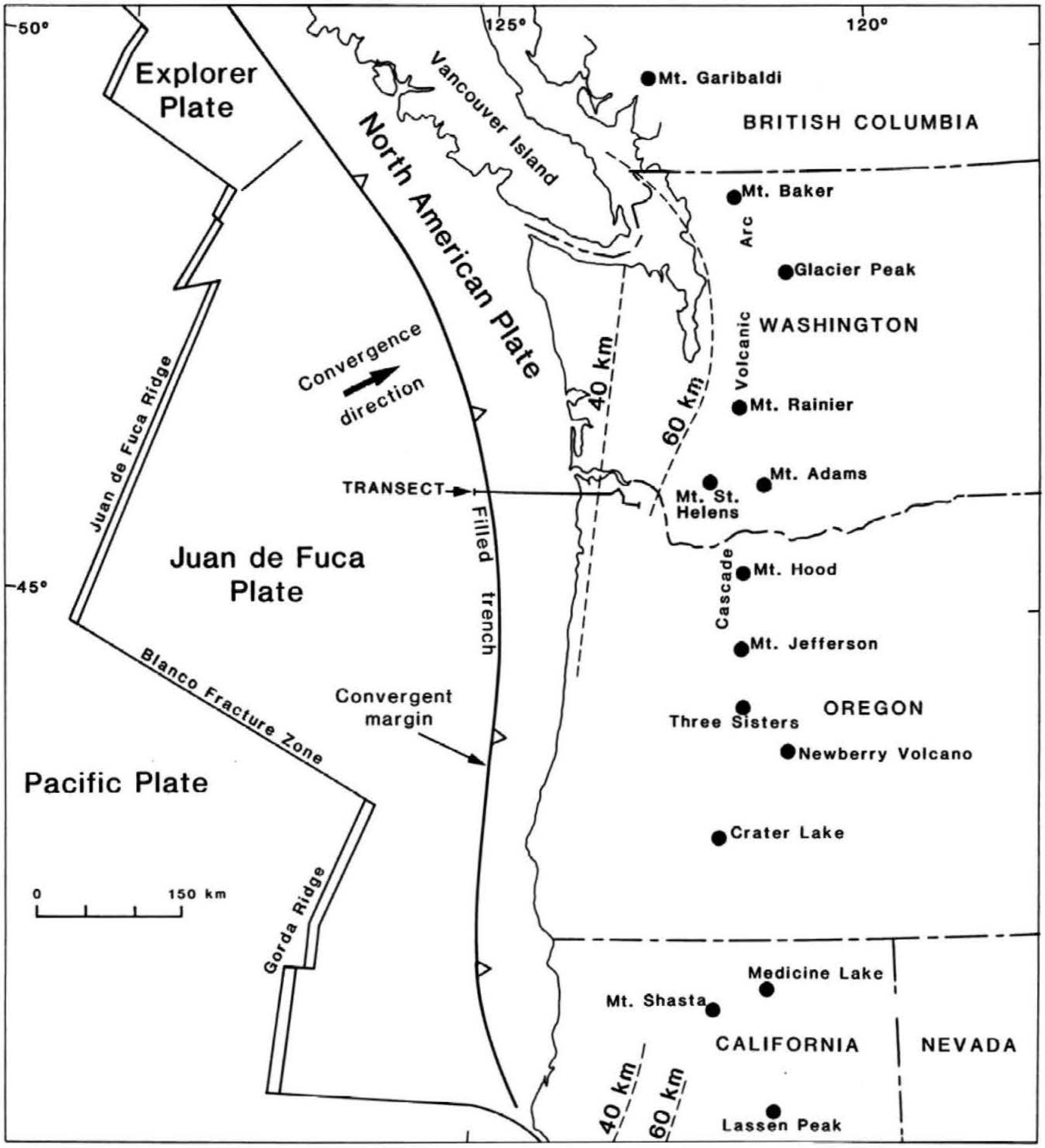


Figure 1. General setting of the convergent margin of the Pacific Northwest, modified from Guffanti and Weaver (1988). Dashed lines are depth contours at top of the Juan de Fuca Plate (Weaver and Baker, 1988); principal stratovolcanoes in the adjacent arc are identified. The abyssal plain of the Juan de Fuca Plate west of the trench is formed of Miocene basalt overlain by Miocene to Quaternary sedimentary strata. East of the trench, the continental slope and outer continental shelf are underlain by Miocene and younger sedimentary rocks. The inner continental shelf and the Oregon Coast Range are underlain by Eocene and younger sedimentary and volcanic rocks.

P-072 drilled on the outer continental shelf to a depth of 8,219 ft (2,505 m). On the inner shelf, acoustical units are tentatively correlated with strata exposed on the west flank of the Oregon Coast Range. On the continental slope, ages are assigned to some acoustical units on the basis of correlations with strata in the filled trench at the base of the slope. These strata overlie upper Miocene basalt of the Juan de Fuca Plate, which forms the abyssal plain and extends at a low angle beneath the continental margin.

ABYSSAL PLAIN

The westernmost part of the cross section traverses the junction between the abyssal plain and continental slope. The abyssal plain is formed of terrigenous and hemipelagic sediment of late Miocene to Holocene age (units Tpa, Qp, and Qh in cross section) in a weakly defined filled trench adjacent to the slope. The sediment overlies Miocene oceanic crust (unit Tmv) that was generated at the Juan de Fuca Ridge and spread laterally from the ridge toward the continent.

Multichannel profiles and Deep Sea drill holes (DSDP) by the *Glomar Challenger* off Washington (Snavely and Wagner, 1983; Snavely, 1987) and Oregon (Kulm and others, 1973; von Huene and Kulm, 1973; Snavely, Wagner, and others, 1980; Snavely, 1987) indicate that the sediments can be divided into two major stratigraphic units. The upper unit (units Qp and Qh) is of Pleistocene and Holocene age, and the lower unit (unit Tpa) is of late Miocene and Pliocene age. The section penetrated in DSDP drill hole site 174A located 140 km southwest of the cross section consists of pelagic and hemipelagic silt and clay abyssal deposits overlain by coarser, deep-sea fan turbidite sands and muds that built the Astoria fan system (von Huene and Kulm, 1973). On seismic-reflection profile EX-1, the stratigraphic boundary that marks the initiation of Astoria fan deposition is inferred at about 4.0 seconds (two-way travel time). The thick Holocene unit (unit Qh) that caps the seismic sequence has fewer turbidite sand layers than does the uppermost Pleistocene section (Nelson and Kulm, 1973). This lithologic change is a consequence of the Holocene rise in sea level and drowning of the Columbia River mouth, which resulted in diminished turbidity-current activity (Carlson and Nelson, 1987).

Upper Miocene, Pliocene, and Pleistocene strata above the upper Miocene oceanic crust are approximately 8,000 ft (2.5 km) thick, as interpreted from velocities obtained by sonobuoy refractions across the abyssal plain about 26 mi (42 km) north of the section (see line 80-16, Figure 10, Snavely, 1987). Pliocene strata form about two-thirds of this thickness on line 80-16, as they most likely do on this cross section. However, the thickness of inferred Holocene sediment is much greater along seismic-reflection profile EX-1 than along line 80-16 because of higher sedimentation rates off the mouth of the Columbia River.

CONTINENTAL SLOPE

A décollement separates the folded and thrust-faulted upper Miocene, Pliocene and Quaternary abyssal sequence (units Tpa and Qp) that has been accreted to the continental slope from an underlying eastward-thickening accretionary wedge of scraped-off Miocene and Pliocene melange(?) sediment (unit Tmpm). The melange(?) sediment in turn overlies Miocene oceanic basalt (unit Tmv) of the subducting Juan de Fuca Plate. The top of the basalt crust (unit Tmv) dips about 1.5°-3° eastward and can be traced for about 34 mi (55 km) east of the base of the slope. The basalt is progressively older eastward, as is the base of the overlying sedimentary strata.

A thick blanket of Holocene sediment (unit Qh) derived from the Columbia River has filled locally developed slope basins and buried most anticlinal highs. The onlapping young sediment has been gently folded and faulted by ongoing deformation. The irregular upper surface of the Holocene sediment most likely is due to tributary channels marginal to the Astoria Canyon. Slumps (unit Qls) of Holocene sediment off anticlinal highs also have contributed to this irregular submarine topography.

OUTER CONTINENTAL SHELF

The 40-mi-wide gently sloping (less than 3°) continental shelf off northwestern Oregon consists of two distinct geologic terranes separated by a major transcurrent fault (fault C). The outer shelf, which is the area west of fault C, is underlain by an accretionary wedge of upper Oligocene to Miocene melange and broken formation (unit Tmo). A major décollement(?) separates this tectonic melange from an overlying broadly folded and faulted sequence of upper Miocene and Pliocene bathyal siltstone and turbidite sandstone (units Tmu-Tpl, Tpm, and Tpu) that generally records an upward-deepening depositional environment.

Stratigraphic control for the sedimentary units on the outer continental shelf is derived from descriptions of strata penetrated in Shell Oil Co. well P-072 drilled during 1966 and 1967 to a depth of 8,219 ft (2,505 m). On the basis of foraminifers studied by Weldon Rau of the Washington Department of Natural Resources (written communication, 1976, to Cooper, 1981), this well penetrated strata that range in age from Pleistocene to late Oligocene (see stratigraphic column). Strata encountered in the well consist of two major units separated by a major décollement at a depth of about 5,100 ft (1,555 m). A predominantly siltstone sequence of late Miocene and Pliocene age (units Tmu-Tpl) is present above the décollement to a depth of about 2,300 ft (701 m). Upper Pliocene (unit Tpu) and Pleistocene (unit Qp—shown in stratigraphic column but not in cross section at well P-072) neritic sandstone and minor siltstone was encountered in the upper part of the well.

The Miocene and Oligocene rocks (unit Tmo) encountered below the décollement are interpreted to correlate with the Hoh melange and broken formation that crops out along the west coast of the Olympic Peninsula (Rau, 1975, 1979; Snavely and Kvenvolden, 1989). The melange unit penetrated in well P-072 consists of calcite- and clay-cemented fine- to medium-grained arkosic sandstone with minor well-indurated siltstone interbeds. Zones of shearing with slickensides are present locally, and some sandstone is fractured. Siltstone interbeds are commonly highly sheared, and siltstone pebbles occur in some sandstone (turbidite?) beds. The upper Oligocene (Zemorrian stage) strata extend from about 6,000 ft (1,830 m) to about 7,590 ft (2,313 m); only non-age-diagnostic arenaceous foraminifers were recovered below this depth.

Interval velocity and bore hole pressure increase markedly in the rocks penetrated below the décollement at about 5,100 ft (1,555 m) (Ziegler and Cassell, 1978). This striking change at the décollement most likely is a consequence of tectonic compaction of the underplated melange wedge.

INNER CONTINENTAL SHELF

The continental shelf east of fault C is geologically part of the Oregon Coast Range terrane, and the stratigraphic units correlate with those mapped and described from onshore exploration wells (Niem and Niem, 1985; Niem, Snavely, and others, 1990). The geology on the inner shelf, nevertheless, is difficult to interpret from seismic-reflection profile EX-1 because the quality of the profile in this structurally complex area is degraded by the following factors:

(1) Shallow water produces multiple sea-floor reflections that mask the structure in the upper 0.3 to 0.5 seconds of the record, in spite of processing.

(2) Thick middle Miocene basalt sills (unit Tmi) and flows (shown as lines of x's on the cross section) at or near the sea floor generate strong multiple reflectors that conceal structure and stratigraphy in the upper part of the profile. In deeper parts of the profile, the sills and dikes produce strong reflectors that obliterate acoustical units that elsewhere are associated with layered strata. However, the sills and dikes in the upper part of the seismic profile do constrain the age of intruded

sedimentary rocks as middle Miocene and older. Niem, Snavely, and others (1990) were able to trace the 300-m-thick middle Miocene sill at Tillamook Head several kilometers offshore using single and multichannel seismic-reflection lines and gravity and magnetics.

(3) The thickness and acoustical character of units change laterally, making correlation across faults difficult.

(4) The lack of offshore surface or subsurface stratigraphic control makes all age assignments of acoustical units open to question. However, a tentative correlation of onshore units in the Standard Oil Co. Hoagland No. 1 well to offshore units is shown.

The inner shelf may be underplated by melange and broken formation below a décollement(?) near the base of strata assumed to correlate with the Eocene Yamhill Formation. Onshore, a major regional unconformity is present at the base of the upper middle Eocene Yamhill Formation (Snavely, 1987; Bukry and Snavely, 1988; Snavely, MacLeod, and others, 1990a,b), and the inferred décollement could lie near this contact. Below the décollement, the seismic-reflection record is characterized by strong acoustical reflectors indicating block-faulted and folded strata. These are interpreted as melange or broken formation (unit Temm). They may be thick-bedded Eocene sandstone beds like those of the Ozette melange and broken formation that crop out along the west side of the Olympic Peninsula (Snavely and Kvenvolden, 1989). On the basis of interpretations of a multichannel profile off southwest Washington, Snavely and Wagner (1982) and Snavely and Wells (1991) conclude that melange underplates Eocene volcanic and younger strata near the coastline.

The major regional unconformity at the base of lower and middle Miocene strata (unit Tmlm, Astoria Formation) provides a rationale for age assignments of units above and below this unconformity. The lowest acoustical unit has layered and irregular strong reflectors and is interpreted as middle and upper Eocene Tillamook Volcanics (unit Ttv). Unit Ttv offshore, however, may not represent the same lithostratigraphic volcanic sequence across the inner shelf, as several eruptive centers for both middle and upper Eocene basalt are present in the northern Coast Range of Oregon and southwest Washington. For example, the Tillamook Volcanics onshore are late middle to early late Eocene in age (Snavely and Wells, 1984; Niem and Niem, 1985), whereas the basalts of Cascade Head (Snavely, MacLeod, and others, 1990b) and Yachats Basalt (Snavely and MacLeod, 1974) are latest Eocene age, and the Goble Volcanics (Phillips, 1987) are latest Eocene and/or early Oligocene in age. Unit Ttv is at a depth compatible with the updip (shoreward) projection of Tillamook Volcanics, which were penetrated at a depth of 5,600 ft (1,707 m) in the Standard Oil Co. Hoagland No. 1 well (Niem and Niem, 1985).

Subsurface data are not available for the rocks that underlie the inner continental shelf along seismic profile EX-1, but a correlative sequence was penetrated in Shell Oil Co. well P-075, 8 mi (13 km) northeast of Shell well P-072 (see index map on accompanying map sheet). The P-075 well penetrated 9,765 ft (2,976 m) of strata overlying volcanic rocks that most likely are the Tillamook Volcanics (unit Ttv on cross section). In this well, Pliocene and Pleistocene siltstone and sandstone extend to a depth of 3,270 ft (997 m) and overlie Pliocene siltstone and claystone (unit Tpa) that extend to a depth of 7,930 ft (2,417 m). Middle and lower Miocene silty claystone (unit Tmlm) in the interval 8,950-9,410 ft (2,730-2,870 m) probably correlates with the Cannon Beach member of the Astoria Formation onshore (Cooper, 1981). Oligocene and upper Eocene siltstone (unit Toe on the cross section) was encountered at 9,765 ft (2,976 m). This siltstone probably correlates with the Smuggler Cove (unit Tsc), Keasey (unit Tk), and Hamlet (unit Th) formations on land that were penetrated by the Standard Oil Co. Hoagland No. 1 well (Niem and Niem, 1985). The Tillamook Volcanics in the Shell P-075 well are intruded by a diabase sill(?) that is petrographically similar to 43-Ma diabase sills that intrude the upper middle Eocene Yamhill Formation and the Tillamook Volcanics in the central and northern Oregon Coast Range. Alternatively, this intrusion may be equivalent to the petrographically similar, but altered, upper Eocene diabase sills and dikes (informally called the Cole Mountain basalt) that are younger than the Tillamook Volcanics onshore (Niem and Niem, 1985; Rarey, 1986; Mumford, 1989; Niem, Snavely, and others, 1990).

COAST RANGE

Several stratigraphic units in the northern Oregon Coast Range have not yet been formally defined, although they have been mapped and described in publications. These include members of the Astoria Formation, the Smuggler Cove formation and its members, the Hamlet formation and its members, the Sager Creek formation, and the Northrup Creek formation. Where these units are mentioned in the following sections, the names are informal.

Eocene volcanic rocks

The Standard Oil Co. Hoagland No. 1 well near the Oregon coast penetrated 5,000 ft (1,524 m) of upper Eocene siltstone and mudstone overlying 2,000 ft (610 m) of Eocene basaltic flows with minor interbedded siltstone and sandstone. The basaltic flows correlate petrographically and chemically with the high-titanium Tillamook Volcanics, which do not crop out along the transect but were encountered in many wells (see also Niem and Niem, 1985; Niem, Snavely, and others, 1990).

The upper middle and upper Eocene Tillamook Volcanics are considered economic basement throughout the area of the transect. They are as much as 10,000 ft (3 km) thick in the Tillamook Highlands of the Coast Range 15 to 30 mi south of the transect (Wells, Niem, and others, 1983; Niem and Niem, 1985). Most of the sequence there is subaerial high-titanium basaltic andesite and basalt flows separated by breccia and tuff; thick pillow lava and palagonite tuff piles occur locally, especially near the base of the unit. Diabasic and dioritic intrusions are associated with the Tillamook Volcanics in the Oregon Coast Range (Wells, Niem, and others, 1983) and with correlative volcanic rocks (e.g., Grays River volcanics) in the southern part of the Washington Coast Range (Wells, 1981; Phillips and others, 1989). Dikes and thin sills are locally abundant. The Tillamook Volcanics are interpreted as forearc coalescing shield volcanoes that built oceanic islands (Magill and others, 1981; Wells, Engebretson, and others, 1984; Rarey, 1986).

In the Tillamook Highlands, the Tillamook Volcanics overlie and interfinger with deep-marine mudstone, siltstone, and minor sandstone of the upper and middle Eocene Yamhill Formation and submarine basaltic rocks of the lower Eocene Siletz River Volcanics (Wells, Niem, and others, 1983). Presumably these rocks also underlie the Tillamook Volcanics along the cross section. The upper part of the Tillamook Volcanics may pinch out eastward along the line of section, although lower parts of the volcanic sequence could be intercalated with the Yamhill Formation below the bottom of the EXXON GPE Fed. Com. No. 1 well at the east end of the cross section. Chemically similar and age-equivalent volcanic rocks (Waverly Heights basalt of Beeson, Tolan, and others, 1989) crop out in the Portland area to the east, suggesting that the Tillamook Volcanics continue in the subsurface beneath the northern Willamette Basin. Bruer and others (1984) have referred to the mudstone unit above the Tillamook Volcanics and below the gas-producing Cowlitz sandstone (unit Tc_l) in Columbia County wells as the Yamhill mudstone, based on subsurface correlations through the western Willamette Valley to the type Yamhill Formation in the north-central Coast Range over 60 mi to the south. Wells, Niem, and others (1983), Niem and Niem (1985), and Niem, Snavely, and others (1990), however, restrict the Yamhill Formation in the northern Coast Range to an Eocene mudstone that underlies and interfingers with the Tillamook Volcanics. They correlate the mudstone above the Tillamook

Volcanics and below the Cowlitz Formation in the Mist Gas Field and in Clatsop County with the Hamlet formation (unit Th).

The upper contact of the Tillamook Volcanics in many places is a well-defined reflector on seismic-reflection profiles, allowing the contact to be traced in the subsurface between wells where the volcanic sequence was encountered. Local strong internal reflectors in the seismic-reflection profiles may result from minor volcaniclastic sedimentary strata such as are interbedded with flows and breccias in outcrop (Niem and Niem, 1985; Rarey, 1986) and in the Standard Oil Co. Hoagland No. 1 well and other wells.

An Eocene volcanic sequence was penetrated at an unexpectedly shallow depth of 3,500 ft (1,067m) in the Westport well, the most northerly point of the transect. The 2,500-ft-thick (762-m) sequence is formed mostly of high-TiO_2 tholeiitic basalt with lesser alkalic basalt similar in chemical composition and petrography (pilotaxitic) to basalt in the Tillamook Volcanics that crop out in southern Clatsop and Columbia Countics (Niem and Niem, 1985; Niem, Snavely, and others, 1990). Basalt at depths of 5,225 and 5,750 ft (1,592 and 1,753 m) in the Westport well yielded K-Ar ages of 42.5±2.0 Ma and 40.2±2.4 Ma, respectively (ARCO Oil and Gas Co., unpublished data). These ages are similar to those reported by Magill and others (1981) and by Niem and Niem (1985) for basalt flows near the top of the Tillamook Volcanics.

Volcanic rocks (unit Tgv) penetrated in the EXXON Co. GPE Fed. Com. No. 1 well at the east end of the transect, on the other hand, do not appear to correlate with the Tillamook Volcanics. They largely overlie the Narizian Cowlitz Formation, are interbedded with Refugian and upper Narizian age strata, and thus are stratigraphically higher than the Tillamook Volcanics (see cross section). The volcanic rocks in the EXXON GPE Fed Com. No. 1 well consist of low-TiO_2 basalt and basaltic andesite similar in composition and age to the upper Eocene Goble Volcanics, which crop out to the northeast near the Columbia River (Wilkinson and others, 1946) and in southwestern Washington (Phillips, 1987). The Goble Volcanics are probably an early part of the Cascade calc-alkalic arc (Phillips and others, 1989). The Goble Volcanics (unit Tgv) in the EXXON well contain considerable intervals of interbedded tuffaceous marine to nonmarine sedimentary rocks of an unnamed unit (unit Tkg) that may be equivalent to the Toutle Formation of southwestern Washington (May, 1980; Phillips, 1987). Both wedgelike sequences of volcanic and sedimentary rocks pinch out westward. The strata appear on seismic line G-H to be truncated by an unconformity at the base of the Keasey Formation (unit Tk). Alternatively, the Keasey/Cowlitz unconformity may extend below the wedge of interbedded volcanic rocks and unnamed sedimentary rocks into the EXXON GPE Fed. Com. No. 1 well and all the unnamed strata above should be assigned to the Keasey Formation. Some basalt interbeds (labeled Tgr) in the Cowlitz Formation near the bottom of the EXXON well may be sills or dikes of Goble Volcanics (Cole Mountain basalts of Niem and Niem, 1985, and Berkman, 1990) or flows of the slightly older Grays River Volcanics. In southwestern Washington, flows of the Grays River Volcanics interfinger with nonmarine to shallow-marine sandstone of the Cowlitz Formation (Phillips, 1987; Phillips and others, 1989).

Eocene and Oligocene sedimentary rocks

A thick sequence of Eocene and Oligocene marine sedimentary rocks overlies the Tillamook Volcanics in the transect area. The sequence is formed dominantly of Foraminifera-bearing deep-marine siltstone and mudstone in the west. Shallow-marine to deltaic sandstone is progressively more abundant toward the east, and conglomerate occurs locally. In the western part of the transect, the massive tuffaceous rocks are uniformly fine grained and difficult to subdivide. The presence of mica, glauconite, and tuff beds, however, can be used to subdivide these mudstone units in the field and in well cuttings of exploration wells (Martin and others, 1985). Toward the east, sequences of mudstone- and sandstone-dominated lithologies can be more easily subdivided into formational units and members.

A depositional basin is present south of Astoria, between the Standard Oil Co. Hoagland No. 1 well and the Westport well. In the middle of this basin, the Eocene and Oligocene sequence is over 9,000 ft (2,700 m) thick. In the Patton 32-9 well (well no. 27 on cross section) near the center of the basin, the base of the sequence consists of nearly 3,000 ft (900 m) of bathyal micaceous mudstone of the upper Eocene (Narizian) Hamlet formation (unit Th). The Roy Creek member of the Hamlet formation (not shown on cross section) was penetrated at the bottom of the hole near a depth of 10,000 ft (3,048 m) and consists of shallow-marine basaltic conglomerate and sandstone (Martin and others, 1985). In outcrops in the nearby Tillamook Highlands, the Roy Creek member unconformably overlies the Tillamook Volcanics (Niem and Niem, 1985); thus these volcanic rocks may occur immediately beneath the bottom of the Patton well. Local interfingering of the Hamlet formation and Tillamook Volcanics is suggested by sequences of intercalated sedimentary and volcanic rocks penetrated in some of the wells along the transect.

The Hamlet formation is cut out or thinned by the overlying Cowlitz basal unconformity on volcanic highs northwest of the Mist Gas Field and thickens in the adjacent basins. The Hamlet and Yamhill mudstones are marginally rich source rocks with mostly Type III terrestrial or gas-prone kerogens (Niem and Niem, 1985; Armentrout and Suek, 1985; Stormberg, 1991). Along with the coals and carbonaceous plant matter in the gas-producing Clark and Wilson sandstone of the Cowlitz Formation (unit Tc_1), these strata could be the source for the thermogenic gas in the Mist Gas Field (Armentrout and Suek, 1985). Although these mudstones are thermally immature in the gas field and in the Astoria Basin to the west (except near local basalt intrusions; Niem and Niem, 1985), they are mature in the deeper parts of the EXXON GPE Fed. Com. No. 1 well in the northern Willamette Basin to the east (Stormberg, 1991). These more deeply buried mudstones could be the downdip source for the Mist gases (Armentrout and Suek, 1985; Stormberg, 1991).

The Sunset Highway member of the Hamlet formation (unit Ths) consists of shallow-marine lithic arkosic sandstone. It crops out locally in eastern Clatsop and western Columbia Counties (Niem and Niem, 1985; Mumford, 1989; Safley, 1989; Berkman, 1990) and has been traced in the subsurface to the Mist Gas Field (Niem, Snavely, and others, 1990). This member is equivalent to the Clatskanie sand of Bruer and others (1984) in the subsurface and occurs in the eastern end of the cross section. It may represent a deeper, but less promising, target of exploration.

The upper Eocene Cowlitz Formation in the central and eastern parts of the transect area is a lateral equivalent of the upper part of the Hamlet formation in the western transect area. The Cowlitz Formation consists of an upper bathyal mudstone (Tc_2), a thick middle shallow-marine sandstone (Tc_1), and locally in the subsurface a lower deep-marine mudstone member that together typically are about 984 ft (300 m) thick. The sandstone member, named the Clark and Wilson sandstone (unit Tc_1), is the principal reservoir in the Mist Gas Field (Newton, 1979; Alger, 1985). It is typically about 300 ft (100 m) thick, consists of friable well-sorted hummocky-bedded micaceous arkosic sandstone and minor coal and was deposited in a storm-dominated inner shelf or shoreface to deltaic environment (Armentrout and Suek, 1985; Farr, 1989; Berkman, 1990). The sandstone pinches out west of the Boise Cascade 11-14 well in bathyal mudstone of the Hamlet formation. A pinchout of a thin arkosic sandstone, the Crown sand, also forms a local stratigraphic trap in the upper mudstone member of the Cowlitz Formation in the Mist Gas Field (Stormberg, 1991).

In the cross section, the gas-producing Clark and Wilson sandstone of the Cowlitz Formation (unit Tc_1) and Hamlet formation (unit Th) are shown onlapping, thinning, and interfingering with the Tillamook Volcanics toward the Westport well. An alternative explanation is that the uppermost volcanic rocks in the Westport well are not the Tillamook Volcanics but are distal flows of the slightly younger(?) Grays River shield volcano complex of southwestern Washington (Phillips and others, 1989). The middle and upper Eocene Grays River volcanics are similar in petrography and chemistry to the subaerial Tillamook Volcanics (Rarey, 1986). They yield similar K-Ar ages (R.E. Wells, personal communication, 1989). However, field mapping by Wells (1981) shows that the Grays River volcanics in southwest Washington overlie the sandstone of the Cowlitz Formation and, thus, may be a slightly younger shield volcano complex than the Tillamook Volcanics, which underlie the Clark and Wilson sandstone of the Cowlitz Formation in outcrop and in most wells (Niem and Niem, 1985; Rarey, 1986; Niem, Snavely, and others, 1990). On the other hand, it is possible that the Tillamook Volcanics in the Westport well are entirely age equivalent to the Grays River volcanics and that the sandstone of the type Cowlitz in southwestern Washington is not equivalent to the Clark and Wilson sandstone of the Mist Gas Field. This subsurface stratigraphic relationship needs further refinement because it has important consequences for exploration drilling.

The upper Eocene (Refugian-Narizian) Keasey Formation (unit Tk) unconformably overlies both Hamlet formation and Cowlitz Formation. It is formed of thin-bedded tuffaceous to glauconitic mudstone and siltstone with minor beds of arkosic and basaltic sandstone. The Keasey Formation is typically 1,300 to 1,650 ft (400 to 500 m) thick. The formation thins across the center part of the transect. Keasey Formation (mudstone and siltstone) crops out along the eastern part of the transect and, together with the upper Cowlitz mudstone (unit Tc_2), forms the seal in the Mist Gas Field. A Refugian-age basal basaltic conglomerate and very thin sequence of tuffaceous mudstone of the Keasey Formation occur in the Westport well above a very thin Clark and Wilson sandstone of the Cowlitz Formation. This basaltic conglomerate and tuffaceous mudstone may correlate with a similar basal basaltic sandstone in southwest Washington mapped by Wells (1981) at the base of the lower Refugian Lincoln Creek Formation, which is also developed on a high of Narizian-age Grays River volcanics (i.e., approximately Tillamook Volcanics equivalent).

About 3,000 ft (1 km) of bathyal tuffaceous to glauconitic siltstone and claystone of the upper Eocene and Oligocene Smuggler Cove formation (unit Tsc) overlie the Keasey Formation in the western part of the area (Clatsop County). Correlative sedimentary rocks toward the east are typically coarser grained and can be subdivided into several units. These include (1) a deep-marine rhythmically bedded sequence of thin, fine-grained, micaceous and carbonaceous turbidite sandstone and mudstone, the Sager Creek formation (unit Ts), which commonly fills broad channels erosionally cut into the Keasey Formation; (2) bioturbated to well-bedded tuffaceous arkosic shallow-marine sandstone and sandy siltstone of the Pittsburg Bluff Formation (unit Tpb); and (3) channelized, well-bedded carbonaceous micaceous mudstone and feldspathic turbidite sandstone of the bathyal Northrup Creek formation (unit Tn). These units crop out in the Columbia County part of the geologic strip map. The Pittsburg Bluff Formation is the most prominent of these and forms the steep bluffs in and around the Mist Gas Field. It has been divided into several informal members on the geologic strip map (ARCO, unpublished mapping, 1987; A.R. Niem, unpublished mapping, 1990).

Miocene sedimentary rocks

Lower and middle Miocene marine sandstone, siltstone, and mudstone of the Astoria Formation underlie parts of the west half of the geologic strip map and cross section and continue onto the inner continental shelf (unit Tmlm). Niem and Niem (1985) subdivide the Astoria Formation in Clatsop County into several informal members. The Cannon Beach member (unit Ta_3) is a sequence of thin-bedded arkosic micaceous turbidite sandstone beds and thick mudstone; the Wickiup Mountain member (unit Ta_1) consists of thick clean friable shallow-marine sandstone. These two members crop out along the line of the cross section. The overlying Youngs Bay member (unit Ta_2) is a canyon head deposit of channelized, thick, friable arkosic sandstone and bathyal mudstone that crops out along the north border of the geologic strip map near the Patton 32-9 well but does not extend into the line of section. The submarine channel sandstone of the Youngs Bay member and friable deltaic to shallow-marine sandstone of the Angora Peak member, which does not crop out along the line of section, are potential reservoir targets for offshore exploration (Cooper, 1981; Niem and Niem, 1985; Niem, Snavely, and others, 1990). The Astoria Formation is a deposit of the mouth of the ancestral Columbia River and adjacent shoreline, shelf, and upper reaches of the ancestral Astoria canyon (Niem and Niem, 1985; Niem, Snavely, and others, 1990).

Miocene basalt

Middle Miocene basalt flows of the Columbia River Basalt Group crop out in the central part of the geologic strip map and cross section near the Westport well and in the eastern part of the area. Two units are represented; the older flows are in the Grande Ronde Basalt (unit Tg) and the younger are in the Frenchman Springs Member (unit Tf) of the Wanapum Basalt. These basalt flows are the distal ends of extensive lavas that flowed from eastern Oregon and Washington through a low area in the ancestral Cascade Range. These flood basalts continued across western Oregon and Washington along and near the former course of the Columbia River to and beyond the middle Miocene strandline. The strandline lay between the Westport and Boise Cascade 11-14 wells. The flows are dominantly subaerial near and east of the Westport well, but thick piles of submarine pillow basalt and glassy volcanic breccia and lava deltas are exposed southwest near the Boise Cascade 11-14 well and farther southwest over much of Clatsop County (Murphy, 1981; Niem and Niem, 1985).

Middle Miocene basalt sills and dikes are widespread from approximately the Miocene strandline southwest to the inner continental shelf. These intrusive rocks are the same age, magnetic polarity, and chemical and isotopic composition as the flows (Snavely, MacLeod, and others, 1973; Choiniere and Swanson, 1979; Niem and Niem, 1985; and others). They are interpreted to be invasions of dense lava from the flows downward into the underlying semiconsolidated light sedimentary strata rather than intrusions from the mantle or lower crust (D.A. Swanson, personal communication, 1977; Beeson, Perttu, and others, 1979; Niem and Niem, 1985). The invasive intrusions may be very complicated. For instance, once lava descended from the surface, it may have flowed considerable distances as sills and then ascended locally as dikes.

Miocene basalt sills were penetrated in the Patton 32-9 well and Boise Cascade 11-14 well. The sills produce sharp reflectors on seismic-reflection lines onshore and on the inner continental shelf. Some reflectors can be correlated with Grande Ronde and Frenchman Springs sills in the wells.

Sedimentary rocks are baked at and near sill contacts. Thick sills have baked zones locally more than 300 ft thick. Niem and Niem (1985) showed that thermogenic gas may have been produced locally as a consequence of the heating effects of thick middle Miocene sills upon the surrounding mudstones. Miocene and Eocene sills (Cole Mountain sills; see Niem, Snavely, and others, 1990) may have been the heat source for maturation of the strata that were the source for thermogenic gas at Mist. Niem, Snavely, and others (1990) concluded that baked sedimentary rocks associated with a 800-ft-thick widespread Miocene basalt sill may represent a thermally mature source of thermogenic gas for future offshore exploration.

Middle Miocene fluvial friable arkosic to basaltic sandstone, lacustrine mud, and basaltic gravel of the Scappoose Formation (unit Tsp) as redefined by Van Atta and Kelty (1985) locally underlie and are interbedded with the subaerial part of the Columbia River Basalt Group. The unit unconformably overlies older sedimentary units but is poorly exposed and its distribution is only approximately shown. The sandstone is, in part, equivalent to sandstone interbedded in Columbia River Basalt Group much farther to the east, e.g., central Washington (Murphy, 1981). The Scappoose Formation mapped in the vicinity of the EXXON GPE Fed. Com. 1 well may include Oligocene shallow-marine fossiliferous arkosic micaceous sandstone, such as is in the originally defined Oligocene Scappoose Formation of Warren and Norbisrath (1946).

No upper Miocene or Pliocene sedimentary or volcanic rocks crop out near the onland part of the transect.

STRUCTURE

The Cenozoic sedimentary and volcanic rocks of the Oregon continental margin and Coast Range are along the boundary between the North American and Juan de Fuca Plates and are folded and complexly faulted. Currently, the boundary is a subduction zone with oblique convergence. Variations in the rate and angle of convergence during the Cenozoic have resulted in episodic periods of deformation (Wells, Engebretson, and others, 1984). The style of deformation changes with distance from the plate boundary. Near the boundary, folds and thrusts are characteristic structures. Far from the boundary, normal and transcurrent faults are common.

A complicating factor in interpreting older structures is that the entire region has rotated with time, as shown by paleomagnetic studies (Wells, Engebretson, and others, 1984; Nelson, 1985). The Tillamook Volcanics in the Coast Range south of the cross section show 45° of clockwise rotation (Magill and others, 1981); north of the section in Washington, rocks of similar age are rotated only 23° (Wells and Coe, 1985).

Continental slope

The gently inclined continental slope is characterized by a group of fault-propagation anticlines separated by broad synclinal basins. These thrust folds have uplifted Pliocene and Pleistocene abyssal strata (Tpa-Qp) as much as 2,250 ft (700 m). Several folds have bathymetric expression, forming elongate north-trending ridges that generally parallel the base of the slope. The thrusts dip eastward with the exception of the youngest thrust (at the base of the slope). Snavely (1987) speculated that the change in the direction of thrust faults along the continental slope of Oregon and Washington may have been controlled by the steepness of the backstop against which the melange wedge accreted.

A décollement can be traced intermittently on seismic-reflection profiles across most of the continental slope but is not well defined on the western end. Subduction of the oceanic plate has shortened the Pliocene and Pleistocene strata (Tpa-Qp) in the overriding upper plate above the décollement, and this shortening is expressed by the east-dipping thrust faults. Most thrusts appear to merge downward into the décollement; however, several thrusts offset the décollement and appear to die out in the accretionary wedge of Miocene and Pliocene strata (unit Tmpm) beneath the décollement.

Northwest-trending sinistral transcurrent faults have segmented the lower slope to upper shelf (Goldfinger and others, 1991). Some fold axes on the northern Oregon shelf in the younger units Qp and Qh are oriented WNW. In the vicinity of EXXON seismic-reflection line EX-1 west of the Shell wells on the outer shelf, fold axes trend north-south (C. Goldfinger, personal communication, 1991).

Continental shelf

The western edge of the outer continental shelf is marked by shelf-edge diapiric uplift. This occurs above fault A. Melange welts also occur at or near the shelf break on the Washington margin (e.g., Snavely and Wagner, 1982), where they form the western margins of some post-middle Miocene shelf basins.

A décollement under the outer continental shelf, presumably different and older than the décollement on the slope, extends from the melange welt above thrust fault A on the west to sinistral(?) fault C on the east. The décollement is complexely folded at the shelf edge above fault A. Fault C truncates the décollement.

The principal structure above the subhorizontal décollement is the faulted anticlinal fold that was the exploration target for Shell Oil Co. P-072 well. The décollement, which is gently arched beneath the fold, truncates the anticline to produce a "rootless" fold. Fault B, an oblique-slip dextral(?) fault just west of the well, cuts the axial part of the fold and also offsets the décollement. This fault extends to or near the sea floor and juxtaposes Pleistocene (unit Qp) strata on the west with upper Pliocene (unit Tpu) strata east of the fault. The Pliocene strata penetrated in the Shell well are downdropped west of fault B where they onlap lower Pliocene and upper Miocene strata on the west flank of the anticline. East of fault B, however, upper Pliocene strata are folded to the same degree as the underlying lower Pliocene and upper Miocene (units Tmu-Tpl) strata. This anomalous stratigraphic relationship of Pliocene strata east and west of fault B suggests that considerable strike-slip movement occurred along the thrust fault.

The stratigraphic and tectonic framework changes markedly beneath the inner shelf east of fault C. Strata to the east correlate with those that crop out in the northern Oregon Coast Range. Fault C displays a flower structure (Harding, 1985), indicating transpressional strike-slip (sinistral?) movement. Fault C, therefore, is most likely a major terrane boundary with an unknown amount of separation. The marked change in the thickness of the upper Miocene and Pliocene strata adjacent to fault C also is consistent with major strike-slip displacement of a thick bathyal sequence on the west and a much thinner shelf(?) sequence underlain by Eocene volcanic basement (unit Ttv) to the east. This terrane boundary fault is also present on other seismic-reflection profiles to the south (e.g., Fulmar fault of Snavely, Wagner, and others, 1980; Niem, Snavely, and others, 1990).

Fault C most likely extends northward on the shelf to southwest Washington, forming the western boundary of the upper middle and lower upper Eocene basalt that crops out at Cape Disappointment (mapped as Crescent Formation by Wells [1989], although younger than Crescent according to D. Bukry [written communication, 1990]).

The structure on the inner shelf east of fault C and above an assumed inner shelf décollement is dominated by landward-dipping high-angle reverse and thrust faults, several of which die out into fault-propagation folds. A dextral(?) fault east of fault C offsets the décollement. This fault and fault C are characterized by flower structures (Harding, 1985) in the anticlinal flexures above them.

The entire inner continental shelf sequence above the décollement(?) is characterized by transpression as the plate above the décollement was shortened during underplating of melange and broken formation.

Coast Range

The tectonic style on the inner continental shelf shows a transition to the tectonic pattern mapped in the adjacent Oregon Coast Range by Niem and Niem (1985). The style of faulting changes from low-angle thrusts on the inner shelf to steeply dipping high-angle faults with normal and reverse to oblique-slip displacement in the Coast Range.

The tectonic framework in the central part of the Oregon Coast Range (Snavely, MacLeod, and others, 1976a,b,c, 1990b; Wells, Niem, and others, 1983) and southwest Washington (Wells, 1981, 1989) is dominated by northwest- and northeast-striking steeply dipping oblique-slip faults, some with lateral displacements.

Niem and Niem (1985) showed that the onshore part of the Astoria Basin is dominated by northwest- and northeast-striking, steeply dipping faults that formed within a broad zone of right-lateral shear in a wrench tectonic setting. Many faults exposed in basalt quarries show subhorizontal slickensides and lateral offset of dikes (Niem and Niem, 1985). Few faults mapped at the surface or shown on seismic-reflection profiles have large offsets. Also, sedimentary strata generally dip at low angles, except near faults, and are locally drag-folded.

Density and magnetic contrasts between sedimentary and volcanic rocks in the Coast Range produce gravity and magnetic anomalies that help interpret regional structure. The magnetic anomalies, however, must be interpreted with caution. Volcanic flows with variable polarity may produce magnetic lows or highs. For example, Elk Mountain southwest of the Boise Cascade 11-14 well is largely composed of reversely polarized pillow lava and breccia of the middle Miocene Columbia River Basalt Group and appears as a negative magnetic anomaly. In contrast, the 3,000-ft-thick Miocene basalt pile at Saddle Mountain to the south is largely normally polarized and appears as a positive anomaly on the magnetic anomaly map by Finn and others (1984).

The magnetic profile shown is rotated to the pole. The anomalies appear as they would if the magnetic field were vertical (as at the north or south pole). Consequently, the shapes of the calculated anomalies are more analogous to gravity profiles than they would otherwise be.

A broad gravity high centered near the Westport No. 1 well has an associated magnetic high and appears to be the result of a shallow occurrence of the Tillamook Volcanics (unit Ttv). The Tillamook Volcanics were encountered in the Westport well from a depth of about 3,500 ft (1,067 m) to the base of the hole near 5,895 ft (1,797 m); the gravity and magnetic data are consistent with a much greater thickness of volcanic rocks beneath the base of the hole. Southeast of the Westport well, the gravity anomaly remains high beyond Mist. This anomaly defines the Nehalem arch of Armentrout and Suek (1985), a broad high in the basement rocks (Tillamook Volcanics and possibly also the underlying Siletz River Volcanics/Crescent Formation, Hembre Ridge volcanics, and lower to middle Eocene intrusions) (R.E. Wells, personal communication, 1990).

The Nehalem arch gravity high extends northeast from the Tillamook Highlands into southwestern Washington. This gravity high is a subsurface saddle of volcanic rocks between outcrops of Eocene Tillamook Volcanics to the south and Eocene Grays River volcanics to the north. In between these areas, the volcanic rocks are overlain by Eocene sedimentary rocks, including the gas-producing Cowlitz sandstone at Mist (Kadri, 1982). The gravity high is flanked by the Astoria Basin to the west (in the vicinity of the Patton 32-9 well) and the North Willamette Basin or Tualatin basin to the southeast (near the EXXON GPE Fed. Com. No. 1 well).

A small gravity low nested on the Nehalem arch gravity high between the Westport well and Mist may be an artifact of the contouring inasmuch as it results from an anomalously low value at only one station.

Between the Standard Oil Co. Hoagland No. 1 well near the coast and the Westport No. 1 well on the Nehalem arch, a thick basin of normal to obliquely faulted Eocene to Miocene strata produces the Astoria Basin gravity low. The cross section in this area is based mainly on surface mapping, because the Vibroseis reflection lines that follow winding roads are relatively distant from the line of section and the stratigraphy and structure on them are locally obscured by strong reflectors from Miocene basalt sills. Consequently, small faults may be more common here than shown on the cross section, especially blind faults that die out at buried unconformities or that do not displace Miocene intrusions.

The Mist Gas Field is developed on the Nehalem arch in an area of normal faults that define the Nehalem graben (Niem, Snavely, and others, 1990). Older normal faults are extension related and display greater vertical separation of Eocene units (i.e., pre-Keasey Formation). Many were reactivated in the late middle Miocene in a wrench tectonic setting with principally oblique-slip movement (Niem and Niem, 1985; Niem, Snavely, and others, 1990); the result was minor vertical and lateral separation of post-Keasey Formation units. Consequently, normal faults appear on the seismic lines to terminate against the unconformity at the base of the Keasey Formation; however, many faults are mapped cutting younger units with less vertical and more lateral separation.

The Nehalem graben may be a pull-apart structure produced by wrench tectonics along oblique-slip faults. Alger (1985) also noted a right-lateral northwest-trending fault in the subsurface of the Mist Gas Field. The gas at Mist is localized in structural traps where the reservoir, the Clark and Wilson sandstone of the Cowlitz Formation, is faulted and drag-folded against less permeable rocks. As noted by Niem, Snavely, and others (1990), faulting in this area is even more complicated than shown on the small-scale geologic strip map and cross section. The structure and stratigraphy are constrained by a large amount of data from gas wells, numerous seismic-reflection profiles, and detailed surface mapping (A.R. Niem, unpublished data).

The Nehalem graben trends northwest-southeast, normal to the gravity high and nearly parallel to most of the geologic strip map. Consequently, except near Mist where the strip map is north-south, few of the faults associated with or subparallel to the graben cross the line of section. These normal faults downstep the strata into the flanking northern Willamette (Tualatin) and Astoria Basins. Exposures are poor in most areas of the transect, so faults are difficult to identify and map. Also, some large downdropped blocks of Columbia River basalt on the geologic strip map may have been displaced by large-scale landslides rather than by faults.

Drag folds with amplitudes of a few hundred feet and axial traces as long as a few miles have been mapped locally associated with oblique-slip and normal faults in the northern Coast Range (Niem and Niem, 1985). The trace of the axial planes is mostly northwest, roughly orthogonal to the convergence direction. Along the transect, the sedimentary strata are only broadly arched. Some apparent folds in the cross section are a consequence of bends in the line of section. Small drag folds near faults, especially in the Mist area, are indicated by locally steeper attitudes on the geologic strip map but are too small to be shown at this scale on the geologic cross section.

The structural pattern of the onshore and offshore area is complex and will need further refinement for continued successful oil and gas exploration. Parts of the transect area have not yet been mapped in detail, and consequently their structure is not well documented. This is especially so for the eastern end of the transect (between the Mist Gas Field and the EXXON GPE Fed. Com. No. 1 well) and the central part of the transect (between the Mist Gas Field and the Clatsop-Columbia County line).

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