NATURAL RESOURCES

AN ASSESSMENT OF THE OIL AND GAS POTENTIAL OF THE WASHINGTON OUTER CONTINENTAL SHELF

by Stephen P. Palmer and
William S. Lingley, Jr.

WASHINGTON
DIVISION OF GEOLOGY
AND EARTH RESOURCES

Reprint 13
Originally published 1989
Reprinted July 2001

WASHINGTON STATE DEPARTMENT OF
Natural Resources
Doug Sutherland - Commissioner of Public Lands

AN ASSESSMENT OF THE OIL AND GAS POTENTIAL OF THE WASHINGTON OUTER CONTINENTAL SHELF

by Stephen P. Palmer and
William S. Lingley, Jr.

WASHINGTON
DIVISION OF GEOLOGY
AND EARTH RESOURCES

Reprint 13
Originally published 1989
Reprinted July 2001

WASHINGTON STATE DEPARTMENT OF
Natural Resources
Doug Sutherland - Commissioner of Public Lands

DISCLAIMER

WASHINGTON DEPARTMENT OF NATURAL RESOURCES

Doug Sutherland—*Commissioner of Public Lands*

DIVISION OF GEOLOGY AND EARTH RESOURCES

Raymond Lasmanis—*State Geologist*
Ron Teissere—*Assistant State Geologist*

This report is available from:

Publications
Washington Division of Geology and Earth Resources
PO Box 47007
Olympia, WA 98504-7007
Phone: (360) 902-1450
Fax: (360) 902-1785
E-mail: geology@wadnr.gov
Website: http://www.wa.gov/dnr/htdocs/ger/

Printed on recycled paper.
Printed in the United States of America

WASHINGTON STATE

AN ASSESSMENT OF THE OIL & GAS POTENTIAL OF THE WASHINGTON OUTER CONTINENTAL SHELF

OFFSHORE OIL & GAS

WASHINGTON SEA GRANT

Stephen P. Palmer &
William S. Lingley, Jr.

AN ASSESSMENT OF THE OIL AND GAS POTENTIAL OF THE WASHINGTON OUTER CONTINENTAL SHELF

Stephen P. Palmer, Washington Sea Grant Program

William S. Lingley, Jr., Washington Department of Natural Resources

Washington Sea Grant Program
University of Washington • Seattle 98195

This assessment of the oil and gas potential of the Washington outer continental shelf was conducted by the Washington State Department of Natural Resources, Division of Geology and Earth Resources. The study and the publication of this report were supported by an appropriation from the Washington State Legislature, under ESSB No. 5533, Laws of 1987, to the Washington Sea Grant Program at the University of Washington. Additional support was provided by grant NA86AA-D-SG044 from the National Oceanic and Atmospheric Administration to the Washington Sea Grant Program, projects R/MS-33 and A/PC-5.

WSG 89-2

ISBN 0-934539-09-X

Contents

List of Figures

List of Tables

List of Plates

About the Ocean Resources Assessment Program

In April 1992, the Minerals Management Service (MMS) of the U.S. Department of the Interior plans to conduct Lease Sale #132 for offshore oil and gas exploration and development in federal waters on the outer continental shelf off the coasts of Washington and Oregon. This has been the driving force behind recent Washington state actions on this issue [earlier, the State Department of Natural Resources had imposed a moratorium on leasing for oil and gas inside state waters].

The Governor of Washington has asked MMS to delete about half of the lease sale area off the Washington coast and has joined Oregon, California, Massachusetts, and the National Resources Defense Council, an environmental group, in lawsuits against DOI, challenging its current Five-Year OCS Oil and Gas Leasing Program. Meanwhile, MMS is sponsoring several pre-lease environmental studies, and, at this writing, the first step in the sale process is less than one year away. In November 1989, MMS plans to request that oil and gas industry members indicate their level of interest in Lease Sale #132. Under the present plan, if industry interest is sufficiently high, successive steps in the lease sale process will proceed.

Through the Western Legislative Conference in 1986, members of the Washington Legislature became concerned that the state was unprepared for the potential development being planned by the federal government. Engrossed Substitute Senate Bill (ESSB) 5533 was the result. It became effective law on July 26, 1987. Of the $800,000 originally requested, the Legislature appropriated $400,000 to Washington Sea Grant to conduct the studies mandated by this law.

Why Sea Grant? First, the University of Washington has a renowned College of Ocean and Fishery Sciences, and Sea Grant is an effective pathway to that expertise. Second, Sea Grant is experienced in interdisciplinary research design, procurement, and administration. Third, Sea Grant has a communications network with other universities, giving Washington State quick access to nationwide expertise. Fourth, part of Sea Grant's mandate is to work with academe, government, and industry, without political advocacy, in a non-regulatory, information-support role. Last, Washington does not have statewide planning and assigning the responsibilities of ESSB 5533 to a mission-oriented state agency might have created concerns about objectivity and fairness.

This law is ocean information oriented, as opposed to Oregon's C-ESB 630, which is ocean management oriented. Management could be the next step for Washington State. Through its Ocean Resources Assessment Program (ORAP), Washington Sea Grant is synthesizing existing scientific information. The Legislature's Joint Select Committee on Marine and Ocean Resources acts as oversight committee for ORAP. In the 1989 Legislative session, convening in January, ORAP is to report its findings about information gaps and research needs and present a plan for future studies.

In designing ORAP, an overall guideline was the determination to benefit from the experience of others but not to duplicate past and current studies. Thus, ORAP has sponsored little original research but has concentrated on synthesis and planning. ORAP consists of seven projects, including the study from which this book is derived:

• ***An Assessment of the Oil and Gas Potential of the Washington Outer Continental Shelf***—the present assessment by the State Department of Natural Resources, to help identify geologic formations that might be of potential interest to industry.

• ***State and Local Influence Over Offshore Oil Decisions***—a study of the roles and mechanisms of state and local governments in offshore oil decision-making, as revealed by experience in other states.

• ***Coastal Washington: A Synthesis of Information***—a report on existing information, information gaps, and research needs.

• ***Coastal Oceanography of Washington and Oregon***—a regional oceanography text, making contributions to science on 15 of the 22 subjects mentioned in the law. Multi-edited and authored, the hardcover book presents the results of many years of research. Sea Grant funded the final efforts needed to make the book available in time to influence OCS decision-making and future research.

• **An Advisory Committee,** as required by law. Sea Grant recognized the need for broad educational base-building among the policy-makers in state and local governments, tribal authorities, and citizen groups. Ten Legislators, equally split by party and body, were members of this advisory committee. Sea Grant devised an innovative approach to help the 32 members of this committee educate themselves quickly about the offshore oil and gas industry and its typical facilities, equipment, operations, and impacts. The committee functioned like a task force and reported to Sea Grant on information needs and priorities. This project is a worthy model for others who must deal on a tight schedule and budget with new, complex issues of high public concern.

• **Conceptual Framework for Future OCS Research**—a workshop to develop a framework that will help determine "what's important?" and help ensure that future research is both well-targeted and well-founded scientifically.

• **OCS Studies Plan: A Report to the Washingon State Legislature**— a plan developed by Washington Sea Grant, as required by law, building upon the other ORAP projects and other studies.

Washington Sea Grant is publishing reports of each of these projects, except for the coastal oceanography text, which is being published commercially by Elsevier Science Publishers. Meanwhile, the Legislature's Joint Select Committee on Marine and Ocean Resources is grappling with statewide policy alternatives and may propose legislation for the 1989 regular session.

B. Glenn Ledbetter, Manager, ORAP
January 1989

Acknowledgments

This assessment of the oil and gas potential of the Washington outer continental shelf was conducted by the Division of Geology and Earth Resources of the Washington State Department of Natural Resources (DNR). Financial support for research, writing and manuscript preparation came from the Ocean Resources Assessment Project, funded by the State of Washington and administered by the Washington Sea Grant Program.

The writers wish to express their gratitude and appreciation to Parke D. Snavely, Jr. of the U.S. Geological Survey (USGS) and Weldon W. Rau of the DNR Division of Geology and Earth Resources. These geologists not only laid the groundwork for all geologic studies of coastal Washington, but they also provided much of the raw data and interpretations used to develop the following petroleum assessment.

We also extend thanks to Glenn Ledbetter and Patricia Peyton, Washington Sea Grant Ocean Resources Assessment Program; Lynn Moses, consulting geologist; and Raymond Lasmanis, the Washington State Geologist, for their contributions and assistance. Our thanks also go to Mark Holmes, Carol Finn, Diane Minasian, Holly Wagner, and Gordon Dolton, USGS; Bruce Grant, National Geophysical Data Center; Vern Kulm, Oregon State University; Frank Webster, Minerals Management Service; Danny Orange and Eli Silver, University of California, Santa Cruz; Stu Smith, Scripps Institute of Oceanography; Brian Lewis, University of Washington; Bob Deacon and Grant Valentine, consulting geologists; and the staff of the Division of Geology and Earth Resources, especially Kitty Reed and Nancy Herman.

The project would not have been completed in a timely fashion without the assistance of our cartographer, Stan McAbee.

Wooden derrick of the Sims No. 1 well, circa 1931, drilled near the Jefferson oil seep in Jefferson County. Numerous exploratory wells have been drilled in this area and elsewhere on the western Olympic Peninsula and adjacent continental shelf. Photograph courtesy of Jones Photo Company, Aberdeen, Washington.

Legislative Summary

The western Olympic Peninsula and adjacent offshore areas of Washington have a history of oil and gas exploration dating from 1901 when an exploratory well [wildcat*] was drilled near Copalis. Subsequently, approximately 116 wildcats have been drilled in this region. Many of these wells had significant indications [shows] of oil and/or gas, but profitable production has not been established. The Minerals Management Service, Department of the Interior, has begun preparation for an auction of oil and gas leases on the Washington and Oregon Outer Continental Shelf [OCS], designated Sale 132. Sale 132 would be scheduled during 1992 if industry interest, as indicated in a formal notification process, is sufficient to assure that the auction will be successful. The following map shows the proposed area on the Washington OCS from which leases could be auctioned during Sale 132. The sale area extends from State territorial waters (the 3-mile limit) westward to the Pacific basin plain and between the Canada-United States and California-Oregon borders. This assessment encompasses the area from the coastline to the western boundary of Sale 132, and from the offshore projection of the Washington-Oregon state boundary north to the Canada-United States international boundary.

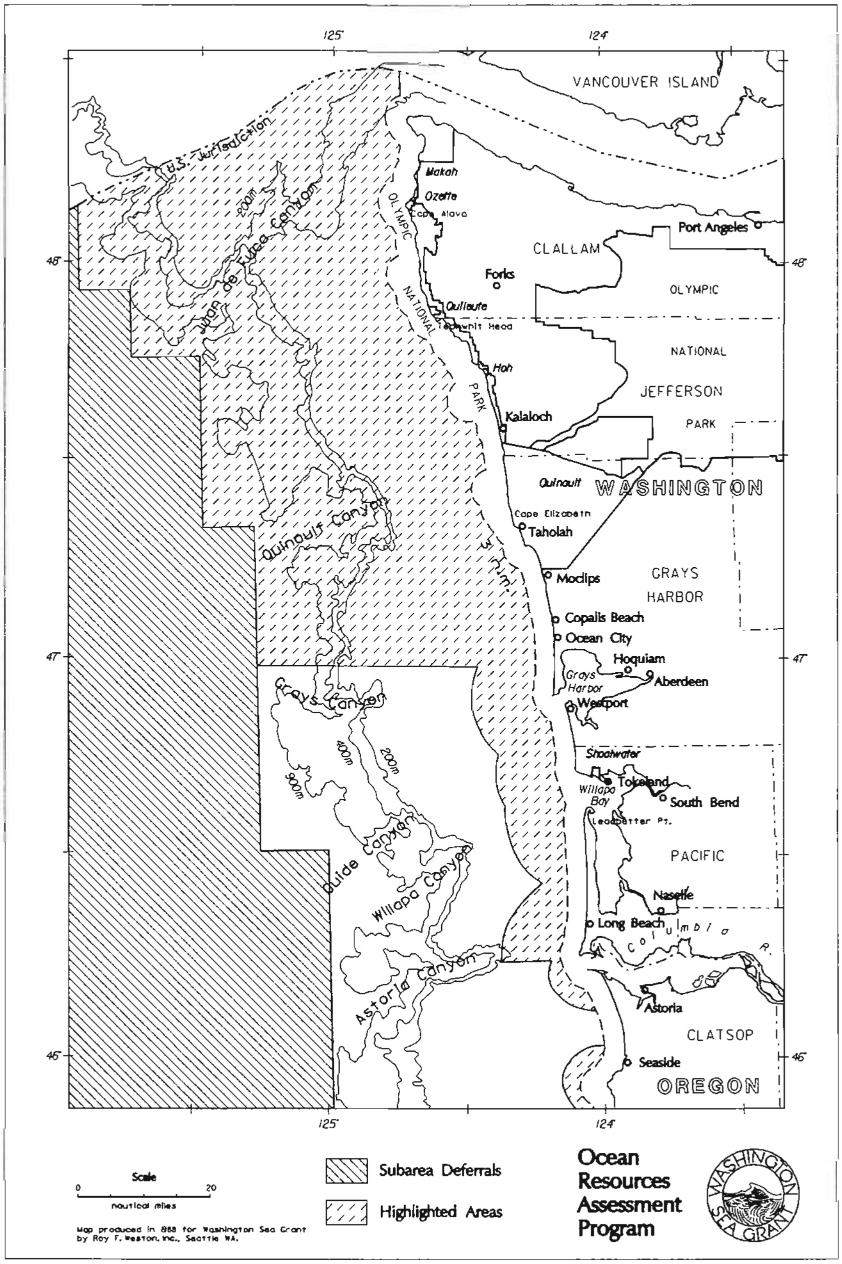
The purpose of this report is to provide a geological and geophysical assessment of the petroleum potential of the Washington OCS for the benefit of the public. A secondary objective of this project is to collect and archive geological and geophysical data in the public-domain that are relevant to hydrocarbon assessment in the Washington OCS. These data, which are available to the public through the library of the Department of Natural Resources, Division of Geology and Earth Resources, are also useful for regional geological studies and geologic hazard assessment.

PETROLEUM GEOLOGY OF THE WASHINGTON CONTINENTAL MARGIN

Petroleum assessments are based on the study of sedimentary rocks that have potential to generate and store commercial quantities of oil and/or gas [petroleum]. Sedimentary rocks buried in the Earth's crust commonly contain fossil algae, wood, leaves, and other organic debris that are [source rocks] for gas and oil. Heating occurs as the rocks are buried under younger sediments. Heating of the source rocks to near the boiling point of water activates chemical reactions that convert the organic debris to petroleum [maturation]. Low-density petroleum floats toward the surface [migrates] from its source through water-filled pores and faults within the rocks. Stratified sedimentary rocks can be folded and/or faulted into domes [traps] which stop the upward migrating petroleum. Porous strata which collect and store the oil and gas [reservoir rocks] must be present within the trap. In addition, these reservoir rocks must be overlain by impermeable rocks [seals] that inhibit the upward migration. Oil and gas fields are large traps which reflect the rare situation in which all of the conditions described above occur in proper sequence (i.e., deposition of source, reservoir, and sealing rocks, followed by development of a trap, and then by maturation and migration of the petroleum into the trap). A petroleum assessment is simply a quantitative analysis of each of these factors based on geologic study of an area.

The geologic history relevant to petroleum accumulation in coastal Washington began with deposition of the area's oldest sedimentary rocks, the Ozette and Hoh sequences. These sequences are mainly composed of sandstones, siltstones, and claystones deposited in deep water on the Pacific Oceanic plate between approximately 50 and 15 million years ago. These sediments were scraped off the Pacific plate and attached [accreted] to the North American continent as the Pacific plate sank [subducted] beneath the continent. During the accretion process, intense faulting and folding created a chaotic mixing of Hoh and Ozette rock types known as melange. Between about 12 and 2 million years ago, accreted Hoh and Ozette melanges were covered by the Montesano and Quinault Formations that are also composed of sandstones, claystones, and siltstones. After deposition, the Montesano and Quinault Formations were deformed, but much less severely than the underlying Ozette and Hoh melanges. This period of deformation created numerous faults and folds [anticlines and synclines] in the Montesano and Quinault rocks. A

* In this summary terms commonly used in the petroleum industry are bracketed.



Map of the western Olympic Peninsula and offshore region relevant to the proposed lease Sale 132. Subarea deferrals and areas highlighted by the Minerals Management Service are indicated.

small number of these anticlines probably are domes and consequently could serve as *potential* traps for the accumulation of oil and gas.

SOURCE ROCKS, MATURATION, AND MIGRATION

Despite the lack of oil or gas production in Washington, the western Olympic Peninsula is a remarkably petroliferous terrain. Oil and gas seep to the surface at many locations on the western Olympic Peninsula, and numerous exploratory wells drilled onshore and offshore encountered significant oil and gas shows. (See Plate 1.) Very dark gray clay layers in Ozette and

Hoh sequences exposed along sea cliffs in the Olympic National Park and adjacent beaches seep oil into the Pacific Ocean. Early inhabitants of the peninsula referred to these clay layers as "smell muds". The Medina No. 1 well, drilled on the beach at Ocean Shores (near Ocean City), produced marginal amounts of oil between 1958 and 1962. These observations indicate that petroleum was generated and has migrated to the surface along the coastal zone adjacent to the Sale 132 area.

Paradoxically, laboratory studies by the U.S. Geological Survey and our own work have failed to identify specific source rock horizons that generated these oil seeps and shows.

RESERVOIR ROCKS AND SEALS

Reservoirs for oil, gas, and underground drinking water usually consist of small gaps or voids [pores] between grains of sand in sandstones. The storage capacity of a sandstone reservoir is determined by the percentage of the rock that is composed of pores [porosity]. A reservoir will not yield profitable petroleum unless fluid can flow from porous rock into the well bore. [Permeability] is the measurement of the ease with which fluids can flow through a reservoir. Porosity and permeability in offshore reservoirs must be especially high in order for the well to produce petroleum at volumes and rates sufficient to recoup the expense of building a production platform. Permeability commonly decreases with decreasing grain size; consequently, sandstones generally are considered as potentially commercial reservoirs, whereas siltstones and claystones seldom produce oil or gas at commercial rates.

Porosity and permeability data obtained from onshore exploratory wells in the coastal Olympic Peninsula indicate that the Hoh and Ozette sequences typically have insufficient permeability to sustain commercial offshore production rates. Most of the pores in these rocks have been filled with mineral cements, thus reducing both the storage capacity and permeability. Furthermore, intense folding, faulting, and fracturing of the Hoh and Ozette sequences that occurred during accretion may limit the lateral extent of Hoh or Ozette sandstone reservoirs.

The porosity and permeability of sandstone sequences within the Montesano and Quinault Formations compare favorably to those of producing reservoirs in some of the world's largest oil fields. Wells drilled in the Ocean City area encountered a continuously porous sandstone unit in the Montesano Formation that is more than 500 feet thick, and in which nearly one-third of the total sandstone volume is composed of void space. This exceptional sandstone reservoir has been drilled only in the Ocean City area and in one offshore well. Our work suggests that a few equivalents of this sandstone may be present elsewhere on the continental margin, but prediction of the distribution of these sandstones, which is critical to successful exploration, will be difficult. Nonetheless, these Montesano sandstone reservoirs present an attractive petroleum exploration target.

Seals are generally composed of impermeable claystone or siltstones layers that inhibit migration of oil and/or gas from the reservoir. Oil and gas seeps occur when seals are not present or are breached by faulting or erosion, and as a result the petroleum migrates to the surface. In some cases faults may seal traps.

Most sedimentary sequences in the western Olympic Peninsula contain impermeable siltstones and claystones suitable for sealing underlying sandstone reservoir horizons. Minor shows recorded in the thick Montesano sandstone unit encountered in the Ocean City area indicate that gas, and possibly oil, have migrated into this sandstone at some time in the past. However, our work suggests that the overlying siltstone seal was breached by erosional processes approximately 5 million years ago, and oil and gas that may have been accumulated in the sandstone escaped.

TRAPS

Anticlinal folds of stratified rocks having potential to trap petroleum can be mapped using seismic reflection surveying. This geophysical technique involves bouncing [reflection] sound waves off buried strata; the reflection data are used to map the geometry and approximate depth of anticlinal folds. Seismic reflection surveying operates in the same fashion as sonar location of submarines. The seismic reflection data are acquired along lines [profiles] laid out on a map as an intersecting grid.

We have used seismic reflection data acquired by the U.S. Geological Survey, the Scripps Institution of Oceanography, and the University of Washington to evaluate possible anticlinal domes on the Washington OCS that may act as oil and/or gas traps. The grid spacing of public-record seismic profiles is generally greater than the size of typical traps; therefore, it is probable that we have been unable to identify many potential traps. Similarly, the wide spacing of seismic profiles prevents accurate mapping of all dimensions of potential traps. However, we can demonstrate that a large number of folded structures exist in the offshore region, and we anticipate that some of these structures may act as traps.

RESULTS OF PREVIOUS OFFSHORE DRILLING

A total of four deep oil and gas exploratory wells have been drilled offshore of Washington State. The State of Washington leased oil and gas rights in its territorial waters (within 3 miles of the shoreline) during the period from 1960 to 1964. The Union Oil Company drilled the first deep offshore exploratory well, the Tidelands State No. 2, in 1962, but no shows or reservoir rocks were encountered. In 1964, an offshore oil and gas lease sale was conducted by the Department of the Interior on the Washington and Oregon OCS. Three Washington OCS exploratory wells were drilled on leases purchased during this sale at prices ranging from $5 to $310 per acre. Indications of petroleum in the Hoh sequence, including small flows of gas, were encountered in two of these OCS wells drilled by the Shell Oil Company. Montesano Formation sandstone reservoirs were not present in two of the OCS wells. In the third OCS well where a thick Montesano sandstone was present the seal was inadequate. All four offshore exploratory wells were abandoned as dry holes; however, many major oil- and gas-producing areas worldwide have had more than 25 dry holes drilled prior to the initial discovery.

OIL AND GAS POTENTIAL OF THE WASHINGTON OCS

Petroleum exploration is an intermittent process that reflects data availability, technical knowledge, results of previous exploration, and economic conditions. Offshore exploration ceased in the late 1960s because of the lack of encouraging results from the four offshore wells. Since that time, geologic and seismic data have improved significantly in both quality and quantity, and technical knowledge has increased exponentially. Increased exploration interest in the Washington continental margin is likely because of these factors and because areas favorable for easy discovery of large oil or gas accumulations are nearly exhausted.

The combination of potential traps, numerous oil shows, and an exceptional quality (if unpredictably distributed) Montesano sandstone reservoir suggest that renewed interest in oil and gas exploration on the Washington OCS is possible. We regard the potential for significant petroleum accumulations seaward of the continental shelf on the continental slope and Pacific Ocean abyssal plain as poor. On the continental shelf, the potential for petroleum generation and for the occurrence of Montesano sandstone reservoirs is greatest near the coastline. The region within 12 miles of the coast and north of 47° latitude encompasses approximately 75% of the area on the Washington OCS which we regard as favorable for significant petroleum accumulations.

The force driving future exploration of offshore Washington would be the potential for discovery of a giant field (500 million barrels of oil or equivalent gas). Giant fields contain more than 70% of the world's recoverable oil. We regard the overall potential to discover a giant field on the Washington continental margin as 2 on a worldwide scale of 10. However, the best remaining unexplored [frontier] basins, such as the Arctic National Wildlife Refuge, are 7 or 8 on this same scale, while most frontier basins worldwide are rated 5 or less.

SUMMARY OF TECHNICAL FINDINGS

1. The following is a brief history of some geologic events that affected the Washington continental margin. It has been prepared using work by Snavely (1987), Snavely and Kvenvolden (1988), Snavely and others (1986), Rau (1975, 1979), Tabor (1975), and Tabor and Cady (1978a,b):

    a. *50 Ma*: Subsidence of a basin in the area of the present Olympic Mountains and partial topographic isolation of this basin by development of thrusted (or constructional-volcanic) highlands north of the Crescent thrust, south and east of the Southern Fault Zone, and on the east side of Willapa Bay. These highlands were composed of lower Eocene Crescent Formation basalts.

    b. *48 to 27 Ma*: Deposition and thrusting of turbidites of the Ozette melange in this basin and on the present continental margin (approximately 48 to 35 Ma). A widespread depositional hiatus may have occurred during the Oligocene (35 to 27 Ma). The nature of the basement under these turbidites is unknown.

    c. *27 to 14 Ma*: Continued thrusting in the northwestern Olympic Peninsula parallel with the Crescent thrust and deposition of the Hoh rock assemblage on the western Olympic Peninsula.

    d. *17 to 12 (?) Ma*: Regional uplift and erosion (?) of the Hoh/Ozette sequences in the area of the present continental margin. Uplift of the Olympic Mountains.

    e. *12 to 8 (?) Ma*: Foundering of eroded Hoh/Ozette sequences westward from the vicinity of the present coastline and subsequent deposition of hemipelagic sediments of the Montesano claystone member and equivalent units.

    f. *8 (?) to 5 Ma*: Development of the present continental shelf and continuous deposition of upper Montesano Formation and equivalent sediments. Uplift was accompanied by strike-slip faulting and intermittent diapiric intrusion.

    g. *5 Ma to present*: Deposition of the Quinault and Quillayute Formations and Pleistocene sediments. Intermittent diapiric intrusion and possible strike-slip faulting.

2. Anticlines are common on the continental margin. Simple anticlines range from 0.5 to 7 mi in profile (as measured from the troughs of adjacent synclines). Diapiric uplifts are commonly greater than 2.5 mi in profile. The orientations and dimensions of these folds and diapirs cannot be mapped with the existing public-record data set. It is not possible to map closure on any of these anticlines from these data.

3. Porosity in the Hoh rock assemblage and Ozette melange sandstones ranges from 5 to 30%, and approximate thickness of sandstones in 14 selected wells averages 34 ft. Permeability in the Hoh/Ozette is low due to large clay volumes and secondary mineralization. It is not possible to distinguish prospective Hoh/Ozette broken formations from nonprospective chaotic turbidites (F facies), or from other melange fabrics on the basis of well data. House-sized sandstone olistostromes crop out as sea stacks along the coast.

4. Montesano Formation porosity ranges from 20 to greater than 30%, and reservoir thickness averages 40 feet. The Montesano sandstone member was drilled in the Ocean City area and in the Shell P-0155 wildcat where wireline log, sidewall core, and seismic data indicate that more than 600 ft of porous sandstone are locally present. Permeability in the Montesano sandstone member is typically greater than 500 md. This sandstone is not sealed in the Ocean City area

or in the P-0155 well. Similar sandstones crop out at Aberdeen and near Point Grenville/Cape Elizabeth. We regard these sandstones as the primary exploration target on the Washington continental margin.

5. The Quinault and Quillayute Formations and equivalent strata are probably not buried to sufficient depths to be considered as conventional petroleum plays.

6. Significant oil and gas shows were tested in the Ocean City, Hoh River, and Forks areas, and oil shows were logged in the Shell P- 0155 offshore wildcat. Numerous coastal outcrops of very dark gray mudstone and siltstone presently seep oil. The Shell P-0150A offshore wildcat tested 10 and 26 MCFGPD in two zones within the Hoh sequence, and several gas seeps have been located onshore.

7. Rocks on the continental margin and western Olympic Peninsula analyzed to date have fair potential to generate natural gas. Although some rocks in the Ozette melange near Forks have two rare biomarkers also found in oil samples from coastal wells and seeps, no oil-prone source rocks have been identified in the study area.

8. Geohistory analysis, thermal alteration indices, vitrinite reflectance, and Tmax determinations indicate that the sections penetrated offshore are generally immature for petroleum generation. Onshore, seeps and significant shows are concentrated between the coast and a parallel line roughly 20 mi to the east.

9. The primary exploration play will probably be for these sweet, paraffinic oils rather than for gas.

10. Structures dissected (or formed?) by strike-slip faults could facilitate migration between the Montesano reservoir sequences and underlying source rocks. These structures may also control deposition and/or distribution of sandstone sequences within the Montesano and Quinault Formations. Similarly, marginal faulting along diapirs could facilitate migration between the Montesano reservoir sequences and underlying source rocks. Structures formed in response to diapiric intrusion are potential hydrocarbon traps.

11. We speculate that an "average" Ozette or Hoh oil pool might contain 10 million barrels of recoverable oil. However, risked reserves for the Ozette/Hoh are only a small fraction of this number owing to complex structure, discontinuous reservoir strata, and the difficulty of defining traps with seismic data.

12. Speculative reserves for a Montesano oil pool, assuming that the reservoir has the average porosity and thickness of those penetrated to date, are 20 million barrels. A 300-ft-thick Montesano sandstone reservoir, 50% full to spill, could contain 250 million barrels of recoverable oil.

13. The entire shelf may have potential to contain gas and/or oil accumulations within the Ozette, Hoh, and Montesano sections. Areas immediately adjacent to the coast are closer to the Montesano provenance and, consequently, are considered as more prospective with regard to sandstone reservoir development than areas farther west. Furthermore, the coastal area is adjacent to the zone of common seeps and shows. The potential of the continental slope and Pacific abyssal plain is considered poor.

1

Introduction

The Minerals Management Service, Department of the Interior, has proposed holding an oil and gas lease sale encompassing the Outer Continental Shelf (OCS) of Washington and Oregon. This sale, Sale 132, is tentatively scheduled for 1992. The location of the proposed sale area adjacent to Washington is shown on Plate 1.

The purpose of this study is to collect relevant public-domain geological and geophysical data and to assess the oil and gas potential of the Washington continental margin. Most of the data and analyses used in this report are from wells and outcrops located onshore. Previous research (summarized in Snavely, 1987) has demonstrated continuity of the onshore and offshore geology.

Geological and Geophysical Data Set

Interpretations contained in this report are based solely on public-domain geological and geophysical data. The Division of Geology and Earth Resources (DGER) library contains a comprehensive collection of maps, reports, journal articles, publications, field notebooks, and other data pertaining to the geology of Washington. DGER also maintains comprehensive well files, including core and cuttings samples, oil samples, and wireline logs, as well as histories for most onshore wells, the four offshore wildcats, and two offshore Canadian exploratory wells. Plate 1 gives the locations of these wells. The numbers beside each well symbol on this plate are for reference to Appendix A -- Well Information. Approximately 30 wells drilled prior to 1930 are not included on Plate 1 or Appendix A because appropriate data are not available.

The geophysical data set was checked to be certain that all public-record data were incorporated in the study by using a computer search. This search was conducted by the National Geophysical Data Center of NOAA, in the latitude-longitude range from 46°0' to 48°30' N, and 124°0' to 126°30' W. Copies of multi-channel seismic reflection profiles collected by the U.S. Geological Survey (Mann and Snavely, 1984; Snavely and McClellan, 1987, 1988) were kindly provided by Parke Snavely. These data were augmented with deeper penetration single channel profiles provided by Eli Silver of the University of California, Santa Cruz, and with shallow single channel reflection data collected by the University of Washington and provided by Mark Holmes of U.S. Geological Survey (USGS). Various gravity and magnetic survey data compiled by Carol Finn of the USGS were also used in this assessment.

History of Oil and Gas Exploration on the Western Olympic Peninsula and Adjacent Offshore Areas

We have divided the search for petroleum on the western Olympic Peninsula and offshore Washington into five periods of drilling activity. Plate 1 and Appendix A give the location of oil and gas exploration wells drilled in the study area.

PHASE I

The earliest phase of oil and gas exploration in the western Olympic Peninsula occurred between 1901 and 1930. Exploration commenced in 1901 with the drilling of a well near the town of Copalis. This well was reported to have had slight gas shows. Small independent operators who drilled most of these early wildcats chose their locations primarily on the basis of proximity to surface oil or gas seeps. Two wells (Nos. 14 and 15, Inset 2, Plate 1) were drilled southwest of Forks near the Jefferson oil seep, and both logged shows of oil and gas. A number of other wells drilled around the town of Forks (Inset 1, Plate 1) encountered high- pressure low-volume gas zones. None of these wells were developed commercially. Two shallow wells (Nos. 30 and 31) were drilled adjacent to the Garfield gas mounds but were soon abandoned. Wells drilled near the Moclips and Copalis Rivers (Nos. 33 and 34) had no significant shows of oil or gas.

PHASE II

During the second phase of exploration, between 1930 and 1940, considerable efforts were made by independent operators in exploring and drilling the area near the Jefferson oil seep (Inset 2, Plate 1). A number of wells had encouraging oil tests in shallow Hoh rock assemblage sandstones, but efforts to achieve commercial production proved futile. The frontispiece is a photograph taken in 1931 of the derrick used in drilling the Sims No. 1 well (No. 16). Some of these Hoh zones might have been capable of stripper production, but shipping costs to San Francisco, the nearest refinery, made such production unprofitable. Some of the oil recovered from these wells was shipped to Seattle and used to make "Velvol", a lubricating product (S. L. Glover, DGER, field notebook, circa 1938).

A well (No. 22) was drilled at the nearby Lacy oil seep and recovered oil, but was abandoned after drilling into shale. Likewise, three wells (Nos. 2, 3, and 7) were drilled in the Forks area, and again only noncommercial gas shows were reported. During this period, a number of wells were drilled in the Grays Harbor Basin near Aberdeen; subcommercial gas and oil shows were reported in many of these wells. (Wells drilled in the Grays Harbor Basin are not shown on Plate 1.)

PHASE III

The third phase of exploration, carried out primarily by major oil companies, occurred between 1945 and 1955. The Union Oil Company of California concentrated its activity around Ocean City, an area that was previously untested. Union conducted a seismic survey, and used these data to choose several exploratory well locations.

Union spudded the first well in this area, the Barnhisel No. 1, on August 7, 1947. Oil shows on the ditch occurred below 1,450 ft, and gas shows in cores (including cores that burned when ignited or "flashed") were ubiquitous below this depth. At 2657 ft, the drill-string was dropped in the hole, and the well was abandoned. All of the shows were logged in the Montesano Formation.

By June of 1949, Union had drilled four more wells in the Ocean City area, the Clapp No. 1, State No. 1, State No. 2, and the State No. 3. These wells had excellent shows of oil and gas in the Hoh rock assemblage and/or the Ozette melange. The Clapp No. 1 logged oil and gas in the ditch below 2,000 ft, and core samples recovered below 2,700 ft contained oil and flashed. No tests were run, and the well was abandoned. Union moved the rig and drilled two wells near the Copalis River north of the Ocean City area and then moved back to drill the State No. 1 about 3/4 mi south of the Clapp No. 1. Production tests of this well within the Hoh sequence between 3,630 and 3,885 ft recovered gas at 1.0 to 1.5 MMCFGD (million cubic ft of gas per day) through a 30/64-in. choke and at 300 psi flowing tubing pressure (FTP). This test also produced approximately 65 barrels of 40° API gravity oil. The well was abandoned when tests of a shallower interval recovered water.

Union skidded the rig back to a location only 200 ft from the Clapp No. 1 and proceeded to drill the State No. 2. The first core was taken in the zone that yielded oil in the Clapp No. 1. These cores had good indications of oil and gas, but an extended test between 3,710 and 3,772 ft failed to produce. The rig was then skidded back to a location 200 ft from the State No. 1, and the State No. 3 spudded. This well, drilled to 9,334 ft, is the deepest onshore well in the western Olympic Peninsula. Cores were taken only in the Hoh/Ozette sequence, and many had indications of oil and gas. Production tests of commingled Hoh/Ozette intervals between 3,670 to 4,400 and 4,663 to 4,676 ft were conducted from October 1949 to May 1950. These recovered approximately 1,000 barrels of oil. Because of these marginal results and the existing economic conditions, Union judged the Ocean City area to be a non-commercial play and farmed out their lease interests in the area to Thomas P. Hawksworth and Associates.

The fifth well in the Ocean City area, the State No. 4 (No. 58), was drilled by Hawksworth, and it encountered significantly better oil and gas shows. During a one-month production test, the State No. 4 flowed wet gas at rates of 500 to 2,000 MCFGPD with 1,200 psi casing pressure, and as much as 35 BOPD (barrels of oil per day). However, this well was not put into production, apparently because of litigation involving the oil and gas leasing rights and because the casing collapsed. Subsequently, the Union leases were passed among various operators until acquisition by the Sunshine Mining Company in 1958.

PHASE IV

The fourth and most significant phase of oil and gas exploration in the western Olympic Peninsula and the adjacent offshore occurred from 1957 to 1967. Further drilling at Ocean City resulted in the sale of small quantities of crude oil and gas from two non-profitable wells. During this phase, the State of Washington and the federal government conducted oil and gas lease sales of offshore parcels that resulted in the drilling of four exploratory tests on the Washington continental shelf.

In the summer of 1957, the Medina No. 1 (No. 56) was drilled by the Sunshine Mining Company in the Ocean City area. This well was located on the beach behind a dike constructed to keep waves from inundating the location. Drillstem tests recovered significant amounts of oil, and the well was completed. Contracts with a shipping company and a Tacoma refinery established a price of $2.71 per barrel of oil after freight costs. By the close of 1961, when the Medina No. 1 was shut-in, a reported 12,000 barrels of oil had been produced. The Humble Oil and Refining Company purchased Sunshine's rights to the Medina No. 1 and abandoned the well in 1962 while it was making a reported 5 BOPD.

Sunshine unitized leases around the Hawkesworth State No. 4 well during the late 1950s. This well was recompleted as the Sampson Johns Unit No. 1. A gas pipeline running from the well to Ocean Shores was constructed in 1960, and a total of 5.5 MMCFG were sold to the real estate development at $0.40/MCF ($2,200 gross revenues). Gas deliveries to Ocean Shores were terminated in December 1961. In 1969, Jack Taylor, owner of a local drilling firm, recompleted the Sampson Johns Unit No. 1 and sold small volumes of gas to a local motel for a short period of time.

By 1962, the Sunshine Mining Company had drilled or recompleted six other wells in the Ocean City area, but it was unsuccessful in establishing profitable production. Sunshine drilled the Medina No. 2 in the fall of 1957 and recovered oil and gas from drillstem tests in the Montesano and Hoh sequences. However, the well was subcommercial and abandoned on November 15, 1957. The Hogan 22-1, a well initially drilled during the 1950s, was acquired by Sunshine in 1960 and recompleted. Sunshine tested gas at 238 MCFGPD with 45 psi FTP through a 3-in. "choke" from perforations between 3,045 and 3,055 feet. This well was not be put on production despite the fact that Sunshine had already finished the pipeline to Ocean Shores.

During the development of the Ocean City area, the Sunshine Mining Company and the Humble Oil and Refining Company drilled three wells near the Moclips River (Nos. 39, 40, and 41). The Montesano and Quinault Formations are absent in these wells, and only minor shows were logged in the Hoh and Ozette sequences.

During the period from 1960 to 1964, the State of Washington leased oil and gas mineral rights on a number of offshore ("tidelands") parcels. In 1962, Union attempted to drill two wells on their offshore State leases, but both were abandoned at shallow depths due to severe weather. In 1964, Union drilled the first significant offshore Washington wildcat, the Tidelands State No. 2 (No. 86), to a depth of 5,073 ft, but no shows were encountered. All State tideland oil and gas leases expired with no further exploratory drilling.

On October 1, 1964, a lease sale was conducted by the federal government for the Washington and Oregon OCS. Of the 113 blocks offered, 101 blocks were leased in this sale. Fifty-seven bids totaling $10,500,000 were received for Washington offshore tracts; the high bid was $310 per acre (Webster, 1985). Three wells, the P-0150 (and the P-0150A redrill), P-0155, and P-0141 (Nos. 84, 85, and 87), were drilled on the OCS by the Shell Oil Company and the Pan American Oil Company. Oil shows were logged in the P-0155, and two drillstem tests in the P-0150A redrill flowed gas at 10 and 26 MCFGPD, respectively. These wells were plugged and abandoned, and the OCS leases expired in 1969.

PHASE V

The fifth and last phase of exploration was limited to the western Olympic Peninsula and occurred from 1969 to 1981. During 1969 and 1970, the Shell Oil Company conducted a seismic survey in the Ocean City area, and then drilled eight shallow stratigraphic test wells on the basis of these data. The apparent purpose of this program was to evaluate Montesano sandstone member reservoirs in this area. Sidewall and conventional cores from the Montesano commonly had cut and fluorescence, but only one well produced gas on a drillstem test.

Independent operators drilled a number of exploratory wells near the Jefferson oil seep and the town of Forks and in the area between the Moclips and Copalis Rivers. Again, a number of these wells had oil and gas shows, but none were considered for commercial development. The most recent exploration well drilled on the western Olympic Peninsula was the Sunburst No. 1 (No. 23), located southeast of the Jefferson oil seep. This well, drilled in 1981, tested a small flow of gas, but was determined to be noncommercial. No further oil and gas exploration activity has occurred since this well was plugged and abandoned.

2

Regional Geology

The regional geology and stratigraphy of the continental margin and adjacent areas is summarized on Figure 2-1 (modified from Snavely, 1987) and Figure 2-2. The following discussion is based mainly on work by Carol Finn (USGS, 1988 written commun.), Henderson and others (1957a-d), MacLeod and others (1977), McFarland (1983), Rau (1975, 1979, 1986), Rau and McFarland (1982), Snavely and others (1986), Stewart (1970), Tabor (1975), and Tabor and Cady (1978a,b).

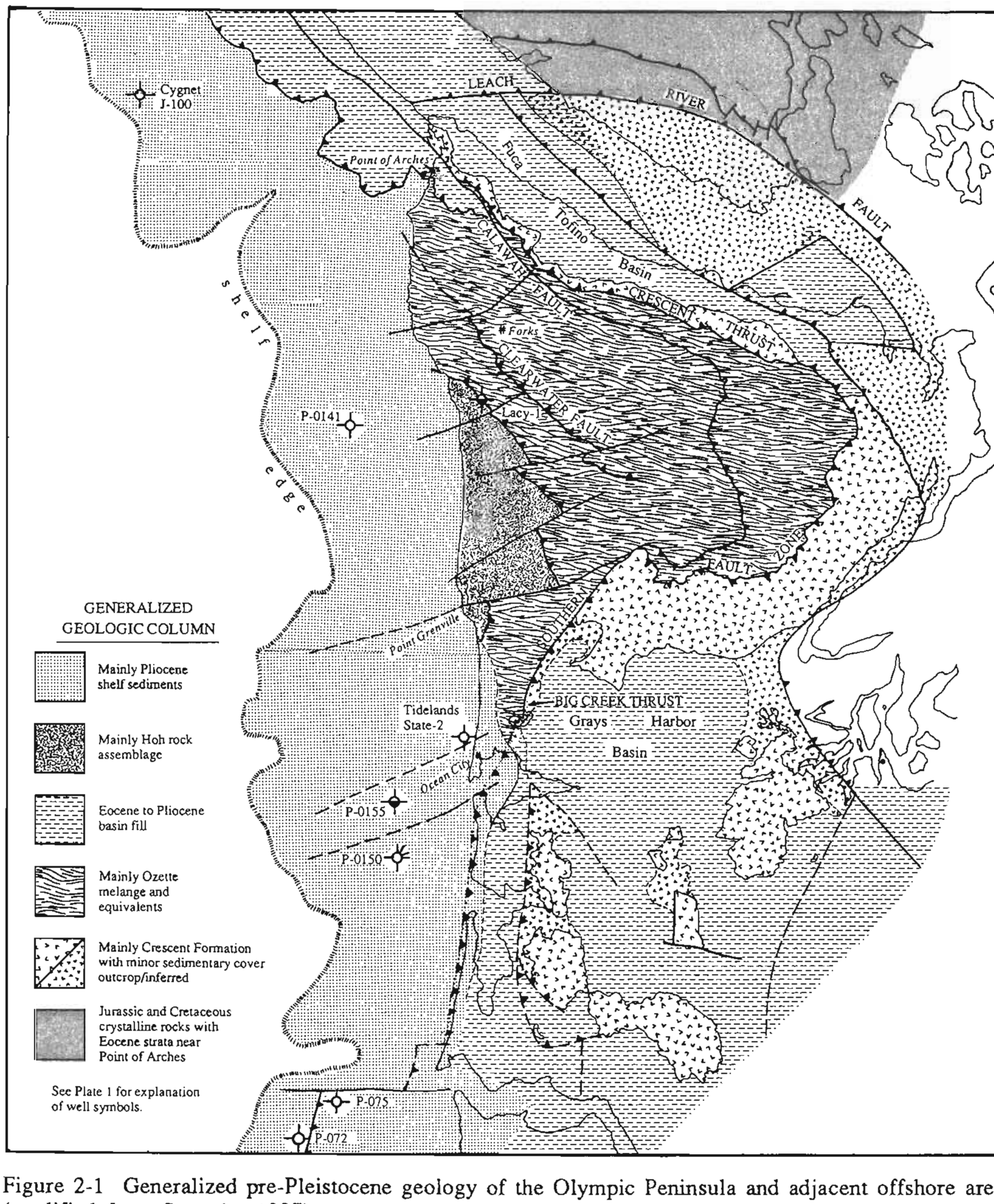


Figure 2-1 Generalized pre-Pleistocene geology of the Olympic Peninsula and adjacent offshore areas (modified from Snavely, 1987).

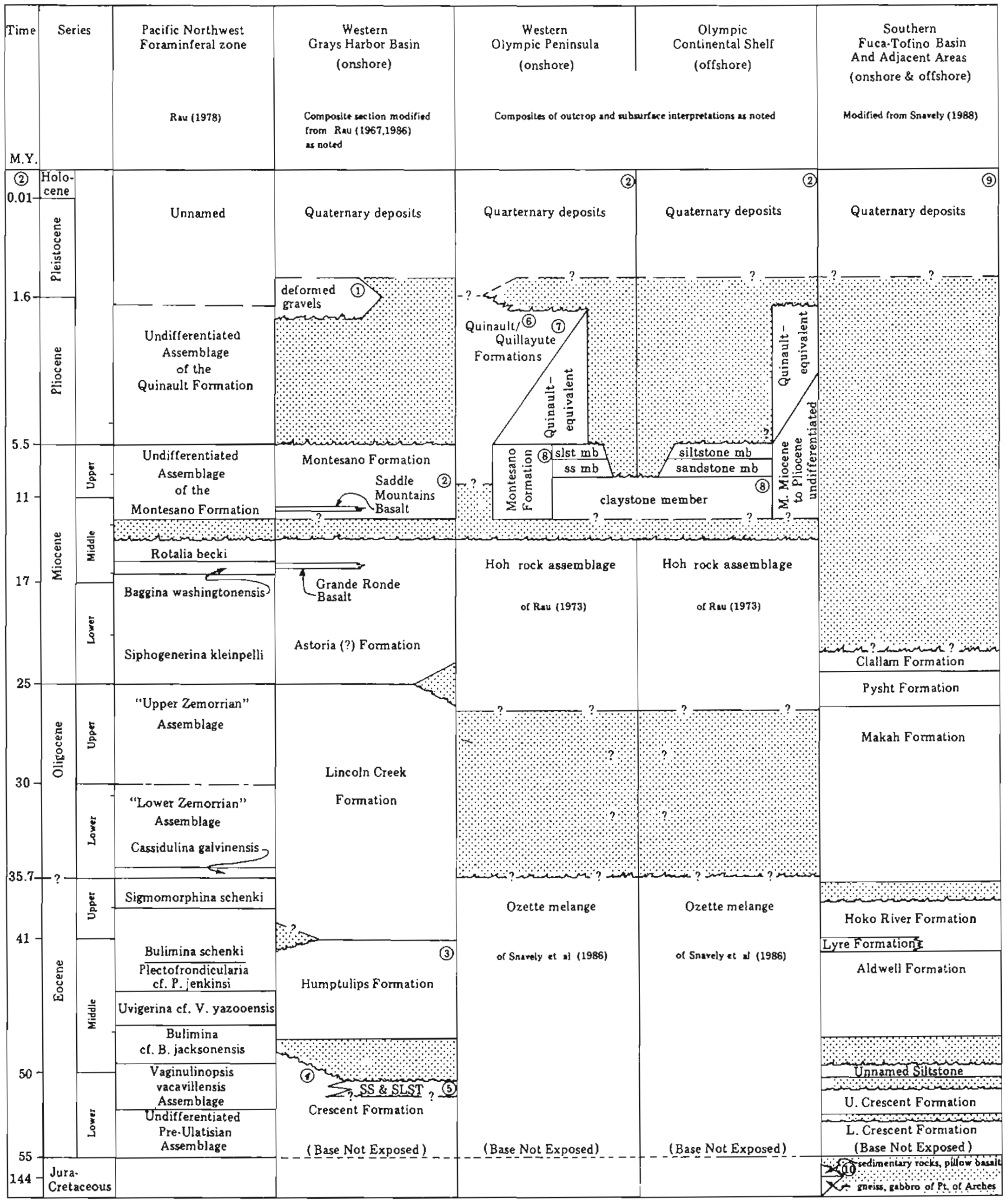


Figure 2-2 Stratigraphic columns for the Olympic Peninsula, Grays Harbor Basin, coastal Washington, and the Washington continental shelf.

The regional structure of the Olympic Peninsula and the continental margin is poorly understood owing to a lack of high resolution geophysical data, the thick vegetative cover on outcrops, and the inherent complexity of the geology. The following is a generalized description of the regional geology as presently understood.

Sedimentary rocks on the Washington continental margin and Olympic Peninsula are mainly composed of lower Eocene (?) to middle Miocene turbidite and melange sequences informally named the Ozette melange (Snavely and others, 1986) and Hoh rock assemblage (Rau, 1975). Middle Miocene and younger shelfal lithologies including the Montesano Formation, the Quinault Formation, the Quillayute Formation, and undifferentiated upper Pliocene to Recent sediments overlie the Ozette and Hoh sequences. These shelfal rocks and sediments extend eastward from the shelf edge to the coast and lap onto the westernmost Olympic Peninsula. All of these grade westward into deformed, Miocene and younger slope and abyssal plain deposits including those of the Nitinat and Astoria Fans.

All of these rocks are bounded on the north, east, and south by lower Eocene Crescent Formation basaltic uplifts which formed by thrusting and constructional-volcanism (?) during the early Eocene. Eocene to Recent basin-fill sequences (e.g., the Humptulips and Astoria Formations and Twin Rivers Group) lie inboard from the Crescent basaltic uplifts. These uplifts created a nearly continuous topographic barrier that appears to have isolated the Hoh and Ozette sequences, which were deposited in a deep-water open-marine setting, from coeval basin-fill sequences to the east (Rau, 1986; Snavely, 1987; Snavely and Wagner, 1982a; Tabor and Cady, 1978a). Westward transport of terrigenous sediments may have been blocked by this barrier. However, a gap in this barrier may have existed on the northeastern Olympic Peninsula where Crescent basalts do not crop out. (See Figure 2-1.) Alternatively, Ozette and Hoh detritus may have been partially deposited in a fan(s) off Oregon which subsequently was translated northward and deformed by imbricate thrusting as these rocks abutted against Vancouver Island (Bates and others, 1981; Beck, 1984).

Mapping by Snavely and others (1986) and Snavely and Kvenvolden (1988) shows that the Ozette and older rocks on the northwestern Olympic Peninsula are thrust-faulted by several west-northwest trending systems. These are traceable for at least 100 mi along strike. The northeasternmost of these systems, the Crescent thrust, underplates Eocene strata below Crescent basalts which form the aforementioned topographic barrier in this area. Snavely and Kvenvolden (1988) note that Eocene strata deposited in the Fuca-Tofino Basin thin southward and lap onto the Crescent basalt in the hanging wall of the Crescent thrust. The southwesternmost fault, the Clearwater fault thrusts Ozette over lower Miocene Hoh (see Snavely and Kvenvolden, 1988). A magnetic data compilation by Carol Finn (USGS, 1987 written commun.) suggests to us that additional fault systems which involve magnetic (volcanic ?) rocks may subcrop below Pleistocene beds near Forks.

Many of these thrusts are cut by strike-slip faults (Figure 2-1). A strike-slip fault juxtaposes Pliocene Quinault beds against Miocene Quinault at Duck Creek. In the Ocean City area, a similar strike-slip fault cuts the middle to upper Miocene Montesano Formation (See Chapter 6.) These faults can be traced offshore on seismic reflection profiles (Wagner and others, 1986; Chapters 3,7).

South of Lake Quinault, Eocene Humptulips Formation siltstones and Crescent Formation basalts overlie Ozette melange (and the Hoh rock assemblage ?) along the Big Creek thrust, an extension of the Southern Fault Zone (Rau, 1986; Tabor and Cady, 1978a). West of the Big Creek thrust, we infer, but are unable to map, thrusts which juxtapose Ozette over the Hoh rock assemblage.

Hoh and Ozette structures at outcrop scale are chaotic. Thrusts, intense folding, broken formations, and melange typical of accretionary margins are exposed along the Olympic beaches (Rau, 1975, 1979; Snavely and Kvenvolden, 1988; Snavely, 1987; Stewart, 1970). High angle reverse faults and minor normal faults having various orientations are also common. Folding ranges from open to isoclinal with near-vertical to overturned axial planes that have a wide range of orientations. Exposed thrusts commonly have east-dipping planes (Rau, 1975, 1979, 1987). Thick sections of very dark gray, siltstone and claystone containing turbidite olistostromes crop out in strike-slip and thrust fault zones. Several of these zones are in excess of 1,000 feet in apparent thickness. Rau and Grocock (1974) and Orange (1987) suggest that the very dark gray siltstones and claystone along these fault planes are diapirs. These probable mud diapirs contain blocks of Ozette and Hoh turbidites and volcanic rocks. Deformation of the Miocene to Pliocene section is less intense; folding appears to be controlled by diapiric intrusion and strike-slip faulting.

3

Stratigraphy

The stratigraphy of the Washington continental margin has been thoroughly described in various reports cited below. This discussion highlights the significance of upper Miocene strata that we believe have the greatest potential to contain significant petroleum accumulations.

The Washington continental shelf and adjacent portions of the Olympic Peninsula contain a sequence of middle Eocene to upper Miocene deep-marine siliciclastic and minor volcanogenic rocks overlying oceanic basement. All of these rocks are overlain by upper Miocene to Recent deep-water or paralic sediments. The total sedimentary section may have a unit thickness in coastal areas as great as 50,000 ft (Connard and others, 1984; Johnson and others, 1984).

Figures 2-1 and 2-2 illustrate the spatial and stratigraphic relations on the Washington continental margin and adjacent areas. Table 3-1 gives tentative unit tops for wildcats drilled on the continental shelf. These tops are based on analysis and correlation of wireline logs, lithologies, mud logs, drilling reports, well histories (Shell 1966, 1967; Pan American, 1967; Union, 1965), and a limited amount of public-record biostratigraphic information (Rau and McFarland, 1982; Snavely and Wagner, 1982a; Snavely, 1987).

These rocks are described in Bigelow (1987), Grady (1985), Horn (1969), Moore (1965), Orange (1987), Rau (1967, 1970, 1973, 1975, 1979, 1980), Rau and Grocock (1974), Rau and McFarland (1982), Rector (1958), Snavely (1987), Snavely and Kvenvolden (1988), Snavely and others (1986), Stewart (1970), Tabor (1975), Tabor and Cady (1978a), Weaver (1912), and Zieglar and Cassell (1978).

Crystalline Basement

Crystalline basement east and north of the Washington continental margin is composed of lower Eocene Crescent Formation basalts. Offshore, Crescent basalts were probably penetrated in the Prometheus H-68 wildcat in Canada (Snavely and Wells, 1984). The aforementioned thrusted uplifts are the apparent western limit of Crescent basalts (Snavely and Wagner, 1982a). Although the Crescent Formation is commonly considered economic basement, Eocene to Miocene sedimentary strata underlie thrusted basalt in the Willapa Bay area (Rau and McFarland, 1982) and in the western Grays Harbor Basin (Snavely and Wagner, 1982a; Cowan and Potter, 1986).

The nature of the basement is unknown in the area from the Crescent sections at Grays Harbor northward to the Point of Arches, where Mesozoic crystalline rocks crop out, and westward to the shelf edge. Nearshore, geophysical interpretations indicate that subducted Miocene seafloor basalt is present at depths in excess of 50,000 feet (Johnson and others, 1984). The magnetic lineation patterns around the Juan de Fuca spreading ridge (Drummond, 1981) suggest that the oldest subducted basement under Washington may be approximately 70 Ma.

Near the Point of Arches, Snavely and others (1986) have mapped crystalline basement (?) comprised of Jurassic gabbro and diorite that are faulted against pillow basalts and minor sedimentary rocks of Cretaceous age. These rocks crop out as tectonic blocks mixed with Eocene strata between the Calawah Fault and Ozette thrust.

Snavely (USGS, 1989, oral commun.) suggests that early-late Eocene basalt (post-Crescent) may be present in the Shell P-075 well in Oregon and as tectonic blocks along Olympic Peninsula beaches. If this interpretation is correct, prospective strata could underlie this early-late Eocene volcanic sequence.

West of the shelf edge, crystalline basement probably consists of Miocene oceanic crust as suggested by the position of the 4A magnetic lineation (Connard and others, 1984).

Ozette Melange

The Ozette melange of Snavely and others (1986) as refined in Snavely and Kvenvolden (1988) includes Eocene turbidites and volcanogenic rocks which crop out in the Olympic core and along the western margin of the Olympic Peninsula. Farther south, on the northern margin of the Grays Harbor Basin, coarse siliciclastic rocks of the Ozette melange (originally mapped as Hoh rock assemblage by Rau, 1986) are overthrust by Crescent basalt along the Big Creek thrust. The basalt is, in turn, unconformably overlain by monotonous, deep-water, siltstones of the middle to upper Eocene Humptulips Formation (Rau, 1986). The Humptulips was deposited on accreted crust within the Grays Harbor Basin, whereas the Ozette was deposited on the continental margin (Figure 2-1). As noted above, the Grays Harbor Basin appears to have been topographically isolated from the continental margin between the middle Eocene and upper Miocene.

Offshore, the Ozette was probably penetrated in the Tidelands State No. 2 and the Pan American P-0141 well. Eocene claystones from 3,307 to 3,922 ft in the Tidelands State No. 2 are interpreted by Rau and McFarland (1982) to be faulted over middle Miocene rocks. However, this zone shows a possible wireline log correlation to claystones of the lower Montesano Formation penetrated in the Shell P-0150 and P-0155 wildcats. It is possible that fauna in this section is reworked (Bergen and Bird, 1972). The Ozette call in P-0141 is based on a marked increase in vitrinite reflectance across a zone barren of a diagnostic fauna (Snavely and Kvenvolden, 1988).

The Ozette melange in outcrop and onshore wells consists of siltstone, claystone, and feldspathic to feldspatholithic sandstone (Figure 3-1) with minor altered basalt. Most of these sandstones are moderately to poorly sorted and have clay volumes in excess of 15% as indicated by wireline log interpretation. Ripup clasts of very dark gray shale are uniformly distributed throughout much of the sandstone, and muscovite is common. Some Ozette sandstones appear compositionally and texturally mature relative to coeval Puget Basin Eocene sandstones. Ozette sandstones in outcrop range from fine lamellae to the "Cat Peak" sandstone which has a aggregate thickness of 300 feet. The "Cat Peak" sandstone extends nearly 20 mi along strike from the Bogachiel River to the Queets Basin east of Mt. Olympus (Tabor, 1975). The inferred Ozette section in the offshore P-0141 well is comprised of feldspatholithic and lithic sandstones, argillaceous and calcareous siltstone, fractured micaceous claystone, and claystone breccia (Pan American, 1967). (See Figure 3-2, 3-3.) In the Tidelands State No. 2, the Eocene section recognized by Rau and McFarland (1982) consists of homogenous sandy claystone and one thin bed of siltstone (Figure 3-4).

In Ozette melange outcrops, we observe Mutti Ricci-Lucchi (1978) facies C and D with subsidiary facies G (mainly Bouma sequences with distal silts and muds). In the P-0141 wildcat,

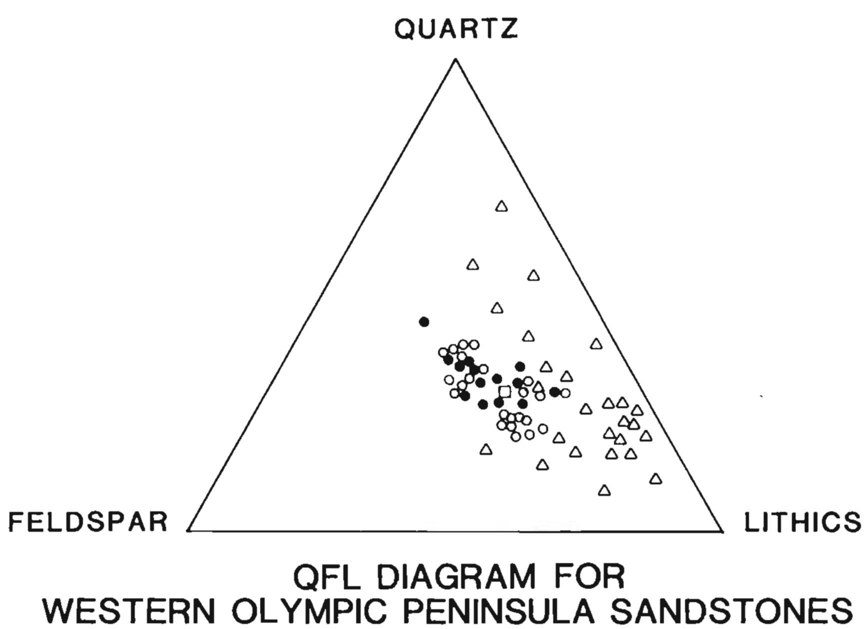


Figure 3-1 QFL plot for various sandstones from the western Olympic Peninsula. Ozette, square; Hoh, dots (Grady, 1985); Montesano, circles (Bigelow, 1987); Quinault, triangles (Horn, 1969).

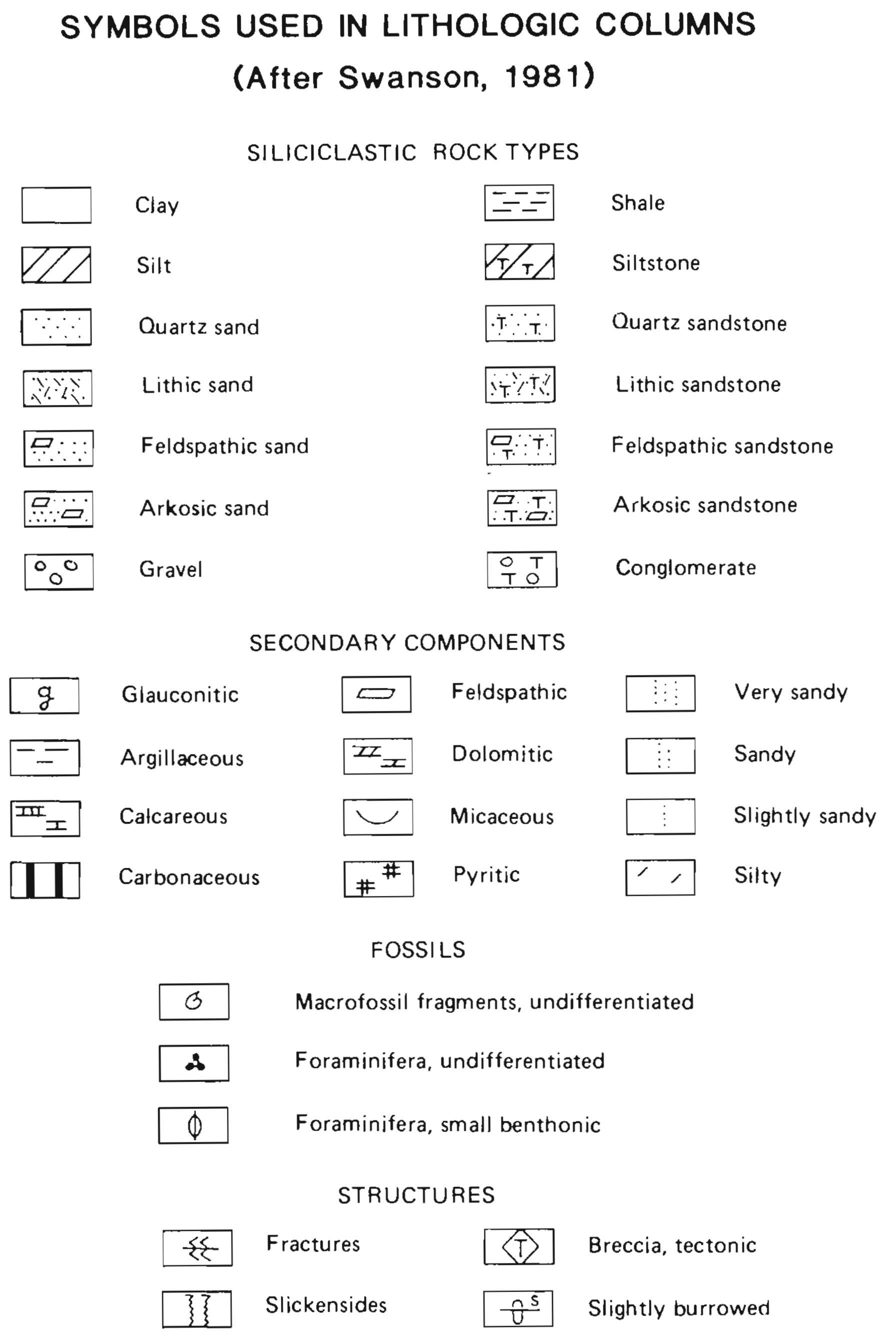


Figure 3-2 Symbols used on lithologic columns (from Swanson, 1981).

the section between 8,100 and total depth is interpreted to comprise mainly facies C and D. The Union Tidelands State No. 2 Ozette section is finer grained, possibly facies G. These interpretations suggest a middle fan association for Ozette strata.

Also included in the Ozette are very dark gray Eocene siltstones and claystones. These are a characteristic "melange" lithology on the Olympic coast. The siltstones and claystones, which crop out 0.1 mi north of Point Grenville, contain numerous tectonic inclusions ranging from pebbles to table-sized blocks of turbidites and altered basalt. These are interpreted as olistostromes (Rau, 1973). These siltstones and claystones, and similar lithologies in the overlying Hoh rock assemblage, apparently crop out only in: (1) thrusts such as Rau's Scott Creek melange zone (1979), (2) along major northeast-trending strike-slip faults such as Stewart's Clearwater River

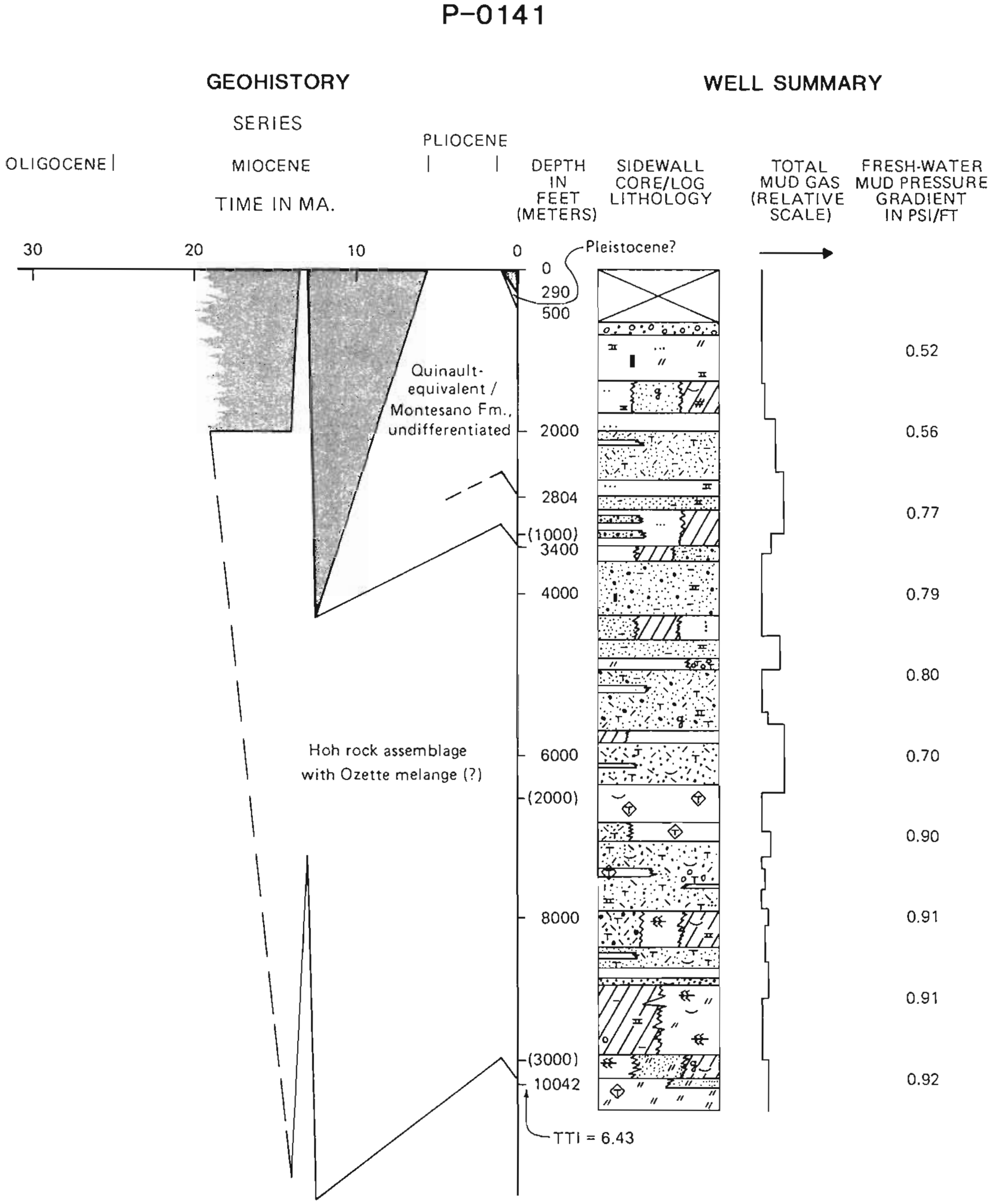


Figure 3-3 Geohistory and well summary for the P-0141 (most data from Pan American, 1967).

shear zone (1970), and, (3) in the core of the Cape Elizabeth diapir (Rau and Grocock, 1974; Orange, 1987).

Oligocene Deposits

Oligocene deposits in the area are not well documented. While many faunal assemblages recovered from these rocks are described as Oligocene to lowermost Miocene undifferentiated, assemblages restricted to the Oligocene are rarely reported on the continental shelf or in the Olympic Mountains (W. W. Rau, DGER, 1988, oral commun.). Bergen and Bird (1972) report an

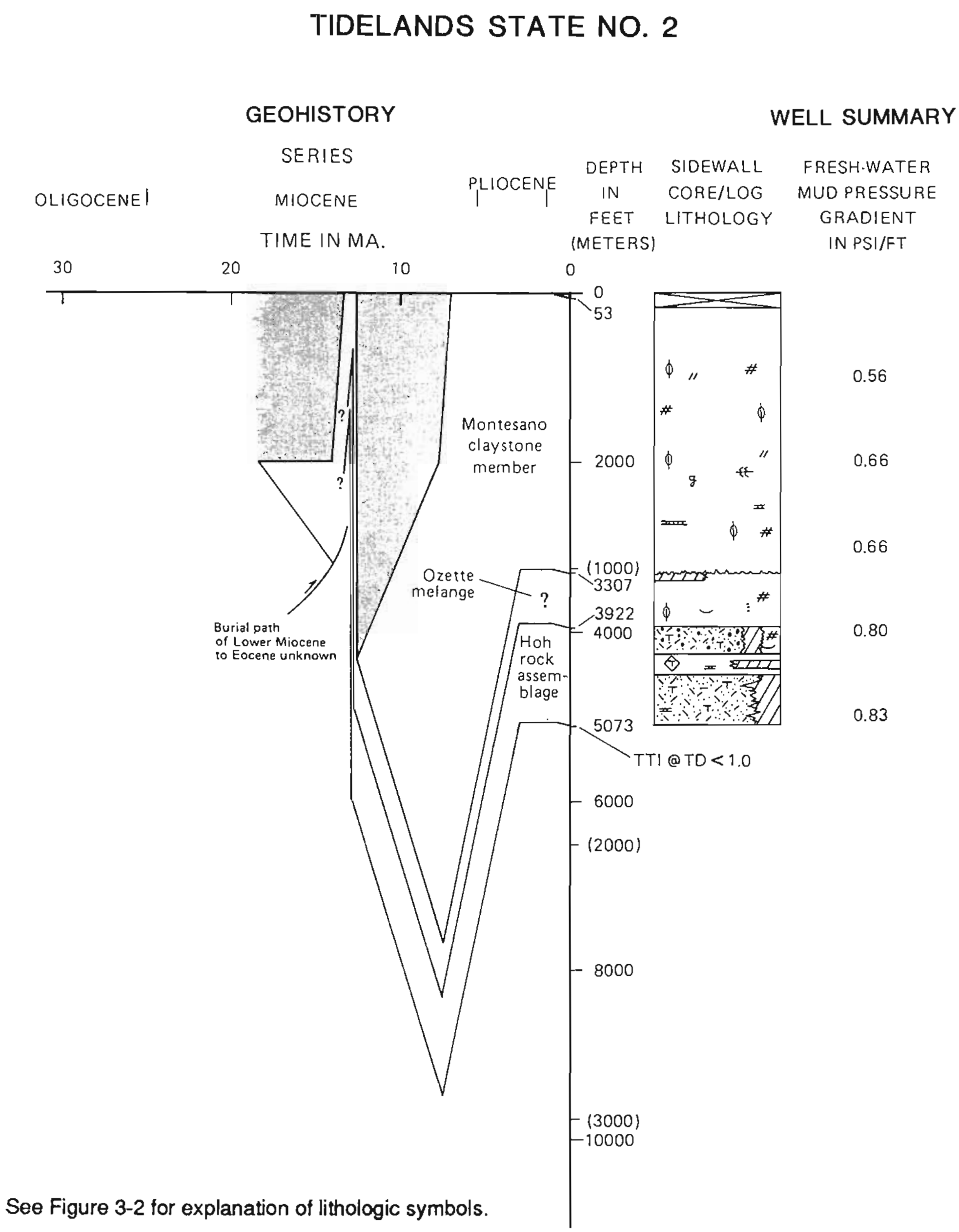


Figure 3-4 Geohistory and well summary for the Tidelands State No. 2 (most data from Union, 1965).

Oligocene fauna at Ocean City near the mouth of Grays Harbor. Figure 2-2 indicates an Oligocene hiatus; an alternative hypothesis is that Oligocene deposition was continuous on the Washington continental shelf but has not yet been documented.

HOH ROCK ASSEMBLAGE

The Hoh rock assemblage of uppermost Oligocene to middle Miocene (Rau, 1973, 1975; Snavely and Kvenvolden, 1988) crops out from the Quillayute River south to the Big Creek thrust. In the subsurface, Hoh rock assemblage lithologies and faunas have been recognized in all offshore Washington wildcats. The easternmost exposure of the Hoh is near Lake Quinault (Snavely, 1987). The Hoh is the time and lithologic equivalent of the Nye Mudstone and Astoria

Formation in Oregon east of the P-075 wildcat (Plate 1). The Hoh is also time equivalent to the Astoria Formation in the Grays Harbor Basin (Rau, 1988, DGER, oral commun.). Rau has observed a lithologic distinction between Hoh rocks and the Astoria where it crops out in the Grays Harbor Basin. The Hoh and Astoria lithofacies are separated by the aforementioned topographic barriers.

The Hoh rock assemblage includes lithologies similar to those of the Ozette melange. Most onshore wildcats near Forks penetrated Hoh rock assemblage consisting of thick sequences of siltstone, claystone, sandstone. Hoh outcrops between the Quillayute River and Point Grenville and the Hoh section penetrated in the P-0141 (Figure 3-3) have higher ratios of sandstone to fine siliciclastics than equivalent rocks south of Point Grenville (Rau, 1975, 1979; Pan American, 1967). The sandstones are grayish green and argillaceous and generally contain numerous very dark gray, 0.1 to 0.25 in. prismatic shale ripup clasts.

Hoh turbidite outcrops are mainly Mutti Ricci-Lucchi (1978) facies C and D and subordinate facies G and E. Hoh sections penetrated in wildcat wells south of Point Grenville are complexly deformed, but most of the rocks are claystones or siltstones which we assume to be relict facies G. The Hoh north of Point Grenville has a middle fan association, whereas the sections to the south are mainly distal fan or basin plain associations.

Very dark gray, siltstone and claystone melanges containing tectonic inclusions of turbidite lithologies are common in Hoh outcrops. These are essentially identical to those described in the Ozette at Point Grenville and include the Ruby Beach smell muds of Snavely and Kvenvolden (1988). These smell muds commonly seep oil at the surface. Minor tectonic blocks of chloritized basalt are present in many Hoh sections. Sheared and brecciated claystone penetrated in numerous wildcats south of Point Grenville (Rau and McFarland, 1982, and Figures 3-4, 3-5, and 3-6) indicates that melange is common in this area.

Farther north, prominent siltstone-filled shear zones at Goodman Creek and Cape Elizabeth give the false impression that siltstone melange is a dominant Hoh lithology in this area. However, wells drilled near Forks and the P-0141 (Figure 3-3) have a uniformly interbedded sequence of sandstone and finer clastics suggestive of turbidite deposition. Outcrops along Olympic National Park beaches and near the Hoh River consist chiefly of coherent turbidite sections, which range from 0.5 to 4.5 miles along strike (Rau, 1975, 1979).

Miocene and Pliocene Strata

Miocene and Pliocene strata form a westward-thickening wedge of siliciclastic rocks and sediments which were deposited across the entire continental margin. Biostratigraphic analysis of the offshore wells (Rau, DGER, 1988, oral commun.) indicates that the section on the continental shelf includes time-equivalents of the Montesano, Quinault, and Quillayute Formations which crop out at various localities along the coast or in the Grays Harbor Basin. The Miocene to Pliocene section unconformably overlies the Ozette or Hoh in the study area (Figure 2-2). Upper Miocene rocks probably overlie Miocene oceanic basalt under the abyssal plain and the rise.

Interpretation of seismic and well data suggests that a regional unconformity/disconformity occurs at the top of the Montesano and cuts to varied depths within the upper Miocene section (Figure 2-2). The limited seismic data set cannot be loop-tied and therefore it cannot be determined whether this is a discrete unconformity or several separate unconformities in offshore areas. However, Snavely and others (1982) report a regional unconformity at the base of Pliocene strata on the Oregon continental shelf.

Biostratigraphic analysis is critical to correlation and subdivision of the Miocene to Pliocene section. However, the distribution of some foraminiferal genera appears to be controlled by paleobathymetry. For example, Bergen and Bird (1972) report that most of the genera in the lower Montesano fauna (early late Miocene) occur in similar proportions to those recovered from core samples of the Recent seafloor off Washington at water depths of 4,300 feet. This Recent assemblage includes *Bulimina subacuminata*, a species used to aid in recognition of the lower Montesano in the subsurface. Bergen and Bird (1972) and Rau (1970; DGER, 1988, oral commun.) suggest that in general, the Miocene to Pliocene section was deposited in progressively shallower water. However, interpretation of seismic data indicates that diapiric and strike-slip structures grew intermittently during deposition of the Miocene and Pliocene section on the shelf. Interpretation by "flattening" the seismic onlap sequence at the B horizon on USGS Line 76-12

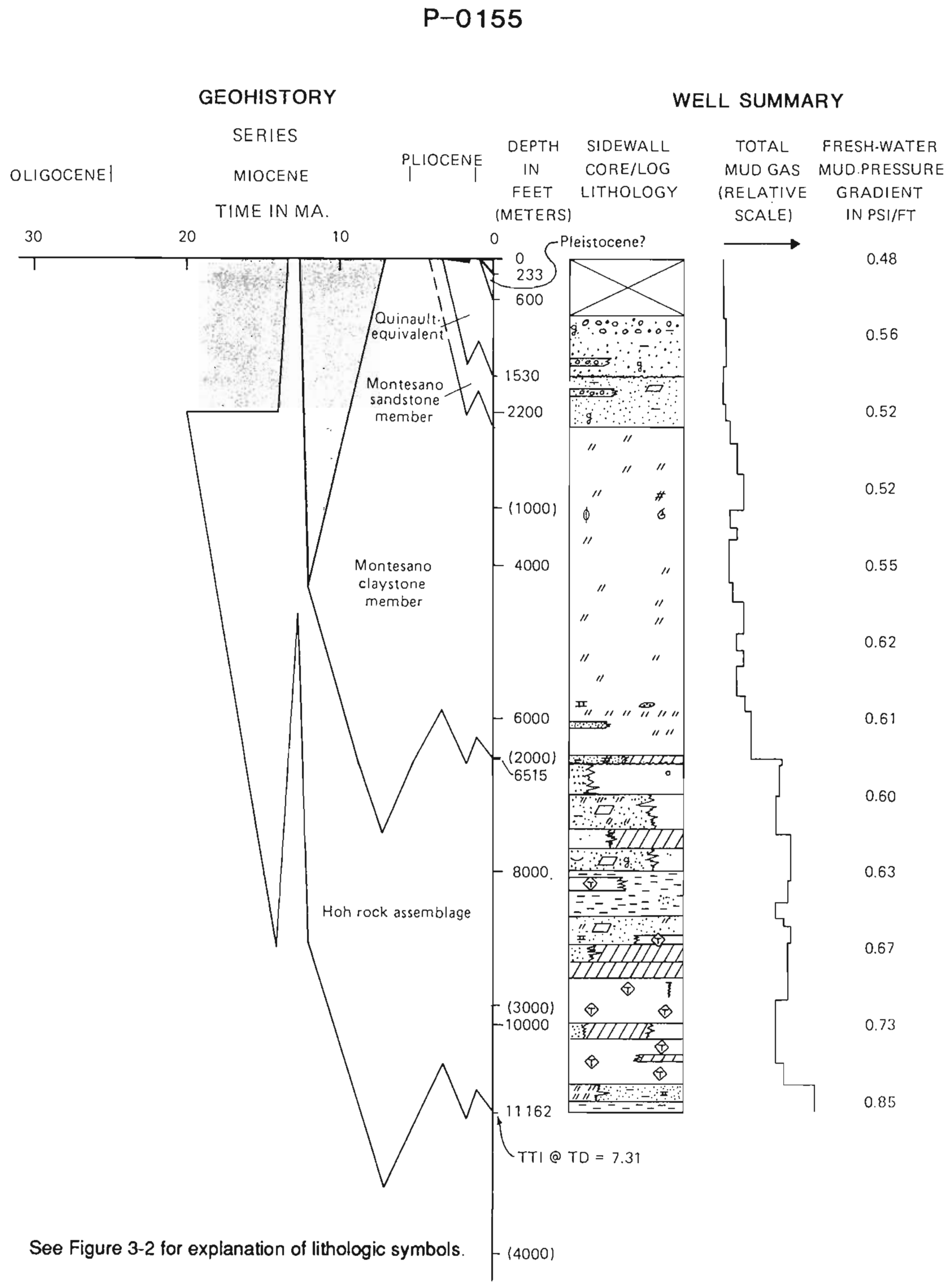
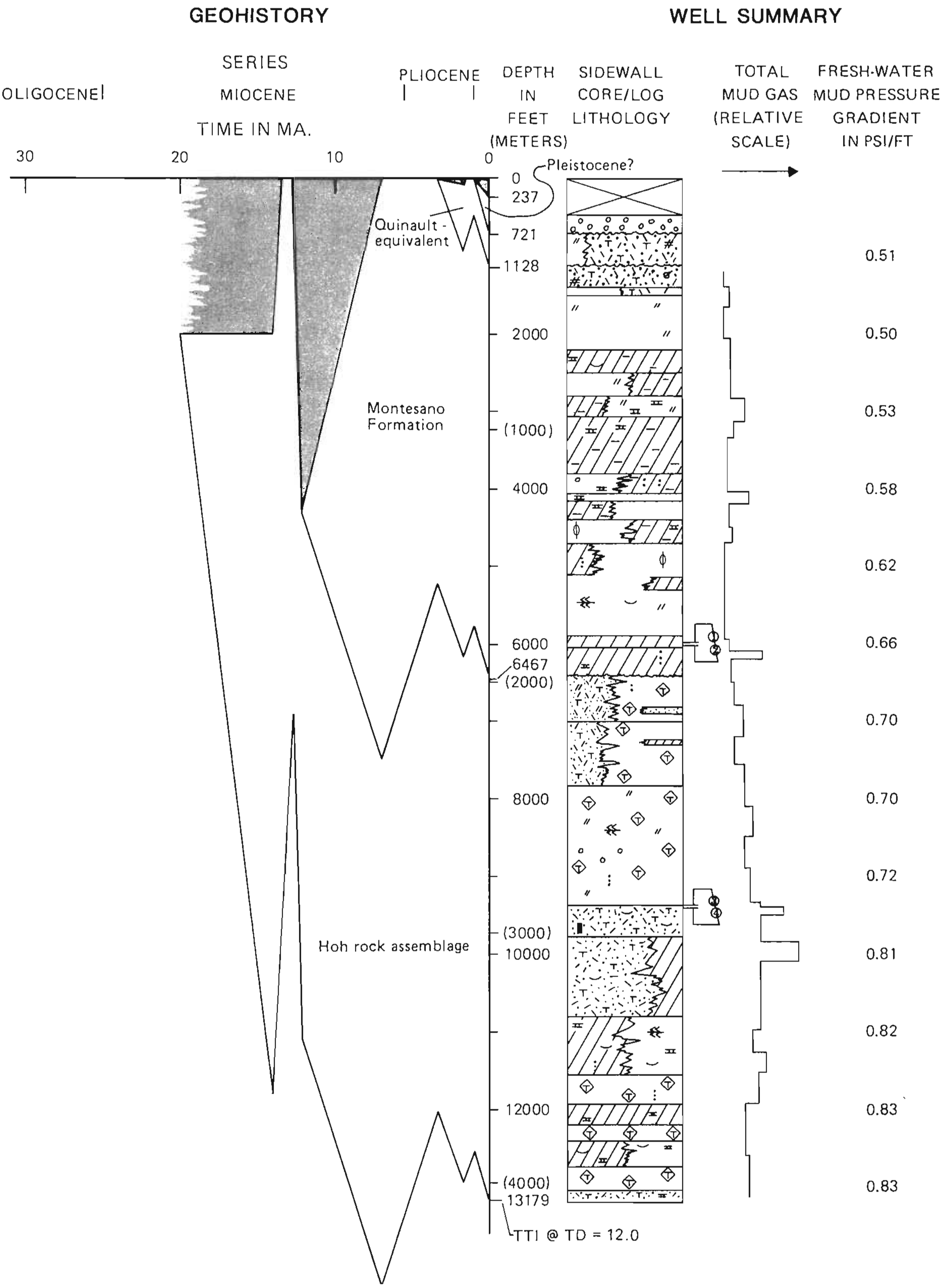


Figure 3-5 Geohistory and well summary for the P-0155 (most data from Shell, 1967).

P-0150 and P-0150A



See Figure 3-2 for explanation of lithologic symbols.

Figure 3-6 Geohistory and well summary for the P-0150/150A (Shell, 1966). DST 1 plugged and DST 2 recovered water (1.32 ohm/m @ 62°F). DSTs No. 3 and 4 recovered 10.5 and 26 MMCFGPD at 4,091 and 3,052 psi IFBHP with 7,736 and 7,260 psi FSIBHP, respectively, on a 0.5 in. choke.

(Plate 2) indicates that there was approximately 1,000 ft of paleobathymetric relief near the end of Montesano deposition in this area.

The Miocene to Pliocene section generally thickens gradually westward across the shelf and down the slope and rise. Seismic data indicate that this section is approximately 7,000 ft thick on the abyssal plain. Isopachous mapping based on seismic interpretation (Wagner and others, 1986) illustrates that deposition (and erosion) of Miocene and Pliocene strata on the shelf was largely controlled by growth of local structure: the thickest sections are present in the troughs of synclines.

Deposition of the upper Miocene to Pliocene section marks the end of intense deformation on the continental shelf. Melange and complex thrusting have not been recorded in the Montesano or younger sections.

MONTESANO FORMATION

The Montesano Formation consists of a siliclastic section that crops out in the Grays Harbor Basin and is present in most localities on the shelf. It was also penetrated in several wells in the Ocean City and Copalis River areas. Bergen and Bird (1972) restrict all the Montesano Formation in the Ocean City area to the Miocene. The base of this formation in the southern Grays Harbor Basin is intruded by the 12 Ma Pomona Member of the Saddle Mountains Basalts (Walsh and others, 1987) indicating that the Montesano ranges from middle to late Miocene.

We have chosen to adopt the stratigraphic nomenclature of Bergen and Bird (1972) for the Montesano section in the subsurface on the Washington continental shelf. They define three informal members of the Montesano Formation in the Ocean City area: (1) a lower claystone member, (2) a middle sandstone member, and, (3) an upper siltstone member. Industry has named a locally massive sandstone facies within the sandstone member the "Ocean City Sand". These three members can be correlated in the Ocean City area and offshore west and north of Grays Harbor using well logs, sidewall core descriptions (Plate 3), reflection seismic, and/or biostratigraphic data. Recognition of the three members aids in understanding regional geology and recognition of prospects.

Onshore, the Montesano crops out in the Grays Harbor Basin, and is time-equivalent to Quinault beds in the lower part of the Duck Creek - Pratt Cliff area a few miles north of Point Grenville (Rau, 1970). This area lies directly north of a major strike-slip fault that parallels the Quinault River valley. All of these sections are younger than the claystone member (Bergen and Bird, 1972).

The Montesano claystone member was penetrated in all of the offshore wells (Table 3-1). The claystone member in the P-0155 and the Tidelands State No. 2 consists of dark gray, silty, pyritic claystone (Figures 3-4, 3-5). In the P-0150, the claystone member is composed equally of claystone and argillaceous, calcareous siltstone (Figure 3-6). Feldspatholithic sandstone beds in the claystone member in the P-0141 (Figure 3-3) and some Ocean City area wells are tentatively interpreted as turbidites. Rau and McFarland (1982) report the first occurrence of the following foraminifers in rocks correlated with the claystone member: *Bolivina sinuata*, *Bulimina subacuminata*, *Sphaeroidina bulloides*, *Bulimina rostrata*, and *Pullenia bulloides*. These species indicate a middle bathyal biofacies corresponding to water depths of 1,560 to 6,250 ft (Ingle, 1980). Paleobathymetric determinations by Bergen and Bird (1972) indicate that the claystone member was deposited in water depths of 2,000 to 4,300 feet.

Deposition of the Montesano claystone member marks an important tectonostratigraphic break on the Washington continental margin. Although hemipelagic claystones lithologically similar to this member were deposited in the Hoh/Ozette section, the Montesano claystone member differs in that it lacks melange-type or other chaotic deformation. A modern analogy of the Montesano claystone member depositional-setting is shown on Line 76-18 (Plate 4). This profile shows a present-day basin-plain at middle bathyal depths (+/- 2,500 ft) west of shot point (SP) 550 and below the shelf break. Sediments deposited here are not being subjected to intense accretionary thrusting or folding.

Deposition of the Montesano sandstone member marks two important tectonostratigraphic breaks: (1) inundation of the topographic barrier that formerly separated the Grays Harbor Basin from the continental margin, and, (2) development of the present continental shelf. Prior to deposition of the sandstone member, the Grays Harbor Basin was isolated from the open ocean. In the upper Montesano, paralic lithofacies were deposited continuously across the aforementioned topographic barriers indicating that the western Grays Harbor Basin was entirely filled with sediment by late Montesano time. The upper Montesano penetrated in offshore wells consists of shallow marine lithofacies indicating that the present continental shelf formed at about 7 Ma. Bergen and Bird (1972) hypothesize that regional uplift was the primary mechanism for development of the present continental shelf, and argue that rapid deposition of the Montesano claystone cannot entirely account for the shoaling.

Eight wildcats drilled within a one-mile radius in the Ocean City area encountered the massive "Ocean City Sand" facies (Plate 1). This massive sandstone facies consists mainly of fine- to medium-grained, feldspatholithic sand with glauconite, mica, carbonaceous detritus, fossil fragments, and a few thin pebbly layers. Sedimentary structures include cross-bedding and bioturbation. The massive sandstone could be interpreted as a barrier bar, tidal bar, spit, or channel sand deposit. South of these eight wells, the massive sandstone facies thins to a depositional zero edge. North of these wells, a probable east-trending fault truncates the massive sandstone. (These relations are described in detail in Chapter 6.) The massive facies of the sandstone member was also penetrated in the Shell P-0155 where it consists of 670 ft of argillaceous feldspatholithic sand and gravel that contain glauconite and volcanic detritus. This unit is the only offshore equivalent of the "Ocean City Sand" identified to date. The massive sandstone facies is missing by erosion in the Tidelands State No. 2 and missing by non-deposition or erosion in the P-0150 and P-0141 wells. A model for the distribution of the massive facies of the Montesano sandstone member is presented in Chapter 6.

The siltstone member consists of fossiliferous and micaceous feldspathic silt with a few beds of fine- to coarse-grained feldspatholithic sandstone. It is difficult to distinguish the siltstone member from the sandstone member in wells such as the P-0150 where the massive sandstone facies is probably not present.

Bergen and Bird (1972) use foraminiferal paleoecology to show that the siltstone member was deposited on the shelf in water-depths less than 500 feet. In siltstone member samples, they found older bathyal faunas including *Bulimina subacuminata, Valvulineria araucana*, and *Plectofrondicularia californica* mixed with the shallow-shelf foraminiferal assemblage. Bergen and Bird speculate that mud diapirs rooted in the claystone member carried the older fauna to the seafloor during deposition of the siltstone. As these diapirs were breached, the older claystone member fauna was redeposited in the siltstone member. However, the older fauna also includes *Valvulineria araucana* and *Plectofrondicularia californica*. These species are typical of lower-bathyal Hoh faunas (Rau, DGER, 1988, oral commun.) suggesting that the diapirs are rooted in the Hoh rock assemblage rather than in the claystone member. Diffraction patterns and cross-cutting relations observed on seismic profiles indicate that diapirs rooted in the Hoh or Ozette sections are common on the continental margin. (See Chapter 7.)

The probable diapir near Cape Elizabeth and others mapped at the present seafloor crop out along faults that cut Pliocene sediments (Rau and Grocock, 1974; Orange, 1987; Wagner and others, 1986). Thick sequences of the very dark gray siltstone that crop out in the core of Cape Elizabeth structure also crop out in broad strike-slip fault zones that cut the Hoh and Ozette farther north on the Olympic Peninsula (Orange, 1987; Stewart, 1970).

QUINAULT FORMATION

The Quinault Formation includes uppermost Miocene rocks cropping out in the basal part of the section near Duck Creek and at the Raft River (Rau, 1970) and Pliocene rocks cropping in a relatively narrow coastal belt essentially between Point Grenville and the Queets River (Rau, 1979). (See Figure 2-2.) The lower part of the Quinault is equivalent to parts of the upper Montesano Formation (Rau, 1970). It may be partially or entirely equivalent to the Quillayute Formation which crops out along the Quillayute River near Forks (Rector, 1958).

Seismic profiles and biostratigraphic data from the offshore wells indicate that Pliocene rocks and sediments all overlie an angular unconformity at the top of the Montesano. We use the term "Quinault- equivalent" for the Pliocene rocks overlying this unconformity on the continental shelf. This definition is consistent with nomenclature in the Ocean City area where Pliocene rocks are only present above an angular unconformity (Bergen and Bird, 1972). The Quinault-equivalent is present throughout the continental shelf except where diapiric intrusions and other uplifts have breached the section (Wagner and others, 1986).

Onshore, Quinault and Quillayute lithologies include siltstone, claystone and conglomerate together with a thick, grey-green fine grained sandstone that crops out directly north of Point Grenville (Rau, 1979, Horn, 1969). The QFL plot (Figure 3-1) shows that Quinault sandstones have varied compositions but are richer in lithic detritus than the Hoh, Ozette, and Montesano sandstones.

Rau (1970) has shown that the Quinault had varied environments of deposition, including an outer continental shelf sequence at Duck Creek and Pratt Cliff, a bathyal section including fauna redeposited from neritic conditions at south Taholah, and a neritic/littoral sequence at Point Grenville. Horn (1969) interprets the Point Grenville sequence having a deltaic environment.

UPPER PLIOCENE AND PLEISTOCENE GRAVELS

Upper Pliocene and Pleistocene gravels crop out continuously along the coast. These gravels are correlative to terrace gravels described by Rau (1973, 1980) and to the deformed gravels of Moore (1965). In the subsurface, these gravels have a distinctive high-resistivity induction log signature (Chapter 4) and are present in every offshore well except the Tidelands State No. 2. In this well the gravels are interpreted to be absent due to Recent uplift and erosion (Figure 3-4).

SEISMIC STRATIGRAPHY

Seismic stratigraphic analysis may yield a means of predicting the distribution of reservoir sandstone facies within the Miocene and Pliocene sections. The following interpretation of Line 76-12 (Plate 2) illustrates the utility of seismic stratigraphic analysis in the Miocene to Pliocene section and serves as an introduction to the seismic horizons discussed elsewhere in the text. Snavely and Wagner (1982a) also published an interpretation of Line 76-12. The following interpretation varies from Snavely and Wagner's in that it concentrates on the post-middle Miocene stratigraphy.

The position of the P-0155 wildcat relative to Line 76-12 is somewhat uncertain. For this study, the well was positioned relative to the line by comparison of acoustical log events with seismic stratigraphic packets and unconformities. The relations discussed below, however, are independent of the location of P-0155 relative to Line 76-12. Time-depth curves (Figure 3-7) were constructed using acoustic logs from the P-0155, Cygnet J-100, and Sunburst No. 1 wells. The P-0155 time-depth curve was used to tie the acoustic log formation tops to Line 76-12 and to flatten several horizons in order to confirm the interpretation given below.

Horizon "A" on Line 76-12 (Plate 2) reflects from the base of massive Pliocene or Pleistocene deformed gravels (Figure 2-2, 3-5, and 3-7). The "A" horizon is generally at constant time across inner continental shelf profiles; however, the "A" horizon appears to be folded and truncated on one limb only of the faulted anticline directly west of the P-0155 structure. This interpretation requires careful scrutiny of the profile because multiples and/or the bubble pulse obscure stratigraphically controlled events. The "A" horizon shows this relationship on several anticlines elsewhere on the shelf. (Note that the events identified in this study cannot be loop tied using the public-record seismic data set. None of the horizons is proven to be regionally extensive or mutually correlative.)

The section between the "A" and "B" horizons corresponds to the Quinault-equivalent. The section between "A" and "B" on the eastern limb of the faulted anticline directly west of the P-0155 anticline thins eastward off structure and laps onto the "B" horizon. This section corresponds to a fill sequence in a valley or submarine canyon controlled by growth of the adjacent anticlines. Sediments entering the valley/canyon from the northwest or southwest began to fill the valley shortly after scouring was complete. This fill sequence inundated the valley/canyon between SP 185 and 386 and spilled over the crest of the P-0155 anticline at 440 milliseconds (msec) two-way-traveltime (T.W.T.). As deposition continued, the valley/canyon continued to subside, but sediment completely inundated this valley/canyon and filled the adjacent valley/canyon located east of the P-0155 anticline between SP 420 and 533.

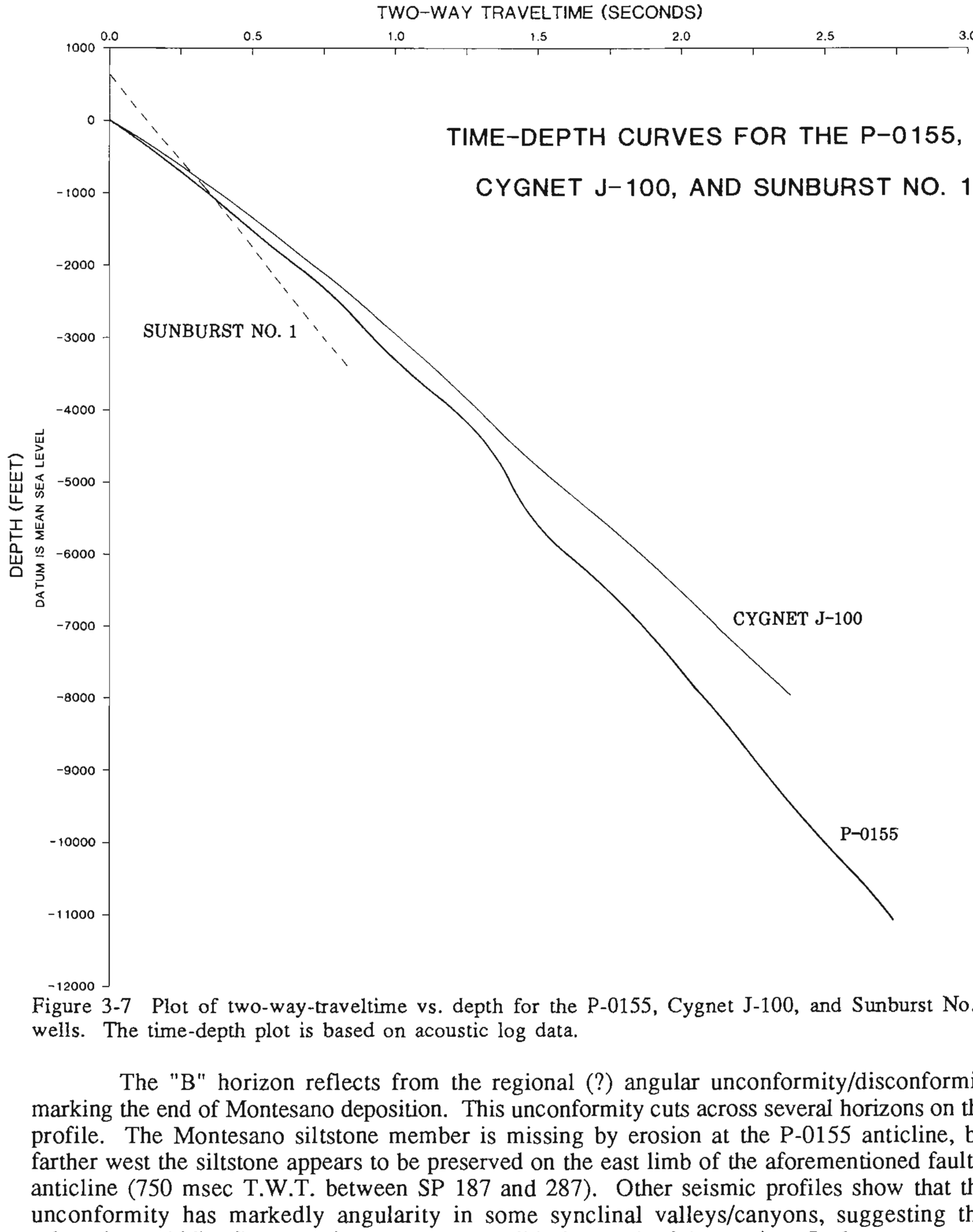


Figure 3-7 Plot of two-way-traveltime vs. depth for the P-0155, Cygnet J-100, and Sunburst No. 1 wells. The time-depth plot is based on acoustic log data.

The "B" horizon reflects from the regional (?) angular unconformity/disconformity marking the end of Montesano deposition. This unconformity cuts across several horizons on this profile. The Montesano siltstone member is missing by erosion at the P-0155 anticline, but farther west the siltstone appears to be preserved on the east limb of the aforementioned faulted anticline (750 msec T.W.T. between SP 187 and 287). Other seismic profiles show that this unconformity has markedly angularity in some synclinal valleys/canyons, suggesting that submarine turbidity flows, or rivers were responsible for much of the erosion. It also suggests the potential for high-energy depositional environments.

The "C" horizon corresponds to regionally continuous (?) reflectors within the Montesano claystone member.

A discontinuous horizon labeled "D" corresponds approximately to the top of the Hoh rock assemblage at the P-0155 well. Reprocessed profiles and good quality data acquired by the Scripps Institute of Oceanography (Silver, 1972) have good coherency to 3.0 seconds T.W.T., suggesting that in places the position of the apparent acoustic basement is mainly a function of data quality.

TABLE 3-1

TENTATIVE UNIT TOPS IN WASHINGTON CONTINENTAL MARGIN WELLS[1]
(depth in feet from wireline log picks, reference Kelly bushing)

Unit	Wildcat Well			
	Shell P-0150	Shell P-0155	Union Tidelands-2	Pan Am P-0141
Sea floor[2]	237	233	53	290
Plio/Pleistocene gravels	237	233	missing	290
Pliocene portions of Quinault and equivalents	721 (?)	600 (?)	missing	500
Montesano	1,128[3]	1,530[3]	53	<2,804 (?)
Montesano siltstone mbr	(?)	missing	missing	(?)
Montesano sandstone mbr	(?)	1,530	missing	(?)
Montesano claystone mbr	1,786	2,200	53	2,804
Hoh rock assemblage	6,467 (?)	6,515	3,922	3,400
Ozette melange	NP	NP	3,307 (?)	8,100[4] (?)
Total Depth	13,179[5]	11,162	5,073	10,042

1. The writers are indebted to W. W. Rau for his assistance in picking these unit tops but any errors are our sole responsibility.
2. Water and total depths from Shell (1966, 1967), Pan American (1967), and Union (1965).
3. Top Montesano picked on acoustic log.
4. Ozette in P-0141 after Snavely (1987).
5. Total depth only, taken from the P-0150A redrill logs.

4

Reservoir Properties and Wireline Log Analysis

The reservoir properties of the Ozette melange, Hoh rock assemblage, Montesano Formation, and Quinault-equivalent sandstones have been assessed using core porosities and permeabilities, wireline log interpretations, and petrography. Hoh rock assemblage and Ozette melange sandstones appear to be marginal quality reservoirs. The Montesano Formation sandstones have excellent reservoir properties and the highest likelihood of producing large volumes of oil or gas if these occur on the Washington continental margin. The Quinault Formation and equivalent sandstones also have excellent reservoir properties.

HOH ROCK ASSEMBLAGE AND OZETTE MELANGE

Conventional core analyses using standard testing procedures were obtained from eight onshore well completion reports on file at DGER. Two hundred forty-seven Hoh and Ozette porosity and permeability measurements from these wells and outcrop samples (Snavely and others, 1977) are listed in Appendix B -- Porosity and Permeability Data, and summarized in Figure 4-1. It must be noted that all but one of these outcrop samples are from Oregon equivalents (?) of the Hoh/Ozette sequences (Snavely, 1989, USGS, oral commun.).

The Hoh rock assemblage and Ozette melange sandstones have similar reservoir properties and can be considered equivalent with regard to storage capacity and producibility. Most Hoh and Ozette sandstones have porosities less than 25% and permeabilities below 100 md. The Hoh rock assemblage and Ozette melange sandstone reservoirs are likely to be marginal exploration targets unless fracture permeability is present.

The Ozette/Hoh invasion profiles on induction logs in coastal and offshore wells are distinctive. The top of this invaded interval can be correlated throughout the study area. A composite of induction, SP, bulk density, and natural gamma ray logs from the Milwaukee Land 1-1 west of Forks illustrates the sandy, interbedded nature of the Hoh/Ozette section north of Point Grenville (Plate 3). Increased resistivity and a moderate invasion between 4,230 and 4,310 ft and between 4,610 and 4,670 ft, coupled with a small SP deflection in the lower sandstone, are representative of the best Hoh/Ozette reservoirs. Inspection of the bulk density curve in these two zones indicates that the upper zone is denser and presumably less porous. The ragged density profile within these zones suggests the sandstones are interlaminated with finer clastics or have varied cementation. Secondary mineral cements including laumontite, calcite, silica, and authigenic clay are common in Hoh and Ozette sandstones. The low SP and lack of mudcake together with shallow invasion is qualitative evidence for low permeability in these intervals. Hoh and Ozette sandstones commonly contain potassium feldspar (Stewart, 1970), and consequently, Vclay gamma ray determinations are unreliable.

In general, the Hoh/Ozette shales and claystones show very low resistivities with little invasion (e.g., 4,025 to 4,140 ft) and low density (2.30 to 2.35 gm/cm^3). The high natural gamma response of shales relative to adjacent sandstones as shown on Plate 3 is unusual.

Figure 4-2 is a core porosity/depth plot for the Hoh rock assemblage and Ozette melange; the zero depth porosities are from outcrop samples (Snavely and others, 1977). Although porosity diminishes with increasing depth of burial, some Hoh/Ozette sandstones with 20% or greater porosity are preserved at depths of 3,000 to 4,000 ft. These sandstones generally have 20 to 200 md permeability (Figure 4-1). Limited petrography on outcrop samples suggests that secondary porosity resulting from favorable diagenesis occurs locally.

A histogram of sandstone bed thicknesses for the Hoh/Ozette is shown on Figure 4-3. The apparent bed thicknesses were determined from log interpretation and are limited to those beds which do not appear to have shale laminations or cemented layers. Invasion profiles, SP development, and density or density/neutron porosities were used to delineate sandstone thicknesses in 14 wells; sandstones having less than 15 ft drilled thickness are not included in this data set. A few dip measurements from core samples were available, but in most cases steep dips were

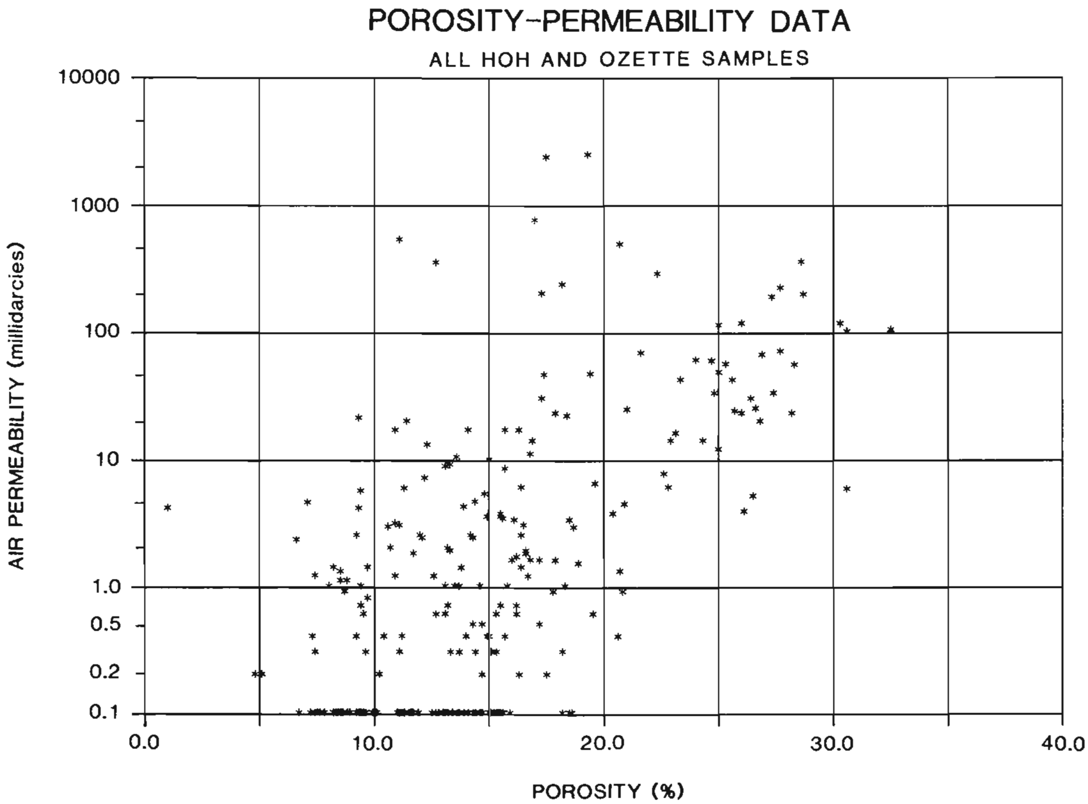


Figure 4-1 Plot of porosity vs. permeability for Hoh and Ozette rocks.

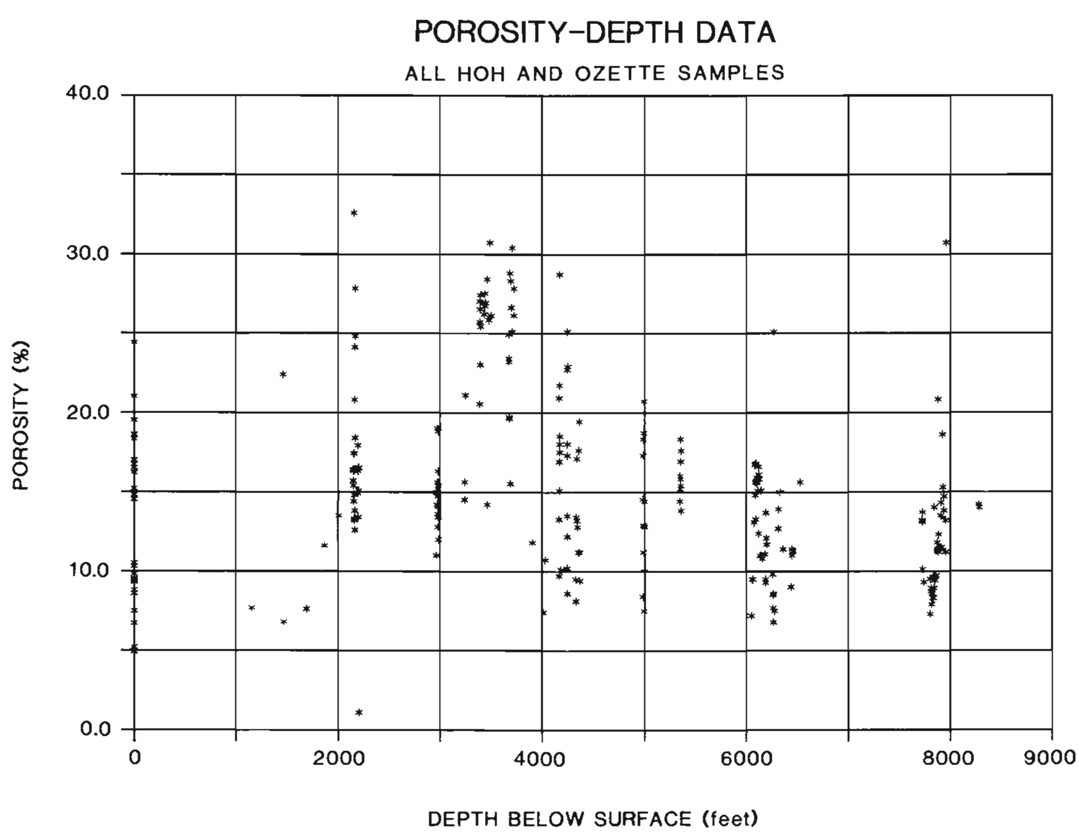


Figure 4-2 Plot of porosity vs. depth for Hoh and Ozette rocks.

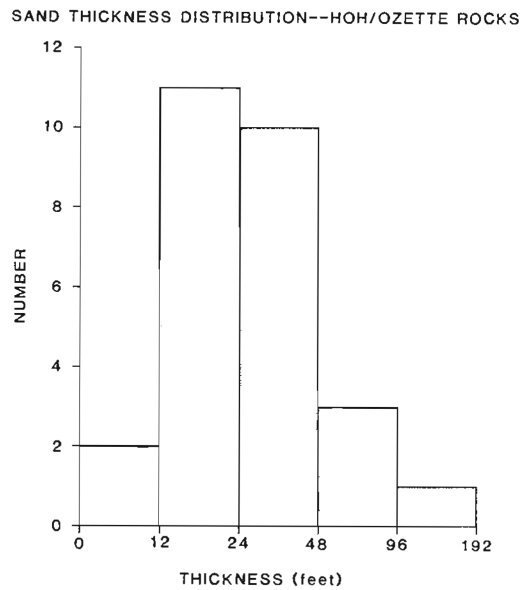


Figure 4-3 Histogram of sandstone thickness for Hoh and Ozette rocks.

assumed and an arbitrary correction factor was applied. Dipmeter logs from several wildcats show only chaotic dips and were not useful in determining true thickness. Thick Hoh and Ozette sandstones are uncommon in the subsurface (Figure 4-3). Sandstone units typically range from 10 to 100 feet with a mean value of 34 feet. At Brown's Point, 20 mi north of Point Grenville, Rau (DGER, 1988, unpublished measured section) reports a sequence of festooned sandstone units, which average about 30 feet in unit thickness.

In outcrop, continuous Hoh/Ozette beds range from hand-specimen scale to the 20-mile-long Cat Peak sandstone (Tabor, 1975). Most Hoh and Ozette outcrops display intense folding and faulting at all scales, which is typical of thrust belts. This structural complexity does not necessarily condemn the play; structure that crops out adjacent to the giant Rickman Creek Gas Field in the Idaho/Wyoming thrust belt is comparable, in terms of complexity, with the structure along the Olympic coast. Coherent outcrops of turbidite sandstone on Olympic beaches are separated by tectonic melange (Stewart, 1970; Rau, 1975, 1979). In several places along the coast, house-size sandstone olistostromes are surrounded by very dark gray, impermeable siltstones. The lateral continuity of subsurface Hoh/Ozette sandstone beds is not known. Analysis of core samples on file at DGER suggests that the Tidelands State No. 2 may have penetrated Hoh melange.

Wireline logs indicate that no significant reservoirs were penetrated in the Hoh/Ozette sections of the four offshore wildcats. East of the coast, reservoir quality diminishes owing to low-grade metamorphism of the section (Tabor and Cady, 1978a).

MONTESANO FORMATION

The core porosity/permeability relation for all Montesano Formation coarse clastics is shown on Figure 4-4. This figure summarizes 71 analyses from six wells drilled in the Ocean City area (Appendix B). These data show that the Montesano Formation generally has porosities greater than 20% and permeabilities ranging from 2 to 2,000 md. Figure 4-5 is a core porosity/permeability plot for only the Montesano sandstone member. Porosities generally range from 25 to 30%, and permeabilities range from 500 to 2,000 md.

A composite of the induction-electric, SP, bulk density, and natural gamma logs recorded in the Sampson Johns 2-15 is given on Plate 3. The Montesano Formation occurs from 940 feet to total depth in the well. The siltstone member/Quinault-equivalent contact appears as a marked curve deflection here and in all other Ocean City area wells. The siltstone member in this well consists of silty claystone with intercalations of siltstone and sandstone. These interbeds have slightly higher resistivities and densities, moderate invasion, and negative SP deflections relative to the silty claystones. The top of the sandstone member is at 1,480 feet. This member exhibits high resistivity, greater than 40 millivolts negative SP, and a deep invasion profile. High resistivities, low natural gamma response, and low densities in the Montesano sandstones enable

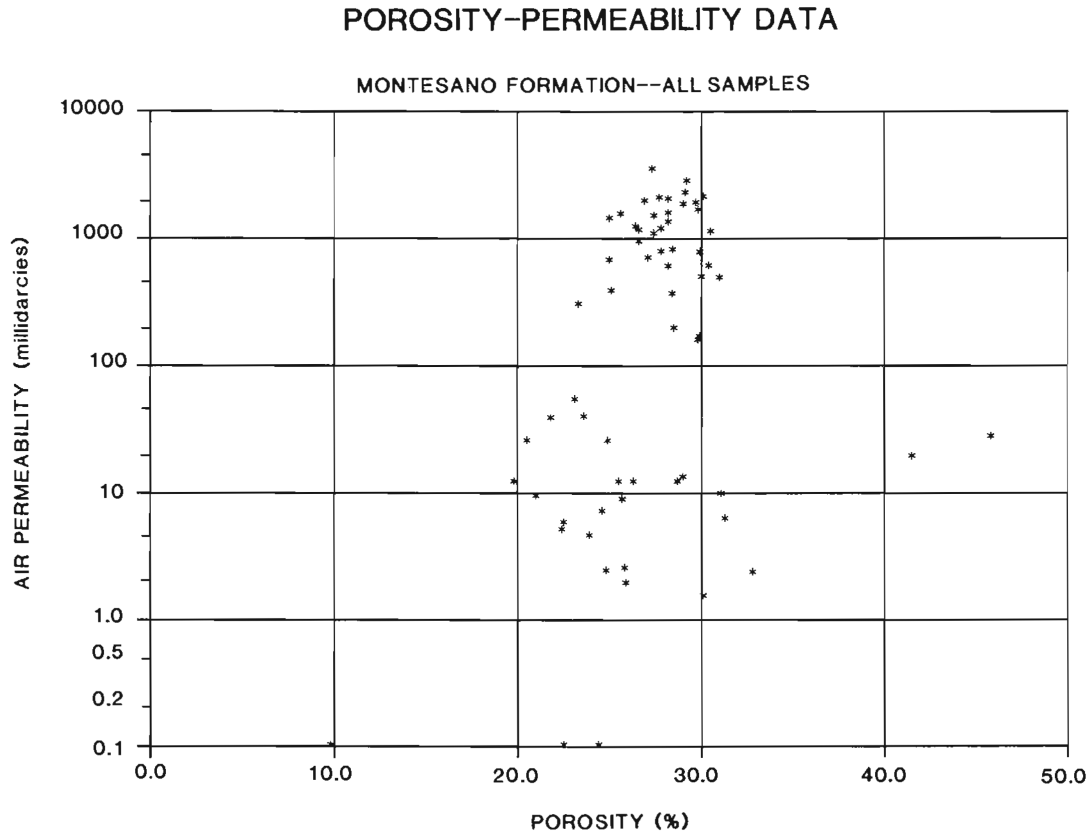


Figure 4-4 Plot of porosity vs. permeability for samples of all samples of the Montesano Formation.

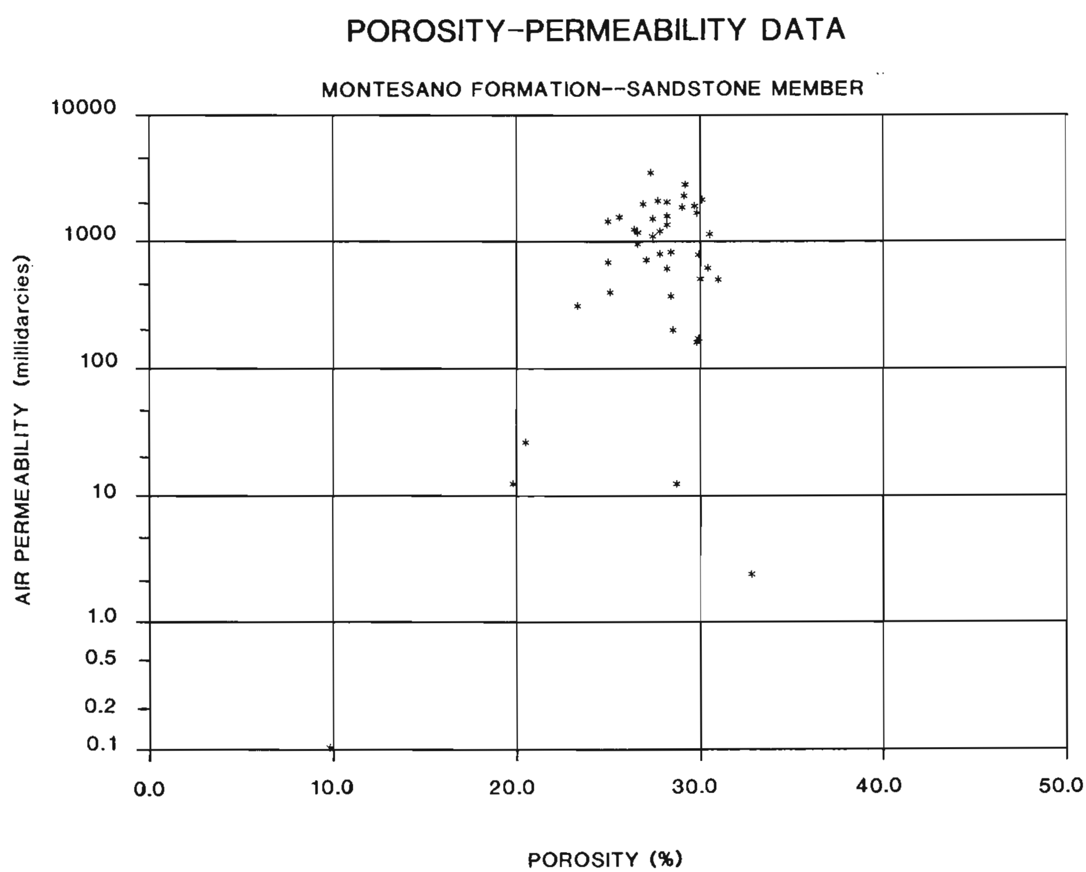


Figure 4-5 Plot of porosity vs. permeability for the sandstone member of the Montesano Formation.

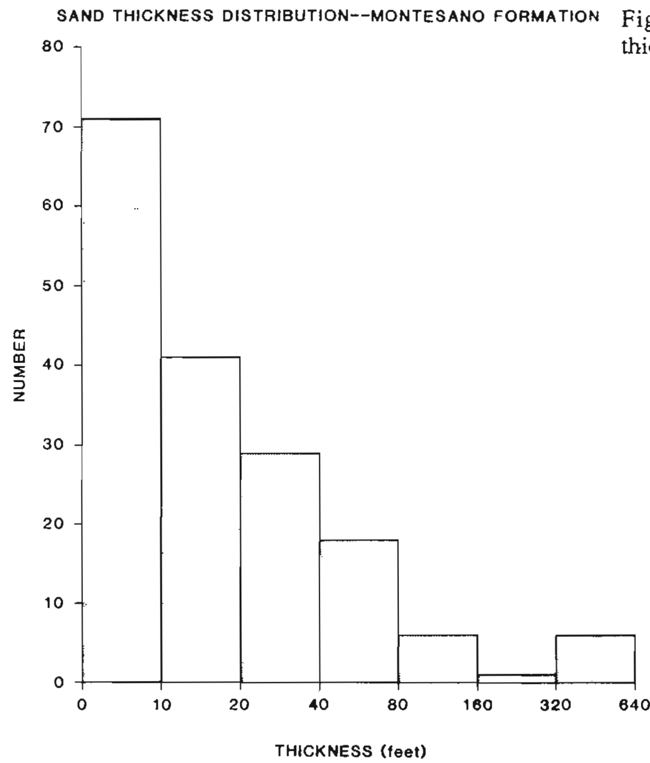


Figure 4-6 Histogram of sandstone thickness for the Montesano Formation.

discrimination between sandstones and claystones in this well. However, such lithologic determinations from wireline logs are rarely reliable in offshore wells. A number of high density spikes are observed in the sandstone member in the Sampson Johns 2-15. Sidewall core data indicate that these are tight, calcite-cemented sandstones.

The top of the claystone member is easily picked at 2,140 ft using the positive SP deflection, the low resistivity, and the absence of an invasion profile. No sandstones interbeds are observed in the Sampson Johns 2-15 claystone member.

The sandstone member was penetrated offshore in the Shell P-0155 wildcat between 1,530 and 2,200 ft. This zone has a featureless induction response and little apparent invasion. Analysis of the bulk density, SP, natural gamma, and sidewall cores indicates that this unit is composed mainly of massive sand and gravel with a few thin clay zones and cemented and/or conglomeratic streaks that are resistive. Structural dip interpreted from reflection seismic data (Plate 2) indicates that the true thickness of this sandstone is greater than 550 feet. It has 24 to 30% density porosity, using the 2.70 gm/cm^3 matrix density measured from core samples and confirmed by Hinkle plots of coastal wireline logs. The Montesano sandstone member in the P-0155 is as thick and porous as the Ocean City sand.

Sandstone beds in the Montesano penetrated in the P-0141 exhibit log responses similar to thinner Montesano sandstone units in the Ocean City area. A 144-foot-thick (uncorrected for dip) sandstone with thin clay interbeds in the P-0141 has 21 to 27% density porosity.

Although all continental margin sandstones have similar compositions (Figure 3-1), porosities and permeabilities in the Montesano are far greater than those of the Ozette and Hoh. Galloway (1974) showed that porosity decreases during burial due to authigenic clay and laumontite cementation at depths below 5,000 ft in the Grays Harbor Basin. The geothermal gradient in the Grays Harbor Basin and on the continental margin are both 1.5°F/100 ft (Blackwell, 1974). Interpretations of seismic reflection profiles and data from wells drilled in the Washington OCS indicate few areas offshore where Montesano or equivalent rocks are buried below 5,000 feet. The Montesano section in the offshore wells has never been deeply buried (Figures 3-3, 3-4, 3-5, and 3-6).

Sandstone unit thickness histograms for 20 onshore wells which penetrated the Montesano Formation are shown on Figure 4-6. Unit thicknesses were determined on the basis of SP response, invasion, and density porosity in homogeneous sandstone units. Drilled thicknesses were corrected using dipmeter logs or dips estimated from structural analysis. No minimum sandstone thickness cutoff was applied to this data set. This figure shows a bimodal distribution in sandstone thickness in the Montesano Formation; massive Montesano sandstone member thicknesses (321 to 640 ft) disrupt the overall trend of decreasing frequency with increasing bed thickness. The mean thickness determined from this data set is 40 feet.

The sandstone bed thickness histogram, coupled with the favorable porosity and permeability data, demonstrate that Montesano Formation sandstones could be excellent reservoirs.

QUINAULT-EQUIVALENT

A plot of porosity and permeability data measured from nine Point Grenville outcrop samples of the Quinault Formation (Horn, 1969) is shown on Figure 4-7. These limited data suggest that some Quinault sandstones have characteristics similar to those of the Montesano Formation and are excellent reservoirs. Quinault-equivalent sandstones and conglomerates commonly have no SP or invasion profile despite visible sidewall core porosity. These responses are apparently due to matching mud filtrate and formation water resistivities in the Quinault-equivalent section. The Sampson Johns 2-15 composite log (Plate 3) shows the base of the Quinault Formation at 940 feet.

In general, the Quinault-equivalent section on the continental shelf is not buried to depths greater than 2,000 ft and is normally pressured. Implications of this observation are discussed in Chapter 7.

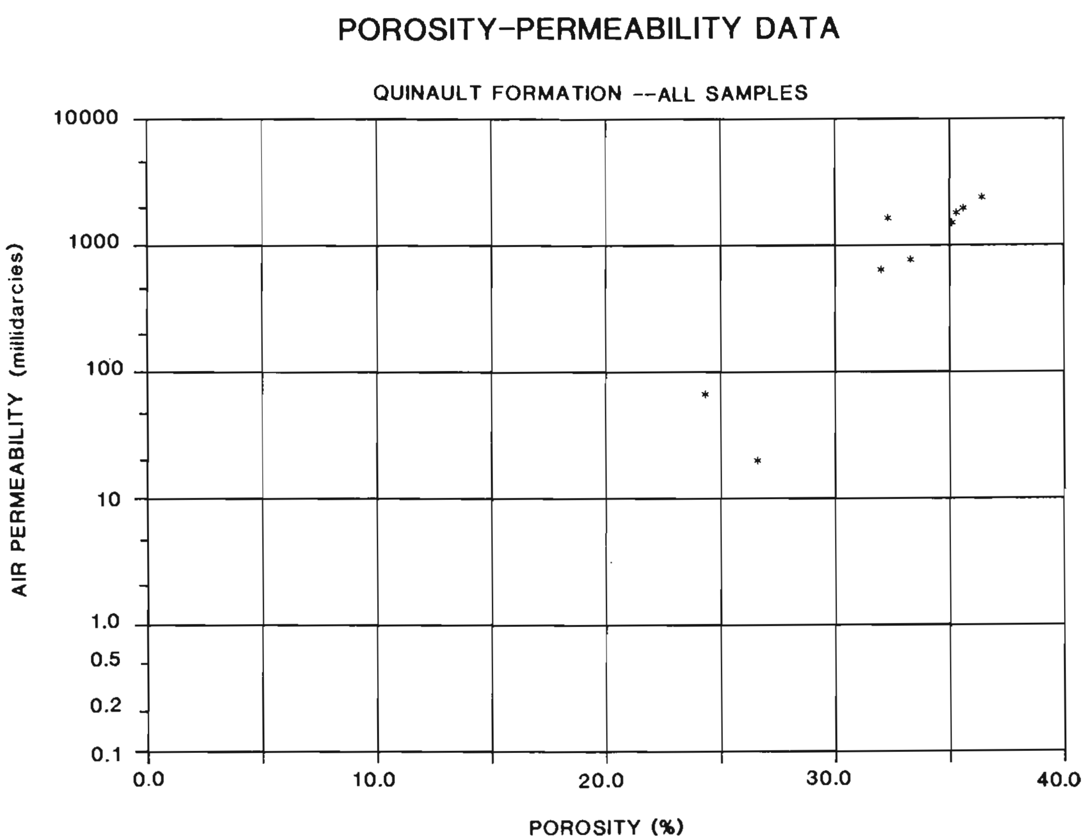


Figure 4-7 Plot of porosity vs. permeability for the Quinault Formation.

5

Petroleum Source Rocks, Maturation, and Migration

The petroleum geochemistry of the Washington continental margin is described thoroughly in Kvenvolden and others (1988a,b), Snavely and Kvenvolden (1988), and Snavely (1987). Grady (1985) provides additional data on the Hoh rock assemblage. Additional detailed geochemical analyses briefly summarized in this section are available from EXLOG, Inc., Houston, Texas (Brown and Ruth Laboratories, Inc., 1982a-e).

Figures 5-1 through 5-3 summarize some geochemical characteristics of the time-stratigraphic units in the study area. The data set used in these figures is not considered statistically representative because of areally and stratigraphically inconsistent sampling. Furthermore, some samples were contaminated by oil-based drilling mud, severe caving, and/or weathering. Nonetheless, the overall homogeneity of geochemical characteristics coupled with the wide geographic sampling range suggests that the tentative conclusions presented in this chapter are valid.

The total organic carbon contents (TOC) of all time stratigraphic intervals (Figure 5-1) are fair to good relative to most petroleum source rocks (Peters, 1986). The Montesano and Quinault-equivalent rocks average 1.12% TOC.

Pyrolysis data indicate that the Hoh and Ozette have fair to good bitumen (S1) levels. However, the data set includes some ditch samples which were immersed in oil-based drilling mud, and many outcrop and offshore well samples which are thought to contain migrated oil. All time-stratigraphic intervals have poor kerogen levels (S2), yet most of the samples for which data are available have low to moderate levels of thermal maturation (Figures 3-3, 3-4, 3-5, 3-6, 5-2, 5-3). Only a few isolated outcrop samples have hydrogen indices in excess of 200 (Snavely and Kvenvolden, 1988). Many Hoh and Ozette samples have oxygen indices less than 25, but, again, low levels of thermal maturation are prevalent.

Van Krevelen diagrams (Figure 5-2) indicate that for samples analyzed to date, Type III and IV kerogens predominate in the Hoh/Ozette sections, and only immature Type III and IV kerogens are present in the Montesano. Hoh/Ozette samples having low oxygen indices could have followed an oil- prone Type II or gas-prone Type III maturation path. However, most of these are immature to moderately mature, and therefore we infer that many samples with low oxygen indices followed the Type III maturation path.

In conclusion, no oil-prone source rocks have been identified to date on the Washington continental margin, and few, if any, have been identified in areas adjacent to the Olympic Peninsula. The gas-generative potential of these areas is fair (Peters, 1984). These conclusions are in reasonable agreement with those of Snavely and Kvenvolden (1988).

SHOWS

Bona-fide shows of live oil are common on the western Olympic Peninsula, in the Ocean City area, and in the Shell P-0155 well (Appendix A). On the Olympic beaches, ubiquitous, very dark gray siltstones (smell muds) actively seep oil as waves erode the coast. Oil shows from smell muds and surface seeps are encountered more commonly on the western Olympic Peninsula than in many oil-productive terranes elsewhere. Our analysis of well histories on file at the DGER and of data from McFarland (1983) indicates that 23 wells in the Ocean City area and 13 wells drilled near Forks had significant oil shows. These areas are 60 mi apart. One stripper well, the Medina No. 1, produced oil at rates of less than 10 BOPD from 1958 to 1962 (Sunshine Mining, 1962).

Significant gas shows not associated with oil are less common. The Shell P-0150 tested 10 and 26 MCFGPD, respectively, from two zones in the Hoh rock assemblage. In the Ocean City area, the Oscar No. 1 tested 339 MCFGPD from the Montesano sandstone member. The Sampson Johns Unit No. 1 sold a small volume of gas produced from the Hoh rock assemblage to the Ocean City Development Company in the early 1960s (Chapter 1).

HISTOGRAMS SHOWING SOME GEOCHEMICAL CHARACTERISTICS OF WASHINGTON CONTINENTAL MARGIN STRATA

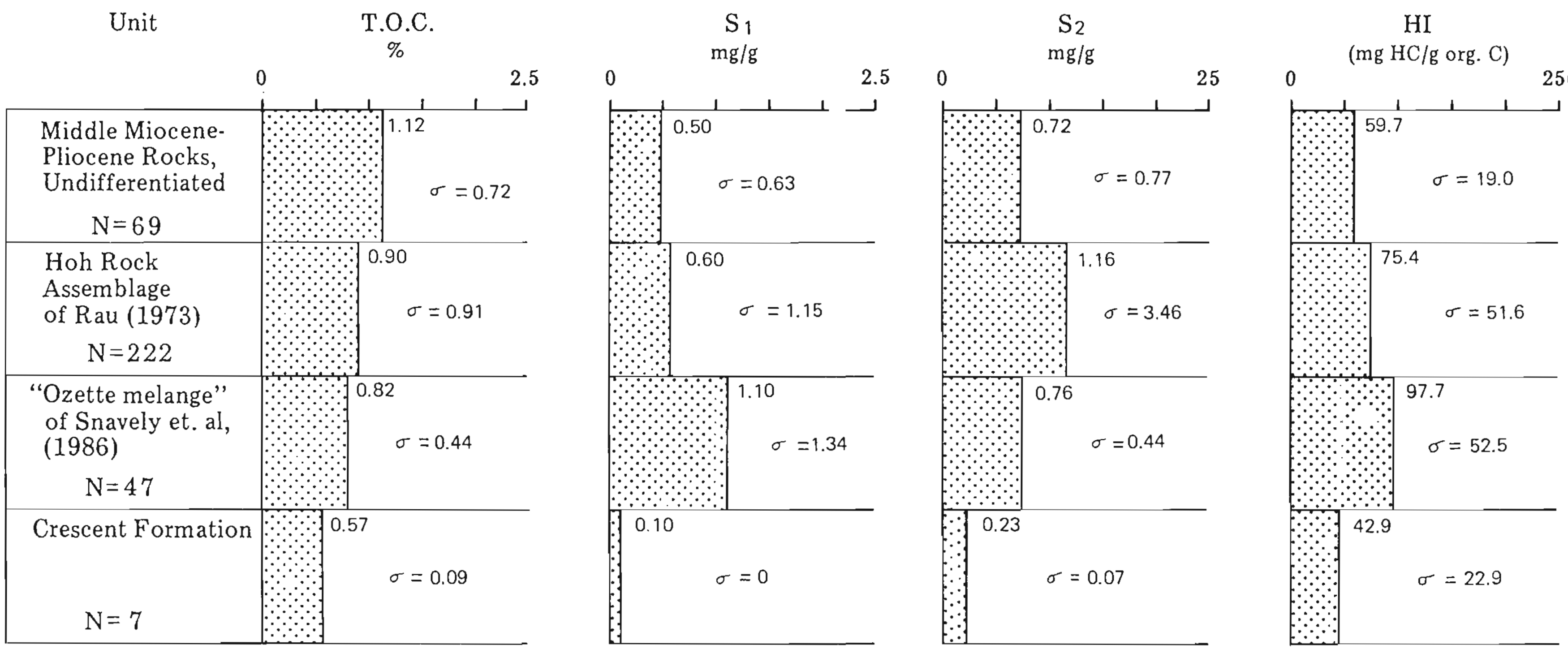


Figure 5-1 Histograms showing some geochemical characteristics of Washington continental margin strata. Some data provided by EXLOG, Inc., 1989.

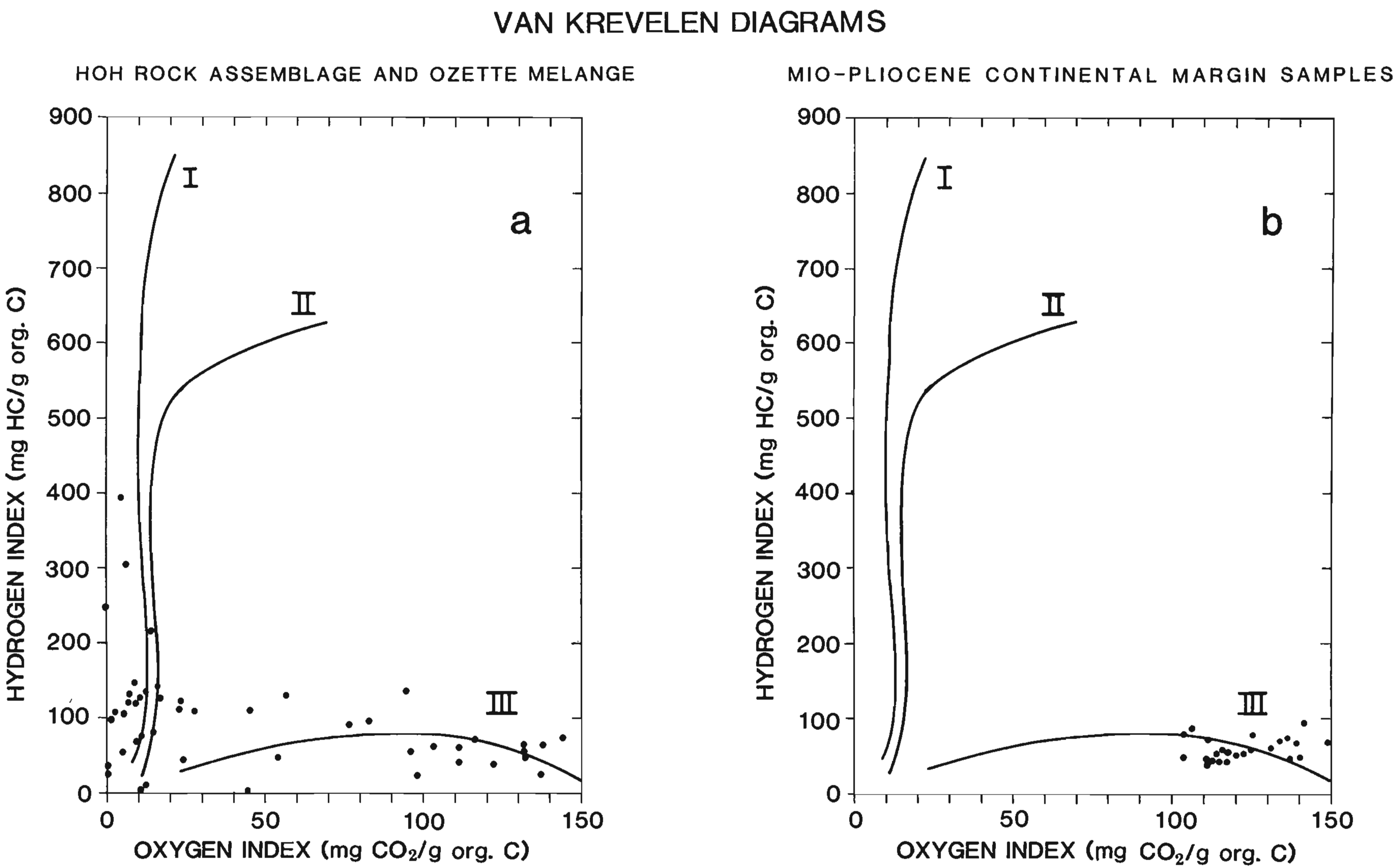


Figure 5-2 Van Krevelen diagrams for the Hoh and Ozette and for the Montesano and Quinalt sequences. Some data provided by EXLOG, Inc., 1989.

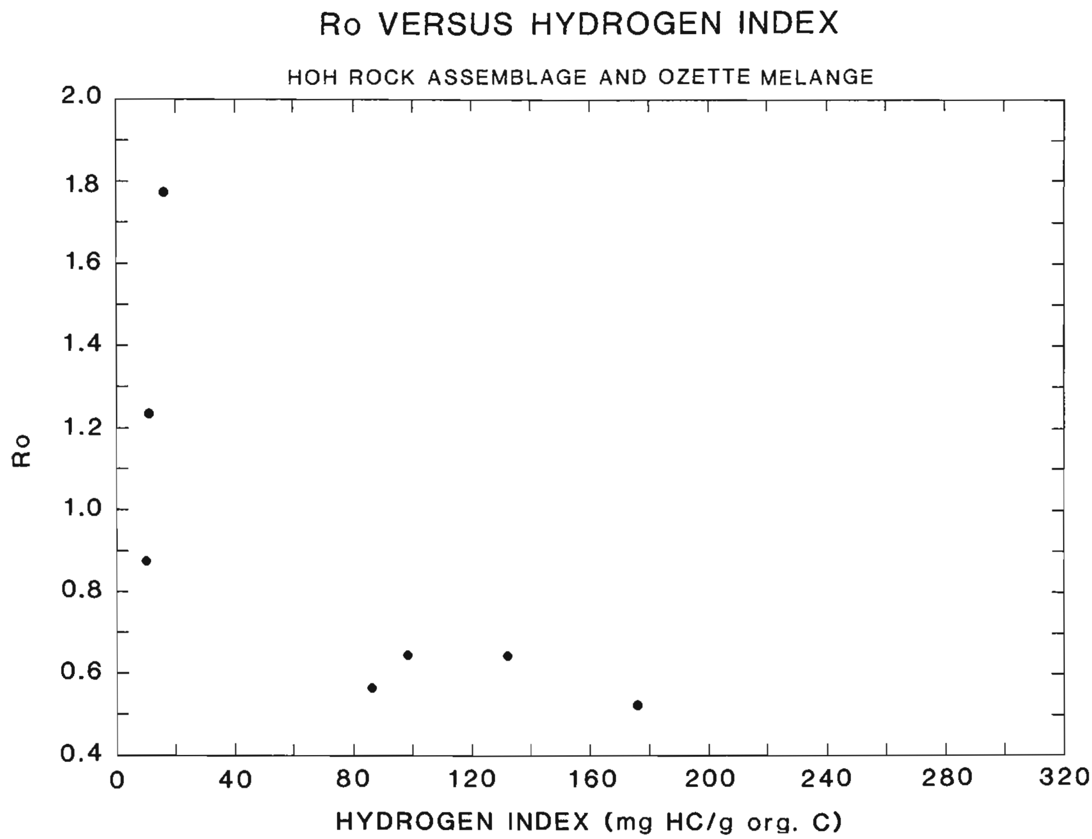


Figure 5-3 Plot of Ro vs. hydrogen indices for the Hoh and Ozette sequence. Some data provided by EXLOG, Inc., 1989.

GEOCHEMISTRY OF OIL AND GAS SAMPLES

Snavely and Kvenvolden (1988) and Kvenvolden and others (1988a,b) describe and interpret oil and gas samples collected from seeps and wells on the Olympic coast. They conclude that the gases are primarily thermogenic and that the oils all have a cogenetic relation despite the distance separating sampling localities.

The following oil samples, archived at the Division of Geology and Earth Resources, were analyzed (Appendix C -- Geochemical Analyses of Oil Samples from the State No.1 and Lacy No.1 Wells):

(1) The State No. 1 drilled in the SW quarter of sec. 15, T18N, R12W, of the Ocean City area. The sample was collected at the beginning of a swab run on March 21, 1948, and "archived" in a whiskey bottle.
(2) The Lacy No. 1 drilled by the Hoh River Oil Co. in the NW quarter of sec. 11, T26N, R13W, in the Forks area. The sample was collected in 1946 from the open casing and stored in an air-tight bottle.

Both sets of analyses show that the oils are paraffinic, have a wide alkane distribution, and probably had a terrigenous, resin-derived source (Type II kerogen). Triterpane and sterane ratios suggest that these oils have a cogenetic relation.

Both the Lacy No. 1 and the State No. 1 oils contain 17-alpha(H) bisnorlupane and 18-alpha(H) oleanane, terpanes considered by Kvenvolden and others (1988a) to give a distinctive signature to oils of the western Olympic Peninsula. Additionally, they found 17-alpha(H) bisnorlupane and 18-alpha(H) oleanane in extracts from a few Ozette outcrop samples near Shi Shi Beach northwest of Forks. The presence of these two compounds suggests to Snavely and Kvenvolden that the Ozette could be the source of western Olympic Peninsula oils.

TABLE 5-1

ANALYSES OF GAS RECOVERED DURING DRILLSTEM TESTS OF COASTAL WELLS

Values in volumetric % or mol %; the Medina No. 2 and Grays Harbor 35-1 analyses are from the Montesano Formation, all other data are from Hoh or Ozette sections

Well Name[1]	Methane	Ethane	Propane	Isobutane	N-Butane	Isopentane	N-Pentane
Sunburst No. 1[2] (No. 23)	97.32	1.40	0.51	0.09	0.13	0.05	0.03
Lacy No. 22-1[3] (No. 26)	97.12	1.60	0.56	0.08	0.15	0.05	0.03
M.A. Baker No. 1-30[3] (No. 43)	89.23	5.11	2.44	0.43	0.64	0.17	0.10
Medina No. 2[3] (No. 55)	85.21	5.11	4.86	0.93	1.53	0.15	0.15
Medina No. 1[3] (No. 56)	84.47	8.46	4.12	0.75	1.23	0.27	0.11
State No. 4[4] (No. 58)	92.32	4.76	2.27	0.44	0.62	0.19	0.15
Sampson-Johns Unit No. 1[5] (No. 58)	92.3	3.8	1.1	0.3	0.5	0.5	0.0
Grays Harbor No. 35-1[3] (No. 52)	97.7	trace	trace	0.0	0.0	0.0	0.0

1. Well numbers in parentheses are keyed to Plate 1 and Appendix A
2. Energy Laboratories, P.O. Box 593, Billings, MT
3. Yapuncich, Sanderson & Brown Laboratories, 13 N. 32nd St., Billings, MT
4. Gas Research and Engineering Service, 3119 Kinsie St., Los Angeles, CA
5. U.S. Bureau of Mines

Table 5-1 gives typical gas compositions from drillstem tests of coastal wells. The gases have high wetness ratios, indicating that these are not biogenic. This observation supports the isotopic studies of Kvenvolden and others (1988b). Total mud-gas curves for the OCS wells are shown on Figures 3-3, 3-5, and 3-6. These curves aid in picking the top of the Hoh rock assemblage.

Maturation

Geohistory analyses of the offshore Washington wildcats are given in Figures 3-3, 3-4, 3-5, and 3-6. These were constructed using the technique of Van Hinte (1978). Biostratigraphic data and correlations of biostratigraphic data to absolute ages on these figures are from Rau and McFarland (1982), Rau (1970; DGER, 1988, oral commun.), Bergen and Bird (1972), and Walsh and others (1987). We used the paleobathymetry of W. W. Rau (1988, DGER oral commun.) for the Hoh and Ozette sections and of Bergen and Bird (1972) for the Miocene and younger sections. Compaction corrections were applied to thick claystone sections, but these corrections are equivocal owing to over-pressure, thrusting, post-depositional brecciation, and solution (D. Orange, University of California, Santa Cruz, 1988, oral commun.) which affected these rocks. Unconformities in the P-0155 were modeled from Line 76-12 (Plate 2) together with the time/depth curves (Figure 3-7). Indicated rates of deposition were compared with modern analogues (Von Huene and Kulm, 1978) as an additional check on the geohistory models.

The peculiar shape of the flagged horizons results from:

(1) Rapid uplift and erosion (?) of the Hoh/Ozette at the end of the middle Miocene. An alternative to the erosion hypothesis is uplift of the Hoh/Ozette section to depths below wave-base accompanied by slow deposition or non- deposition. However, a marked angular unconformity at the top Hoh/Ozette is everywhere present onshore.

(2) Continuous deposition of the Montesano claystone member synchronous with rapid, late Miocene uplift (Bergen and Bird, 1972).

Waples/Lopatin (Waples, 1981) time-temperature indices (TTI) were calculated as a first approximation of the levels of thermal maturity in each wildcat. The 1.5°F/100 ft (27°C/km) geothermal gradient observed in three nearshore gradient bores (Blackwell, 1974) was used in these calculations. This gradient matches gradients in offshore wells derived by correcting wireline log temperatures using Horner plots of estimated lag-time and time-since-circulation versus logged temperature.

The greatest TTI in the continental shelf wildcats is 12 in the P- 0150A at 13,179 ft RKB. These low maturation levels are supported by present-day subsurface temperatures, which indicate that the 212°F (100°C) isotherm is at an approximate depth of 12,150 feet. In the Tidelands State No. 2, there is good agreement between TTIs and thermal alteration indices (TAI), vitrinite reflectance (Ro), and Tmax pyrolysis values, (Brown and Ruth, 1982b). In the P- 0141 wildcat, TAI, Tmax, and Ro data indicate the section is submature to at least 8,100 feet, (Brown and Ruth, 1982a). Below this depth, Ro data indicate markedly increased maturation, which Snavely and Kvenvolden (1988) ascribe to underplating of strata correlative with the Ozette, beneath the Hoh.

These data suggest to us that wildcats on the continental margin generally would have to be drilled to 10,000 ft or more in order to penetrate thermally mature source rocks juxtaposed against reservoirs. Hoh/Ozette reservoir quality diminishes with depth (Figure 4-2).

Despite these low levels of maturation, bona-fide oils shows were logged in the P-0155 well between 8,000 to 9,000 ft RKB. More than 13,000 barrels of oil were recovered from four Ocean City area wells (McFarland, 1983) where bottom-hole temperatures are less than 160°F. We conclude that oil shows observed in the P-155 and in most onshore Olympic Peninsula wells result from migration into the horizons in which these were recorded.

Oil seeps and wells having oil shows are commonly adjacent to strike-slip or thrust faults. Therefore, we agree with the conclusions of Snavely and Kvenvolden (1988) that oil is actively migrating along faults planes at the present time. Thrusting of tight, oil-saturated rocks from depths at which maturation occurred to the shallower horizons in which shows have been recorded may be a possible migration mechanism.

That numerous oil shows occur in a terrane devoid of demonstrable oil-prone source rocks, much less organically rich source rocks, is a paradox. One simple solution suggested by Snavely and Kvenvolden (1988) is that enriched oil-prone Ozette source rocks are present, but have not been sampled, in thrust slices under the westernmost Olympic core and western Grays Harbor Basin. Higher thermal gradients and/or greater depths of burial generated oil in these thrust slices. Thrust faults, strike-slip faults, and/or unconformities provide migration paths.

We conclude that the potential for charging traps on the continental margin with oil migrating out of rocks equivalent to the Hoh/Ozette sections is good.

6

Analysis of Ocean City Exploratory Wells

Ocean City area wildcats that encountered the massive facies of the Montesano sandstone member and encouraging oil and gas shows created an "oil boom" during the 1950s. Although the boom fizzled, data from these wells suggest that an analogous play for Montesano sandstone member reservoirs may exist offshore. Plates 5 through 8 show the known distribution of the Montesano sandstone member at Ocean City. Mapping the distribution of the massive sandstone facies or its equivalents elsewhere is a key to successful exploration on the Washington continental margin. The following discussion describes the detailed geology of this important stratigraphic interval and suggests a means of predicting sandstone distribution.

Pre-Upper Miocene Geology of the Ocean City Area

A generalized lithostratigraphic sequence penetrated in Ocean City wells is shown in Figure 6-1. This figure is based on paleontological data from Bergen and Bird (1972) and Rau and McFarland (1982) and lithologic and wireline log data from the Ocean City wells. A crucial feature of this lithostratigraphic sequence is the repetition of the Hoh rock assemblage beneath the Ozette melange.

The Hoh and Ozette sections penetrated in the Ocean City area are mainly fine siliciclastic rocks with minor thin-bedded sandstone. These contain bathyal foraminifers (Rau and McFarland, 1982). The Hoh and Ozette in this area were probably deposited in basin plain and/or distal fan environments. Deformation subsequently created numerous shear zones and claystone breccias. Slickensides are ubiquitous in core samples from these intervals.

Thrust faulting and thrust-generated folding appear to be the dominant structures below the middle Miocene unconformity near Ocean City. The Tidelands State No. 2, the Rayonier No. 1A, and the State No. 3 drilled sections of Ozette overlying younger Hoh sequences (Rau and McFarland, 1982). The Minard No. 1 and the Smith No. 1 are interpreted by Snavely and Wagner (1982a) to have penetrated Crescent basalts overlying younger Hoh or Ozette sequences. While the nature of these inverted sections is unknown, repetition of section observed in Hoh and Ozette outcrops results mainly from thrusting (Rau, 1979; Snavely and Kvenvolden, 1988). Cowan and Potter (1986) show a thick sequence of Hoh and/or Ozette underplating (or overthrust by) the western Grays Harbor Basin for a distance of more than 15 miles. Structure in the pre-Montesano section may be analogous to deformation occurring at the present abyssal plain/continental rise contact. Both east- and west-dipping thrusts appear to be present on USGS seismic profiles crossing the western edge of the rise (McClellan and Snavely, 1988; Cowan and Potter, 1986). In places, west-dipping thrust planes may be cut by east-dipping thrusts.

Figure 6-2 is a schematic cross section extending through the Ocean City area to the Grays Harbor Basin. Various structural models can explain the relation of Hoh and Ozette rocks shown in this cross section. Alternatively, the upper Hoh section penetrated in Ocean City wells could be in depositional contact with the underlying Ozette sequence. Auxiliary faulting related to the underthrusting of Hoh rocks could have caused the shear zones, slickensides, and other tectonic features observed in these wells.

Geology of the Upper Miocene to Recent Section at Ocean City

Plate 5 is a map showing the percentage of sandstone to finer clastics in the Montesano Formation. The map was constructed by measuring the cumulative thickness of all Montesano Formation sandstone beds logged in each well and dividing this value by the total thickness of the Montesano Formation logged in the well. Plate 6 is a true-scale, north-to-south cross section of the Ocean City area which complements those of Bergen and Bird (1972). This cross-section incorporates all available wireline log data, core descriptions, and paleontologic data. Dipmeter

GENERALIZED LITHOSTRATIGRAPHIC SEQUENCE PENETRATED IN OCEAN CITY AREA WELLS

QUATERNARY AND PLIOCENE	**QUATERNARY DEPOSITS AND QUINAULT FORMATION** Shallow marine and continental sandstones, conglomerates and siltstones
MIDDLE TO UPPER MIOCENE	**MONTESANO FORMATION SILTSTONE MEMBER** Shallow marine siltstones, and claystones with minor interbedded sandstones
	MONTESANO FORMATION SANDSTONE MEMBER Thick shelfal sandstones with very minor shale interbeds
	MONTESANO FORMATION CLAYSTONE MEMBER Middle bathyal claystones with some interbedded sandstones
MIDDLE MIOCENE TO UPPER OLIGOCENE	**HOH ROCK ASSEMBLAGE** Predominately sandstones with abundant siltstones and claystones
	? —— ? —— ?
UPPER TO MIDDLE (?) EOCENE	**OZETTE MELANGE** Interbedded sandstones, siltstones and claystones
MIDDLE MIOCENE TO UPPER OLIGOCENE	**HOH ROCK ASSEMBLAGE** Interbedded sandstones, siltstones and claystones

Figure 6-1 Generalized lithostratigraphic penetrated in Ocean City wells.

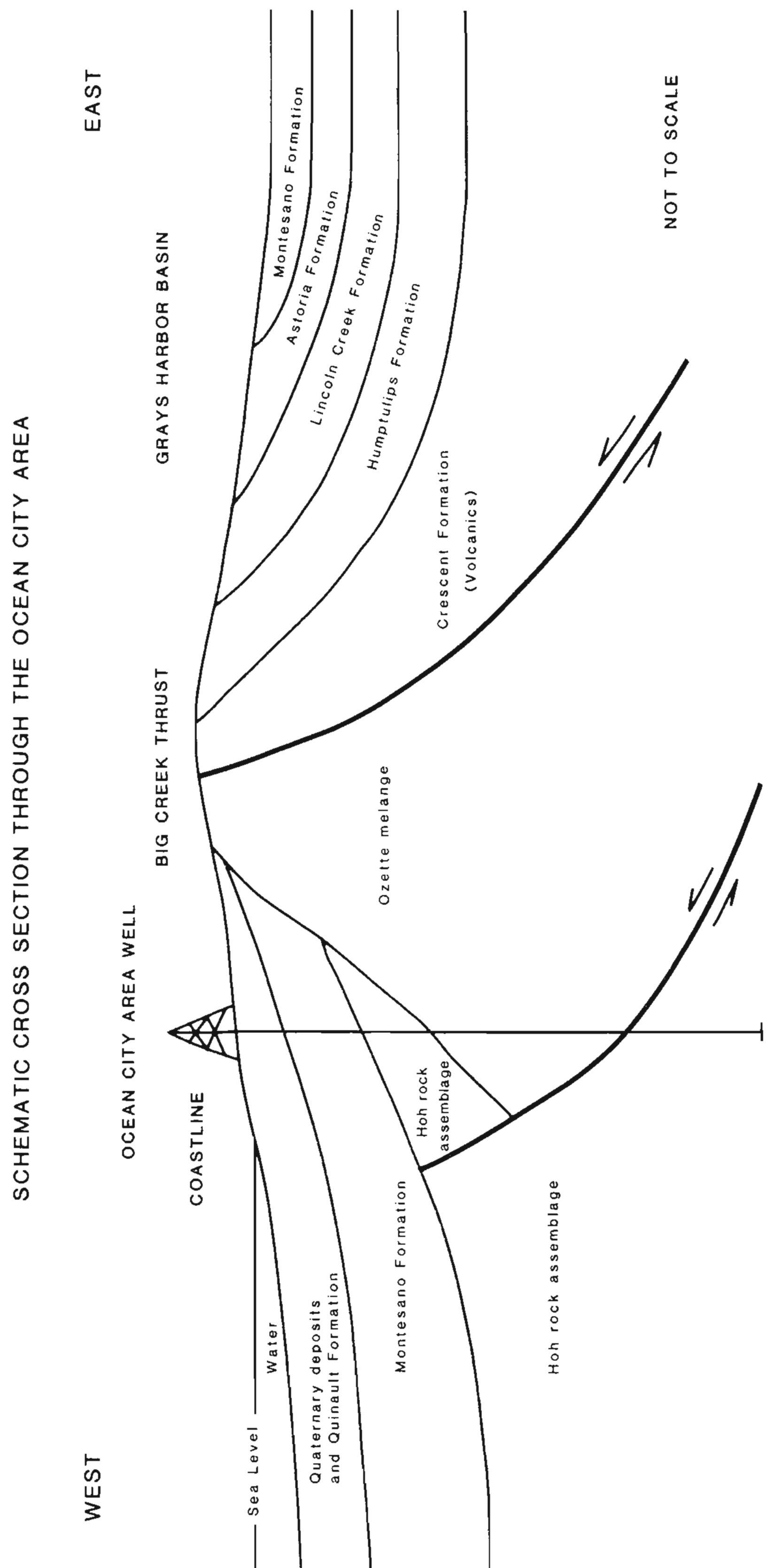


Figure 6-2 Schematic cross section through the Ocean City area.

data corroborate the correlation of the Montesano members, the attitudes of strata, and the positions of unconformities. The first occurrences of important foraminifers, *Bolivina sinuata*, *Bulimina subacuminata*, *Bulimina rostrata*, and *Rotalia garveyensis* confirm the interpretation (Rau and McFarland, 1982; Bergen and Bird, 1972). Plate 7 is a map of apparent thicknesses (isochore) of the sandstone member drawn on the basis of wireline log correlations.

The 200-ft contour on Plate 7 delineates the approximate outline of the massive facies of the Montesano sandstone member (the "Ocean City Sand"). The eastern and southern limits of the massive sandstone facies are interpreted as depositional zero edges. The western zero edge between Ocean City and the Tidelands State No. 2 offshore is probably erosional.

Stratigraphic and structural relations indicate that the northern limit of the massive sandstone facies is controlled by a northeast-trending fault. A marked change from the massive facies of the sandstone member (the Ocean City Sand) to a silty facies of the sandstone member occurs in the central part of the mapped area between the Sampson Johns 2-15 and State No. 1 wells (Plate 6). The siltstone and claystone members also display lithofacies variations between the Oscar No. 1 and the State No. 1. Both of these wells penetrated relatively complete sections (Plate 6). The contours outlining the highest percentages of coarse clastic lithologies generally trend northeast across the Ocean City area (Plate 5). Plate 5 includes sandstone beds within the claystone and siltstone members; if only the sandstone member were depicted, this northeastward trend would be more pronounced. Similar northeastward-trending contours are present on Plate 7.

Lithologic correlations indicate that dips north of the Sampson Johns 2-15 are near-horizontal, whereas dipmeter dips from the Sampson Johns 2-15 south are approximately 40° to the southeast.

The sandstone member is thickest in the Sampson Johns 1-15 and in the Oscar No. 1; in both it has a true thickness of more than 600 ft (Plate 6). The sandstone thins abruptly north of the Sampson Johns 2-15 well. This abrupt thinning over a distance of 1,250 ft cannot be explained by sandstone depositional morphology alone; the thickness variation of the sandstone member across this fault or unconformity is too abrupt to have resulted from stratigraphic thinning at the margin of a channel, bar, or other prismatic sand depositional unit. A high-angle fault or cliff- unconformity is the best explanation of this phenomenon. However, biostratigraphic data suggest that no significant unconformity is present in this section. The linear strike of this thinning trend (Plate 7) indicates that this area is probably cut by a northeast-trending fault as shown on Plate 6.

This probable fault is interpreted to have significant strike-slip displacement. The fault also displays some down-to-the-north displacement; the claystone member is thickest, and the top-Montesano unconformity removed less section north of the fault (Plate 6). However, the massive sandstone is preserved only on the upthrown (southern) block. Preservation of section on the upthrown block of a steep fault is characteristic of strike-slip displacement. Strike-slip faults parallel to this probable fault are common in the Olympic Peninsula (Figure 2-1). (Also see Snavely and Kvenvolden, 1988; Rau 1979, 1986; Stewart, 1970.) Seismic data acquired on the shelf show faults which appear to have strike-slip displacement. (See Chapters 3 and 7.) It is likely that this fault is an onshore extension of a fault exposed on the seafloor southwest of Ocean City (Wagner, 1986). This cross section cannot be geometrically balanced nor can the positions of the first occurrences of *Bulimina subacuminata* and *B. rostrata* be accommodated using a thrust fault model.

This probable fault is not shown cutting the unconformity at the top of the Montesano on Plate 6, but offset of this horizon cannot be dismissed without additional well or seismic control. The cross-cutting relations shown on Plate 6 indicate that movement on this probable fault occurred during the late Miocene and may have continued through the Pliocene.

The northern limit of the massive sandstone facies at Ocean City is apparently controlled by the probable fault: the fault could have offset the massive sandstone laterally, or the fault could have established a paleotopographic setting suitable for sand accumulation. Sand could have accumulated: (1) in a valley/submarine canyon -- this accumulation model implies that the valley/submarine canyon has moved laterally along the fault to a position where it appears to be on the upthrown block, or, (2) on a topographically high area created by the fault where barrier bar or similar marine sand deposition occurred.

A Strike-Slip Fault Model for Distribution of the Montesano Sandstone Member, Massive Sandstone Facies

Regional geology suggests that equivalents of the massive sandstone facies could be present elsewhere on the continental margin. Westward- directed river drainages were established subsequent to the uplift of the Olympic Mountains at about 17 Ma and prior to deposition of the Montesano Formation (Tabor, 1972, 1975). Strike-slip faulting controls the location of present-day and Pleistocene river drainages (Tabor and Cady, 1978a) on the western Olympic Peninsula and may have controlled these drainages during the late Miocene and Pliocene. Such rivers are known to have deposited at least two Montesano deltaic systems in the Grays Harbor Basin (Bigelow, 1987). A massive Quinault deltaic sandstone (Horn, 1969) crops out at the mouth of the Quinault River near the trace of a strike-slip fault which controls the location of river valley. We speculate that thick Miocene to Pliocene sandstones may be present along the offshore extensions of these and other strike-slip faults.

Sand issuing from the Olympic Mountains was probably carried westward and deposited on the continental margin. Most coarse detritus would have been deposited in the vicinity of the present coastline. However, turbidity flows could have eroded canyons and carried detritus past the narrow, late Miocene shelf and into the Montesano claystone member bathyal environment. This could have resulted in deposition of turbidite sequences such as those interpreted in the P-0141 well.

Petroleum Geology of the Ocean City Area

Results of drilling in the Ocean City area indicate that reservoirs in the Hoh and Ozette sections are not of sufficient quality to support commercial petroleum production on the Washington OCS. In contrast, sandstones of the Montesano Formation have excellent reservoir characteristics. Good shows in this section indicate that petroleum has migrated through the upper Miocene section.

Structure on the unconformity at the top of the Montesano Formation is shown on Plate 8. A structural culmination is present in sections 14 and 15, T18N, R12W WM. The Sampson Johns 2-15 and France No. 1 wells are nearest to the crest of this culmination and to the faulted crest of the Montesano sandstone member homocline. These structural relations indicate that a trap is present at Ocean City.

No significant hydrocarbons were recovered in the Ocean City wells which tested the sandstone member because: (1) significant migration of petroleum into the sandstone member did not occur, and/or, (2) an adequate seal above the massive sandstone was not present. However, indications that at least minor migration through the massive sandstone facies has occurred include cut and fluorescence in cores from the Oscar No. 1 and Sampson Johns 2-15 wells and small amounts of gas recovered from a drillstem test in the Oscar No. 1. This gas appears to be trapped by a localized tight streak at the top of the massive sandstone rather than by structure. The homoclinal culmination at the massive sandstone facies horizon was removed by erosion. Consequently, the breached top of the massive sandstone facies reservoir appears to be in contact with porous Quinault beds between the Sampson Johns 2-15 and State No. 1 (Plate 6).

Further evidence that petroleum migrated into Montesano sandstones is provided by drillstem tests in the Grays Harbor 1-35 drilled 2 mi northeast of Ocean City and the Medina No. 2 (Plate 6). The Grays Harbor 1-35 recovered gas at a rate of 1.33 MMCFGD on a 28/64-in. choke with a final flow pressure of 338 psi from a sandstone bed within the claystone member. In a test of the Media No. 2 from 3,087 to 3,118 ft, 5 barrels of 46.9° API oil and 780 MCFGPD were recovered from a zone of fractured claystone within the claystone member. It is possible that this zone is a splay from the probable fault shown in Plate 6.

7

Petroleum Plays on the Washington OCS

Data and interpretations presented in Chapters 4 and 6 indicate that the primary reservoir play on the Washington continental shelf is for sandstones in the Montesano Formation. Hoh rock assemblage and Ozette melange sandstone reservoirs are considered secondary targets due to their poor permeability and high risk of lateral discontinuity. Quinault-equivalent and Quaternary reservoirs are not considered important exploration objectives because of shallow burial and a lack of adequate seals above these reservoirs. Normal (to subnormal ?) pressure gradients in these younger rocks probably preclude accumulation of large shallow gas reserves on the shelf. While all source rocks identified to date in the study area are gas prone, ubiquitous oil shows indicate that future explorationists will key on the oil potential of the Washington OCS. However, the potential for making gas discoveries using direct detection (bright spot) analysis may also provide incentive for exploration.

Seven public-record reflection seismic data sets were interpreted in order to identify potential structural or combined structural and stratigraphic traps on the continental margin. These seismic lines are too widely spaced to prove structural closure, but this data set is sufficiently complete to give a first approximation of the potential for trap development.

Primary Petroleum Plays

We have recognized four plays on the Washington OCS and State territorial waters. While there may be numerous "exotic" structural and/or purely stratigraphic plays, it is unlikely that these could be defined with existing technology, much less promoted and drilled. Table 7- 1 summarizes the four primary plays, which are listed in order of decreasing favor.

Geophysical Data

Seismic reflection data acquired by the USGS during the 1976, 1977, and 1980 cruises of the RV *S. P. Lee* provided the majority of the coverage on the continental shelf (McClellan and Snavely, 1987, 1988; Mann and Snavely, 1984). Single channel seismic data acquired by the Scripps Institution of Oceanography as Leg 9A of the Seven Tow Expedition also provided data usable for mapping deep structure (Silver, 1972). Single channel seismic data obtained by the Department of Oceanography, University of Washington, provided some information on Pliocene and Pleistocene stratigraphy and shallow (less than 250 msec T.W.T.) structure including seafloor-breaching diapirs. These data were acquired during Cruises 13 and 24 of the RV *Thomas G. Thompson* and Cruise 10 of the RV *Oceaneer* (Bennett et al., 1969a,b; Bennett and Henry, 1969).

Locations of the USGS and Scripps seismic profiles are compiled on Plate 9. The Scripps data are located using a GMT time, rather than a shot point reference. The 1976, 1977, and 1980 USGS seismic lines are denoted respectively as 76-XX, 77-XX, and 80-XX (where XX is the specific line number). Likewise, the Scripps seismic lines are denoted as 7-XX. Paper stretch and different map projections presented problems during the compilation of Plate 9. The locations of the various survey lines are not exact: the shot points shown on Plate 9 are accurate to 2 mi +/- only.

The quality of the data varies greatly within and among the various surveys. For the USGS data, quality varies because of subsurface geologic conditions, differences in recording parameters, processing systems, and weather during acquisition. The 1980 USGS cruise used a short (600 m) streamer with only 12 channels due to severe weather conditions. Data quality on profiles from this cruise differs greatly from that of data recorded during previous cruises. The Scripps seismic data were collected in real time on an analog chart recorder, and consequently they suffer from varied pen quality. Nonetheless, Scripps data quality is second only to the reprocessed USGS multichannel data. None of the seismic data were acquired in a conventional grid. Consequently, these data are more useful for regional tectonic studies than for prospect delineation.

TABLE 7-1

PETROLEUM PLAYS ON THE WASHINGTON CONTINENTAL MARGIN

PLAY TYPE 1 - Montesano sandstone member, massive facies, or equivalents within strike-slip or diapiric anticlines

Reservoir/quality:	Montesano sandstone mb, massive facies/excellent
Stacked reservoirs(?):	unlikely
Trap type/probability of closure	anticlinal/good
Number of anticlines identified:	13+
Source rocks/quality:	Ozette/good nearshore, unknown farther west
Maturation:	mature below 10,000 ft
Migration:	vertical along strike-slip faults or diapirs is probable
Seal/quality:	Miocene/Pliocene claystones/varied
Prospects definable(?):	with difficulty due to the discontinuous nature of sand facies
Potential reserves:	250 MMBO +/-

PLAY TYPE 2 - Other Montesano Formation sandstones within strike-slip or diapiric anticlines

Reservoir/quality:	claystone or siltstone mb sandstones/average
Stacked reservoirs(?):	possible
Trap type/marginal probability of closure:	anticlinal/good
Number of anticlines identified:	13+
Source rocks/quality:	Ozette/good nearshore, unknown farther west
Maturation:	mature below 10,000 ft
Migration:	vertical along strike-slip faults or diapirs is probable
Seal/quality:	Miocene/Pliocene claystones/varied
Prospects definable(?):	Structural closure likely
Potential reserves:	small unless reservoirs are stacked

PLAY TYPE 3 - Montesano sandstone member, laterally sealed by diapirs

Reservoir/quality:	Montesano Fm. sandstones/average to excellent
Stacked reservoirs(?):	possible
Trap type/marginal probability of closure:	updip truncation/possible
Number of diapirs identified:	6 +/-
Source rocks/quality:	Ozette/good nearshore, unknown farther west
Maturation:	mature below 10,000 ft
Migration:	vertical along diapirs or faults
Seal/quality	Miocene/Pliocene claystones and diapirs/varied
Prospects definable (?):	depends on locating sandstone facies and truncations
Potential reserves	small unless reservoirs are stacked

PLAY TYPE 4 - Hoh/Ozette sandstones in anticlines or in buried paleotopographic culminations

Reservoir/quality:	Hoh/Ozette sandstones in coherent blocks/poor
Stacked reservoirs:	likely
Trap type/probability of closure:	faulted anticlines, topography at unconformities/poor
Number of potential traps identified:	none
Source:	Ozette/good nearshore, unknown farther west
Maturation:	mature below 10,000 feet is probable
Migration:	juxtaposition of source & reservoir or along faults
Seal/quality:	Hoh/Ozette/Montesano claystones/good
Prospects definable(?):	not with existing public-record seismic data
Potential reserves	small

In addition, vertical and horizontal scales used in plotting the profiles are inconsistent, and as noted above, navigation is equivocal. Consequently, it was not possible to tie the various survey lines reliably.

The University of Washington single channel data are of limited utility because these penetrate to only 250 msec and because seafloor multiples and bubble pulse effects preclude correlation of the shallow and deep penetrating seismic data sets.

Offshore Seismic Interpretation

A number of geologic features relevant to the petroleum potential of the Washington OCS are identified on the following interpretations of USGS and Scripps reflection seismic profiles. These include: (1) strike-slip faulting, (2) a possible upper Miocene submarine canyon, (3) a seismic bright spot possibly caused by gas accumulation at shallow depth, (4) diapiric and strike-slip anticlines, and, (5) truncation of strata against diapirs. Horizon identification is based solely on tenuous character correlations, except for those lines that tie the three OCS wildcats. We were unable to obtain a seismic profile across the Tidelands State No. 2 location. Acoustic log data obtained from the P-0155 and Cygnet J-100 are used to convert seismic traveltime to depth (Figure 3-7).

The four horizons shown on these profiles are described in Chapter 3. Briefly, the "A" horizon corresponds to the base of the Pliocene and Pleistocene gravels; the "B" horizon generally corresponds to the unconformity/disconformity at the top of the Montesano Formation; the "C" horizon is composed of continuous (?) intra-Montesano claystone member reflectors; and, the "D" horizon is an intra-Hoh rock assemblage/Ozette melange phantom reflector.

The locations of some structural culminations, diapirs, and a few strike-slip (?) faults as interpreted from the deep penetration seismic data are shown on Plate 10. The main purpose of this mapping exercise is to demonstrate the frequency of anticlinal folds insofar as possible using public-record data.

It is essential to note that four-way closure cannot be demonstrated much less proven for any anticlines depicted on Plate 10 because of a lack of gridded seismic data and because of the large distances between adjacent profiles.

Profiles of anticlines depicted on Plate 10 are measured from synclinal trough to synclinal trough (across the apparent T.W.T. "spill point") along continuous reflectors or phantoms. These anticlinal rollovers are generally measured in a time window from 700 msec to 1,200 msec T.W.T., which corresponds to the approximate level of prospective Montesano sandstone member intervals. For example, the mapped length of the anticlinal culmination directly west of the P-0155 well on Line 76-12 was determined from the troughs of adjacent synclines at horizon "C" (Plate 2). The profile of this anticline shown on Plate 10 extends from SP 375 to 430.

The orientations and extents of diapirs and anticlines on Plate 10 cannot be determined with the existing data set. It appears that there may be a correlation between the orientations of fold hinges and those of elongate, northwest-trending submarine ridges near the contact of the abyssal plain and the continental rise. However, attempts to correlate bathymetry with seismic structure on the shelf were unsuccessful. Anticlines that bend upper Miocene and younger strata are sufficiently controlled to indicate that some fold hinges on the shelf are oriented sub-perpendicular to the coastline (19:07 to 20:17, and 7:07 to 7:33 GMT on Line 7-10 and at the intersection of Lines 76-12 and 7-11). Anticlines at the intersections of Lines 76-11 with 7-11 and Lines 76-12 with 7-11 appear to enclose about 9,000 acres each.

Diapirs plotted on Plate 10 are mainly those present between 700 msec T.W.T. and the seafloor. Seafloor multiples and bubble pulse effects generally preclude identification of diapirs which are breached at the seafloor. The diapirs shown on Plate 10 have insignificant anticlinal rollover except for those that have a diapir symbol within an anticline symbol. In these instances, anticlinal rollover is significantly longer than the subtended diapir. (See Line 76-14, Plate 4, and Plate 10.) These combination diapiric/anticlinal structures have potential for extensive closure against the margins of the diapir (Play Type 3).

Some of the onshore strike-slip faults mapped by Snavely and Kvenvolden (1988) are shown on Plate 10. Offshore extensions of these faults interpreted from seismic data are also shown on this plate. The interpretation of strike-slip displacement is based on criteria described in Chapter 3, Seismic Stratigraphy.

Plate 10 shows approximately 30 anticlinal rollovers ranging in size from 2 to 8 mi in profile. Wagner and others (1986) map anticlines at the surface longer than 50 mi using these seismic data and seafloor geology. We are unable to map these anticlines at the Montesano horizons shown on Plate 10 because the jump-ties that are necessary to correlate between adjacent lines are equivocal. The rollovers are associated primarily with strike-slip faulting (e.g., Lines 76-12 and 80-8; Plates 2, 12) and diapiric intrusion (e.g., Lines 76-14 and 80-8; Plates 4, 12). The abundance of mapped anticlinal rollovers and diapirs shown on Plate 10 is chiefly a function of the data base; undoubtedly, numerous folds, faults, and diapirs occur offshore that we are unable to identify. For example, the abundance of structures decreases northward from the Willapa Bay - Grays Harbor area in proportion to diminishing data quality and increasing line spacing. The USGS and Scripps Institute did not record data within 10 mi of the coastline. Consequently, deep penetration seismic data are unavailable for the federally controlled OCS and the Washington State territorial waters within this 10 mi strip.

Line 76-11 (Plate 11) shows the approximate position of the Shell P-0150. This well penetrated a normal section from the Montesano claystone through the Hoh rock assemblage, which is composed mainly of sheared claystone breccia (Shell, 1966). The interpretation of diapiric intrusion below the P-0150 anticlinal apex is equivocal. The diffraction patterns on this line could result from thrusts and/or topography on the Hoh unconformity. Two subtle anticlines directly west of this structure share a common "spill point" at horizon "C" and are mapped as such on Plate 10. Rollover on these subtle anticlines diminishes directly above horizon "B". The section between horizons "B" and "C" is probably equivalent to parts of the Montesano sandstone and claystone members.

Faulting and uplift on the west-central part of Line 76-11 are interpreted to result from strike-slip faulting. East of the fault, horizon "A" and "B" are uplifted and truncated at the seafloor, whereas west of the fault horizons "A" and "B" are flat-lying. This interpretation requires careful scrutiny of the profile because multiples and/or the bubble pulse obscure stratigraphically controlled events. This probable strike-slip structure is similar to faulted anticlines observed on Line 76- 12 (Chapter 3, Seismic Stratigraphy; Plate 2) and Scripps Line 7-3. The structures interpreted on Lines 76-11 and 7-3 appear to be a single strike- slip fault which continues eastward into the Grays Harbor estuary (Plate 10) and offsets magnetic contours (Finn, USGS, 1988, written commun.; Henderson and others, 1958a-d). The sense of offset observed on magnetic contours is right lateral. Many strike-slip faults elsewhere along the coast (Snavely and Kvenvolden, 1988) are mapped as having right-lateral offset.

Line 76-10 (Plate 11) is a north-trending profile located approximately 10 mi west of Willapa Bay. The stratigraphic package between horizons "B" and "C" consists of a sequence of continuously parallel, moderate frequency reflectors from SP 1 to 360. Between SP 360 and 600, these reflectors become discontinuous and have lower frequency content. The total time interval between "B" and "C" (or between "A" and "C" where "B" is missing north of SP 455) increases by addition of section at the base of the interval. The sequence from SP 328 to the fault near SP 600 and between 1.3 and 2.3 seconds T.W.T. appears to have filled a topographic depression interpreted as a submarine canyon. The continuous and parallel reflectors above the fill sequence represent deposition of siltstones and claystones in a quiescent basinal setting. These continuous reflectors abruptly terminate at the canyon depression where channel scour-and-fill sequences exhibit little lateral or vertical continuity. Other possible canyon-fill sequences are interpreted at the north and south ends of the profile.

Line 80-8 (Plate 12) is a north-trending profile located approximately 20 mi west of the mouth of the Hoh River. The high-amplitude reflector at 300 msec T.W.T. between SP 1516 and 1583 is interpreted as an acoustic bright spot possibly indicating the presence of shallow gas. This reflector cuts apparent bedding, is bound by anticlinal closure, and exhibits phase reversal, all of which can be characteristic of gas-water interfaces. The symmetrical anticline between SP 1520 and 1590 may be due to diapiric intrusion at depth. This possible diapir can be outlined on the seismic profile by tracing disrupted reflectors between 1.5 and 2.5 seconds T.W.T. A similar bright spot occurs at 300 msec T.W.T between SP 1685 and 1740 where it is limited by a fault.

Line 76-14 (Plate 4) is an east-trending profile located approximately 12 mi offshore of the mouth of the Moclips River. A large anticline lies between SP 40 and 220 and represents Play Types 1 and 2 (Table 7-1). A diapiric intrusion is interpreted between SP 168 and 112 on the basis of diffractions below 1.5 seconds T.W.T. A complexly anticlinorium below horizon "C" appears to result from intermittent growth of this probable diapir. The section above the "B"

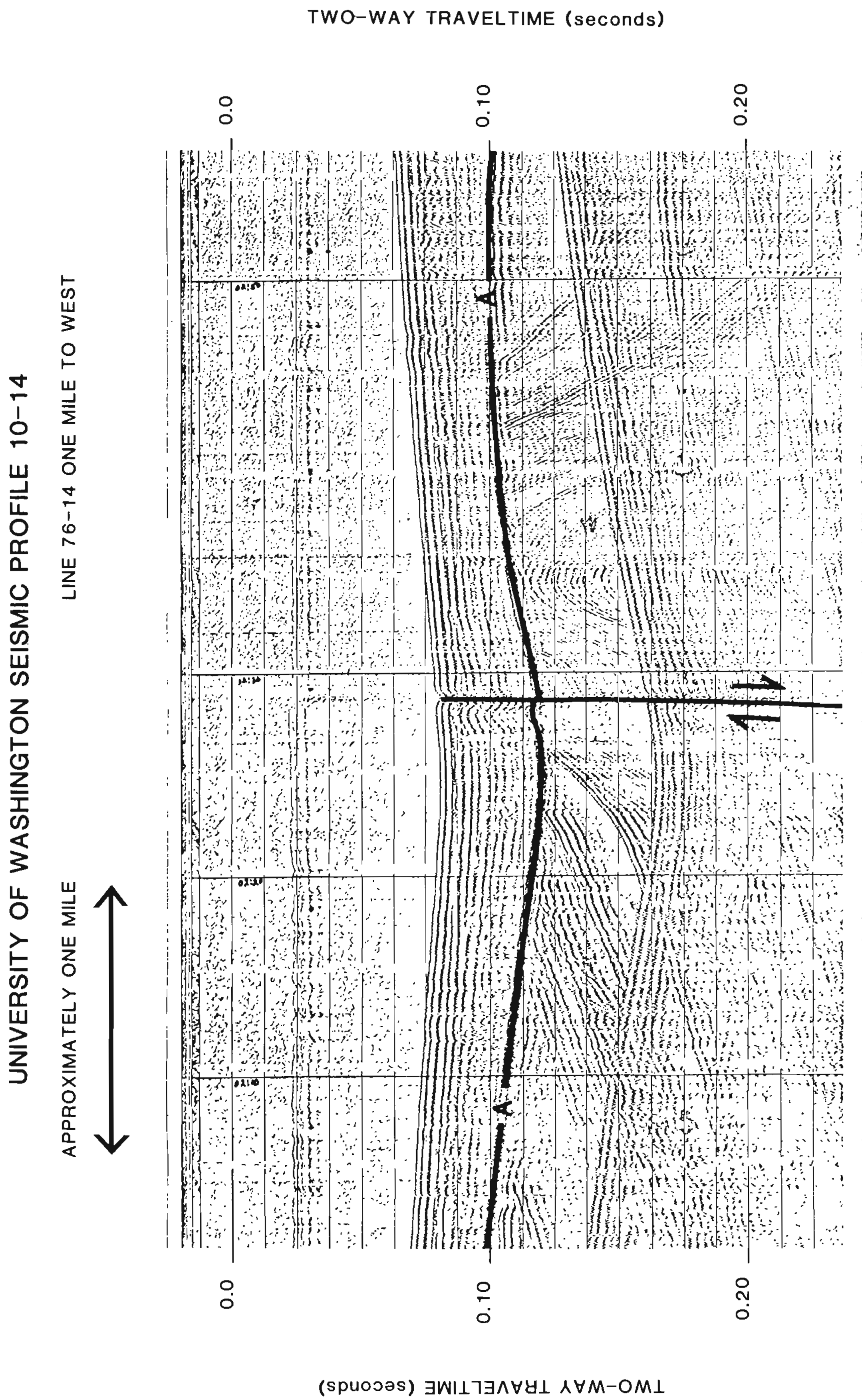


Figure 7-1 University of Washington seismic profile 10-14.

horizon corresponds to the thickest Quinault-equivalent sequence observed on the Washington shelf. Numerous local unconformities on the west flank of the anticlinorium between "A" and "C" may be channels, foresets, and/or slumps.

Line 76-17 (Plate 12) trends north and lies approximately 12 mi west of the mouth of the Queets River. Three diapiric intrusions are depicted on this profile. Figure 7-1 is a segment of Line 14 of *Oceaneer* Cruise 10 located approximately 1 mi east of SP 337 on Line 76-17. Figure 7-1 shows tight folding associated with diapiric intrusion, and truncation of tilted reflectors by an unconformity. This unconformity is correlated to horizon "A" on Line 76-17. Thick sequences of coherent reflectors below horizon "C" on Line 76-17 separate the three diapirs. Each of these layered sequences is terminated updip against the central diapir (Play Type 3).

8

Possible Petroleum Reserves on the Washington Continental Margin

A comparison of previous assessments of the petroleum potential of the combined Washington and Oregon continental margins is given in Table 8-1. These studies conclude that potential exists for petroleum accumulation on the Washington continental margin. The following discussion outlines possible reserves for hypothetical *individual* accumulations on the Washington OCS. These interpretations indicate that the Washington continental margin could contain a significant petroleum resource. The potential, unrisked recoverable oil reserves for a single trap can be expressed as follows:

$$\text{Recoverable Oil (in barrels)} = \frac{A \times T \times N/GP \times FTS \times Phi \times (1-Sw) \times RF \times 7{,}758}{Bo}$$

where:

A = area of the trap in acre/ft	T = thickness of the reservoir in ft
N/GP = net to gross pay ratio	FTS = ratio of oil-fill in trap to reservoir thickness
Phi = average porosity	Sw = average water saturation
RF = recovery factor	7,758 = barrels per acre/ft
Bo = formation volume factor	

The critical variable in this equation, as applied to the Washington OCS, is the area of the trap because this variable can vary greatly. As noted above, structural closure on the shelf cannot be proven with the public-record seismic data set. Spill point profiles of anticlines at intra-Montesano Formation horizons range from 0.5 to 7 miles (Chapter 7). Wagner and others (1986) map several anticlinal hinges longer than 20 miles on the shelf and slope using seismic data and seafloor geology, but do not indicate four-way closure on these structures.

A crude estimate of possible trap size can be determined for two anticlines on the shelf where seismic lines intersect over the apparent culminations. Anticlines at the intersections of Line 76-11 with 7-11 and Line 76-12 with 7-11 appear to enclose about 9,000 acres each.

This estimate of the area of these two possible traps together with variables that are quantified in this report (reservoir thicknesses and average porosity) were used to determine a first approximation of the potential reserves that might be contained in Play Types 1, 2, and 4 (Table 7-1). The other variables in the volumetric equation were estimated by comparison with producing oil fields that have geology similar to that of the Washington OCS. Substituting the average reservoir properties for the Hoh/Ozette sequences given in Chapter 4, Phi = 0.15 and T = 34 ft, and assuming A = 9,000 acres, N/GP = 0.75, FTS = 0.5, Sw = 0.4, RF = 0.15, and Bo = 1.25 in the volumetric equation gives about 10 million barrels of recoverable oil. However, no structures have been mapped at these horizons and Hoh/Ozette reservoirs are likely to be discontinuous. Furthermore, the average porosity estimate from Chapter 4 is probably greater than the effective porosity due to large clay volumes in these Hoh/Ozette sandstones. Therefore, 10 million barrels of potential recoverable oil is likely to be very optimistic and risked Hoh/Ozette reserves would be a fraction of this number.

A first approximation of potential reserves in an average Montesano Formation sandstone (e.g. the turbidite sandstone reservoirs in the P-0141) using Phi = 0.20 and T = 40 ft together with the assumptions given above (except for RF = 0.2) is about 20 million barrels recoverable oil.

A first approximation of potential reserves in a Montesano sandstone member massive-facies or equivalent reservoirs using the above assumptions except for N/GP = 1.0, Phi = 0.25 and T = 300 ft are about 250 million barrels of recoverable oil. Risked reserves using this analysis would be a fraction of this value because this sandstone is known to be developed only at Ocean City and in the P-0155. There is only a small probability that this sandstone occurs elsewhere on the OCS in a sealed structural trap.

TABLE 8-1

COMPARISON OF PETROLEUM POTENTIAL ASSESSMENTS OF THE WASHINGTON CONTINENTAL MARGIN

Braislin and others (1977)

"a favorable geologic environment, including sources rocks, reservoir rocks, and structure, is an incentive to future petroleum exploration."

Scott (1982)

Mean, unrisked, recoverable reserves from a Monte Carlo simulation for Washington and Oregon are:

240 million barrels of oil and
600 billion cubic ft of gas

Cooke (1985)

Mean, unrisked, recoverable reserves from a probablistic simulation (PRESTO) are:

180 million barrels of oil and
3,260 billion cubic ft of gas

Snavely (1987)

"Potential exploration targets exist where Eocene and/or Oligo-Miocene melanges are underplated beneath the Eocene oceanic basalt."

Dunkel (1988)

"geologic conditions that favor hydrocarbon generation, accumulation, and entrapment have existed along the Washington and Oregon continental shelf and that appreciable hydrocarbon resources may be present".

Palmer and Lingley (1989) — This Report

Volumetric estimates suggest that an *individual* accumulation could contain:

10 million barrels of recoverable oil in average Hoh/Ozette reservoirs

20 million barrels of recoverable oil in average Montesano reservoirs

250 million barrels of oil in Montesano massive sandstone facies (Ocean City Sand) reservoirs

Selected References

Addicott, W. O., 1976, Neogene molluscan stages of Oregon and Washington. *In* Fritsche, A. E.; Ter Best, Harry, Jr.; Wornardt, W. W., editors, 1976, The Neogene symposium—Selected technical papers on paleontology, sedimentology, petrology, tectonics and geologic history of the Pacific coast of North America: Society of Economic Paleontologists and Mineralogists Pacific Section, 51st Annual Meeting, p. 95-115.

Anderson, Roger; and others, 1980, Final report of the 105(b) economic and policy analysis: U.S. Department of the Interior, Office of Minerals Policy and Research Analysis, 145 p.

Barnard, W. D., 1973, Late Cenozoic sedimentation on the Washington continental slope: University of Washington Doctor of Philosophy thesis, 255 p.

Barron, J. A.; Keller, Gerta, 1982, Widespread Miocene deep-sea hiatuses—Coincide with periods of global cooling: Geology, v. 10, no. 11, p. 577-581.

Bates, R. G.; Beck, M. E., Jr.; Burmester, R. F., 1981, Tectonic rotations in the Cascade Range of southern Washington: Geology, v. 9, p. 184-189.

Beck, M. E., Jr., 1984, Has the Washington-Oregon coast range moved northward?: Geology, v. 12, no. 12, p. 737-740.

Bennett, L. C., Jr.; Henry, M.; and Lewis, L., 1967a, Preliminary report, RV *Thomas G. Thompson* Cruise 13, Continental Shelf Survey, 17 March to 25 March, 1967: Office of Naval Research Contract No-447(37), Project NR 083 012, unpaginated.

Bennett, L. C., Jr.; Henry, M., 1967b, Preliminary report, RV *Oceaneer* Cruise 10, Continental Shelf Survey, 10 June to 18 June, 1967: U.S. Geological Survey Contract 14-08-0001-10924, unpaginated.

Bennett, L. C., Jr.; Henry, M.; and Lewis, L., 1967c, Preliminary report, RV *Thomas G. Thompson* Cruise 24, Continental Shelf Survey, 8 December to 15 December, 1967: Office of Naval Research Contract Nonr-447(37), Project NR 083 012, unpaginated.

Bergen, F. W.; Bird, K. J., 1972, The biostratigraphy of the Ocean City area, Washington. *In* The Pacific Coast Miocene Biostratigraphic Symposium, Proceedings: Society of Economic Paleontologists and Mineralogists Pacific Section, p. 173-191.

Bigelow, P. K., 1987, The petrology, stratigraphy and basin history of the Montesano Formation, southwestern Washington and southern Olympic Peninsula: Western Washington University Master of Science thesis, 263 p.

Blackwell, D. D., 1974, Terrestrial heat flow and its implications on the location of geothermal reservoirs in Washington. *In* Washington Division of Geology and Earth Resources, 1974, Energy resources of Washington: Washington Division of Geology and Earth Resources Information Circular 50, p. 21-33.

Braislin, D. B.; Hastings, D. D.; Snavely, P. D., Jr., 1971, Petroleum potential of western Oregon and Washington and adjacent continental margin *In* Cram, I. H., editor, Future petroleum provinces of the United States—Their geology and potential: American Association of Petroleum Geologists Memoir 15, p. 229-238.

Brown, Kevin; Westbrook, G. K., 1988, Mud diapirism and subcretion in the Barbados Ridge accretionary complex—The role of fluids in accretionary processes: Tectonics, v. 7, no. 3, p. 613-640.

Brown and Ruth Laboratories, Inc., 1982a, Pacific Northwest—Regional petroleum geochemistry of the onshore and offshore sediments of Washington and Oregon—Pan American Petroleum Company OCS-P-0141, offshore Jefferson County, Washington, T.D. 10,368'; Proprietary report: Brown and Ruth Laboratories, Inc., 1 v., 2 plates.

Brown and Ruth Laboratories, Inc., 1982b, Pacific Northwest—Regional petroleum geochemistry of the onshore and offshore sediments of Washington and Oregon—Union Oil of California tidelands state no. 2 well, sec. 30, T18N, R11W (projected); offshore Grays Harbor County, Washington, T. D. 5,073'; Proprietary report: Brown and Ruth Laboratories, Inc., 1 v.

Brown and Ruth Laboratories, Inc., 1982c, Pacific Northwest—Regional petroleum geochemistry of the onshore and offshore sediments of Washington and Oregon—Tideland Oil and Gas Corp. Weyerhaeuser No. 7-11 well, sec. 7, T11N, R10W; Pacific County, Washington, T. D. 5,988'; Proprietary report: Brown and Ruth Laboratories, Inc., 1 v.

Brown and Ruth Laboratories, Inc., 1982d, Pacific Northwest—Regional petroleum geochemistry of the onshore and offshore sediments of Washington and Oregon—Sharples Corporation Weyerhaeuser - Clemons No. 1, sec. 7, T16N, R7W; Grays Harbor County, Washington, T. D. 6,855'; Proprietary report: Brown and Ruth Laboratories, Inc., 1 v.

Brown and Ruth Laboratories, Inc., 1982e, Pacific Northwest—Regional petroleum geochemistry of the onshore and offshore sediments of Washington and Oregon—El Paso Products Company Lacey No. 22-1 well, sec. 22, T26N, R13W; Jefferson County, Washington, T. D. 5,722'; Proprietary report: Brown and Ruth Laboratories, Inc., 1 v.

Clowes, R. M.; Brandon, M. T.; Green, A. G.; Yorath, C. J.; Sutherland Brown, A.; Kanasewich, E. R.; Spencer, C., 1987, LITHOPROBE—Southern Vancouver Island—Cenozoic subduction complex imaged by deep seismic reflections: Canadian Journal of Earth Sciences, v. 24, no. 1, p. 31-51.

Connard, G.; Couch R.; Ness, G.; and Troseth, S., 1984, Magnetic anomaly identifications. *In* Kulm, L. D., and others, 1984, Western North American continental margin and adjacent ocean floor off Oregon and Washington: Marine Science International, Woods Hole, 32 p.

Cooke, L. W., 1985, Estimates of undiscovered, economically recoverable oil and gas resources for the outer continental shelf as of July 1984: U.S. Minerals Management Service OCS Report MMS 85-0012, 45 p.

Couch, R.; Kienle, C.; and Connard, G., 1978, The Continental Margin of the Pacific Northwest; A Summary of the Geological and Geophysical Data: School of Oceanography, Oregon State University [GTF780816], 96 p.

Cowan, D. S.; Potter, C. J., compilers; Brandon, M. T.; Fountain, D. M.; Hyndman, D. W.; Johnson, S. Y.; Lewis, B. T. R.; McClain, K. J.; Swanson, D. A., 1986, B-3 Juan de Fuca spreading ridge to Montana thrust belt: Geological Society of America Centennial Continent/Ocean Transect 9, 3 sheets, scale 1:500,000, with 12 p. text.

Drummond, K. J., chairman, and others, 1981, Plate-tectonic map of the circum-Pacific region, northeast quadrant: American Association of Petroleum Geologists, 1 plate, scale 1:10,000,000.

Dunkel, C. A., 1988, A qualitative assessment of the hydrocarbon potential of the Washington and Oregon continental shelf. *In* Oceans '88, a partnership of marine interests; Proceedings: Marine Technology Society, v. 1, p. 208-212.

Florer, L. E., 1972, Quaternary paleoecology and stratigraphy of the sea cliffs, western Olympic Peninsula, Washington: Quaternary Research, v. 2, no. 2, p. 202-216.

Galloway, W. E., 1974, Deposition and diagenetic alteration of sandstone in northeast Pacific arc-related basins—Implications for Graywacke Genesis: Geological Society of America Bulletin, v. 85, no. 3, p. 379-390.

Grady, M. T., 1985, Stratigraphy, sedimentology, and hydrocarbon potential of the Hoh turbidite sequence (Miocene), western Olympic Peninsula, Washington: University of Idaho Master of Science thesis, 192 p.

Grim, M. S.; Bennett, L. C., Jr., 1969, Shallow sub-bottom geology of the Washington shelf off Grays Harbor [abstract]: Eos (American Geophysical Union Transactions), v. 50, no. 2, p. 63-64.

Henderson, J. R.; Tyson, N. S.; McGowan, E. F.; and others, 1958a, Aeromagnetic map of the Aberdeen quadrangle, Grays Harbor and Pacific Counties, Washington: U.S. Geological Survey Geophysical Investigations Map GP-177, 1 sheet, scale 1:62,500.

Henderson, J. R.; Tyson, N. S.; McGowan, E. F.; and others, 1958b, Aeromagnetic map of the Cape Shoalwater quadrangle, Pacific County, Washington: U.S. Geological Survey Geophysical Investigations Map GP-183, 1 sheet, scale 1:62,500.

Henderson, J. R.; Tyson, N. S.; McGowan, E. F.; and others, 1958c, Aeromagnetic map of the Grayland quadrangle, Grays Harbor and Pacific Counties, Washington: U.S. Geological Survey Geophysical Investigations Map GP-176, 1 sheet, scale 1:62,500.

Henderson, J. R.; Tyson, N. S.; McGowan, E. F.; and others, 1958d, Aeromagnetic map of the Sound Bend quadrangle, Pacific County, Washington: U.S. Geological Survey Geophysical Investigations Map GP-184, 1 sheet, scale 1:62,500.

Heusser, C. J., 1972, Palynology and phytogeographical significance of a late-Pleistocene refugium near Kalaloch, Washington: Quaternary Research, v. 2, no. 2, p. 189-201.

Horn, A. D., 1969, The sedimentary history of the Quinault Formation, western Washington: University of Southern California Master of Science thesis, 179 p.

Hubert, K. A., 1979, Physical properties of selected basalt and greywacke and the inferred seismic structure of the Olympic Peninsula, Washington: University of Washington Master of Science thesis, 96 p.

Ingle, J. C., Jr., 1980, Cenozoic paleobathymetry and depositional history of selected sequences within the southern California continental borderland. *In* Sliter, W. V., editor, 1980, Studies in marine micropaleontology and paleoecology—A memorial to Orville L. Bandy: Cushman Foundation Special Publication 19, p. 163-195.

Johnson, S. Y.; Brandon, M. T.; Stewart, R.J.; McClain, K. J.; Lewis, B. T. R.; Tabor, J. J; and Crosson, R. S., 1984, Cross section DD'D", Western Washington. *In* Kulm, L. D. and others, 1984, Western North American continental margin and adjacent ocean floor off Oregon and Washington: Marine Science International, Woods Hole, 1 sheet.

Kvenvolden, K. A.; Golan-Bac, Margaret; Snavely, P. D., Jr., 1988a, Preliminary evaluation of the petroleum potential of the Tertiary accretionary terrane, west side of the Olympic Peninsula, Washington—Part 3. Composition of natural gases in seeps, outcrops, and a test well: U.S. Geological Survey Open-File Report 88-75, p. 50-62.

Kvenvolden, K. A.; Rapp, J. B.; Hostettler, F. D.; Snavely, P. D., Jr., 1988b, Preliminary evaluation of the petroleum potential of the Tertiary accretionary terrane, west side of the Olympic Peninsula, Washington—Part 2. Comparison of molecular markers in oil and rock extracts: U.S. Geological Survey Open-File Report 88-75, p. 27-49.

Kulm, Vern, 1983, Western Washington/Oregon Juan de Fuca Project; draft report: Washington Public Power Supply System, 35 p.

McClellan, P. H.; Snavely, P. D., Jr., 1987, Multichannel seismic-reflection profiles collected in 1976 off of the Washington-Oregon coast: U.S. Geological Survey Open-File Report 87-607, 2 p., 1 plate.

McClellan, P. H.; Snavely, P. D., Jr., 1988, Multichannel seismic-reflection profiles collected in 1980 off of the Washington and northern Oregon coast: U.S. Geological Survey Open-File Report 88-205, 4 p., 1 plate.

McFarland, C. R., 1983, Oil and gas exploration in Washington, 1900-1982: Washington Division of Geology and Earth Resources Information Circular 75, 119 p.

MacLeod, N. S.; Tiffin, D. L.; Snavely, P. D., Jr.; Currie, R. G., 1977, Geologic interpretation of magnetic and gravity anomalies in the Strait of Juan de Fuca, U.S.-Canada: Canadian Journal of Earth Sciences, v. 14, no. 2, p. 223-238.

Mann, D. M.; Snavely, P. D., Jr., 1984, Multichannel seismic-reflection profiles collected in 1977 in the eastern Pacific Ocean off of the Washington/Oregon coast: U.S. Geological Survey Open-File Report 84-5, 3 p., 1 plate.

Moore, J. L., 1965, Surficial geology of the southwestern Olympic Peninsula: University of Washington Master of Science thesis, 63 p., 1 plate.

Mutti, E.; Ricci Lucchi, F., 1978, Turbidites of the northern Apennines—Introduction to facies analysis [trans. by T. H. Nilson]: International Geology Review, v. 20, no. 2, p. 125-166.

Newton, V. C., Jr., 1967, Summary of oil and gas exploration off the coast of Oregon and Washington, 1961-1966: Ore Bin, v. 29, no. 2, p. 17-32.

Orange, D. L., 1987, Hoh melanges in Washington—Emplacement by diapirism and shear zone deformation [abstract]: Eos (American Geophysical Union Transactions), v. 68, no. 52, p. 1816.

Peters, K. E., 1986, Guidelines for evaluating petroleum source rock using programmed pyrolysis: American Association of Petroleum Geologists Bulletin, v. 70, n. 3, p. 318-329.

The Pan American Oil Company, 1967, Pan American/Shell P-0141 wildcat well completion report: [report on file with Washington Division of Geology and Earth Resources], 22 p.

Rau, W. W., 1964, Foraminifera from the Northern Olympic Peninsula, Washington: U.S. Geological Survey Professional Paper 374-G, 33 p.

Rau, W. W., 1967, Geology of the Wynoochee Valley quadrangle, Grays Harbor County, Washington: Washington Division of Mines and Geology Bulletin 56, 51 p., 1 plate.

Rau, W. W., 1970, Foraminifera, stratigraphy, and paleoecology of the Quinault Formation, Point Grenville-Raft River coastal area, Washington: Washington Division of Mines and Geology Bulletin 62, 41 p.

Rau, W. W., 1973, Geology of the Washington coast between Point Grenville and the Hoh River: Washington Division of Geology and Earth Resources Bulletin 66, 58 p.

Rau, W. W., 1975, Geologic map of the Destruction Island and Taholah quadrangles, Washington: Washington Division of Geology and Earth Resources Geologic Map GM-13, 1 sheet, scale 1:63,360.

Rau, W. W., 1977, General geology of the southern Olympic Coast. *In* Brown, E. H.; Ellis, R. C., editors, 1977, Geological excursions in the Pacific Northwest; Geological Society of America annual meeting, 1977: Western Washington University, p. 63-83.

Rau, W. W., 1979, Geologic map in the vicinity of the lower Bogachiel and Hoh River valleys and the Washington coast: Washington Division of Geology and Earth Resources Geologic Map GM-24, 1 sheet, scale 1:62,500.

Rau, W. W., 1980, Washington coastal geology between the Hoh and Quillayute Rivers: Washington Division of Geology and Earth Resources Bulletin 72, 57 p.

Rau, W. W., 1981, Pacific Northwest Tertiary benthic foraminiferal biostratigraphic framework—An overview: Geological Society of America Special Paper 184, p. 67-84.

Rau, W. W., 1986, Geologic map of the Humptulips quadrangle and adjacent areas, Grays Harbor County, Washington: Washington Division of Geology and Earth Resources Geologic Map GM-33, 1 sheet, scale 1:62,500.

Rau, W. W., 1987, Melange rocks of Washington's Olympic coast. *In* Hill, M. L., editor, 1987, Cordilleran section of the Geological Society of America: Geological Society of America DNAG Centennial Field Guide 1, p. 373-376.

Rau, W. W.; Grocock, G. R., 1974, Piercement structure outcrops along the Washington coast: Washington Division of Geology and Earth Resources Information Circular 51, 7 p.

Rau, W. W.; McFarland, C. R., 1982, Coastal wells of Washington: Washington Division of Geology and Earth Resources Report of Investigations 26, 4 sheets.

Rector, R. J., 1958, Some lithologic and paleontologic observations on the Quillayute Formation: University of Washington Bachelor of Science thesis, 40 p.

The Shell Oil Company, 1966, Shell P-0150, P-0150A wildcat completion report: [report on file with Washington Division of Geology and Earth Resources], 35 p.

The Shell Oil Company, 1967, Shell P-0155 wildcat completion report: [report on file with Washington Division of Geology and Earth Resources], 35 p.

Silver, E. A., 1972, Pleistocene tectonic accretion of the continental slope off Washington: Marine Geology, v. 13, no. 4, p. 239-249.

Snavely, P. D., Jr., 1981, Geophysical data collected on the continental midway between Washington State and Vancouver Island, B. C., along line 19, USGS R/V *S.P. Lee* cruise 3-76: U.S. Geological Survey Open-File Report 81-895, 1 sheet, scale 1:250,000.

Snavely, P. D., Jr., 1987, Tertiary geologic framework, neotectonics, and petroleum potential of the Oregon-Washington continental margin. *In* Scholl, D. W.; Grantz, A.; Vedder, J. G., editors, 1987, Geology and resources potential of the continental margin of western North America and adjacent ocean basins—Beaufort Sea to Baja, California: Circum-Pacific Council for Energy and Mineral Resources, Earth Science Series 6, p. 305- 335.

Snavely, P. D., Jr.; Kvenvolden, K. A., 1988, Preliminary evaluation of the petroleum potential of the Tertiary accretionary terrane, west side of the Olympic Peninsula, Washington—Part 1. Geology and hydrocarbon potential: U.S. Geological Survey Open-File Report 88-75, p. 1-26, 1 plate.

Snavely, P. D., Jr.; MacLeod, N. S.; Niem, A. R.; Minasian, D. L., 1986, Geologic map of the Cape Flattery area, northwestern Olympic Peninsula, Washington: U.S. Geological Survey Open-File Report 86-344B, 10 p., 1 plate, scale 1:48,000.

Snavely, P. D., Jr.; Pearl, J. E.; Lander, D. L., 1977, Interim report on petroleum resources potential and geologic hazards in the outer continental shelf—Oregon and Washington Tertiary province; with a section on Resource appraisal estimate, by E. W. Scott: U.S. Geological Survey Open-File Report 77-282, 64 p.

Snavely, P. D., Jr.; Wagner, H. C., 1982a, Geologic cross section across the continental margin of southwestern Washington: U.S. Geological Survey Open-File Report 82-459, 10 p., 1 sheet.

Snavely, P. D., Jr.; Wagner, H. C., 1982b, Geophysical data collected on the southern Washington continental shelf along line 12, USGS R/V *S.P. Lee* cruise 3-76: U.S. Geological Survey Open-File Report 82-424, 1 sheet.

Snavely, P. D., Jr.; Wells, R. E., 1984, Tertiary volcanic and intrusive rocks on the Oregon and Washington continental shelf: U.S. Geological Survey Open-File Report 84-282, 17 p., 3 plates.

Stewart, R. J., 1970, Petrology metamorphism and structural relations of graywackes in the western Olympic Peninsula, Washington: Stanford University Doctor of Philosophy thesis, 123 p., 5 plates.

The Sunshine Mining Company, 1962, Tanner-Sunshine Medina No. 1 well completion report: [report on file with Washington Division of Geology and Earth Resources], 52 p.

Swanson, R. G., 1981, Sample examination manual: American Association of Petroleum Geologists, 35 p., 4 appendices.

Tabor, R. W., 1972, Age of the Olympic metamorphism, Washington—K-Ar dating of low-grade metamorphic rocks: Geological Society of America Bulletin, v. 83, no. 6, p. 1805-1816.

Tabor, R. W.,1975, Guide to the geology of Olympic National Park: University of Washington Press, 144 p., 1 plate.

Tabor, R. W.; Cady, W. M., 1978a, Geologic map of the Olympic Peninsula, Washington: U.S. Geological Survey Miscellaneous Investigations Series Map I-994, 2 sheets, scale 1:125,000.

Tabor, R. W.; Cady, W. M., 1978b, The structure of the Olympic Mountains, Washington—Analysis of a subduction zone: U.S. Geological Survey Professional Paper 1033, 38 p.

Tissot, B. P.; Welte, D. H., 1984, Petroleum formation and occurrence; 2nd rev. ed.: Springer-Verlag, 699 p.

Union Oil Co. of California, 1967, Union Tidelands State No. 2, well completion report: [report on file with the Washington Division of Geology and Earth Resources], 20 p.

Van Hinte, J. E., 1978, Geohistory analysis--Application of micropaleontology in exploration geology: American Association of Petroleum Geologists Bulletin, v. 62, no. 2, p. 201-222.

Von Huene, Roland; Kulm, L. D., 1973, *In* Kulm, L. D., Von Huene, R, and others, 1973, Initial Reports of the Deep Sea Drilling Project, v. 18: U.S. Government Printing Office, p. 961-976.

Wagner, H. C., 1967, Preliminary geologic map of the Raymond quadrangle, Pacific County, Washington: U.S. Geological Survey Open-File Report 67-265, 1 sheet, scale 1:62,500.

Wagner, H. C., Batatian, L. D.; Lambert, T. M.; Tomson, J. H., 1986, Preliminary geologic framework studies showing bathymetry, locations of geophysical tracklines and exploratory wells, sea floor geology and deeper geologic structures, magnetic contours, and inferred thickness of Tertiary rocks on the Continental shelf and upper Continental slope off southwestern Washington between latitudes 46oN. and 48o30'N. and from the Washington coast to 125o20'W.: Washington Division of Geology and Earth Resources Open File Report 86-1, 10 p., 6 plates.

Wagner, H. C.; Tomson, J. H., 1987, Offshore geology of the Strait of Juan de Fuca, State of Washington and British Columbia, Canada: Washington Division of Geology and Earth Resources Open File Report 87-1, 16 p., 7 plates.

Walsh, T. J.; Korosec, M. A.; Phillips, W. M.; Logan, R. L.; Schasse, H. W., 1987, Geologic map of Washington—Southwest quadrant: Washington Division of Geology and Earth Resources Geologic Map GM-34, 2 sheets, scale 1:250,000, with 28 p. text.

Waples, Douglas, 1981, Organic geochemistry for exploration geologists: Minneapolis, Burgess Publishing Company, 151 p.

Webster, F. L., 1985, Pacific OCS lease sale, October 1, 1964, Oregon and Washington: U.S. Minerals Management Service Pacific OCS Region Report 85-0101, 36 p.

Wells, R. E., 1981, Geologic map of the eastern Willapa Hills, Cowlitz, Lewis, Pacific, and Wahkiakum Counties, Washington: U.S. Geological Survey Open-File Report 81-674, 1 sheet, scale 1:62,500.

Weaver, C. E., 1912, A preliminary report on the Tertiary paleontology of western Washington: Washington Geological Survey Bulletin 15, 80 p.

Yorath, C. J.; Green, A. G.; Clowes, R. M.; Sutherland Brown, A.; Brandon, M. T.; Kanasewich, E. R.; Hyndman, R. D.; Spencer, C., 1985, Lithoprobe, southern Vancouver Island—Seismic reflection sees through Wrangellia to the Juan de Fuca plate: Geology, v. 13, no. 11, p. 759-762.

Zieglar, D. L.; Cassell, J. K., 1978, A synthesis of OCS well information, offshore central and northern California, Oregon, and Washington. *In* Hill, F.L.; Wilkinson, E.R.; Schneider, R. H., coordinators, 1978, Energy exploration and polities; pre-prints: California Division of Oil and Gas, 27 p.

Appendices

APPENDIX A — WELL INFORMATION

(All depths in ft, RKB)

Location No. on Plate	Well Name, API No., State Permit No.	Spud Date, Total Depth	Shows
1	Bloedel-Ruddock No. 1 009-00045 188	12/16/63 4,403'	No shows.
2	Bloedel-Ruddock 009-00010 CM-10	6/25/37 6,210'	Gas shows at 2,268', 4,204', 3,210-6210'; tested gas TSTM @ 3000'; gas used for rig boilers. Gas analysis on file @ DGER.
3	Rosalie No. 1 009-00009 CM-9	1932 - 2,188' 1937 redrill- 2,035'	Tr gas, oil shows "colors".
4	Forks No. 2 009-00004 CM-4	1924 2,035'	Gas and oil shows; "shale grease" common.
5	Washington (Old) 009-00001 CM-1	1912 2,035'	Oil in bailers and stained sandstone. Gas kick with gas and mud over derrick.
6	Forks No. 1 009-00002 CM-2	5/3/19 2,250'	Numerous gas & oil shows; gas pressure greater than mud gradient.
7	Olympic No. 1 009-00008 CM-8	1932 2,940' (2,898'?)	Tr gas.
8	Soleduck No. 1 009-00048 287	5/21/73 1,550'	Tr gas; "bubbling mud" at 774'; 18" high flame from 8-5/8" casing; oil-stained sandstones from 904-960'.
9	Town of Forks No. 1 009-00039	7/15/55 1,120'	Briefly tested 10 MCFGPD after zone was perfed and dynamited. Died in 85 minutes.
10	Sniffer-Forks No. 1 009-00049 290	8/29/73 3,095'	No shows.
11	Rayonier No. 1 009-00036 CM-15	10/14/48 2,350'	Below 1,147', cores flashed (burned); gas shows below 1,370'.
12	Milwaukee Land 1-1 031-00024 209	1/14/66 6,880'	No data available.
13	Pyramid-Shearing No. 1 031-00027 333	9/3/79 4,925'	No data available.

Location No. on Plate	Well Name API No., State Permit No.	Spud Date, Total Depth	Shows
14	Hoh Head 1 031-00002 J-2	1902 901'	Gas reported at various depths; oil reported on driller's log from 691-901'.
15	Hoh Head No. 2 031-00003 J-3	1914 986' 1919 redrill 1,120'	Good gas shows at 960' and 1,110'. Oil at 960' and at 1,120' (?).
16	Sims No. 1, Gilkey No. 1 031-00004 J-4	7/28/31 2,069', 2,155'	Good oil shows 770'-790' and at 865'; also 2,069' to TD gas reported.
17	Gilkey No. 2 031-00005 72X	1933 866'	Good oil shows at 768' and 865'.
18	Kipling No. 1, Gilkey No. 3 031-00012 J-11	4/5/36 316' 1937 808'	Good oil shows between 287-314'. Produced several bbl oil per week. Oil analysis on file @ DGER.
19	Kipling No. 2 031-00013 75X	1936 656'	No shows.
20	Consolidated No. 2, Gilkey No. 5 031-00015 77X	1937 1,070'	Good oil shows in cuttings.
21	Churchill No. 1, 031-00016 78X	9/29/37 1,600' +/-	Tr gas.
22	Lacy No. 1 031-00011 74X	1934 803'	Oil reported from sanstone near surface
23	Sunburst No. 1 031-00028 336	6/24/81 7,500'	DST produced gas; gas analysis on file @ DGER
24	Barlow No. 1 031-00023 189, 189A	1/12/64 5,015'	Oil droplets in mud at 2,240'. Gas bubbles in mud tank at 4,005'.
25	Woodis No. 1 031-00022 180	6/25/63 460'	No shows.
26	Lacy 22-1 031-00026 299	12/18/74 5,722'	Gas bubbles in core 4,979-5,000' and 5,341-5,358'. DST recovered tr gas 4,952-5,000'. Gas analysis on file @ DGER.

Location No. on Plate	Well Name, API No., State Permit No.	Spud Date, Total Depth	Shows
27	Milwaukee Land Co. No. 1 031-0020 J-20	6/28/48 5,600'	Tests thru perfs @ 4,700-4,800' and 1,950-2,150' no rec.
28	C.C. Cook - Quinault No. 2 031-00019 J-19	7/23/47 3,010'	No shows.
29	C.C. Cook - Quinalt No. 1 031-00018	5/2/47 1,412'	Gas bubbles and oil "colors" on cores 829-835', 1,126-1,132', 1,400-1,412'
30	Quinault No. 1 027-00003 GH-3	1913 560'	Results unknown; drilled 100' S of Garfield gas mound.
31	Quinault No. 2 027-00004 GH-4	10/1914 820'	"Strong" gas reported.
32	Northwestern No. 1 027-00005 GH-28	7/12/19 639'	No shows.
33	Northwestern No. 2 027-00006 GH-5	1/19/20 3,805'	Tr oil; small amount of gas 2,687-3,805'.
34	Washington State No. 1 027-00007 GH-6	12/5/20 4,130'	Tr oil and gas 1,537-1,690' & 3,375-3,460'.
35	Polson No. 1 027-00036 GH-36	10/4/47 2,108'	"Faint odor" on core 940-965' and 1,009-1,034'.
36	Carlisle Estate No.1 027-00091 141	8/16/59 3,596'	DST shows 3,400-3,500'; also noted in Sunshine-Medina annual report. Production test on 12/22/59 made 23 bbl oil in 8 hours.
37	Carlisle No. 1-23 027-00124 292	3/21/74 4,100'	Swabbed oil cut, gassy mud; 1 gallon yellow oil at 3,797'.
38	Brett Cardinal 027-00106 208	10/28/65 3,972'	DST and core analysis rec tr gas and oil. No other well data.

Location No. on Plate	Well Name, API No., State Permit No.	Spud Date, Total Depth	Shows
39	Rayonier No. 1 027-00106 145 and Rayonier No. 1-A 027-00094 145A	6/16/60 1,220' 7/14/60 6,500'	Used Medina No. 1 oil to displace water on 8/8/60. Recovered 5.2 barrels of "new" oil 24/64" choke on 10/8/60. Good gas show at 3,800'. Excellent oil and gas show in mud at 5,710'. Good oil show in pit at 6,000'. Production tests rec strong gas blow after shutin 12/6/60. 12/8-9/60, may have recovered 25 bbl of new? oil. Test 12/4/60 50 MCFGPD +/- 10/31/60 rec 34 bbl "formation" oil. 11/1/60 standing well "full of oil".
40	Everett Trust No. B-1 027-00101 161	8/5/61 4,180'	Shows in core similar to #41 below.
41	Ollar State No. 1	6/14/61 5,000'	5% oil saturation from core analysis; petrol odor and light blue flourescence 2,170-2,190'. Core shows, pale yellow/brown stain, pale yellow fluor and pale yellow/white/lt brown cut 3,207-3,225' and 3,226-3,239'. Cores at 3,239-3,249' and 3,722-3,742' as above with gas bubbles. DSTs 3,088-4,165', no rec.
42	Abel No. 1 027-00034 GH-34	7/17/47 1,818'	No shows.
43	M.A. Baker No. 1-30 027-00123 291	10/11/73 4,200'	Core 3,381-3,403'; gold fluor, retorted 29° API oil/wet gas; Core 2,142-2,166 dull yellow fluor; blue-white cut.
44	McCleave No. 1-33 027-00115 258	6/3/70 1,344'	Pale yellow/green cut fluor on SWS at 1,150'; Core 1,323-1,344' pale straw cut after 12 hours.
45	Lamb No. 1 027-00037 GH-37	10/31/47 2,379'	Gas odor in cores below 296' in Hoh rock assemblage.
46	Parker No. 1 027-00032 GH-32	7/16/47 1,931'	Tr gas in 8 cores below 1,230'.
47	Grays Harbor County No. 1-15 027-00111 252	6/11/70 2,032'	Volcanics in core - 1,885-1,895' (olivine basalt). Tr cut & fluor in core at 2,010-2,032' (Hoh breccia); yellow-green fluor in SWS at 1,815-1,993'.
48	Grays Harbor County No. 1 027-00055	7/15/54 3,453'	Used diesel mud; odor in core @ 1,511-1,526'.

Location No. on Plate	Well Name, API No., State Permit No.	Spud Date, Total Depth	Shows
49	Trambitas No. 1-28 027-00118 263	5/22/70 3,120'	Green fluor; straw/amber cut; straw/amber, cut & green fluor & odor in SWS at 2,796' and core from 3,091-3,111'.
50	Grays Harbor Co. No. 36-1 027-00128 298	11/27/74 2,647'	No shows.
51	Grays Harbor Co. No. 1-35 027-00121 266	7/23/70 2,528'	Gasoline odor from SWS below 2,371'. DST 1,970-2,050', flowed 1.33 MMCFGPD at final flowing pressure of 338 psi on 28/64" choke. Gas analysis on file @ DGER.
52	Grays Harbor Co. No. 35-1 027-00125 294	4/19/74 2,495'	Gas kick @ 2,495' after swabbing 4-6' flare (5/1/74). After perf (5/5/74) from 2,098-2,112'; gas bubbles in mud. Perfs @ less than 2,000' (11/1/74) tested 11.6 MCFGPD on 13/64" choke at 80 psi FTP.
53	Clapp No. 1 027-00035 GH-35	9/3/47 3,997'	Gas bubbles on cores 1,511-1,521'. 1,760-1,770' and 2,696-2,719'. Kerosene odor on cores 2,025-2,041' and 2,969-2,719'. Cores flashed 3,321-3,339', 3,746-3,757' and 3,992-3,730'. "Colors on ditch" above 1,000'. Good colors from 2,460-2,470'. Excellent oil and gas shows 3,650-3,730' and 3,992-3,997'.
54	State No. 2 027-00041 GH-41	11/18/48 3,805'	Gas flowed @ 250 psi while attempting to P&A; Swabs 12/17/48 rec water with oil scum and gas; "Colors" on ditch 3,595-3,600'. Cores flashed 3,600-3,629', 3,674-3,805'.
55	Medina No. 2 027-00088 131	9/27/57 5,125'	DST 3,010-3,041'; rec 5-7 bbl oil/hr, 47° API; Core @ 3,328-3,344' had odor, yellow fluor, no cut. DST @ 4162-4187' recovered 220' of 37° API oil. [Oil and gas analysis on file @ DGER]
56	Medina No. 1 027-00087 126, 126A	6/19/57 4,140'	Well initially flowed 178 bbl oil in 23 hr. Stabilized at less than 10 BOPD. Produced oil for 4 years. Oil and gas analysis on file @ DGER.
57	Barnhisel No. 1 027-00033 GH-33	8/7/47 2,657'	Good gas shows in core below 1,850'; "colors" in cores below 300'; Some cores flashed, others bubble.
58	State No. 4 027-00043 GH-43 and	6/15/51 3,711'	Gas and oil analysis on file @ DGER. Tested gas from two zones. Tested 85 BOPD.
	Sampson Johns Unit 027-00090	1/6/59 4,522'	Well renamed and completed. Produced and sold 6.5 MMCFG. Oil and gas analyses on file @ DGER.

Location No. on Plate	Well Name, API No., State Permit No.	Spud Date, Total Depth	Shows
59	State No. 1 027-00038 GH-38	11/24/47 6,278'	Ditch "colors" below 1,500'. Some odor in core and on rig floor; gas bubbles and colors in ditch. Sheared core with gas bubbles from 2,355-2,361'. Core flashed. Cut color in core below 3,698' as in State 3. Swabbed 40 BO on 3/23/48 but rapid drop in pressure. 3/24/48 swabbed 10 bbl; 3/26/48 swabbed 20 bbl oil.
60	State No. 3 027-00042 GH-42	2/16/49 9,344'	Cores from 3,782-4,531', oil saturated, gas bubbles, flashed. Other cores had varied oil & gas shows; Core at 7,880-7,890' in "very permeable" sandstone. Initial swab rec 5 BO plugged at 5,070' after rec 10 BO w/gas on each run; total rec: 35 BO; other tests produced a total of 100 BO. Oil analysis on file @ DGER.
61	Sampson Johns No. 2-15 027-00117 260	4/23/70 2,390'	Pale straw cut and yellow green fluor in SWS from 1,250-1,441' and 2,012-2,022'.
62	Oscar No. 1-A 027-00096 149	10/13/60 4,137'	5-15% residual oil in core analysis at 1,955-1,979', but diesel used in mud.
63	Sampson Johns No. 1-15 027-00113 255	3/19/70 2,795'	No shows.
64	Oscar No. 1 027-00095 146	8/14/60 5,280'	8/24/60 stopped mud pumps, hole unloaded gas, mud, and brackish water. DST at 3,687-3,780' failed, DST at 4,333-4,340'; flowed gas @ 2400 psi FSIP.
65	Beach No. 1 027-00098 154	3/18/61 3,115'	DST rec gas (2" flare); Tr fluor & gas bubbles in core.
66	Swanson No. 22-1 027-00086 124,124A	4/12/57 4,381'	DST (?) rec 10 BO.
67	Hogan No. 22-1 027-00044 GH-44 and	1/14/53 4,918'	No information.
	Hogan No. 1 027-00099 156	2/1/61 4,918'	Rework of Hogan 22-1. Some residual oil in core analysis. Absolute open flow of 238 MCFGPD.
68	Grays Harbor No. 1-11 027-00110 251	4/8/70 3,240'	Blue/white and light yellow cut fluor on SWS below 3,058'; pale straw.

Location No. on Plate	Well Name, API No., State Permit No.	Spud Date, Total Depth	Shows
69	Hogan No. 1-13 027-00106 248	3/5/70 2,922'	No shows, some cut mineral fluor.
70	France No. 1 027-00097 150	12/10/60 3,240'	No shows.
71	Hogan No. 1-8 027-00107 247	2/10/70 1,395'	No shows.
72	Ocean City Land Co. et al No. 1-14 027-00120 265	6/19/70 4,268'	Distillate odor, some bright green fluor; "sharp distillate odor"; milky green cut fluor, pale straw cut on SWS below 3,509'.
73	Luse No. 1-23 027-00122 267	8/6/70 3,602'	No shows in SWS. Minor mud gas shows.
74	Minard No. 1-34 027-00016 259	5/6/70 4,600'	Yellow/green cut fluor from 3,471-3,483' core. Pale yellow/green cut fluor from 3,420-4,555' from SWS.
75	Minard No. 1 027-00089 132	1/21/58 5,038'	No shows.
76	Smith No. 1 049-00003 PF-3	4/19/48 4,927'	Core 1,044-2,053' showed colors and "evidence" of gas. Shows gas on core at 1,828-1,852'; 1,951-1,966', 2,977-3,134'. Tr gas at pits; Cores flashed for 3 to 5 minutes 3,305-3,319', 3,536-3,545', 3,856-3,683', 4,105-4,108' and 4,323-4,332'.
77	Oysterville State No. 1 049-00043 63	2/21/55 4,035'	Blue white cut and yellow fluor from SWS 2,810-2,830', 2,799-2,805'. Similar results from core at 3,877'.
78	Weyerhauser No. 7-11 049-00043 139	6/2/59 5,988'	No shows (?)
79	Long Beach No. 2 049-00007 8	4/14/54 670'	No shows.
80	Long Beach No. 1 049-00004 PF-4	6/30/53 2,103'	No shows.
81	McGowan No. 1 049-00002 PF-2	2/19/29 4,385'	No shows.

Location No. on Plate	Well Name, API No., State Permit No.	Spud Date, Total Depth	Shows
82	P-072-1 56-097-20001 (Oregon)	10/28/65 8,219'	Gas cut mud from 5,121' to TD. Cut colors and fluor on core and SWS below 2,042'.
83	P-075-1 56-099-20002 (Oregon)	6/10/66 10,160'	No shows.
84	P-0150-1 56-099-20001 and P-0150-1A 56-099-20001001	3/24/66 8,699' 4/17/66 13,179'	Cut fluor on SWS below 6,960'. Two DST's produced 10 and 26 MCFGPD, at 9,408-9,423' and 9,381-9,403', respectively.
85	P-0155-1 56-099-20002	7/11/67 11,162'	Cut and fluor on core and SWS below 6,547'.
86	Tidelands State No. 2 027-00104 169	7/17/64 5,073'	No shows.
87	P-0141-1 56-098-20001	5/23/67 10,368'	No shows.
88	Cygnet J-100 No API number. (Canada)	1/26/69 8,070'	No shows.
89	Prometheus H-68 No API number. (Canada)	6/11/67 7,662'	No shows.

APPENDIX B — POROSITY AND PERMEABILITY DATA

WELL NAME	FORMATION	DEPTH (FT. RKB)	POROSITY (%)	AIR PERM (md)
Rayonier 1	Hoh	1151	7.6	0.1
Rayonier 1	Hoh	1456	22.3	281.0
Rayonier 1	Hoh	1463	6.7	0.1
Rayonier 1	Hoh	1688	7.5	0.1
Rayonier 1	Hoh	1864	11.5	0.1
Rayonier 1	Hoh	2004	13.4	0.1
Lacy 22-1	Hoh	4980	8.3	0.1
Lacy 22-1	Hoh	4981	14.4	0.3
Lacy 22-1	Hoh	4984	18.2	0.1
Lacy 22-1	Hoh	4985	17.2	0.5
Lacy 22-1	Hoh	4987	12.8	0.1
Lacy 22-1	Hoh	4988	11.1	0.3
Lacy 22-1	Hoh	4992	20.6	0.4
Lacy 22-1	Hoh	4993	18.6	0.1
Lacy 22-1	Hoh	4996	7.4	0.1
Lacy 22-1	Hoh	4997	12.7	0.1
Lacy 22-1	Hoh	4998	9.9	0.1
Lacy 22-1	Hoh	4999	14.3	0.1
Lacy 22-1	Hoh	5344	14.3	0.5
Lacy 22-1	Hoh	5347	15.9	0.1
Lacy 22-1	Hoh	5350	15.1	0.1
Lacy 22-1	Hoh	5353	15.7	0.4
Lacy 22-1	Hoh	5353	16.8	1.6
Lacy 22-1	Hoh	5354	15.3	0.3
Lacy 22-1	Hoh	5356	18.2	0.3
Lacy 22-1	Hoh	5358	17.5	0.2
Lacy 22-1	Hoh	5358	13.7	0.3
Barnhisel 1	Montesano	1948	22.4	5.0
Barnhisel 1	Montesano	1952	22.5	5.7
Barnhisel 1	Montesano	1955	23.6	39.0
Barnhisel 1	Montesano	1958	24.4	0.1
Barnhisel 1	Montesano	1961	22.5	0.1
Barnhisel 1	Montesano	1964	25.5	12.0
Barnhisel 1	Montesano	1967	21.0	9.2
Barnhisel 1	Montesano	1968	25.8	2.5
Barnhisel 1	Montesano	1972	25.9	1.9
Barnhisel 1	Montesano	1977	26.3	12.0
Barnhisel 1	Montesano	1980	31.3	6.1
Barnhisel 1	Montesano	2002	31.1	9.6
Barnhisel 1	Montesano	2016	21.8	38.0
Barnhisel 1	Montesano	1993	24.8	2.4

WELL NAME	FORMATION	DEPTH (FT. RKB)	POROSITY (%)	AIR PERM (md)
Barnhisel 1	Montesano	2061	24.9	25.0
Barnhisel 1	Montesano	2075	25.7	8.7
Barnhisel 1	Montesano	2140	23.9	4.5
State 1	Montesano	1610	29.0	13
State 1	Montesano	1620	24.6	7.0
State 1	Montesano	1630	23.1	53.0
State 1	Hoh/Ozette	3904	11.7	1.8
State 1	Hoh/Ozette	6269	25.0	112.0
State 3	Hoh/Ozette	4324	9.4	1.0
State 3	Hoh/Ozette	4326	8.0	1.0
State 3	Hoh/Ozette	4329	13.3	9.0
State 3	Hoh/Ozette	4336	13.1	1.0
State 3	Hoh/Ozette	4339	17.0	748.0
State 3	Hoh/Ozette	4345	12.7	346.0
State 3	Hoh/Ozette	4350	11.1	3.0
State 3	Hoh/Ozette	4355	17.5	2335.0
State 3	Hoh/Ozette	4359	19.3	2435.0
State 3	Hoh/Ozette	4362	11.1	523.0
State 3	Hoh/Ozette	4365	9.3	21.0
State 3	Hoh/Ozette	6052	7.1	4.5
State 3	Hoh/Ozette	6059	9.4	5.6
State 3	Hoh/Ozette	6064	9.4	0.1
State 3	Hoh/Ozette	6075	13.0	0.1
State 3	Hoh/Ozette	6083	16.6	1.9
State 3	Hoh/Ozette	6084	15.5	3.5
State 3	Hoh/Ozette	6087	14.7	0.5
State 3	Hoh/Ozette	6091	16.7	1.2
State 3	Hoh/Ozette	6094	13.2	0.7
State 3	Hoh/Ozette	6098	15.8	1.0
State 3	Hoh/Ozette	6099	15.6	0.1
State 3	Hoh/Ozette	6101	15.5	0.1
State 3	Hoh/Ozette	6108	15.0	0.1
State 3	Hoh/Ozette	6114	15.7	17.0
State 3	Hoh/Ozette	6117	12.3	13.0
State 3	Hoh/Ozette	6121	16.5	3.0
State 3	Hoh/Ozette	6122	16.0	1.6
State 3	Hoh/Ozette	6128	15.7	8.4
State 3	Hoh/Ozette	6134	10.9	3.1
State 3	Hoh/Ozette	6143	15.0	0.1
State 3	Hoh/Ozette	6153	10.7	2.0
State 3	Hoh/Ozette	6183	11.0	0.1

APPENDIX B — POROSITY AND PERMEABILITY DATA (CONT'D)

WELL NAME	FORMATION	DEPTH (FT. RKB)	POROSITY (%)	AIR PERM (md)
State 3	Hoh/Ozette	6186	9.4	0.1
State 3	Hoh/Ozette	6189	9.2	0.1
State 3	Hoh/Ozette	6192	13.6	10.4
State 3	Hoh/Ozette	6195	12.0	2.5
State 3	Hoh/Ozette	6198	11.6	0.1
State 3	Hoh/Ozette	6258	9.7	0.8
State 3	Hoh/Ozette	6261	7.6	0.1
State 3	Hoh/Ozette	6262	8.4	0.1
State 3	Hoh/Ozette	6264	8.5	0.1
State 3	Hoh/Ozette	6267	6.7	0.1
State 3	Hoh/Ozette	6276	7.4	1.2
State 3	Hoh/Ozette	6313	12.6	1.2
State 3	Hoh/Ozette	6319	13.8	1.4
State 3	Hoh/Ozette	6331	14.9	0.4
State 3	Hoh/Ozette	6358	11.3	0.1
State 3	Hoh/Ozette	6440	8.9	0.1
State 3	Hoh/Ozette	6445	10.9	1.2
State 3	Hoh/Ozette	6447	11.3	0.1
State 3	Hoh/Ozette	6456	11.2	0.4
State 3	Hoh/Ozette	6526	15.5	0.1
State 3	Hoh/Ozette	7723	13.1	0.6
State 3	Hoh/Ozette	7725	13.6	0.1
State 3	Hoh/Ozette	7727	13.0	0.1
State 3	Hoh/Ozette	7730	10.0	0.1
State 3	Hoh/Ozette	7739	9.2	2.5
State 3	Hoh/Ozette	7801	7.2	0.1
State 3	Hoh/Ozette	7803	9.4	0.1
State 3	Hoh/Ozette	7808	8.6	0.1
State 3	Hoh/Ozette	7812	8.8	0.1
State 3	Hoh/Ozette	7817	7.8	0.1
State 3	Hoh/Ozette	7822	8.5	0.1
State 3	Hoh/Ozette	7827	8.2	1.4
State 3	Hoh/Ozette	7830	9.5	0.6
State 3	Hoh/Ozette	7832	8.2	0.1
State 3	Hoh/Ozette	7834	8.2	0.1
State 3	Hoh/Ozette	7839	8.8	1.1
State 3	Hoh/Ozette	7841	13.9	4.2
State 3	Hoh/Ozette	7846	9.5	0.1
State 3	Hoh/Ozette	7850	9.3	0.1
State 3	Hoh/Ozette	7861	9.6	0.1
State 3	Hoh/Ozette	7870	11.2	0.1

WELL NAME	FORMATION	DEPTH (FT. RKB)	POROSITY (%)	AIR PERM (md)
State 3	Hoh/Ozette	7873	11.7	0.1
State 3	Hoh/Ozette	7876	11.3	0.1
State 3	Hoh/Ozette	7878	20.7	1.3
State 3	Hoh/Ozette	7882	11.1	0.1
State 3	Hoh/Ozette	7884	12.2	7.1
State 3	Hoh/Ozette	7888	11.3	5.9
State 3	Hoh/Ozette	7906	13.4	0.1
State 3	Hoh/Ozette	7911	14.2	2.5
State 3	Hoh/Ozette	7913	11.4	20.0
State 3	Hoh/Ozette	7923	18.5	0.1
State 3	Hoh/Ozette	7928	15.2	0.1
State 3	Hoh/Ozette	7936	14.6	0.1
State 3	Hoh/Ozette	7939	13.7	0.1
State 3	Hoh/Ozette	7950	13.1	0.1
State 3	Hoh/Ozette	7953	30.6	5.8
State 3	Hoh/Ozette	7955	11.1	0.1
State 3	Hoh/Ozette	8281	14.1	0.1
State 3	Hoh/Ozette	8282	13.9	0.1
Medina 2	Montesano	3329	30.1	1.5
Medina 2	Montesano	3335	45.8	27.0
Medina 2	Montesano	3341	41.5	19.0
Medina 2	Montesano	3343	32.8	2.3
Medina 2	Hoh/Ozette	4163	20.8	0.9
Medina 2	Hoh/Ozette	4164	9.6	0.3
Medina 2	Hoh/Ozette	4165	13.2	2.0
Medina 2	Hoh/Ozette	4166	16.8	11.0
Medina 2	Hoh/Ozette	4167	15.0	9.9
Medina 2	Hoh/Ozette	4168	21.6	68.0
Medina 2	Hoh/Ozette	4169	17.9	23.0
Medina 2	Hoh/Ozette	4170	18.4	22.0
Medina 2	Hoh/Ozette	4171	28.6	351.0
Medina 2	Hoh/Ozette	4172	17.4	46.0
Medina 2	Hoh/Ozette	4182	10.0	0.1
Oscar 1-A	Montesano	1955	30.5	1100.0
Oscar 1-A	Montesano	1956	29.9	755.0
Oscar 1-A	Montesano	1957	29.1	2220.0
Oscar 1-A	Montesano	1958	28.4	793.0
Oscar 1-A	Montesano	1959	29.8	1620.0
Oscar 1-A	Montesano	1960	29.0	1805.0
Oscar 1-A	Montesano	1961	28.2	1300.0
Oscar 1-A	Montesano	1962	26.4	1200.0

Appendix B — Porosity and Permeability Data (Cont'd)

WELL NAME	FORMATION	DEPTH (FT. RKB)	POROSITY (%)	AIR PERM (md)
Hogan 1	Hoh/Ozette	4245	8.5	1.3
Hogan 1	Hoh/Ozette	4245	17.9	1.6
Ollar State 1	Ozette	2190	17.8	0.9
Ollar State 1	Ozette	2192	14.8	5.3
Ollar State 1	Ozette	2193	13.3	0.3
Ollar State 1	Ozette	2194	16.2	0.7
Ollar State 1	Ozette	2198	15.0	0.4
Ollar State 1	Ozette	2199	16.4	1.4
Ollar State 1	Ozette	2201	16.4	6.0
Ollar State 1	Ozette	2203	1.0	4.1
Ollar State 1	Ozette	3241	14.4	4.6
Ollar State 1	Ozette	3244	15.5	3.7
Ollar State 1	Ozette	3245	21.0	24.7
Ollar State 1	Ozette	3722	26.0	115.9
Ollar State 1	uzette	3723	27.7	219.7
Brett Cardinal	Ozette	3431	26.1	3.9
Brett Cardinal	Ozette	3437	26.6	25.0
Brett Cardinal	Ozette	3439	27.4	33.0
Brett Cardinal	Ozette	3443	26.8	20.0
Brett Cardinal	Ozette	3459	28.3	55.0
Brett Cardinal	Ozette	3463	14.1	0.1
Brett Cardinal	Ozette	3476	25.7	24.0
Brett Cardinal	Ozette	3485	30.6	100.0
Brett Cardinal	Ozette	3498	26.0	23.0
Brett Cardinal	Ozette	3671	23.3	42.0
Brett Cardinal	Ozette	3673	24.8	33.0
Brett Cardinal	Ozette	3674	23.1	16.0
Brett Cardinal	Ozette	3677	19.6	6.4
Brett Cardinal	Ozette	3680	19.5	0.6
Brett Cardinal	Ozette	3683	28.7	195.0
Brett Cardinal	Ozette	3686	15.4	0.1
Brett Cardinal	Ozette	3691	28.2	23.0
Brett Cardinal	Ozette	3698	26.5	5.1
Brett Cardinal	Ozette	3705	30.3	115.0
Brett Cardinal	Ozette	3709	25.0	48.0
M.A. Baker 1-30	Ozette	2143	16.3	17.0
M.A. Baker 1-30	Ozette	2145	15.3	0.1
M.A. Baker 1-30	Ozette	2146	15.6	3.4
M.A. Baker 1-30	Ozette	2147	16.2	1.7
M.A. Baker 1-30	Ozette	2148	14.3	2.4
M.A. Baker 1-30	Ozette	2149	17.3	200.0
M.A. Baker 1-30	Ozette	2152	32.5	103.0

WELL NAME	FORMATION	DEPTH (FT. RKB)	POROSITY (%)	AIR PERM (md)
Hogan 1	Hoh/Ozette	4245	8.5	1.3
Hogan 1	Hoh/Ozette	4245	17.9	1.6
Ollar State 1	Ozette	2190	17.8	0.9
Ollar State 1	Ozette	2192	14.8	5.3
Ollar State 1	Ozette	2193	13.3	0.3
Ollar State 1	Ozette	2194	16.2	0.7
Ollar State 1	Ozette	2198	15.0	0.4
Ollar State 1	Ozette	2199	16.4	1.4
Ollar State 1	Ozette	2201	16.4	6.0
Ollar State 1	Ozette	2203	1.0	4.1
Ollar State 1	Ozette	3241	14.4	4.6
Ollar State 1	Ozette	3244	15.5	3.7
Ollar State 1	Ozette	3245	21.0	24.7
Ollar State 1	Ozette	3722	26.0	115.9
Ollar State 1	Ozette	3723	27.7	219.7
Brett Cardinal	Ozette	3431	26.1	3.9
Brett Cardinal	Ozette	3437	26.6	25.0
Brett Cardinal	Ozette	3439	27.4	33.0
Brett Cardinal	Ozette	3443	26.8	20.0
Brett Cardinal	Ozette	3459	28.3	55.0
Brett Cardinal	Ozette	3463	14.1	0.1
Brett Cardinal	Ozette	3476	25.7	24.0
Brett Cardinal	Ozette	3485	30.6	100.0
Brett Cardinal	Ozette	3498	26.0	23.0
Brett Cardinal	Ozette	3671	23.3	42.0
Brett Cardinal	Ozette	3673	24.8	33.0
Brett Cardinal	Ozette	3674	23.1	16.0
Brett Cardinal	Ozette	3677	19.6	6.4
Brett Cardinal	Ozette	3680	19.5	0.6
Brett Cardinal	Ozette	3683	28.7	195.0
Brett Cardinal	Ozette	3686	15.4	0.1
Brett Cardinal	Ozette	3691	28.2	23.0
Brett Cardinal	Ozette	3698	26.5	5.1
Brett Cardinal	Ozette	3705	30.3	115.0
Brett Cardinal	Ozette	3709	25.0	48.0
M.A. Baker 1-30	Ozette	2143	16.3	17.0
M.A. Baker 1-30	Ozette	2145	15.3	0.1
M.A. Baker 1-30	Ozette	2146	15.6	3.4
M.A. Baker 1-30	Ozette	2147	16.2	1.7
M.A. Baker 1-30	Ozette	2148	14.3	2.4
M.A. Baker 1-30	Ozette	2149	17.3	200.0
M.A. Baker 1-30	Ozette	2152	32.5	103.0

APPENDIX B — POROSITY AND PERMEABILITY DATA (CONT'D)

WELL NAME	FORMATION	DEPTH (FT. RKB)	POROSITY (%)	AIR PERM (md)
Horn, 1969	Quinault	0	26.6	19.2
Horn, 1969	Quinault	0	32.3	1569.0
Horn, 1969	Quinault	0	24.3	64.3
Horn, 1969	Quinault	0	35.1	1447.0
Horn, 1969	Quinault	0	35.6	1885.0
Horn, 1969	Quinault	0	32.0	621.0
Horn, 1969	Quinault	0	33.3	744.0
Horn, 1969	Quinault	0	36.4	2298.0
Horn, 1969	Quinault	0	35.3	1733.0
Snavely et al.	Hoh	0	14.4	0.1
Snavely et al.	Hoh	0	10.2	0.2
Snavely et al.	Hoh	0	18.2	234.0
Snavely et al.	Hoh	0	14.7	0.1
Snavely et al.	Hoh	0	24.3	14.0
Snavely et al.	Ozette	0	8.5	1.1
Snavely et al.	Ozette	0	9.4	0.7
Snavely et al.	Ozette	0	7.4	0.3
Snavely et al.	Ozette	0	9.7	1.4
Snavely et al.	Ozette	0	8.7	0.9
Snavely et al.	Ozette	0	6.6	2.3
Snavely et al.	Ozette	0	9.2	0.4
Snavely et al.	Ozette	0	5.1	0.2
Snavely et al.	Ozette	0	16.9	14.0
Snavely et al.	Ozette	0	15.1	0.3
Snavely et al.	Ozette	0	19.4	47.0
Snavely et al.	Ozette	0	16.6	1.8
Snavely et al.	Ozette	0	9.3	4.1
Snavely et al.	Ozette	0	4.8	0.2
Snavely et al.	Ozette	0	16.1	3.3
Snavely et al.	Ozette	0	18.5	3.3
Snavely et al.	Ozette	0	16.4	2.5
Snavely et al.	Ozette	0	20.9	4.4
Snavely et al.	Ozette	0	10.4	0.4

WELL NAME	FORMATION	DEPTH (FT. RKB)	POROSITY (%)	AIR PERM (md)
M.A. Baker 1-30	Ozette	2153	13.2	0.1
M.A. Baker 1-30	Ozette	2155	20.7	480.0
M.A. Baker 1-30	Ozette	2156	13.1	8.8
M.A. Baker 1-30	Ozette	2157	17.3	30.0
M.A. Baker 1-30	Ozette	2158	14.7	0.2
M.A. Baker 1-30	Ozette	2159	13.7	1.0
M.A. Baker 1-30	Ozette	2160	12.5	0.1
M.A. Baker 1-30	Ozette	2161	16.3	0.2
M.A. Baker 1-30	Ozette	2162	24.7	59.0
M.A. Baker 1-30	Ozette	2163	24.0	60.0
M.A. Baker 1-30	Ozette	2164	18.3	1.0
M.A. Baker 1-30	Ozette	2165	27.7	70.0
M.A. Baker 1-30	Ozette	2962	14.9	3.5
M.A. Baker 1-30	Ozette	2964	10.9	17.0
M.A. Baker 1-30	Ozette	2970	14.1	17.0
M.A. Baker 1-30	Ozette	2974	15.5	0.7
M.A. Baker 1-30	Ozette	2975	18.9	1.5
M.A. Baker 1-30	Ozette	2976	13.5	1.0
M.A. Baker 1-30	Ozette	2977	12.7	0.6
M.A. Baker 1-30	Ozette	2978	14.6	1.0
M.A. Baker 1-30	Ozette	2979	15.3	0.6
M.A. Baker 1-30	Ozette	2980	14.0	0.4
M A. Baker 1-30	Ozette	2981	13.3	1.9
M.A. Baker 1-30	Ozette	2982	16.2	0.6
M.A. Baker 1-30	Ozette	2983	18.7	2.9
M.A. Baker 1-30	Ozette	2984	11.9	0.1
M.A. Baker 1-30	Ozette	3388	20.4	3.7
M.A. Baker 1-30	Ozette	3389	25.6	42.0
M.A. Baker 1-30	Ozette	3390	26.9	66.0
M.A. Baker 1-30	Ozette	3391	27.3	186.0
M.A. Baker 1-30	Ozette	3392.	22.9	14.0
M.A. Baker 1-30	Ozette	3393	26.4	30.0
M.A. Baker 1-30	Ozette	3397	25.3	56.0

APPENDIX C — GEOCHEMICAL ANALYSES OF OIL SAMPLES FROM THE LACY NO 1 AND STATE NO 1 WELLS

The text, figures, and tables given in this appendix summarize the results of geochemical analyses of oil samples from the Lacy No. 1 and State No. 1 wells (Nos. 22 and 59, respectively, Plate 1). These analyses were performed for the Washington State Department of Natural Resources, Division of Geology and Earth Resources by the Global Geochemistry Corporation, 6919 Eton Avenue, Canoga Park, CA, in November, 1988. The Lacey-1 and Union-1 wells mentioned in this appendix refer to the Lacy No. 1 and State No. 1, respectively.

SUMMARY AND CONCLUSIONS

A total of two oil samples from the Union-1 and Lacey-1 wells havebeen geochemically investigated. Following conclusions have been reached:

- Both oil samples analyzed are relatively rich in alkanes.
- Both oils show a wide alkane distribution, with oil samples from the Union-1 well being relatively richer in waxy n-alkanes above C_{25}.
- Triterpane (m/z 191) and sterane (m/z 217) distributions of both oils display very similar pattern, making a generic relationship highly possible.
- Relatively high pristane/phytane ratio and high abundances of oleanane and diterpenoid "fichtelite" ($C_{19}H_{34}$) are possibly indicative of generation from a terrigenous source (land plant organic matter) deposited in an oxic environment.
- To support above conclusion, we recommend carbon isotope analyses to be performed on saturate and aromatic fractions of these oils.

INTRODUCTION

Two light oil samples from the State No. 1 and Lacey No. 1 wells drilled in Grays Harbor County and Jefferson County, respectively (WSDNR letters of October 12, 1988 and October 20, 1988) were submitted for liquid (column) and gas chromatography and aliphatic biomarker gas chromatography- mass spectrometry (GC-MS) analyses. The results are presented in Tables C1- C3 and shown in Figures C1-C10.

RESULTS AND DISCUSSION

Column chromatography results indicate that the Union-1 and Lacey-1oil samples are rich in saturated hydrocarbons (78.8% and 79.8%,respectively) characteristic of oils paraffinic types.

Alkane gas chromatogram of the Union-1 oil sample (Figure 1) shows awide distribution with n-alkanes in the n-C8 to n-C33 range. This oilsample is fairly rich in waxy n-alkanes above C25, with a slight odd-over-even predominance. The oil sample from the Lacey-1 well shows a narrow alkane distribution pattern with a maximum at n-C11 (Figure 2). Pristane (Pr) is strongly abundant in both oil samples and is dominant over phytane (Ph) with a Pr/Ph ratios in the 2.82-5.47 range (Table 1) typical of oils generated mainly from a terrestrially derived kerogen deposited in an oxic environment.

The saturated fractions of the oil samples were analyzed by GC-MS using Multiple Ion Detection Mode (MID). The GC-MS analysis is based on the distribution patterns of characteristic fragments (m/z 191 and m/z 217) formed by triterpanes and steranes respectively. The identified triterpane and sterane isomers are presented in Tables 5 and 6 whereas the biomarkerparameters calculated are summarized in Tables 2 and 3.

Triterpane (m/z 191) distributions of both oil samples (Figures 3-6) display very similar patterns, showing 17a(H)-hopanes in the C_{27}-C_{34} range, and a fair proportion of tricyclic terpanes. Both oil samples are rich in 18a(H) oleanane and the diterpane "fichtelite" (C19H34). Presence of oleanane and fichtelite in these oil samples indicates that they have been generated from a resin derived (terrigenous) kerogen. To support this conclusion we recommend carbon isotope analyses to be performed on the saturate and aromatic fractions of these oils.

Biomarker maturity parameters (i.e. 1, 2, 3, 4 in Table 2 and A, B, E, F and J in Table 3) suggest that both oils analyzed are generated at high maturity level with the oil from the Lacey-1 being slightly more mature.

Table C1: Analytical results obtained for oil samples analyzed

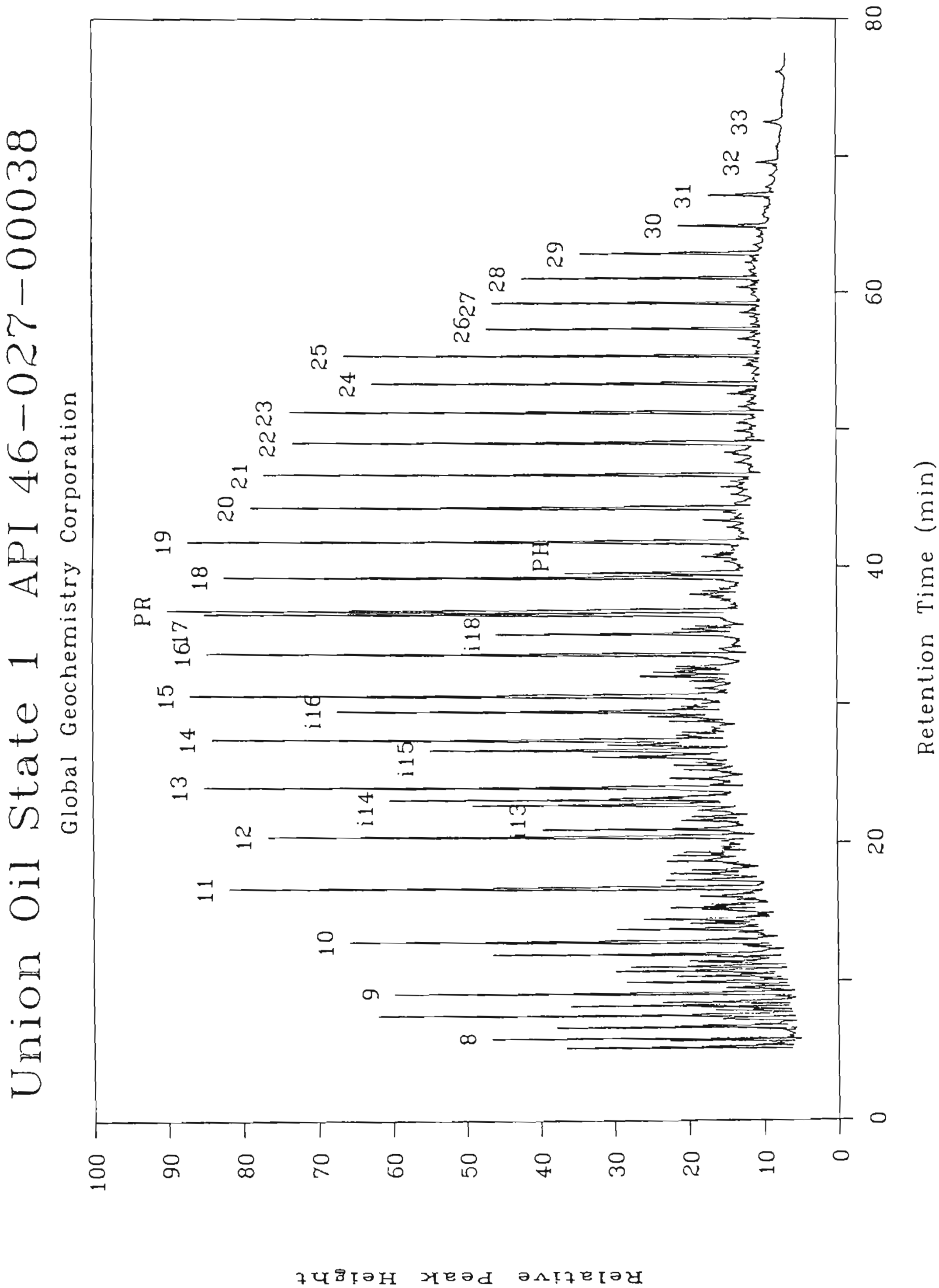
				OIL COMPOSITION 0% OF OIL				ALKANE PARAMETERS		
GGC#	**Well name**	**Operator**	**Location**	**Saturate**	**Aromatics**	**Polars**	**Pr/Ph**	**Pr/n-C_{17}**	**Ph/n-C_{18}**	**CPI**
4130	State-1	Union Oil	Grays Harbor County	78.8	19.7	1.5	2.82	1.06	0.39	1.15
4134	Lacey-1	Hoh River Oil	Jefferson County	79.8	18.2	2.0	5.47	1.15	0.23	1.10

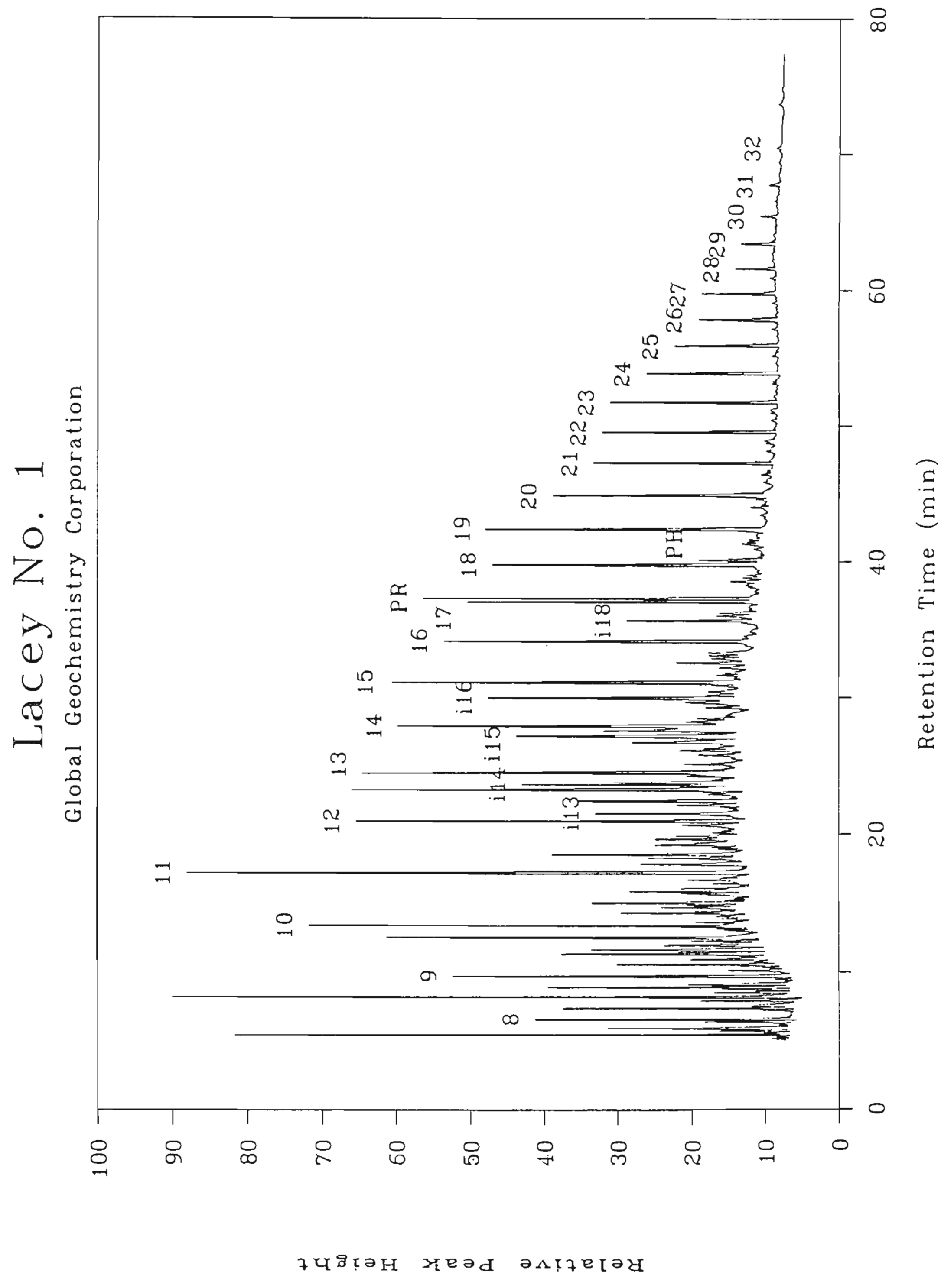
Table C2: Triterpane biomarkers parameters calculated for oil samples analyzed

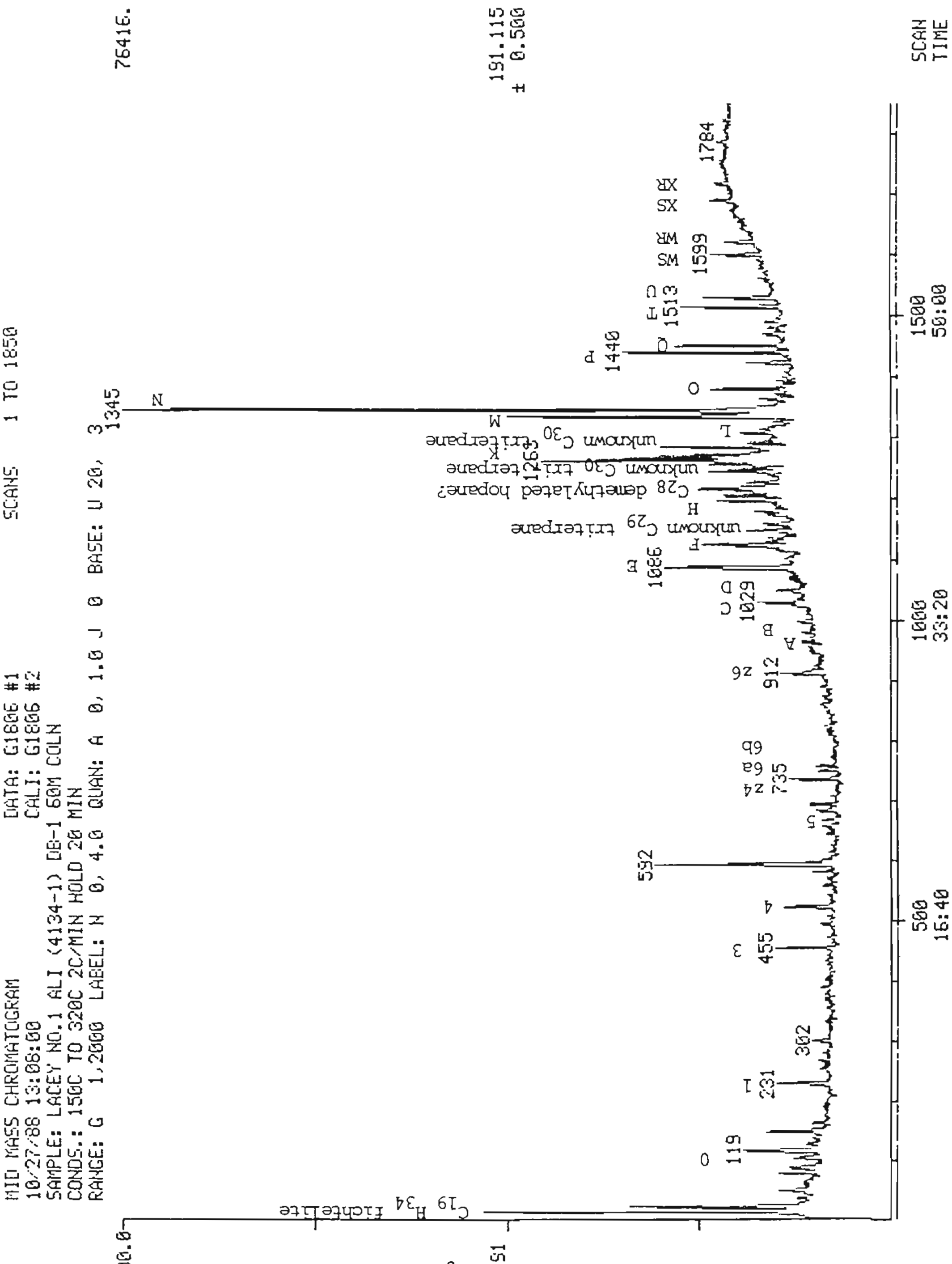
GGC#	Well name	1	2	3	4	5	6	7	8	9	10	11	12	13
4130	Union-1	1.44	1.23	0.17	0.13	1.09	0.16	0.07	0.53	4.5	0.16	0.81	0.47	2.5
4134	Lacey-1	1.37	1.24	0.33	0.11	0.93	0.25	0.11	0.35	3.3	0.18	0.74	0.53	1.46

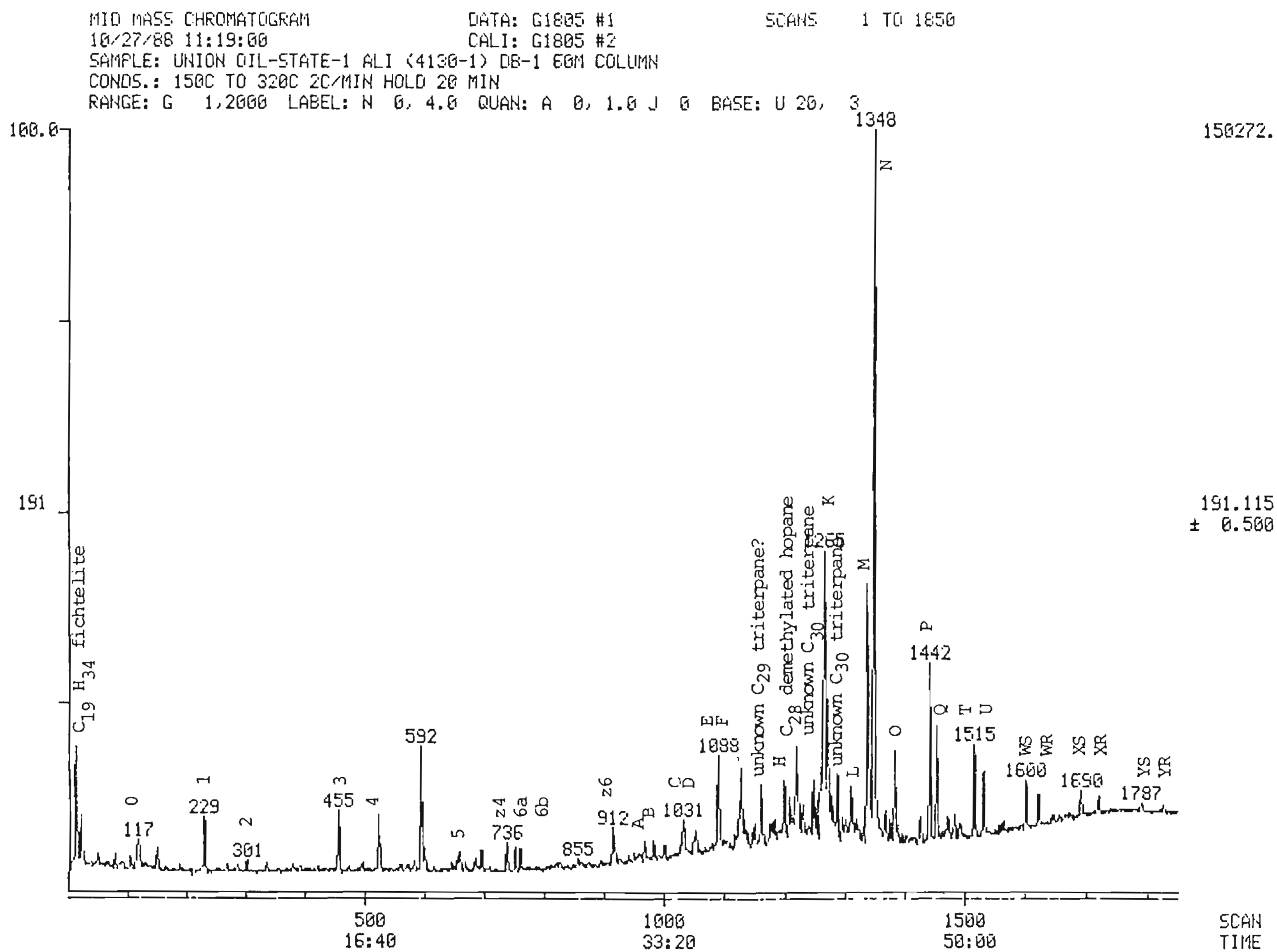
Table C3: Sterane biomarker parameters calculated for oil samples analyzed

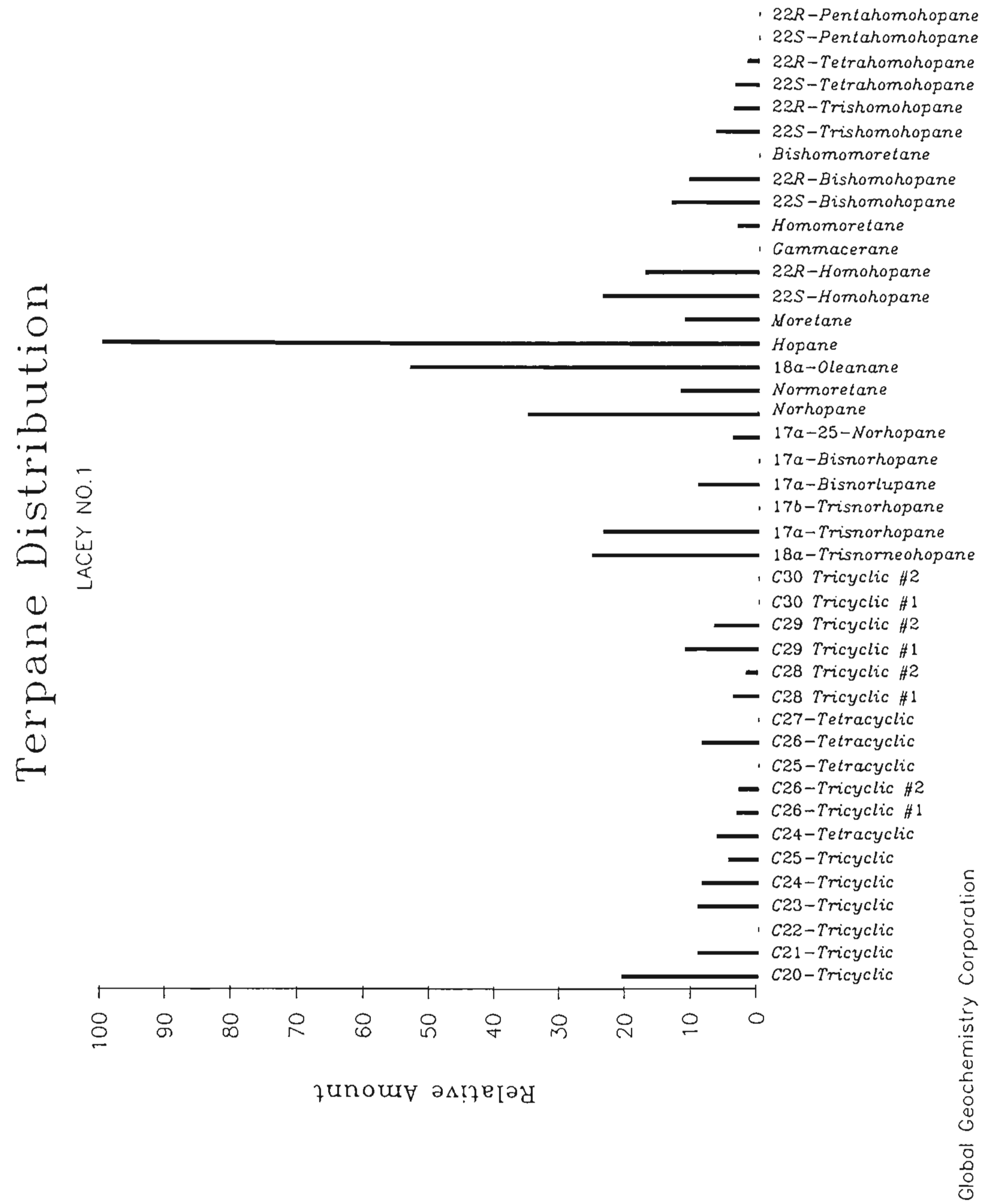
GGC#	Well Name	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
4130	Union-1	1.5	1.18	1.56	1.29	49.3	60.8	0.98	0.49	1.29	62.3	0.54	1.23	2.05	26.1	33.2	40.7	0.67
4134	Lacey-1	1.77	1.54	3.3	1.6	53.1	63.9	0.99	0.28	1.64	63.0	0.63	0.90	1.64	16.0	30.3	53.6	0.79

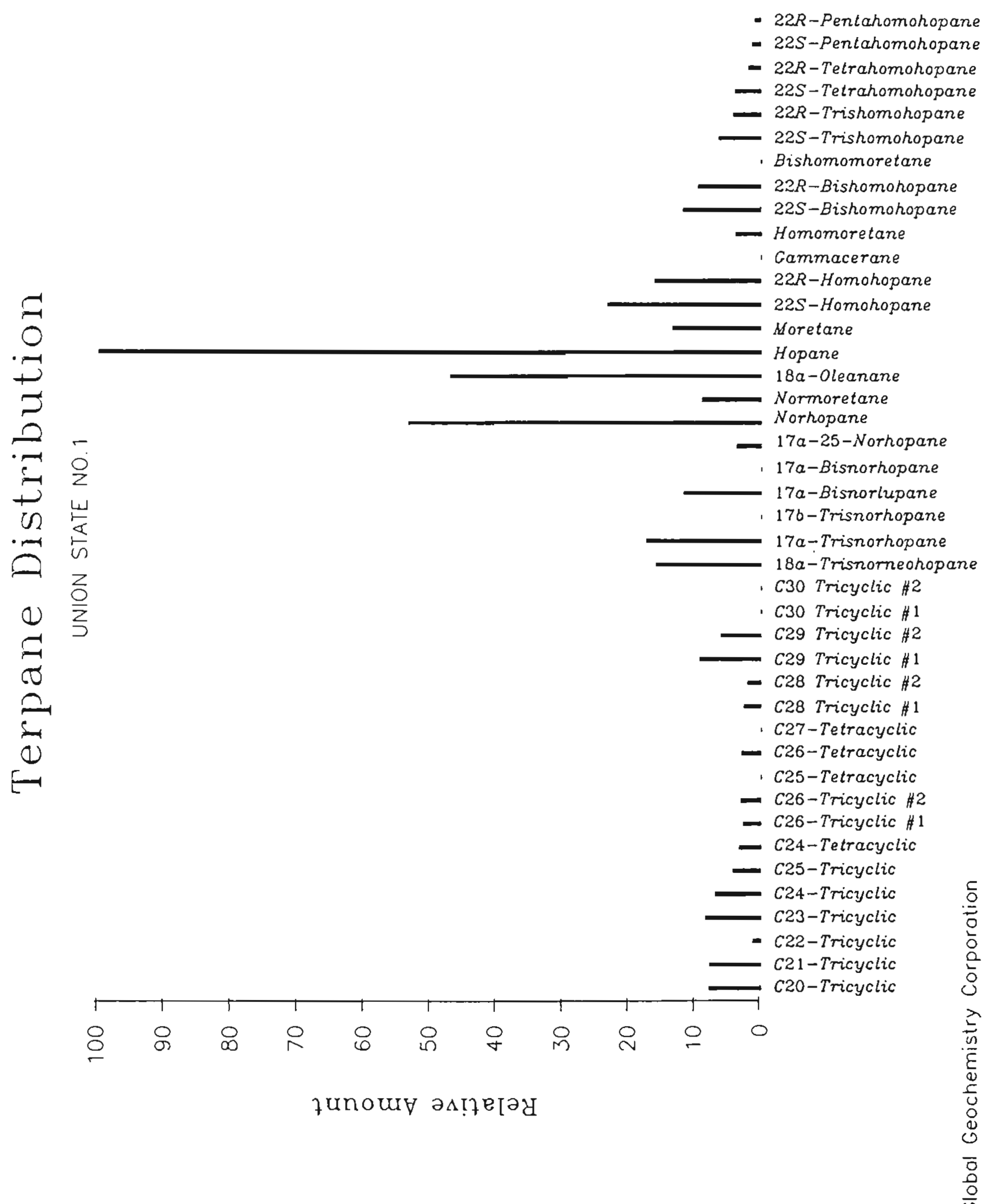

Union Oil State 1 API 46-027-00038
Global Geochemistry Corporation
Relative Peak Height
Retention Time (min)
0
10
20
30
40
50
60
70
80
90
100
0
20
40
60
80
8
9
10
11
12
i13
13
i14
14
i15
15
i16
1617
i18
PR
18
PH
19
20
21
2223
24
25
2627
28
29
30
31
32
33

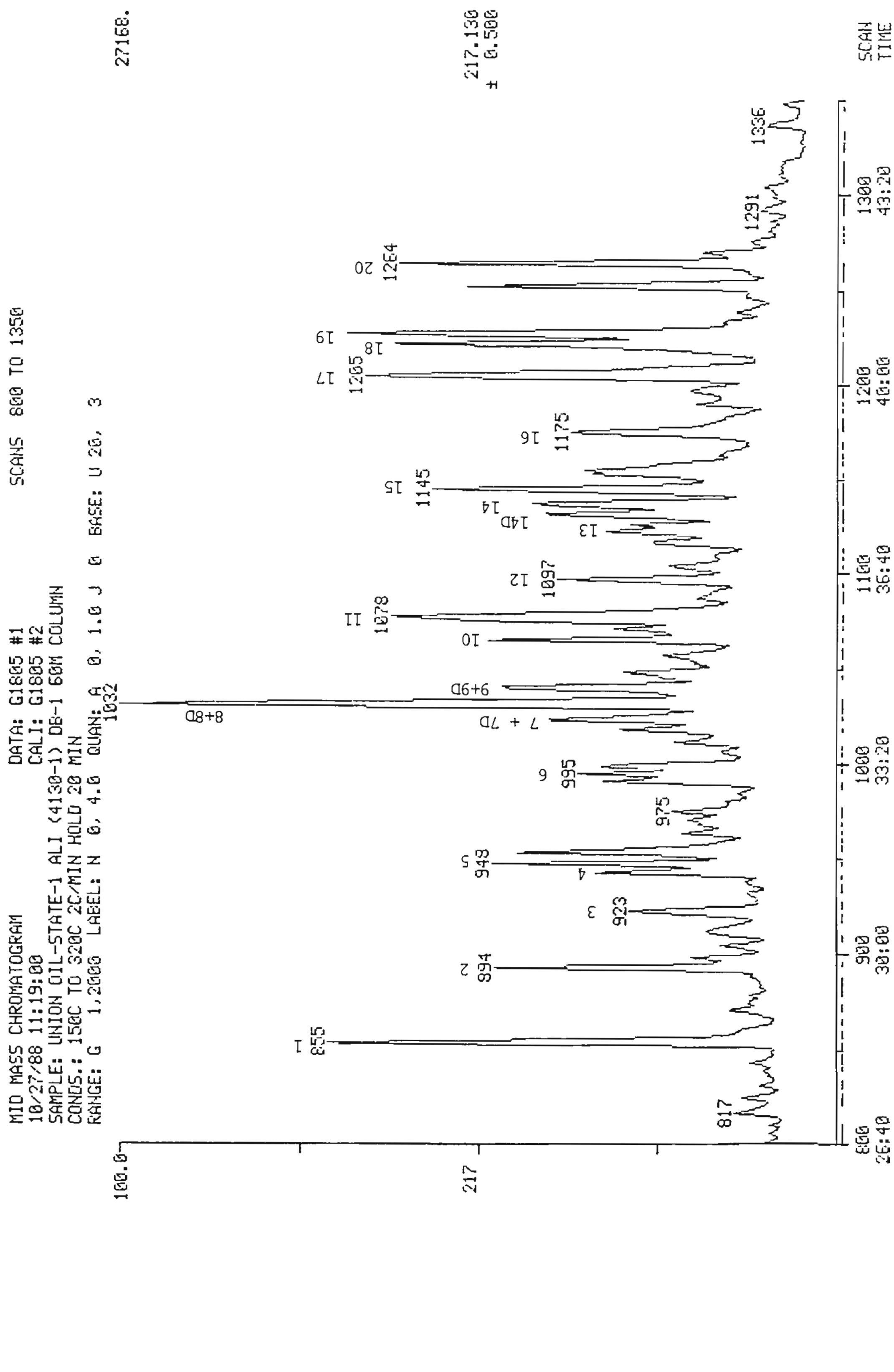

Lacey No. 1
Global Geochemistry Corporation
Relative Peak Height
Retention Time (min)
0
10
20
30
40
50
60
70
80
90
100
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
i13
i14
i15
i16
i18
PR
PH

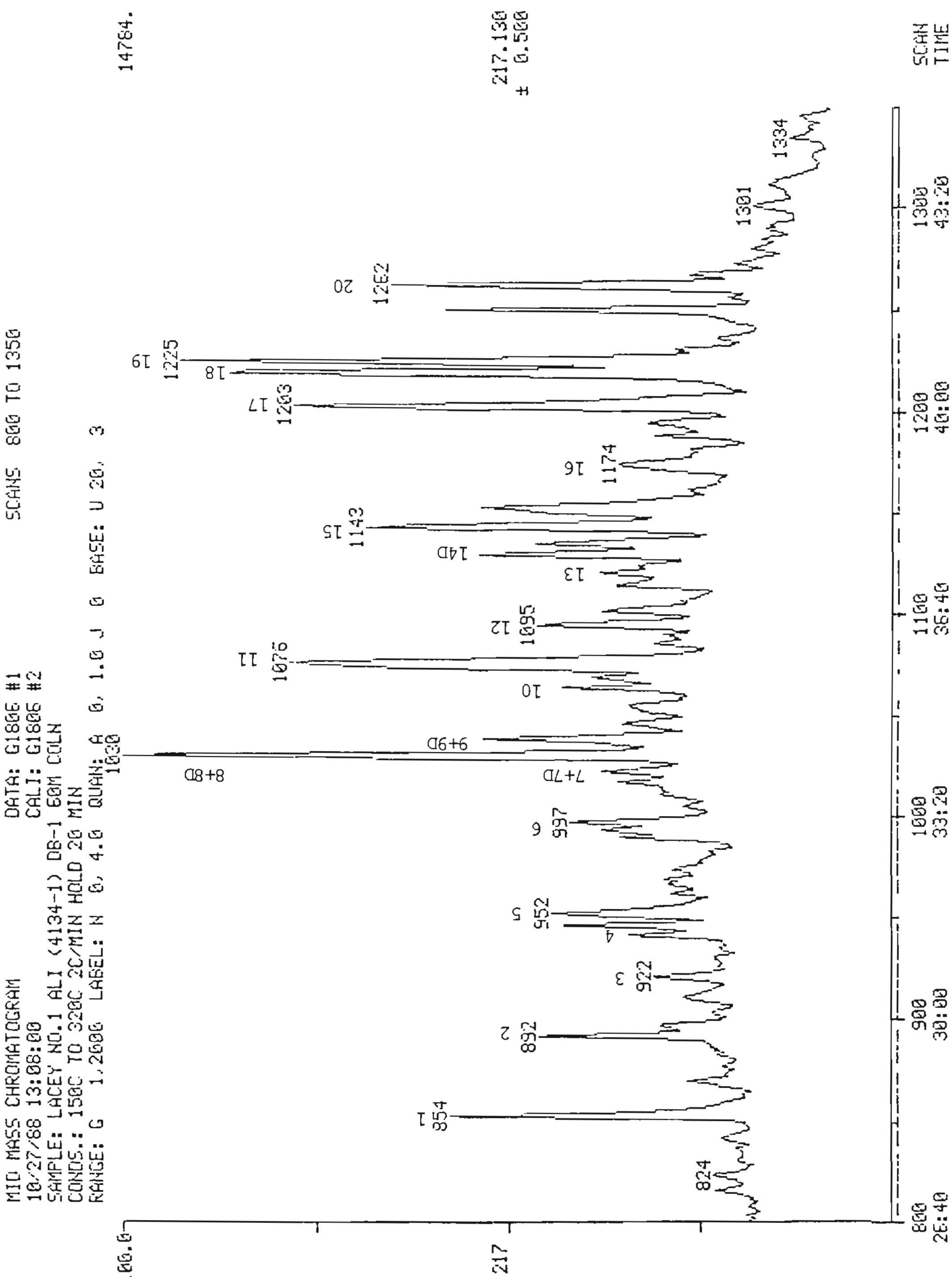

MID MASS CHROMATOGRAM
DATA: G1806 #1
SCANS 1 TO 1850
10/27/88 13:06:00
CALI: G1806 #2
SAMPLE: LACEY NO.1 ALI (4134-1) DB-1 60M COLN
CONDS.: 150C TO 320C 2C/MIN HOLD 20 MIN
RANGE: G 1,2000 LABEL: N 0, 4.0 QUAN: A 0, 1.0 J 0 BASE: U 20, 3
100.0
76416.
151
191.115
± 0.500
$C_{19}H_{34}$ fichtelite
unknown C_{29} triterpane
C_{28} demethylated hopane?
unknown C_{30} triterpane
unknown C_{30} triterpane
119
231
302
455
592
735
912
1029
1086
1263
1345
1440
1513
1599
1784
SCAN
TIME
500
16:40
1000
33:20
1500
50:00

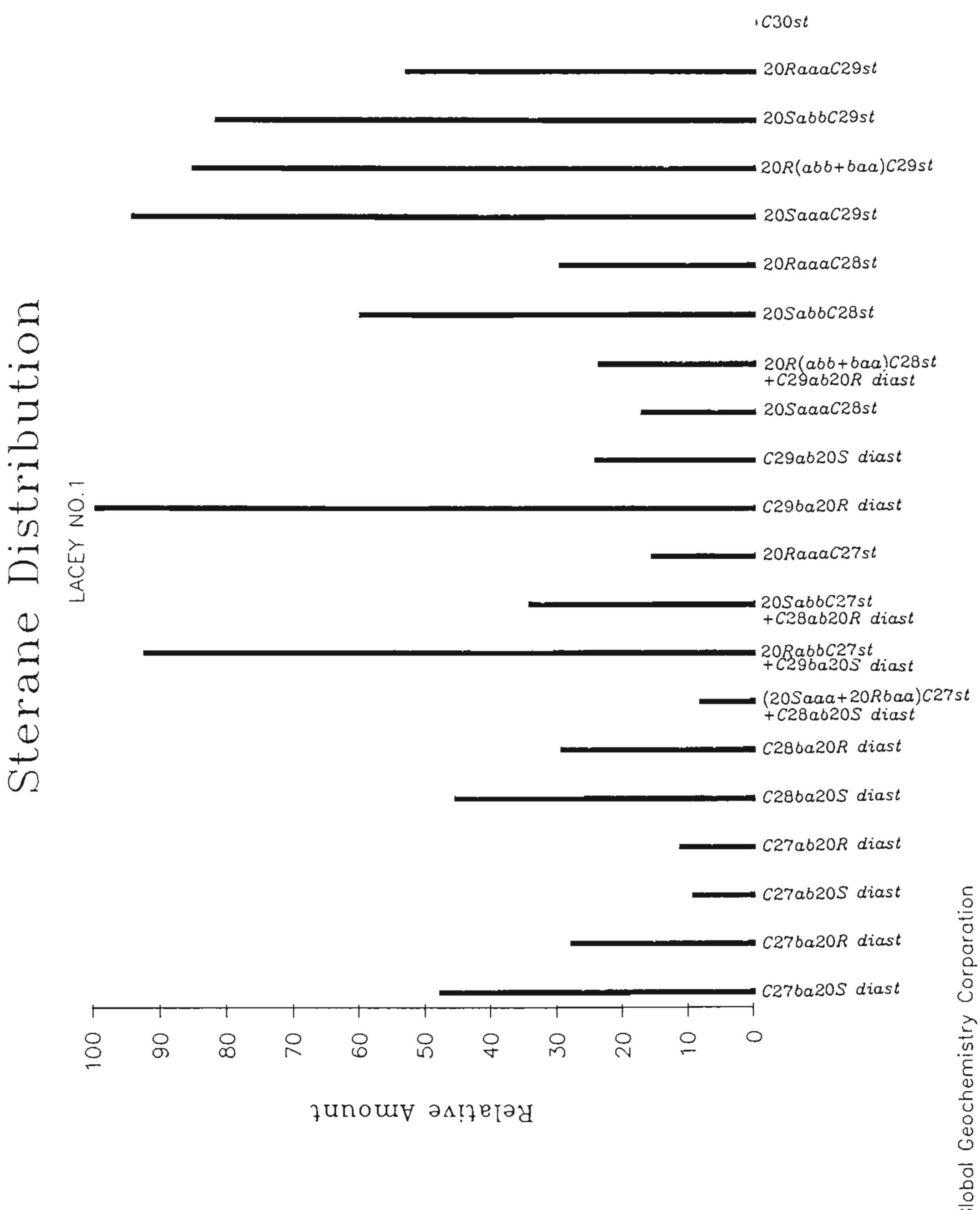

MID MASS CHROMATOGRAM
DATA: G1805 #1
SCANS 1 TO 1850
10/27/88 11:19:00
CALI: G1805 #2
SAMPLE: UNION OIL-STATE-1 ALI (4130-1) DB-1 60M COLUMN
CONDS.: 150C TO 320C 2C/MIN HOLD 20 MIN
RANGE: G 1,2000 LABEL: N 0, 4.0 QUAN: A 0, 1.0 J 0 BASE: U 20, 3
100.0
191
150272.
191.115
± 0.500
$C_{19}H_{34}$ fichtelite
unknown C_{29} triterpane?
C_{28} demethylated hopane
unknown C_{30} triterpane
unknown C_{30} triterpane
1348
1442
1515
1600
1650
1787
1088
1031
912
855
736
592
455
301
229
117
SCAN
TIME
500
16:40
1000
33:20
1500
50:00

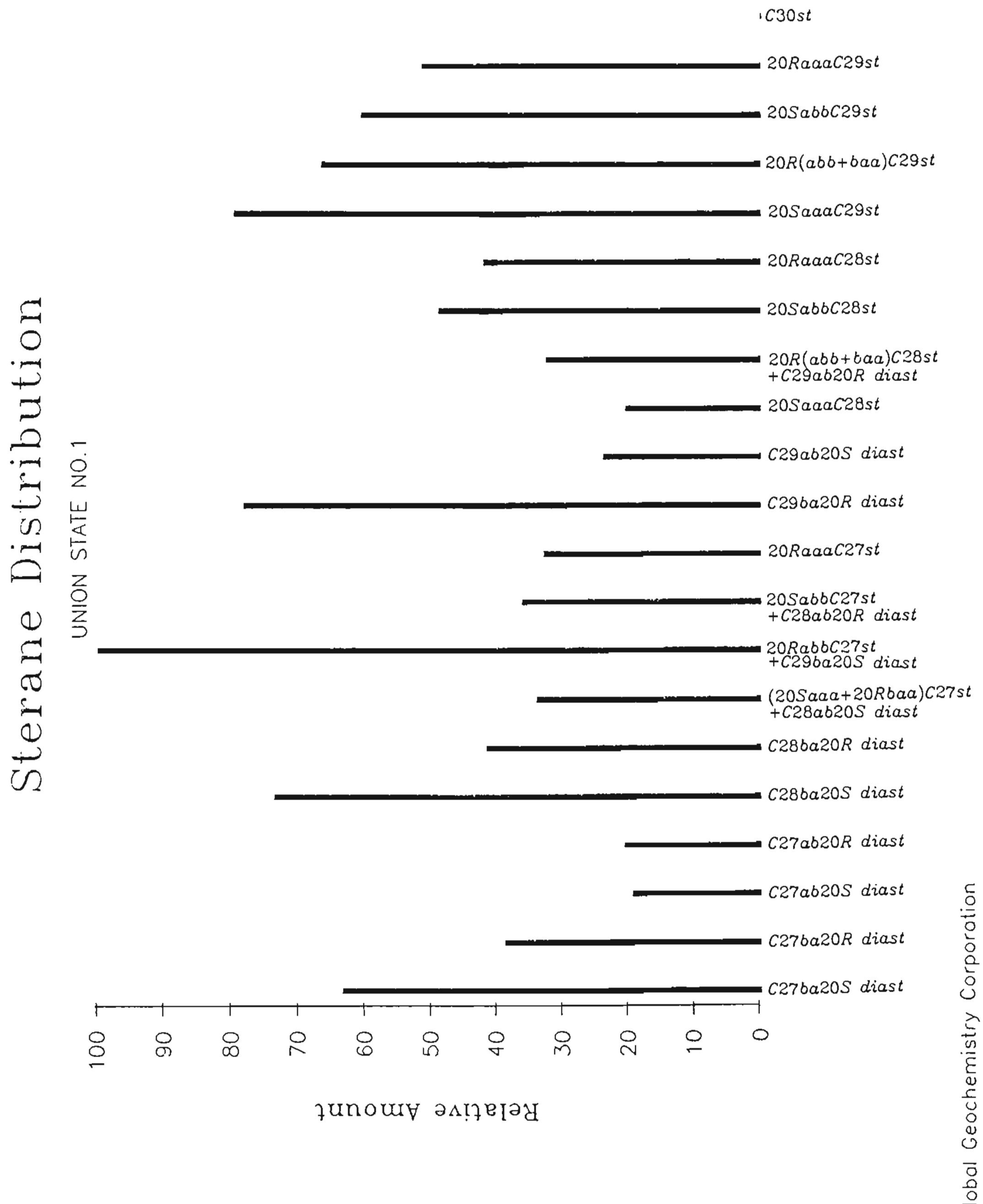

Terpane Distribution
LACEY NO.1
22R-Pentahomohopane
22S-Pentahomohopane
22R-Tetrahomohopane
22S-Tetrahomohopane
22R-Trishomohopane
22S-Trishomohopane
Bishomomoretane
22R-Bishomohopane
22S-Bishomohopane
Homomoretane
Gammacerane
22R-Homohopane
22S-Homohopane
Moretane
Hopane
18a-Oleanane
Normoretane
Norhopane
17a-25-Norhopane
17a-Bisnorhopane
17a-Bisnorlupane
17b-Trisnorhopane
17a-Trisnorhopane
18a-Trisnorneohopane
C30 Tricyclic #2
C30 Tricyclic #1
C29 Tricyclic #2
C29 Tricyclic #1
C28 Tricyclic #2
C28 Tricyclic #1
C27-Tetracyclic
C26-Tetracyclic
C25-Tetracyclic
C26-Tricyclic #2
C26-Tricyclic #1
C24-Tetracyclic
C25-Tricyclic
C24-Tricyclic
C23-Tricyclic
C22-Tricyclic
C21-Tricyclic
C20-Tricyclic
100
90
80
70
60
50
40
30
20
10
0
Relative Amount
Global Geochemistry Corporation


Terpane Distribution
UNION STATE NO.1
22R-Pentahomohopane
22S-Pentahomohopane
22R-Tetrahomohopane
22S-Tetrahomohopane
22R-Trishomohopane
22S-Trishomohopane
Bishomomoretane
22R-Bishomohopane
22S-Bishomohopane
Homomoretane
Gammacerane
22R-Homohopane
22S-Homohopane
Moretane
Hopane
18a-Oleanane
Normoretane
Norhopane
17a-25-Norhopane
17a-Bisnorhopane
17a-Bisnorlupane
17b-Trisnorhopane
17a-Trisnorhopane
18a-Trisnorneohopane
C30 Tricyclic #2
C30 Tricyclic #1
C29 Tricyclic #2
C29 Tricyclic #1
C28 Tricyclic #2
C28 Tricyclic #1
C27-Tetracyclic
C26-Tetracyclic
C25-Tetracyclic
C26-Tricyclic #2
C26-Tricyclic #1
C24-Tetracyclic
C25-Tricyclic
C24-Tricyclic
C23-Tricyclic
C22-Tricyclic
C21-Tricyclic
C20-Tricyclic
100
90
80
70
60
50
40
30
20
10
0
Relative Amount
Global Geochemistry Corporation

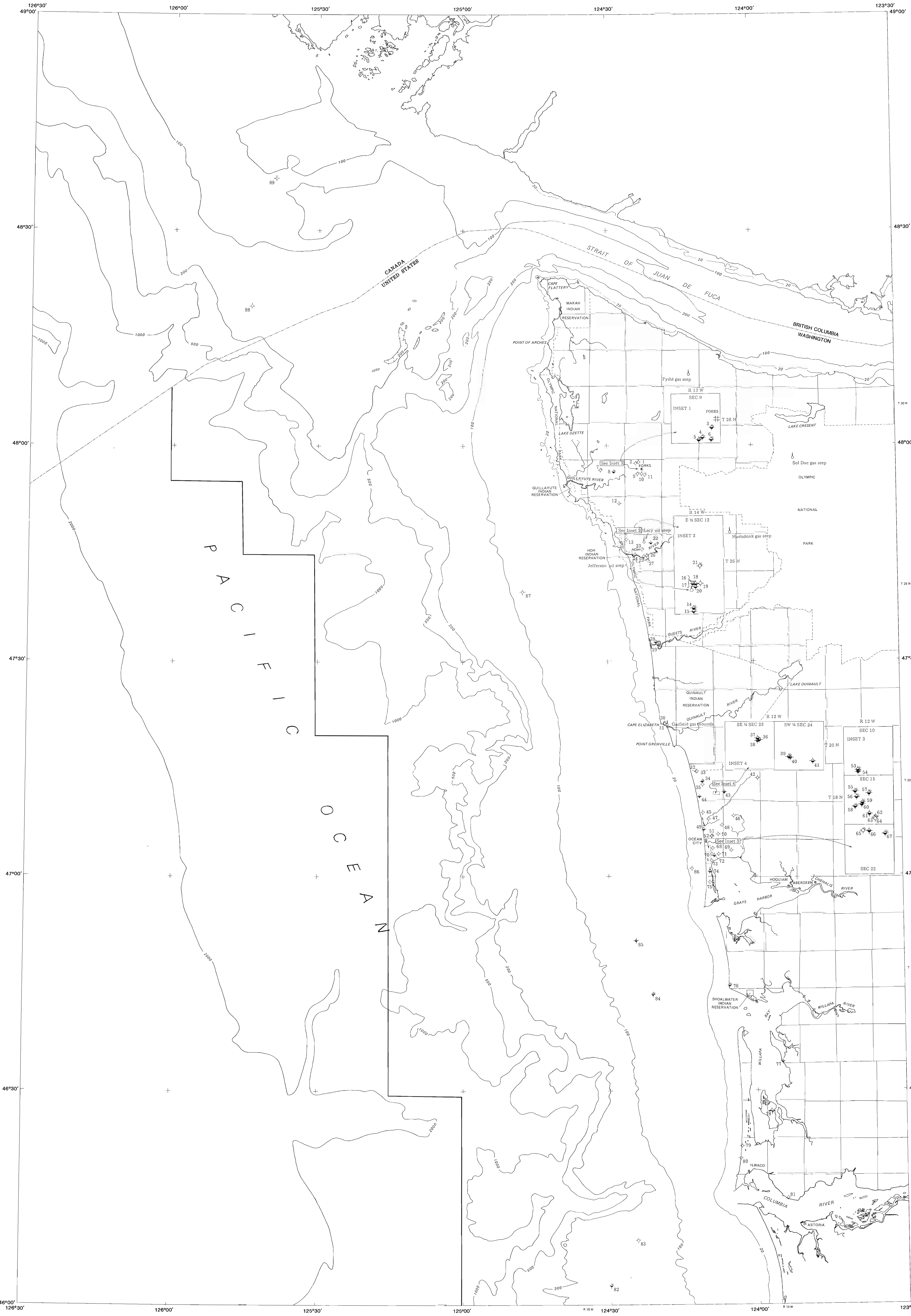

MID MASS CHROMATOGRAM
DATA: G1805 #1
SCANS 800 TO 1350
10/27/88 11:19:00
CALI: G1805 #2
SAMPLE: UNION OIL-STATE-1 ALI (4130-1) DB-1 60M COLUMN
CONDS.: 150C TO 320C 2C/MIN HOLD 20 MIN
RANGE: G 1,2000 LABEL: N 0, 4.0 QUAN: A 0, 1.0 J 0 BASE: U 20, 3
100.0
217
27168.
217.130
± 0.500
SCAN
TIME
800 26:40
900 30:00
1000 33:20
1100 36:40
1200 40:00
1300 43:20
817
1 855
2 894
3 923
4
5 948
975
6 995
7 + 7D
8+8D 1032
9+9D
10
11 1078
12 1097
13
14D
14
15 1145
16 1175
17 1205
18
19
20 1264
1291
1336


MID MASS CHROMATOGRAM
DATA: G1806 #1
SCANS 800 TO 1350
10/27/88 13:06:00
CALI: G1806 #2
SAMPLE: LACEY NO.1 ALI (4134-1) DB-1 60M COLN
CONDS.: 150C TO 320C 2C/MIN HOLD 20 MIN
RANGE: G 1,2000 LABEL: N 0, 4.0 QUAN: A 0, 1.0 J 0 BASE: U 20, 3
14784.
217.130
± 0.500
100.0
217
824
854
1
892
2
922
3
4
952
5
997
6
7+7D
1030
8+8D
9+9D
10
1076
11
1095
12
13
14D
1143
15
1174
16
1203
17
18
1225
19
1232
20
1301
1334
800
26:40
900
30:00
1000
33:20
1100
36:40
1200
40:00
1300
43:20
SCAN
TIME


Sterane Distribution
LACEY NO.1
C30st
20RaaaC29st
20SabbC29st
20R(abb+baa)C29st
20SaaaC29st
20RaaaC28st
20SabbC28st
20R(abb+baa)C28st
+C29ab20R diast
20SaaaC28st
C29ab20S diast
C29ba20R diast
20RaaaC27st
20SabbC27st
+C28ab20R diast
20RabbC27st
+C29ba20S diast
(20Saaa+20Rbaa)C27st
+C28ab20S diast
C28ba20R diast
C28ba20S diast
C27ab20R diast
C27ab20S diast
C27ba20R diast
C27ba20S diast
100
90
80
70
60
50
40
30
20
10
0
Relative Amount
Global Geochemistry Corporation


Sterane Distribution
UNION STATE NO.1
C30st
20RaaaC29st
20SabbC29st
20R(abb+baa)C29st
20SaaaC29st
20RaaaC28st
20SabbC28st
20R(abb+baa)C28st
+C29ab20R diast
20SaaaC28st
C29ab20S diast
C29ba20R diast
20RaaaC27st
20SabbC27st
+C28ab20R diast
20RabbC27st
+C29ba20S diast
(20Saaa+20Rbaa)C27st
+C28ab20S diast
C28ba20R diast
C28ba20S diast
C27ab20R diast
C27ab20S diast
C27ba20R diast
C27ba20S diast
100
90
80
70
60
50
40
30
20
10
0
Relative Amount
Global Geochemistry Corporation

Oil and gas exploratory wells. © 1989
An Assessment of the Oil and Gas Potential of the Washington Outer Continental Shelf
Stephen P. Palmer & William S. Lingley, Jr.



1 0 5 10 MILES
5000 0 10000 30000 50000 FEET

Base from U.S. Geological Survey 1:100,000-scale topographic maps Chehalis River (1979), Copalis Beach, Westport, Ilwaco (1980), Cape Flattery, Forks, Astoria (1981).
Bathymetry from Wagner (1986,1987), Kulm et al. (1984).
Compiled by Washington Sea Grant Program, in cooperation with the Washington State Department of Natural Resources.
Drafted by Stanley McAbee.

EXPLANATION

- DRY HOLE
- WELL WITH GAS SHOWS
- WELL WITH OIL SHOWS
- WELL WITH SHOW OF OIL AND GAS
- APPROXIMATE WESTERN BOUNDARY OF SALE 132

PLATE 1

OIL AND GAS EXPLORATORY WELLS

(Well numbers, names, and additional data given in Appendix A)

WASHINGTON STATE DEPARTMENT OF
Natural Resources
Brian Boyle - Commissioner of Public Lands
Art Stearns - Supervisor
Division of Geology and Earth Resources
Raymond Lasmanis, State Geologist

U.S. Geological Survey seismic profile 76-12. © 1989
An Assessment of the Oil and Gas Potential of the Washington Outer Continental Shelf
Stephen P. Palmer & William S. Lingley, Jr.

PLATE 2 U.S.G.S. SEISMIC PROFILE 76-12

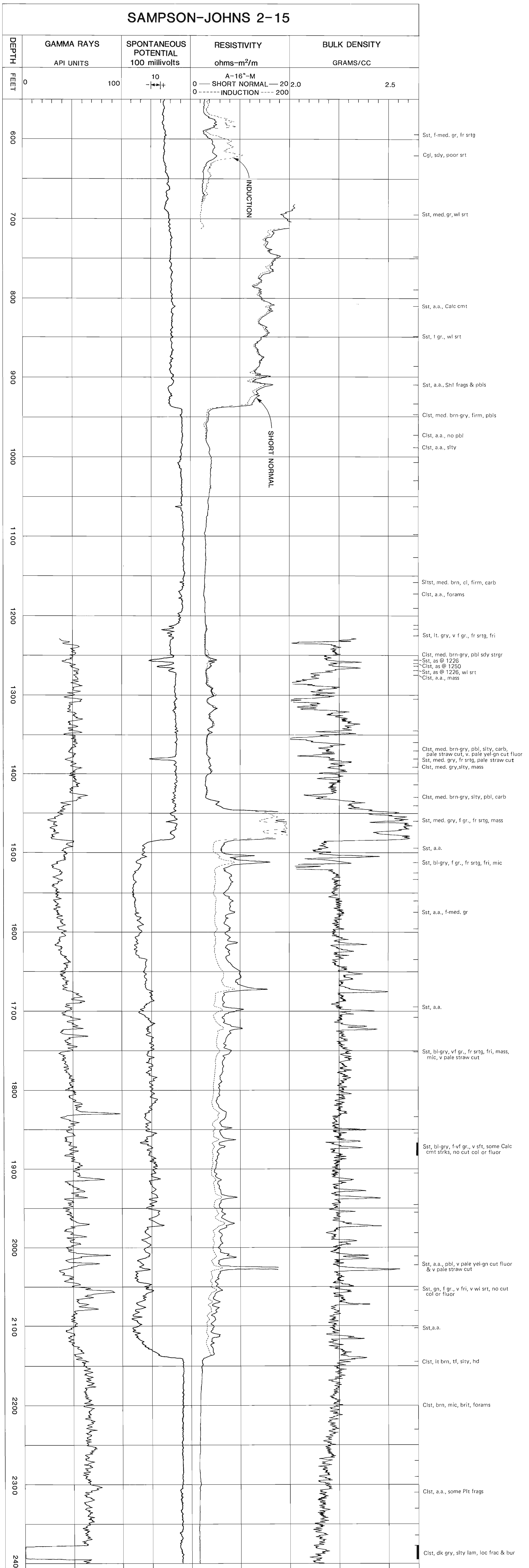
See Plate 9 for profile and shotpoint locations.

Reflectors A, B, C, and D are as noted in text.

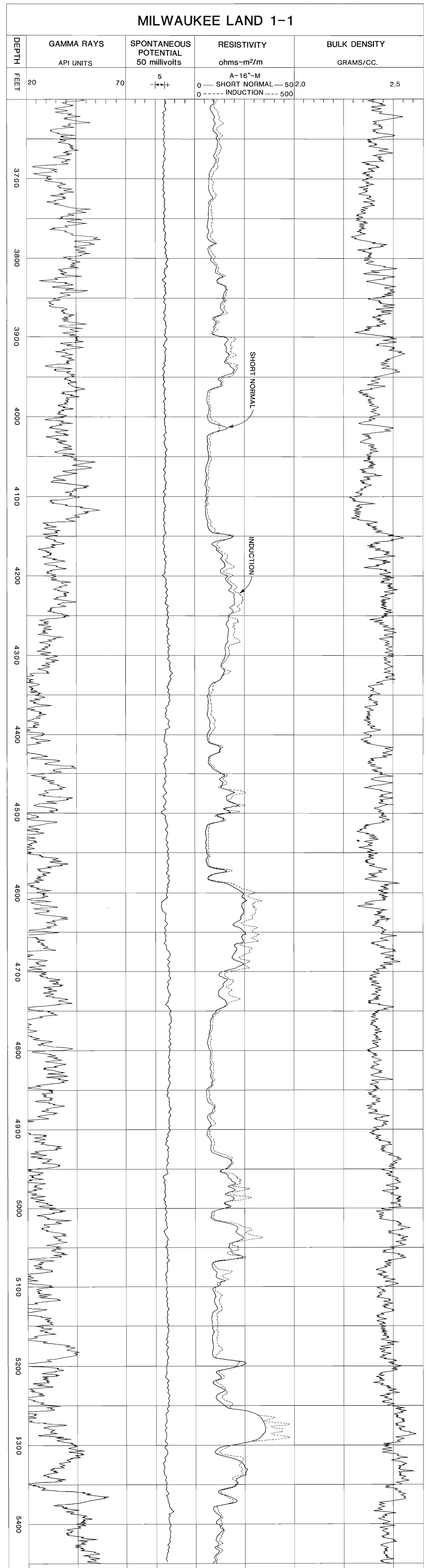
Natural Resources
Division of Geology and Earth Resources
Raymond Lasmanis, State Geologist

PLATE 3

COMPOSITE WIRELINE LOG DATA



MONTESANO FORMATION AND YOUNGER ROCKS



HOH AND OZETTE SEQUENCES

Plate 3 of 12
Composite wireline log data for both the Hoh/Ozette sequence, and the Montesano Formation and younger rocks.
An Assessment of the Oil and Gas Potential of the Washington Outer Continental Shelf
Stephen P. Palmer & William S. Lingley, Jr.

WASHINGTON STATE DEPARTMENT OF
Natural Resources
Brian Boyle Commissioner of Public Lands
Art Stearns Supervisor
Division of Geology and Earth Resources
Raymond Lasmanis, State Geologist
WASHINGTON SEA GRANT

U.S. Geological Survey seismic profiles 76-18 and 76-14. © 1989
An Assessment of the Oil and Gas Potential of the Washington Outer Continental Shelf
Stephen P. Palmer & William S. Lingley, Jr.

PLATE 4

U.S.G.S. SEISMIC PROFILE 76-18

U.S.G.S. SEISMIC PROFILE 76-14

See Plate 9 for profile and shotpoint locations.

Reflectors A, B, C, and D are as noted in text.

WASHINGTON STATE DEPARTMENT OF
Natural Resources
Division of Geology and Earth Resources
Raymond Lasmanis, State Geologist

Formline contours showing the percentage sandstone of the Montesano Formation, Ocean City area, Grays Harbor County.

An Assessment of the Oil and Gas Potential of the Washington Outer Continental Shelf

Stephen P. Palmer & William S. Lingley, Jr.

Base from U.S. Geological Survey 1:24,000-scale topographic maps Copalis Beach, Copalis Crossing (1973).
Compiled by Washington Sea Grant Program, in cooperation with the Washington State Department of Natural Resources.
Drafted by Stanley McAbee.

Washington State Department of Natural Resources
Division of Geology and Earth Resources

Cross section of Ocean City area wells. © 1989
An Assessment of the Oil and Gas Potential of the Washington Outer Continental Shelf
Stephen P. Palmer & William S. Lingley, Jr.

PLATE 6

CROSS SECTION OF OCEAN CITY AREA WELLS

(See Plate 5 for location of profile line A–A′.
Refer to Figure 5–2 for explanation of symbols)

WASHINGTON STATE DEPARTMENT OF
Natural Resources
Brian Boyle - Commissioner of Public Lands
Art Stearns Supervisor
Division of Geology and Earth Resources
Raymond Lasmanis, State Geologist
WASHINGTON SEA GRANT

Formline isochore map of the Montesano sandstone member, Ocean City area, Grays Harbor County. © 1989
An Assessment of the Oil and Gas Potential of the Washington Outer Continental Shelf
Stephen P. Palmer & William S. Lingley, Jr.

Base from U.S. Geological Survey 1:24,000-scale topographic maps Copalis Beach, Copalis Crossing (1973).
Compiled by Washington Sea Grant Program, in cooperation with the Washington State Department of Natural Resources.
Drafted by Stanley McAbee.

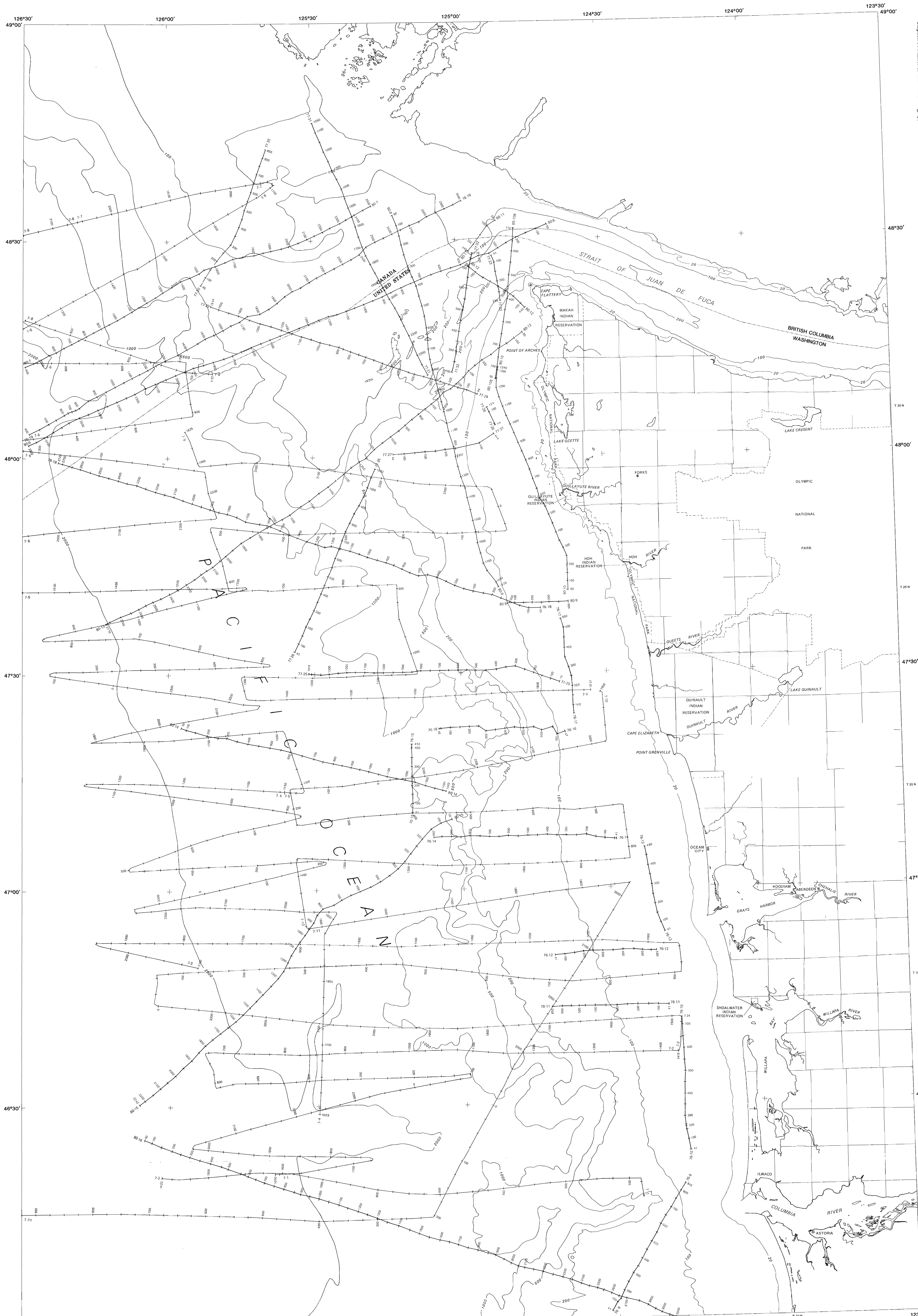
WASHINGTON STATE DEPARTMENT OF Natural Resources
Brian Boyle - Commissioner of Public Lands
Art Stearns - Supervisor
Division of Geology and Earth Resources
Raymond Lasmanis, State Geologist

Preliminary formline structural contour map on top—Montesano Formation angular unconformity, Ocean City area, Grays Harbor County © 1989
An Assessment of the Oil and Gas Potential of the Washington Outer Continental Shelf
Stephen P. Palmer & William S. Lingley, Jr.

Base from U.S. Geological Survey 1:24,000-scale topographic maps Copalis Beach, Copalis Crossing (1973).
Compiled by Washington Sea Grant Program, in cooperation with the Washington State Department of Natural Resources.
Drafted by Stanley McAbee.

WASHINGTON STATE DEPARTMENT OF Natural Resources
Brian Boyle Commissioner of Public Lands
Art Stearns Supervisor
Division of Geology and Earth Resources
Raymond Lasmanis, State Geologist

Plate 9 of 12
Deep penetration seismic shotpoint base map. © 1989
An Assessment of the Oil and Gas Potential of the Washington Outer Continental Shelf
Stephen P. Palmer & William S. Lingley, Jr.



Base from U.S. Geological Survey 1:100,000-scale topographic maps Chehalis River (1979), Copalis Beach, Westport, Ilwaco (1980), Cape Flattery, Forks, Astoria (1981).
Bathymetry from Wagner (1986,1987), Kulm et al. (1984).
Compiled by Washington Sea Grant Program, in cooperation with the Washington State Department of Natural Resources.
Drafted by Stanley McAbee.

EXPLANATION

- 7-XX Scripps Institution of Oceanography, leg 9A of the Seven Tow Data Expedition, 1970
- 76-XX U.S.G.S. R.V. S. P. Lee, 1976 cruise, line XX
- 77-XX U.S.G.S. R.V. S. P. Lee, 1977 cruise, line XX
- 80-XX U.S.G.S. R.V. S. P. Lee, 1980 cruise, line XX

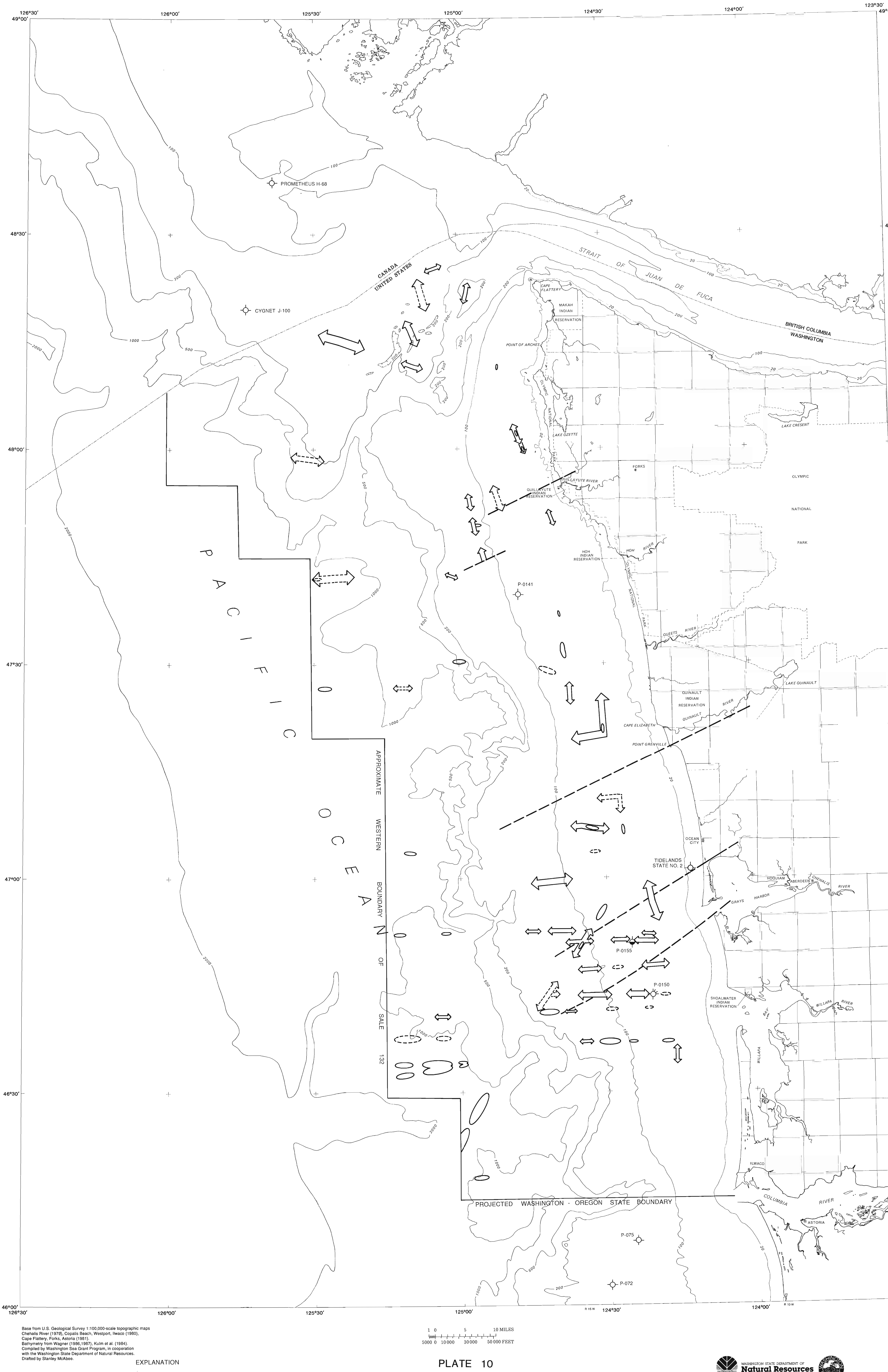
1 0 5 10 MILES
5000 0 10000 30000 50000 FEET

PLATE 9

DEEP PENETRATION SEISMIC SHOTPOINT BASE

WASHINGTON STATE DEPARTMENT OF
Natural Resources
Brian Boyle - Commissioner of Public Lands
Art Stearns - Supervisor
Division of Geology and Earth Resources
Raymond Lasmanis, State Geologist
WASHINGTON SEA GRANT

Plate 10 of 12
Identifiable anticlinal rollovers, faults, and diapirs in the study area. © 1989
An Assessment of the Oil and Gas Potential of the Washington Outer Continental Shelf
Stephen P. Palmer & William S. Lingley, Jr.



Base from U.S. Geological Survey 1:100,000-scale topographic maps Chehalis River (1979), Copalis Beach, Westport, Ilwaco (1980), Cape Flattery, Forks, Astoria (1981).
Bathymetry from Wagner (1986,1987), Kulm et al. (1984).
Compiled by Washington Sea Grant Program, in cooperation with the Washington State Department of Natural Resources.
Drafted by Stanley McAbee.

1 0 5 10 MILES
5000 0 10000 30000 50 000 FEET

EXPLANATION

Anticlinal rollover as interpreted from seismic data (see shotpoint base and seismic profiles). Arrows are measured from synclinal trough across the anticlinal culmination to the adjacent synclinal trough at constant T.W.T.

Diapiric intrusion as interpreted from seismic data

Possible fault (numerous unmappable faults observed on seismic profiles are not shown).

DRY HOLE

WELL WITH GAS SHOWS

WELL WITH OIL SHOWS

PLATE 10

IDENTIFIABLE ANTICLINAL ROLLOVERS, FAULTS, AND DIAPIRS IN THE STUDY AREA

NOTE: NEITHER STRUCTURAL CLOSURE NOR ALL CULMINATIONS CAN BE MAPPED WITH THIS DATA SET

WASHINGTON STATE DEPARTMENT OF
Natural Resources
Brian Boyle Commissioner of Public Lands
Art Stearns Supervisor
Division of Geology and Earth Resources
Raymond Lasmanis, State Geologist

U.S. Geological Survey seismic profiles 76-11 and 76-10. © 1989
An Assessment of the Oil and Gas Potential of the Washington Outer Continental Shelf
Stephen P. Palmer & William S. Lingley, Jr.

PLATE 11

U.S.G.S. SEISMIC PROFILE 76-11

U.S.G.S. SEISMIC PROFILE 76-10

See Plate 9 for profile and shotpoint locations.

Reflectors A, B, C, and D are as noted in text.

WASHINGTON STATE DEPARTMENT OF
Natural Resources
Division of Geology and Earth Resources
WASHINGTON SEA GRANT

Plate 12 of 12
U.S. Geological Survey seismic profiles 76-17 and 80-8. © 1989
An Assessment of the Oil and Gas Potential of the Washington Outer Continental Shelf
Stephen P. Palmer & William S. Lingley, Jr.

WASHINGTON STATE DEPARTMENT OF
Natural Resources
Brian Boyle · Commissioner of Public Lands
Art Stearns · Supervisor
Division of Geology and Earth Resources
Raymond Lasmanis, State Geologist
WASHINGTON SEA GRANT

PLATE 12

U.S.G.S. SEISMIC PROFILE 76-17

U.S.G.S. SEISMIC PROFILE 80-8

See Plate 9 for profile and shotpoint locations.

Reflectors A, B, C, and D are as noted in text.