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Exploration for coalbed methane in upper Raging River drainage, King County, Washington.

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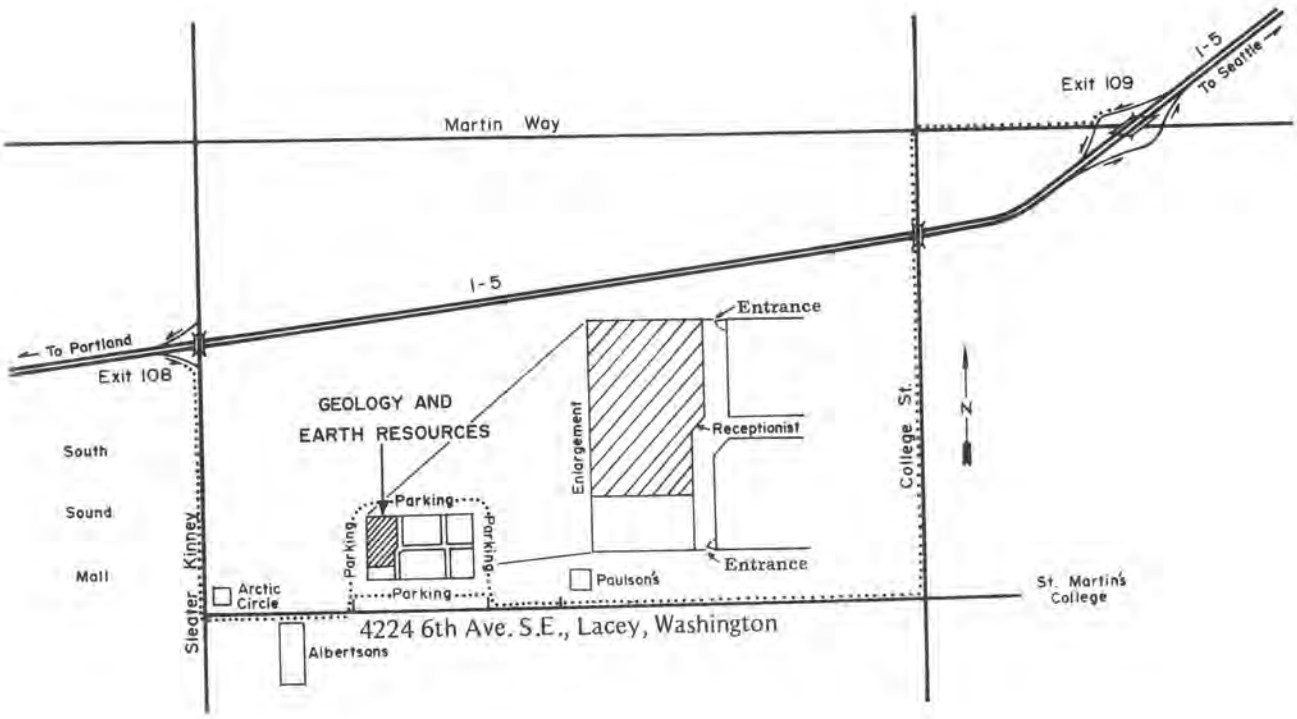

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THE HUMPTULIPS FORMATION – A NEW EOCENE FORMATION OF SOUTHWEST WASHINGTON

By Weldon W. Rau *

INTRODUCTION

During the course of geologic mapping and biostratrigraphic studies conducted by the writer in the northern part of the Grays Harbor basin, major outcrop areas of Eocene sedimentary rocks were encountered. Until now these strata have been informally referred to as "sedimentary rocks of late Eocene age" (Rau, 1966, 1967). With mapping in the Humptulips quadrangle and adjacent areas nearly completed, the extent of outcrop of these rocks is now known. Because these strata do not extend to outcrops of known formations with similar stratigraphic position, and because their lithology and fauna are unique, they are regarded as a new formation and herein named the Humptulips Formation. The name, believed to mean in Native American either "hard to pole" or "chilly region," is derived from the East Fork of the Humptulips River where a major section of these strata is exposed.

DISTRIBUTION

Sedimentary strata of the Humptulips Formation are best exposed in the East Fork of the Humptulips River from its confluence with the West Fork upstream to the volcanics of the Crescent Formation (see map). A belt of outcrop lying in fault contact south of the Crescent Formation extends from the East Fork of the Humptulips River both northwest to the West Fork and southeast for several miles. Although poorly exposed, the formation also underlies much of the upland area between Brittian Creek and Big Creek and flanks the east side of the Crescent volcanics in the upland area between Big Creek and Deep Creek. In addition, the formation is exposed in the main fork of the Wishkah River and its tributaries both north and south of the Aberdeen reservoir. It is poorly exposed in the Wynoochee River for several miles south of the gorge formed by the Crescent volcanics but probably extensively underlies the nearby area between the Wynoochee and Wishkah Rivers. The Humptulips Formation also includes strata exposed immediately south of the Crescent Formation in both the West Fork of the Satsop River and Little River and was mapped both to the west and east of these rivers as "sedimentary rocks of late Eocene age" (Rau, 1966). This term was also applied to strata mapped in the Wynoochee and Wishkah Rivers (Rau, 1967).

Although the known extent of outcrops of the Humptulips Formation is limited to those areas described herein, the formation is believed to be far more extensive and probably underlies, at depth, much of the area southward at least to the Chehalis Valley. It has been penetrated through in both the Continental Oil Co. City of Hoquiam No. 1 well, about 5 miles north of Hoquiam and the Ohio Oil Co. Berry-Robinson No. 1 well in Aberdeen. In addition, a thickness of some 800 ft of the upper part of the formation has been penetrated in the El Paso Products Montesano No. 1-X well near Montesano.

THICKNESS

The thickness of the formation in both the City of Hoquiam and Berry-Robinson wells is in excess of 2,500 ft. Preliminary observations of surface sections indicate that probably the thickest and most continuous section is exposed in the East Fork of the Humptulips River. This section forms the south limb of a syncline and extends for severals miles upstream from the confluence of the East Fork with the West Fork of the Humptulips River. Its thickness may be in excess of 3,000 ft. Some 2,000 ft of section has also been measured in the East Fork of the Humptulips River for approximately one-half mile downstream from the last (southernmost) outcrop of volcanic rocks of the Crescent Formation. Additional surface sections are known in the eastern area in the West Fork of the Satsop River and Little River, The West Fork section has been estimated to be in excess of 2,900 ft (Rau, 1967).

LITHOLOGY

The Humptulips Formation consists primarily of siltstone and mudstone. Many of the beds are massive sandy siltstone. Sandstone beds are not common but are present in places. One of the thicker sequences is exposed in the East Fork of the Humptulips River a few hundred yards downstream from the volcanics of the Crescent Formation. There, a thickness of some 100 ft of sandstone beds varying from 1 inch to perhaps 10 ft in thickness are interbedded with siltstone. Minor thicknesses of

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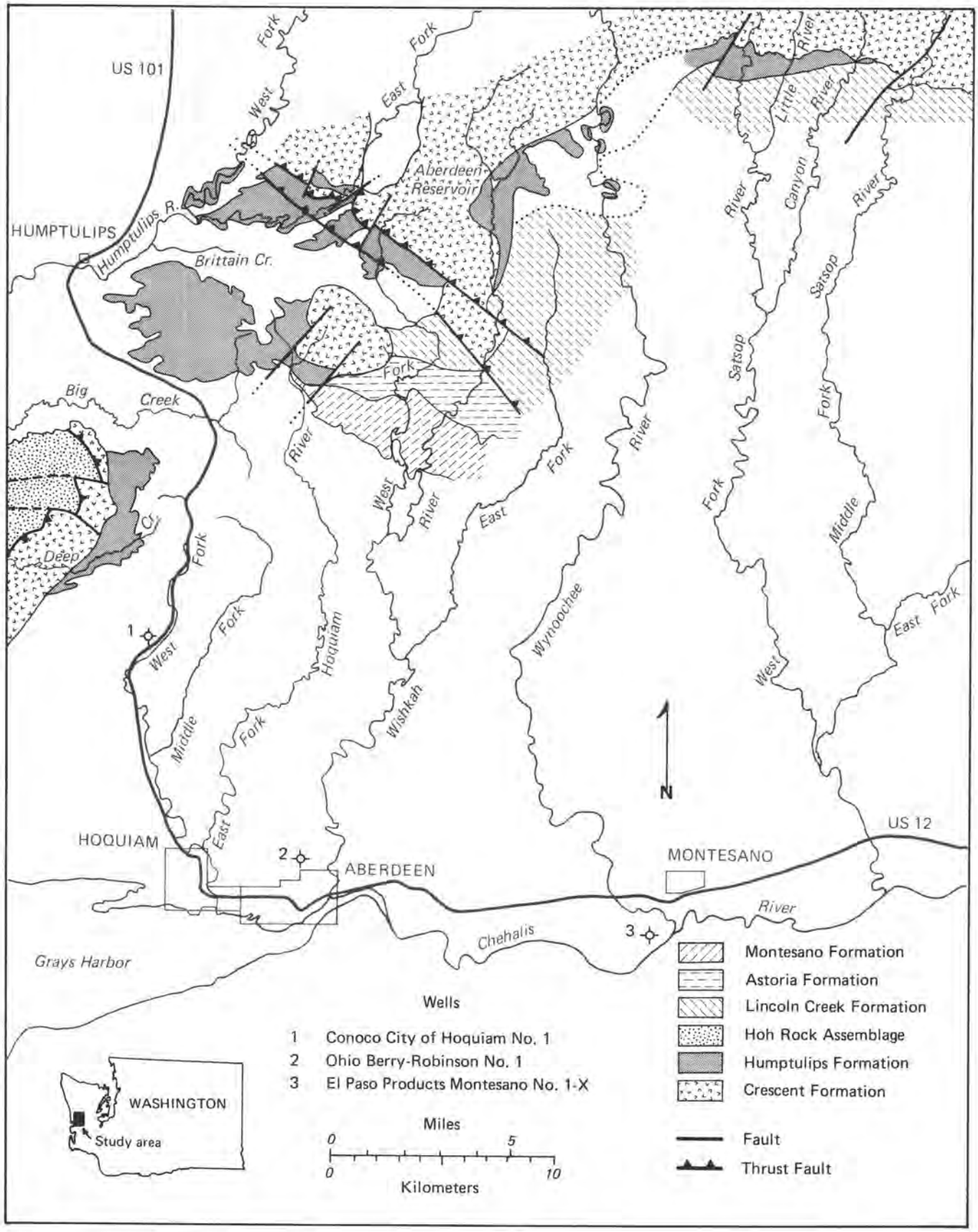

Geologic sketch map showing outcrop distribution of the Humptulips Formation.

sandstone are also found occasionally throughout the formation and are most prevalent in the West Fork of the Satsop River and Little River area where, in places, they are thinly laminated with siltstone. Bedding varies from thick massive beds to thinly laminated strata. Mica is noticeably common throughout the formation. In places, macerated carbonaceous material is common, particularly in outcrops of the Satsop River tributaries where it is particularly noticeable in the thinly laminated strata. Scattered calcareous concretions and concretionary layers occur throughout the formation, especially in the massive siltstone parts. A particularly large calcareous zone approximately 25 ft thick is exposed just downstream from the above-mentioned sandstone strata in the East Fork of the Humptulips River. Stringers of glauconite occur in several sections. Tuffaceous strata are prevalent in the lower part of the East Fork section near the confluence of the East Fork with the West Fork of the Humptulips River. These beds are particularly noticeable because they weather a very light gray or nearly white color. The Humptulips Formation is moderately indurated but is somewhat more indurated in calcareous or concretionary zones. Also, in some places, the tuffaceous beds are brittle, becoming nearly flaggy. The formation as a whole becomes somewhat unctuous when exposed and is therefore subject to the forming of landslides.

STRATIGRAPHIC POSITION

The Humptulips Formation lies stratigraphically below the Lincoln Creek Formation and above the Crescent Formation. In the Satsop drainages, of the eastern area, the basal basaltic sandstone unit of the Lincoln Creek Formation (Refugian Stage) is mapped as resting with apparent conformity on strata of the Humptulips Formation (sedimentary rocks of late Eocene age) (Rau, 1966), and the base of the Humptulips Formation is mapped in unconformable contact with the Crescent Formation (Ulatisian Stage). At depth, in the Ohio Oil Co. Berry-Robinson No. 1 well of the Aberdeen area the Lincoln Creek Formation also overlies the Humptulips Formation with apparent conformity, and the base of the Humptulips Formation rests with apparent unconformity on the Crescent Formation.

BIOSTRATIGRAPHY AND PALEOBATHYMETRY

Foraminifera of the Humptulips Formation from sections of the Satsop tributaries have been listed and discussed by Rau (1966). All represent the Narizian Stage of Mallory (1959). Furthermore, they can be compared with faunas of the *Bulimina schencki-Plectofrondicularia* cf. *P. jenkinsi* zone and to some extent the *Uvigerina* cf. *U. yazooensis* zone of Rau (1958, 1981) of southwest Washington. Numerous additional faunas have been examined not only from the East Fork of the Humptulips River sections but from both the Continental Oil Co. City of Hoquiam No. 1 well and the Ohio Oil Co. Berry-Robinson No. 1 well as well as the El Paso Products Montesano No. 1-X well. Although a formal report is not yet prepared on the faunas of these sections and wells, preliminary studies indicate that they too represent the Narizian Stage and contain faunas of both the *Bulimina schencki-Plectofrondicularia* cf. *P. jenkinsi* zone and the *Uvigerina* cf. *U. yazooensis* zone, as well as at least a part of the *Bulimina* cf. *B. jacksonensis* zone of Rau (1958, 1981). According to current usage (Armentrout and others, 1983), the Narizian Stage ranges through much of the middle Eocene and into late Eocene time.

Essentially all foraminiferal faunas examined from the Humptulips Formation represent substantial water depths of deposition ranging variously within bathyal depths (150-2500 m). The Humptulips Formation therefore represents deepwater deposition during much if not the entire Narizian time.

CORRELATIONS

Within southwest Washington, correlations can be made of the Humptulips Formation with both the Skookumchuck Formation and at least part of the McIntosh Formation of the Centralia-Chehalis area (Snavely and others, 1951a, 1951b, and 1958). To the north, a correlation is also suggested to formations of the north flank of the Olympic Peninsula, where foraminifers similar to those of the Humptulips Formation occur in an upper part of the Aldwell Formation and a lower part of the Twin River Group (Rau, 1964; Snavely and others, 1978). To the south, in the southernmost part of western Washington and in northwest Oregon, the term Cowlitz Formation of Weaver (1912) has been applied extensively to strata containing similar Narizian faunas (Warren and Norbistrath, 1946; Hendrickson, 1956; Roberts, 1958; Livingston, 1966; Newton, 1969, 1976; Van Atta, 1971; Wells, 1981; Wells and others, 1983). Thus, these strata can be regarded as broad correlatives of the Humptulips Formation. Other stratigraphic units of southwest Washington where foraminiferal faunas suggest broad correlation to the Humptulips Formation are unit B of Wolfe and McKee (1968, 1972), siltstone of Cliff Point of Wells (1979), and possibly siltstone of Skamokawa Creek of Wells (1981), as well as the Cowlitz and McIntosh Formations of this same area. Beds in Oregon referred to as the Yamhill Formation (Baldwin and others, 1955) also, in part, contain foraminifers similar to some found in the Humptulips Formation and therefore this Oregon formation may in part correlate with the Humptulips Formation.

DISTINGUISHING FEATURES

The Humptulips Formation differs from the over-

lying Lincoln Creek Formation in that it is noticeably micaceous throughout, far better bedded, and generally less tuffaceous than the Lincoln Creek Formation although tuffaceous beds are present in places in the Humptulips Formation. Furthermore, the fossil content is distinct from that of the Lincoln Creek Formation primarily indicating an older age. The Humptulips Formation differs from the underlying Crescent Formation in that it is entirely sedimentary whereas the Crescent Formation is largely volcanic. Those sedimentary beds present in the Crescent Formation are noticeably more indurated than those of the Humptulips Formation. Furthermore, foraminiferal faunas of the two formations are distinct mainly in that those of the Crescent Formation are of the Ulatisian Stage or older whereas those of the Humptulips Formation are of the Narizian Stage.

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LOW TEMPERATURE GEOTHERMAL RESOURCES OF THE COLUMBIA BASIN, EASTERN WASHINGTON

By Keith L. Stoffel and Mike A. Korosec *

INTRODUCTION

Many intermediate to deep irrigation, municipal, or domestic water supply wells in the Columbia Basin of eastern Washington intersect warm water aquifers. Geohydrologists first noted warm water wells in the basin as early as the turn of the century (Smith, 1901), but few investigations of their distribution and quality were undertaken until the 1970's. Well temperature data collected during the last decade suggest that much of the Columbia Basin could be underlain by low temperature geothermal resources. In light of these findings, the Division of Geology and Earth Resources launched a Geothermal Resources Assessment Program for the Columbia Basin in 1979.

GEOTHERMAL RESOURCES ASSESSMENT PROGRAM

The initial task of the Geothermal Resources Assessment Program staff was to obtain and compile all available well temperature data for nearly 700 wells in the Columbia Basin. Calculated geothermal gradients for 330 of these wells were then plotted and published as the Washington State Geothermal Resources Map (Korosec and others, 1981). Subsequent collection of temperature data for 180 additional wells, in refinement of geothermal gradient calculations, led to the preparation of a more detailed gradient contour map one year later (Korosec and others, 1982).

As a general picture of the distribution of low temperature geothermal resources in the Columbia Basin began to emerge, more detailed geohydrologic studies of the basin were initiated. Geohydrologic investigations completed to date include a study of the low temperature geothermal resources of the Yakima region (Biggane, 1981, 1982, 1983) and an evaluation of geothermal resources in the Moses Lake-Ritzville-Connell region (Widness, 1984). Geophysical well log studies are currently being conducted to learn more about the relationship between stratigraphy, structure, and warm water aquifers in the Columbia Basin (Stoffel, 1984; Stoffel and Widness, 1983a; Stoffel and Widness, 1983b).

DATA COLLECTION AND PROCESSING

Well temperature data collected for the Geothermal Resources Assessment Program were taken from several different sources representing different degrees of quality and reliability. Accurate, reliable data include well temperatures reported by the Washington State University

*Division of Geology and Earth Resources geologists.

Geological Engineering Section, D. D. Blackwell of Southern Methodist University, and the Division of Geology and Earth Resources staff. Well temperatures reported by the U.S. Geological Survey Water Resources Division (from well logs, water supply papers, and the WATSTORE computer data bank) and the Washington State Division of Water Resources (from water supply bulletins) are less reliable because of temperature probe calibration problems or inaccurate data reporting practices (it is often unclear whether the reported temperature is a downhole reading or a flowing temperature measured at the well head).

For each well studied, an effort was made to collect a name, location, total drilled depth, logged depth, and bottom-hole temperature. Geothermal gradients were either measured directly from fluid temperature logs or calculated using bottom-hole and land surface temperatures.

GEOTHERMAL GRADIENTS *

Intermediate to deep wells in the Columbia Basin commonly intersect several aquifers. When these wells are cased to the bottom, intra-borehole flow between aquifers does not occur and fluid temperatures in the well reflect the geothermal gradient of the surrounding rock formation. Fluid temperature logs of cased wells are, therefore, normally straight line temperature/depth plots (fig. 1). Geothermal gradients can be measured directly from these plots. Unfortunately, cased wells are rare in the Columbia Basin. More commonly, wells are wholly or partially uncased and water flows freely between aquifers. Because waters of different temperatures mix, fluid temperatures in an uncased well do not reflect the geothermal gradient of the surrounding rock. Fluid temperature logs of uncased wells are, therefore, stair-step temperature/depth plots with large isothermal sections separated by high gradient "temperature recovery" sections (fig. 2). "Average" geothermal gradients must be calculated from these plots using the equation

$$GG = \frac{BHT - LST}{BHD},$$

where

GG = geothermal gradient,
LST = land surface temperature,
BHT = bottom-hole temperature, and
BHD = bottom-hole depth.

* A geothermal gradient is the rate of increase of temperature in the earth with depth. The geothermal gradient near the surface of the earth varies from place to place, depending upon the heat flow of the region and on the thermal conductivity of the rock. The average geothermal gradient of the earth's crust is approximately 25°C/km.

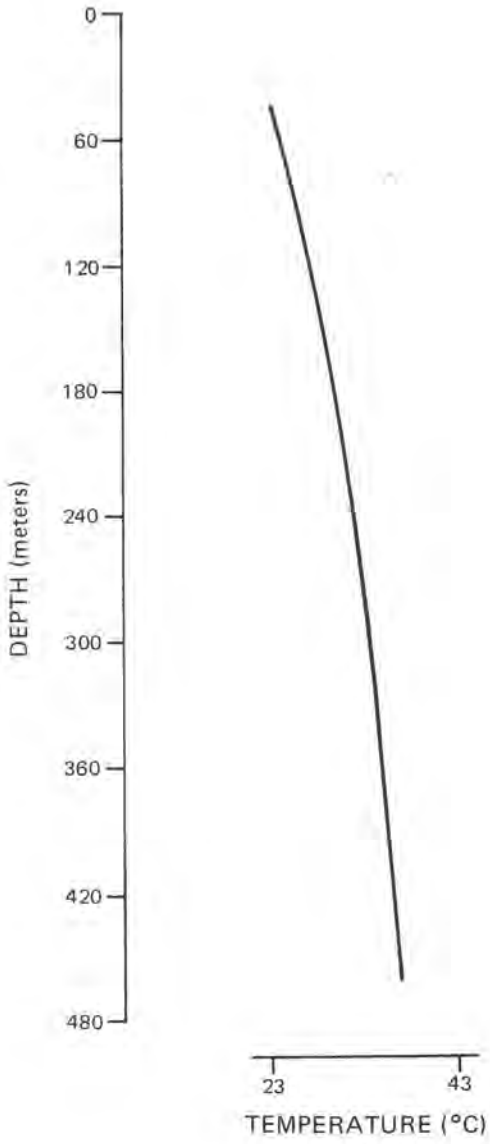

Figure 1. — Fluid temperature log (temperature/depth plot) of a water well cased to the bottom, showing characteristic straight-line gradient.

The accuracy of calculated geothermal gradients is dependent upon the accuracy of the land surface temperature, bottom-hole temperature, and bottom-hole depth data used in the calculations.

Land Surface Temperature Data

Mean annual air temperatures in the Columbia Basin range from 10°C to 14°C and average approximately 11.5°C. Reported mean annual land surface temperatures are slightly higher and more variable. Variations in surface temperatures are primarily controlled by latitude, elevation, vegetation, slope angle, and slope orientation.

Early in the Geothermal Resources Assessment Program, an average mean annual surface temperature of

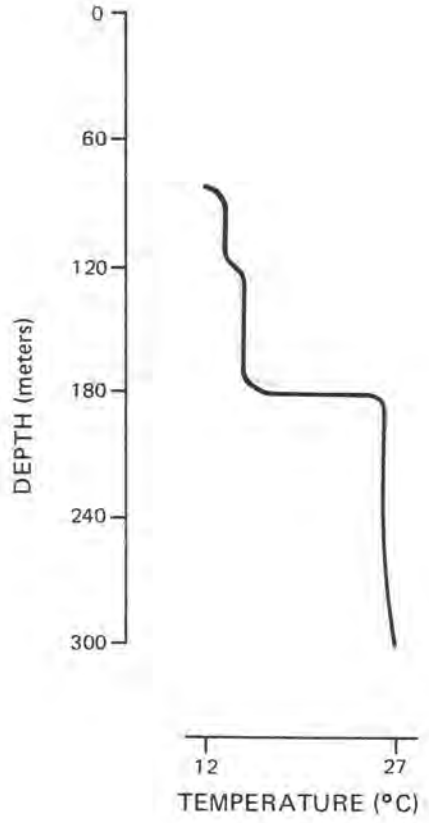

Figure 2. — Fluid temperature log (temperature/depth plot) of an uncased water well, showing characteristic stair-step gradient.

12°C was used in calculations of geothermal gradients for all Columbia Basin wells. The size of the error introduced by using average mean annual surface temperature for geothermal gradient calculations is dependent upon both the total depth and the bottom-hole temperature of the well. Since the difference between the true and assumed land surface temperatures becomes less significant with increased well depth or bottom-hole temperature, the deeper the well or the higher the bottom-hole temperature, the lower the error. As an example, consider a typical Columbia Basin well with a geothermal gradient of 45°C/km and a true land surface temperature of 10°C. For a 100-meter-deep well, use of the average mean annual surface temperature of 12°C (instead of the real 10°C) in the calculation of the geothermal gradient produces a 44.4 percent error. For a 300-meter-deep well, the error is reduced to 14.9 percent; for a 500-meter-deep well, the error is only 8.9 percent.

Bottom-Hole Temperature and Depth Data

An accurate bottom-hole temperature can only be measured at the true bottom of a well. Unfortunately, temperature probes blocked by caved zones, casing step-downs, and other obstructions often measure "bottom-hole" temperatures far short of the well bottom. A "bottom-hole" temperature measured short of the well bottom is potentially distorted by intra-borehole flow and may not be representative of undisturbed thermal conditions in the rock near the well.

The quality of a calculated geothermal gradient can be determined by comparing logged depth and total drilled depth. In general, the closer the values, the higher the gradient quality. Korosec and others (1982) rated the quality of calculated geothermal gradients as follows:

Highest quality gradients are straight line temperature/depth plots (observed over most of the length of the well). These gradients, designated "A" gradients, are generally obtained only from cased wells with no intra-borehole flow.

The next best quality gradients, designated "G," are gradients calculated from wells with logged depth equal to total depth. These gradients are high quality if water in the well flows uphole or is nearly static, but the gradients can be low quality if strong downhole flow occurs.

Gradients calculated for wells logged short of the total drilled depth are designated "S." These gradients are generally not reliable and are considered low quality.

Gradients calculated for wells whose total drilled depth is unknown are designated "U." The quality of these gradients is unknown. Since some of the gradients are from wells logged to total depth and others from wells logged short of total depth, their quality ranges from high to low.

Low quality gradients calculated from flowing wells are designated "F." For these wells, it is assumed that the flowing temperature is equal to bottom-hole temperature. But, since water generally cools as it rises through the well and(or) mixes with cooler water from upper aquifers, these calculated gradients are usually only minimum values.

WASHINGTON STATE GEOTHERMAL RESOURCES MAP

The Division of Geology and Earth Resources published the Washington State Geothermal Resources Map as a first attempt to delineate regions within the Columbia Basin underlain by low temperature geothermal resources (Korosec and others, 1981). Temperature data from 330 wells in the basin were used to crudely define the known extent of the resources. "Favorable" areas outlined on the map are areas with geothermal gradients in excess of 45°C/km; "nonfavorable" areas are dominated by wells with gradients less than 45°C/km. Data reported for each well include location, logged depth, bottom-hole temperature, and a measured and(or) calculated geothermal gradient. The accuracy of the individual gradients plotted on the Geothermal Resources Map varies from high to low, since (1) a land surface temperature of 12°C was used in the calculations of all gradients, (2)

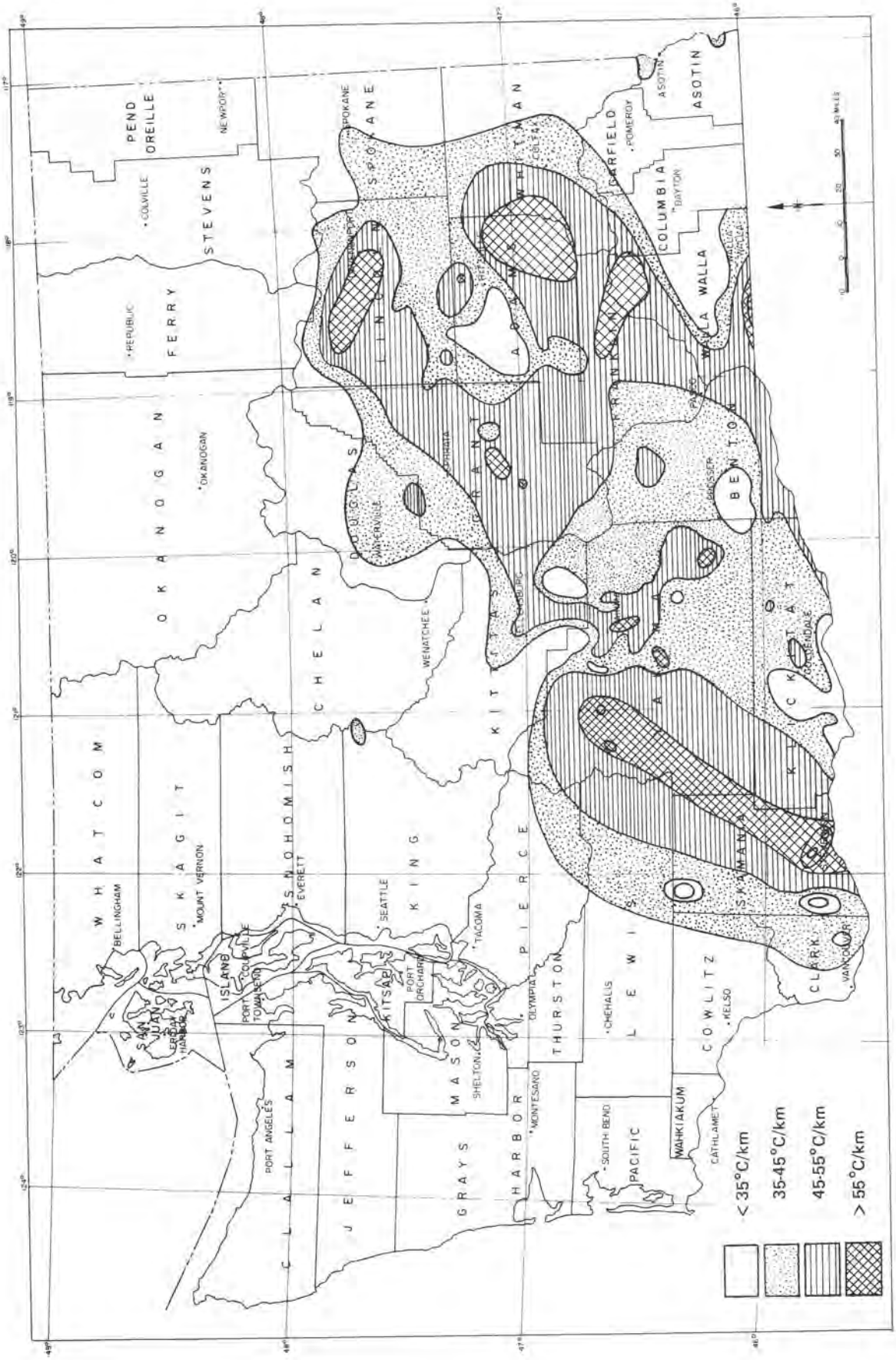

Figure 3. — Temperature gradient contour map of Washington (after Korosec and others, 1982).

wells as shallow as 16.0 meters were included in the data set, and (3) high and low quality gradients (A, G, S, U, and F) were included in the data set.

GEOTHERMAL GRADIENT CONTOUR MAP

Following publication of the Washington Geothermal Resources Map, a geothermal gradient contour map was drawn from a limited set of geothermal gradients. The accuracy of these 150 gradients is high, since (1) land surface temperatures less than 12°C were used to calculate gradients for wells in the northern Columbia Basin (mean annual land surface temperatures are cooler there than in the southern part of the basin), (2) only wells greater than 120 meters deep were included in the data set, and (3) only high quality gradients (A and G) were included in the data set.

The geothermal gradient contour map of eastern Washington is complex (fig. 3). It clearly shows several areas of high gradients (greater than 55°C/km) surrounded by moderate gradients. But, is this map an accurate portrayal of geothermal gradients of the earth's crust in eastern Washington?

It has become obvious from past studies that the single greatest obstacle to the measurement of geothermal gradients in the Columbia Basin is downhole flow. When a well bottoms in an underpressured aquifer, cooler water from the upper portion of the well flows downhole to and into this zone, artificially lowering the water temperature at the bottom of the well. A geothermal gradient calculated from an artificially low bottom-hole temperature will itself be artificially low. The calculated gradient should therefore be considered a minimum value. Downhole flow occurs in most of the low gradient wells (less than 45°C/km) in the Columbia Basin. This suggests that low gradient areas on the contour map simply represent areas dominated by wells with downhole flow. True geothermal gradients for these areas could be significantly higher. If so, geothermal gradients in the Columbia Basin may be far less variable than the gradient contour map suggests.

GEOHYDROLOGIC INVESTIGATION OF SELECTED AREAS

Detailed geohydrologic studies of two "warm areas" in the Columbia Basin were undertaken after publication of the Washington Geothermal Resources Map. The goals of these investigations were (1) to better define the geothermal resources of the basin, and (2) to attempt to correlate known geothermal resources with stratigraphic units and(or) structural features.

Yakima Region

Biggane (1981, 1982, 1983) felt that intra-borehole flow is so common in the Yakima region that well temperature data is of limited use in geothermal resource assessment work. He contended that the traditional method of calculating geothermal gradients from bottom-hole temperatures and assumed land surface temperatures is unsatisfactory in that region. To measure geothermal gradients, Biggane divided the wells into 14 well data groups based upon their geographic proximity, land slope azimuth, and position within the regional ground-water flow system. He then calculated geothermal gradients for each well data group by plotting bottom-hole temperatures against bottom-hole depths (BHT/BHD) and determining the best-fit gradient through these points with linear regression analysis (fig. 4). Geothermal gradients calculated for the 14 well data groups range from 25°C/km to 52°C/km. Unfortunately, the Biggane method of geothermal gradient calculation is subject to the same error that plagues the traditional gradient calculation method. Downhole flow produces artificially low bottom-hole temperatures, so gradients calculated by plotting bottom-hole temperatures against bottom-hole depths will only be minimum values. For this reason, the true range of geothermal gradients in the Yakima region is probably much narrower than reported by Biggane.

Biggane (1982) concluded that local and regional ground-water flow in the Yakima region is largely controlled by geologic structures. The complex distribution of warm water aquifers in the region reflects a high degree of structural complexity.

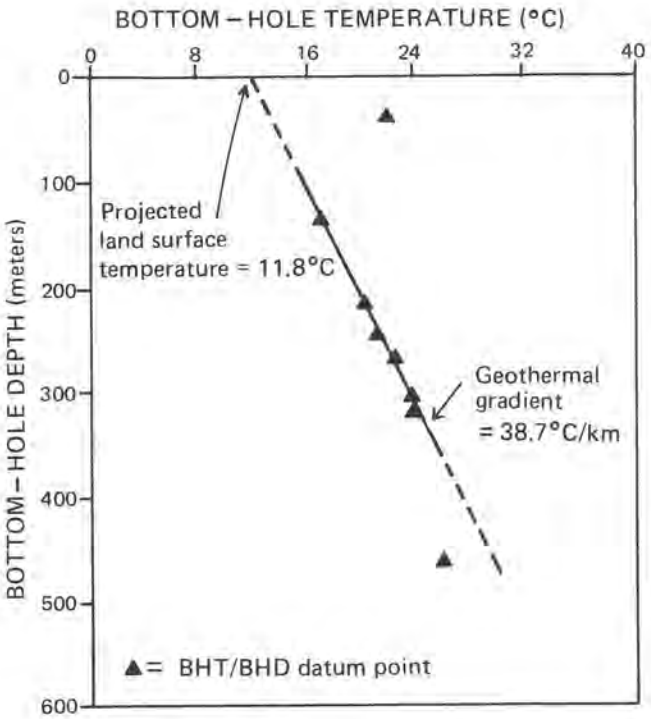

Figure 4. — Bottom-hole temperature/bottom-hole depth plot for a well data group in the Yakima region (after Biggane, 1982).

Moses Lake-Ritzville-Connell Region

Widness (1984) subdivided wells in the Moses Lake-Ritzville-Connell region into five well data groups and calculated geothermal gradients for them by the Biggane method. Calculated gradients range from 25°C/km to 55°C/km, but true geothermal gradients are difficult to obtain from this region because downhole flow occurs in most wells. Therefore, the gradients calculated from the BHT/BHD plots for well groups in the Moses Lake-Ritzville-Connell region are probably significantly lower than the true geothermal gradients in the region.

Widness concluded that both stratigraphic and structural features control local and regional ground-water flow in the east-central Columbia Basin. In this relatively undeformed portion of the basin, ground-water flow is more influenced by stratigraphic complexities than by structures.

GEOPHYSICAL LOG INTERPRETATIONS

All past Geothermal Resources Assessment Program studies have concentrated on delineating the distribution of shallow, warm water aquifers in the Columbia Basin by measuring geothermal gradients of wells. Attention has now turned to defining the nature and extent of the rock formations which enclose the aquifers. Physical properties of both the aquifers and the surrounding rock formations have been measured by interpreting geophysical log suites from wells throughout the Columbia Basin (Stoffel, 1984; Stoffel and Widness, 1983a, 1983b).

The 27 geophysical log suites studied by the Division staff are part of the Columbia Basin log collection gathered by the personnel of the Washington State University Geological Engineering Section since 1967. The suite of geophysical logs for each well includes gamma gamma (density), neutron-epithermal-neutron (porosity), neutron-gamma (porosity), natural gamma (natural radioactivity), spontaneous potential, wall resistivity, caliper (borehole diameter), fluid temperature, fluid resistivity, and flowmeter (fluid velocity and direction) logs.

Information obtained from the study of these geophysical logs for each well include (1) the thickness and nature of stratigraphic units in the well, (2) the location and hydraulic head (pressure) of aquifers in the well, (3) the temperature, flow direction, and flow velocity of borehole fluids in the well, and (4) the geothermal gradient of the well. The quality of the calculated gradient for the well is easily determined, since the relationship between the logged depth and total drilled depth is known and the direction of intra-borehole flow (if any) is evident.

Stratigraphic units have been tentatively correlated between the widely scattered wells studied to date. Log interpretations from more closely spaced wells are needed to better define stratigraphic and structural features in the Columbia Basin, which control the distribution of warm water aquifers.

FUTURE INVESTIGATIONS

Geothermal Resources Assessment Program studies have proven that low temperature geothermal resources do indeed underlie much of the Columbia Basin in eastern Washington. But, how much? Our initial geothermal gradient contour map suggests that distribution of geothermal resources in the basin is complex. It shows several areas with high geothermal gradients (45° to 65°C/km) surrounded by much lower gradients. Unfortunately, gradient contour lines on the map are distorted by poor data from wells with strong downhole flow.

A more accurate gradient contour map of the Columbia Basin can be drawn by eliminating wells with downhole flow from the data set. But, since downhole flow occurs in many areas in the basin, much of the map will have no data. To fill in the blank areas, future investigators must measure "true" geothermal gradients for wells with strong downhole flow. Wells would need to be sealed to prohibit downhole flow, so accurate bottomhole temperatures could be measured and true geothermal gradients determined. Since sealing existing water wells in the Columbia Basin is impractical, an aggressive exploration drilling program would be required. The program would be expensive, but necessary to fully understand the distribution and extent of the low temperature resources in the Columbia Basin.

Future investigations should also include more geophysical well log studies, which will better define relationships between stratigraphic units, structural features, and warm water aquifers in the Columbia Basin. Continuation of the Washington State University geophysical logging program, with the measurement of new wells as they are drilled, would provide hydrologists and geologists an opportunity to update and refine the developing hydrologic models. Present and future investigations will bring us closer to developing the great potential of this source of space heating energy for much of the Columbia Basin.

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METHANE RECOVERY FROM UNDERGROUND COALBEDS

by Steven P. Pappajohn *

INTRODUCTION

In response to the changing energy supply and demand factors of the past decade, increased attention has been focused on alternate supplies of natural gas. The production of methane from unmined or unminable coal seams represents an important frontier in energy exploration and a resource of great economic significance. The United State Bureau of Mines (USBM), the U.S. Department of Energy (DOE), various research organizations, and private industry have all contributed to research and development activities toward the goal of successful commercialization. The future development of coalbed methane reserves depends on detailed investigation and knowledge of the resource and state-of-the-art technology for exploration, recovery, and utilization.

The production of methane from coalbeds can be accomplished through the drilling of vertical boreholes from the surface or horizontal boreholes within underground mines. Conventional oil industry technology can be used in the drilling, completion, and production phases of these projects. In most cases, pipeline quality natural gas is produced directly from underground coalbeds without need for remedial treatment.

Coalbed methane drainage differs greatly from either coal gasification or liquefaction. In-situ coal gasification requires the subsurface retorting (burning) of coal and produces a hydrogen-rich gas of low Btu value (<500 Btu). Coal liquefaction is an above-ground process which requires the addition of hydrogen to coal under high temperatures and pressures. The type and quality of the coal liquids produced depend on the degree of hydrogenation (Lee, 1982).

The environmental impact of coalbed methane resource development is minimal. Drilling operations require a minimum of cleared space, are usually located in remote areas, and do not affect noise or air quality standards in any significant way. Produced water is seldom difficult to handle and can be disposed of and, in some cases, utilized through a number of established methods. Production and pipeline equipment are simple and unobtrusive. Further, the natural gas produced can be used efficiently and cleanly at the site to power production equipment so that the operation can be self-sustaining. Finally, the purity of the gas produced and its clean and efficient reputation as a fuel enhance the possibility of local and regional end-use projects for industry, commerce, and residential sectors. In this manner, produced gas may be consumed locally to power electrical generation, to fuel industrial processes, or to provide heating fuel for homes.

HISTORY

The USBM initiated research on underground coalbed methane drainage in 1964 as part of its efforts to increase underground mine safety and productivity. Coalbeds were degassed ahead of mining operations using vertical and horizontal boreholes to drain the methane. Much of the methane produced in these tests was vented (wasted) to the atmosphere.

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As the data base on coalbed reservoir behavior began to grow and the value of natural gas began to increase in the 1970's, further studies were directed by the DOE. These studies were initiated to identify the magnitude of the coalbed methane resource and to explore the feasibility of commercial production. Motivated by the domestic and strategic need for alternate energy supplies, the DOE solicited and gained the involvement of private industry in research programs and helped establish economic incentives for the production of natural gas from unconventional sources including coalbeds (Natural Gas Policy Act, 1978; Economic Recovery Tax Act, 1981).

Most recently, transfer of research and development activities has been shifted to the private sector. Organizations such as the Gas Research Institute of Chicago (GRI) have cooperated with numerous industrial and energy concerns to develop and implement efficient techniques for the identification and production of coalbed methane reserves. In addition, coalbed methane resources are now being successfully exploited commerically by several private companies in the Appalachian, Black Warrior (Alabama), and San Juan (Colorado and New Mexico) Basins. Exploration efforts are being conducted in several other areas, including the Raton and Piceance Basins in Colorado and selected areas of the Pacific Northwest.

BACKGROUND

Domestic coal resources are nearly 4 trillion tons to depths of 6,000 ft. Significant coal reserves have been identified in 26 states, including Washington (fig. 1). The wide geographical distribution of coal reserves makes local and regional development of coalbed methane resources attractive, with or without ongoing underground mining operations. Although current estimates of coal reserves in Washington are about 6.5 billion tons, actual coal resources may be as much as 60 billion tons based on the great thickness and wide distribution of coal-bearing formations (Choate and Johnson, 1980).

The generation and retention of methane in coalbeds is dependent upon a number of geologic and coal-quality factors, including depth of overburden, thickness and extent of a coalbed, and coal rank. The USBM estimates the in-place coalbed methane resources in United States to be 700 to 800 trillion cubic feet (tcf) of gas, 200 to 300 tcf of which is thought to be recoverable (Duel and Kim, 1978). Approximately 200 tcf represents a 10-year supply at current rates of consumption. The coalbed methane resource in Washington is estimated on the order of 20 tcf in-place. Assuming just 20 percent recovery, those reserves would be enough to satisfy the industrial natural gas needs of Washington for about 40 years at the current rate of consumption (Choate and Johnson, 1980; Washington State Energy Office, 1981).

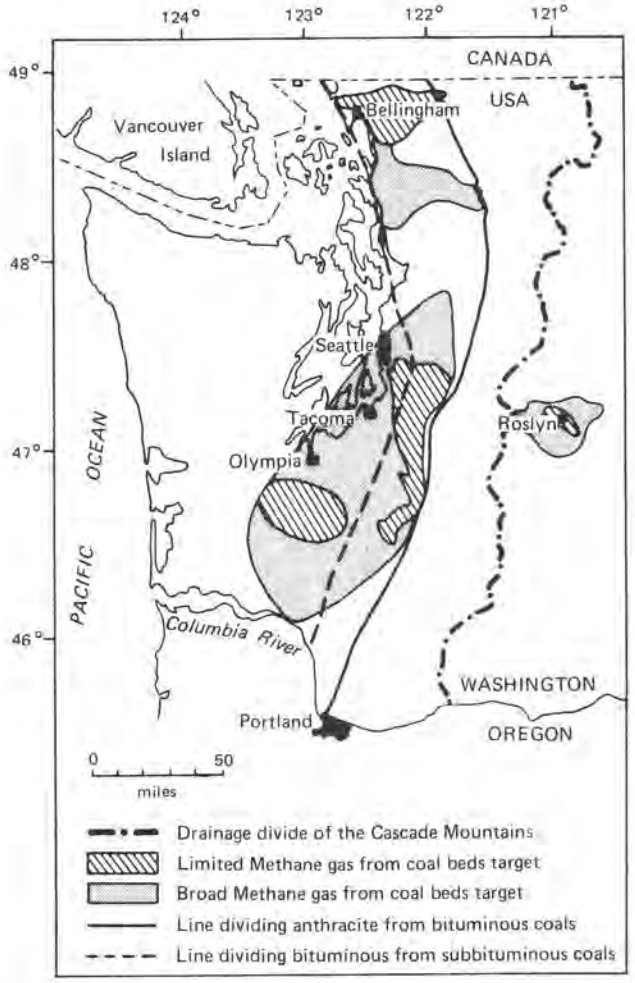

Figure 1. — Coalbed methane target areas in western Washington (after Choate and Johnson, 1980).

COALBED GAS ORIGIN AND COMPOSITION

Natural gas (predominantly methane, CH_4) is generated from primarily carbonaceous material which is indurated and metamorphosed into coal by heat and pressure through geologic time. As the coalification process proceeds, methane and subordinate amounts of other gases (carbon dioxide, nitrogen, and heavier hydrocarbons) are generated by and retained by the source coalbed. Typically, up to 5,000 cubic feet of gas per ton of coal is generated through this process, although only a fifth to a third is retained and stored within coalbed reservoirs (Rightmire, 1984).

Nonassociated ("dry") natural gas, generated from the largely nonmarine (humic) substances that comprise coal, is very similar in composition to associated ("wet") natural gas. Wet natural gas is derived from marine (sapropelic) source rocks and stored in "conventional" reservoirs (see fig. 2). As a result, the Btu value of coalbed methane approximates that of conventional natural

gas. Most coalbed methane is of pipeline quality (1,000 Btu/ft^3), can be used as fuel at the production site, and seldom needs remedial treatment. No documented cases of sour gas (H_2S) have been reported, even from high sulfur coals (Borek and Strever, 1980; Kim, 1973).

MINING HAZARDS

The emission of methane from coalbeds during underground mining operations has always represented a hazard to the industry. Methane (firedamp) is an odorless, colorless gas that is highly combustible in the presence of oxygen (5 to 15 percent methane). Methane-related mining accidents have caused thousands of deaths to miners in the United States since the mid-1800's. In the past, mines were designed to vent as much methane as possible. Presently, increasingly costly ventilation systems and reduced extraction rates are necessary to keep methane concentrations at safe levels as mining takes place in deeper and deeper seams. According to the USBM, over 200 million cubic feet (mmcf) of gas is vented (wasted) to the atmosphere daily by U.S. underground coal mines (Irani and others, 1977).

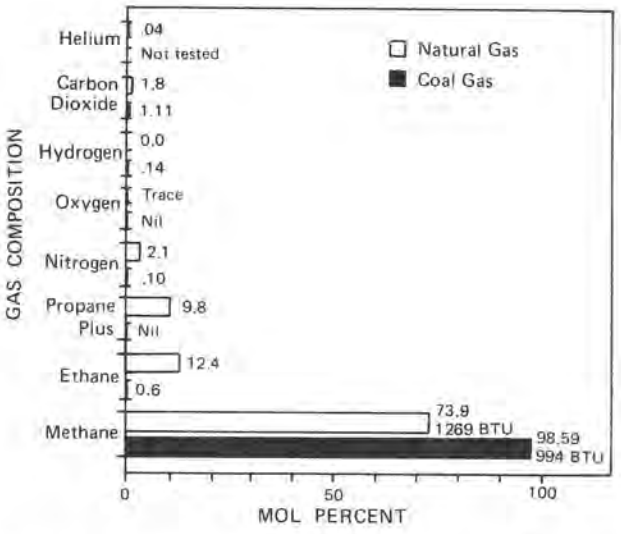

Figure 2. — Comparison of the composition of coalbed with conventional gas (from a well in Adams County, Colorado; Murray and Tremain, 1979).

As the efficiency of pre-mining coalbed methane production and collection systems has improved, more mine operators have supported methane drainage programs. Large-scale projects, such as those being conducted in the Black Warrior Basin in Alabama, have realized several economic advantages of pre-mining methane drainage. The advantages include: (1) increased mine safety, (2) increased coal extraction rates, (3) decreased ventilation system costs, (4) offset of onsite energy costs through utilization of produced methane, and (5) direct sales to gas pipelines to enhance mining economics.

Historical accounts of the gassiness of underground coal mines can be a valuable exploration tool to identify areas of high degasification potential. Reports on the frequency and severity of methane-related mining accidents in Washington have been used to identify the gassiest coal regions of the state. Such studies were conducted several years ago under contract to the DOE for a number of prospective coal basins in the United States (Choate and Johnson, 1980).

COALBED RESERVOIR CHARACTERISTICS

The unconventional behavior of coalbed reservoirs is caused primarily by the complex nature of coal and its dual role as source and reservoir for methane gas. The interactive nature of coal with the stored methane is in contrast with the nonreactive conventional gas-sand reservoir. In order to better understand coalbed reservoir behavior, it is necessary to examine some of the pertinent characteristics of coal.

The basic carbonaceous constituents of coal are extremely small (colloidal size) and, upon aggregation and induration into the organic "structural matrix" of coal, produce exceedingly small pores (typically 5 to 40Å diameter; Å angstrom = .0000001 mm). This finely disseminated "microporosity" system accounts for the majority of the porosity of coal. The most important and startling consequence of the micropore system is the amount of surface area (or micropore "wall space") that is available for the adsorption of gas. Typically, surface area dimensions are 200 to 300 $meters^2$/gram (1.5 million ft^2/lb) compared with 1 m^2/g for conventional sandstone reservoirs (Cervik, 1969).

Filtration qualities, long recognized as a characteristic for carbonaceous substances, such as coal, charcoal, and coke, are dependent on the availability of coal surfaces. Molecules of certain types of gas, such as methane, are preferentially adsorbed to coal surfaces where they are "tightly packed and closely held" (Patching, 1970). In this manner, methane generated within solid coal is adsorbed throughout the micropore network and wherever coal surfaces are present.

The implications for methane storage within coalbeds are very significant. Even at the relatively low reservoir pressures commonly found in coalbeds, coal can store several times as much gas per unit volume as a nonreactive conventional reservoir with 10 percent porosity (see fig. 3). Potential gas reserves for a 1-foot-thick bituminous coalbed covering one acre at optimum conditions of burial, temperature, pressure, etc. are over 1 mmcf of gas (approximately 650 ft^3 gas/ton X 1,800 tons/acre-ft = 1.17 mmcfg) (Cervik, 1969).

A second, more conventional type of porosity system, consisting of fractures or "cleats," occurs naturally

in coalbeds. However, the total contributed porosity by the "macro-porosity" cleat system is far subordinate to the volume contributed by the microporosity system. The dual porosity system is connected by microfracturing within individual blocks of coal bounded by cleats. Fluid behavior in the cleat system responds to hydrostatic pressures and can be described by Darcy fluid flow equations.

In nature, the cleat system is usually saturated with water and some amount of free methane gas. The pressure in the fracture system and the concentration of methane in the micropores are in equilibrium (Cervik, 1969). When equilibrium conditions are disturbed, for instance, by pumping through a vertical borehole to remove water present in the cleat system, two important changes occur in reservoir conditions.

First, the relative permeability of gas increases with decreasing water saturation so that the amount of gas produced increases as water is removed (see fig. 4). As a secondary consequence, methane molecules begin to migrate out of the micropore system and into the cleats in response to decreased concentrations of methane. The diffusion rate of methane from the micropores to the cleats is controlled in large part by the size of the coal blocks which in turn is related to the amount of cleating and microfracturing.

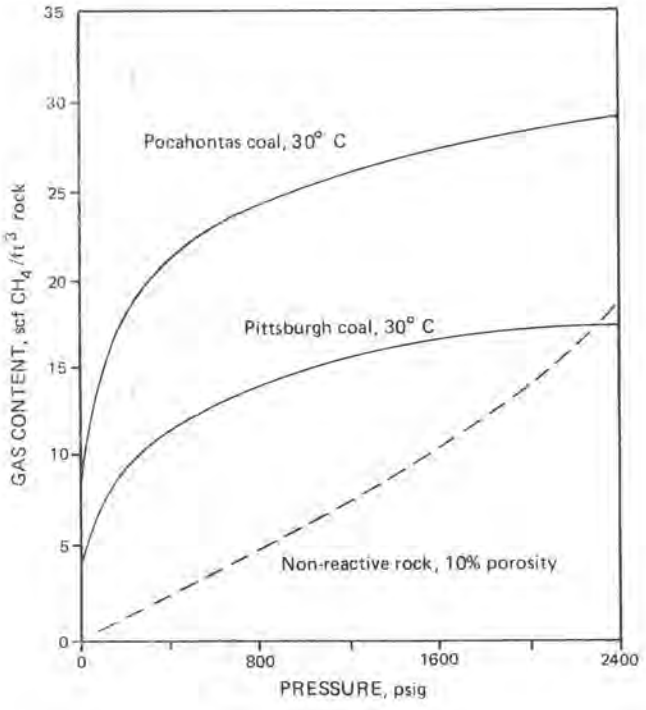

Figure 3. — Comparison of the gas storage potential of coal and 10 percent porosity nonreactive reservoir rock versus reservoir pressure (from Price, 1980).

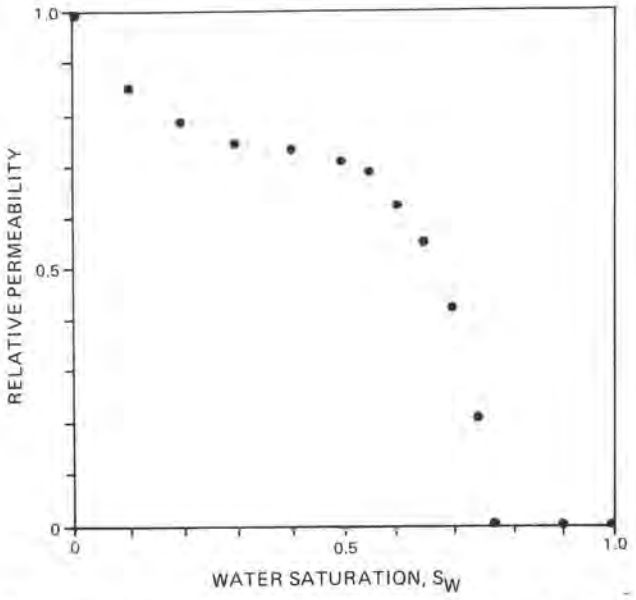

Figure 4. — Gas permeability relative to water saturation (from Lambert and others, 1980).

NEGATIVE DECLINE PRODUCTION CURVES

The phenomenon of "negative decline" (increasing gas production with time) is characteristic of coalbed reservoirs and has been observed in widely separated geographical areas including the Warrior, San Juan, and Appalachian Basins (Harrison and Gordon, 1984; Dunn, 1984; Diamond, 1982; TRW Energy Engineering Division, 1981). As detailed above, the production of gas is likely to increase with time as dewatering occurs in the reservoir. Figure 5 displays water and gas production trends in a degasification-ahead-of-mining project in Alabama. Figure 6 shows the production history of the No. 1 Amoco Cahn Gas Comm. in the San Juan Basin. Both examples contain the characteristic divergence of increasing gas production and decreasing water production over varying time periods. Of particular interest is the production history of the Phillips Petroleum well no. 1-17, also in the San Juan Basin, that has shown increasing gas production over a 20-year period (see fig. 7).

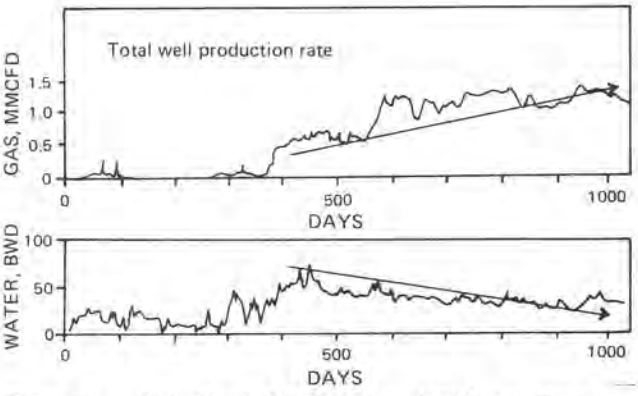

Figure 5. — U.S. Steel Oak Grove project (from Harrison, 1984).

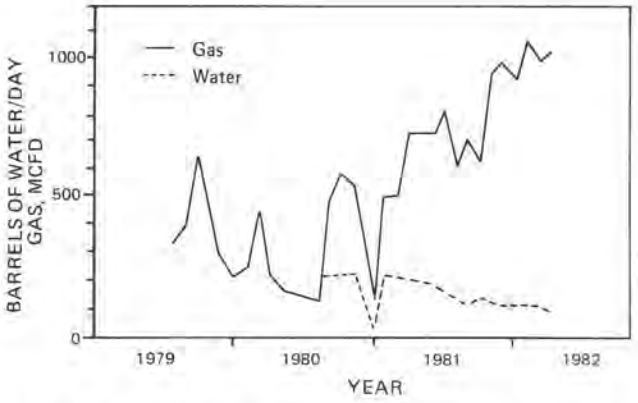

Figure 6. — Cahn Gas Comm. No. 1, 1979-1982 production, NW¼ sec. 33, T. 32 N., R. 10 W. (from Harrison, 1984).

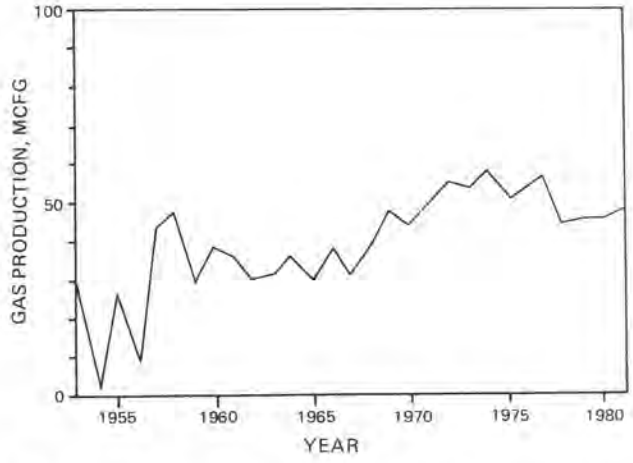

Figure 7. — Annual gas production (from Phillips Petroleum well 6-17; Harrison, 1984).

LEGAL ASPECTS OF COALBED METHANE PRODUCTION

In cases where oil and gas ownership has been separated from coal ownership and legal precedent addressing the disposition of coalbed methane has not been determined, the potential for litigation exists if either or both resources are to be developed. The oil and gas leaseholder may feel that all hydrocarbons, regardless of stratigraphic interval, are covered by the oil and gas lease. But the existence of gas exclusively within a minable coalbed may concern the coal leaseholder more directly. Historically, the courts have been influenced to rule in favor of coal owners in areas dominated by coal mining and in favor of gas owners in oil and gas production regions (Maslowski, 1984).

The Solicitor General of the United States has rendered an opinion on this question that has served as a guideline for federal lands (Memorandum M-36935, 1981). Essentially, the analysis concludes ". . . that a reservation of 'coal' does not include coalbed gas; and that a reservation of 'gas' encompasses coalbed gas." However, when dealing with any type of lease (federal, state, fee, etc.) in preparation for coalbed methane projects, care should be exercised. It is, of course, preferable to control all minerals, oils, coal, and gas, to eliminate ownership questions. Lacking total control, specific language addressing coalbed methane needs to be included in either or both cases. In any case, the promotion of cooperation among all parties involved is necessary for the most efficient development of the natural resources concerned.

COALBED METHANE DEVELOPMENT AND UTILIZATION

The considered aspects of coalbed methane resource development, including the magnitude and distribution of U.S. coal reserves, benefits to mining development, relatively inexpensive drilling programs, and the longevity of well production, make such programs attractive, especially in regions where natural gas demand is high. As a consequence of a series of energy supply and demand factors, the Pacific Northwest contains significant coalbed degasification potential. Reasons for this development potential include: (1) substantial coal resources of suitable depth, rank and quality, (2) indications of gassy coal, (3) limited regional coal mining or natural gas production, (4) major population and industrial centers in proximity to areas of high potential, (5) numerous municipalities, farm and dairy co-ops, government facilities, and timber operations within areas of high potential, (6) rapidly rising utility rates and (7) a populus acutely aware of the need for dependable, uninterruptable, and environmentally acceptable local energy sources.

The versatility of natural gas as an energy source enhances its range of utility. Normally, methane produced from coalbeds requires very little remedial treatment, so that it may be used onsite to power certain production equipment. Onsite generation of electricity or use in nearby facilities to power generating equipment or industrial processes is also possible. Direct sales to pipelines or utility companies may also be achieved. In any eventuality, the cooperation of resource developers with governmental and industrial concerns will be required for successful ventures and to serve best the needs of the public.

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NWMA ANNOUNCES 90TH ANNUAL CONVENTION

The Northwest Mining Association will hold its 90th annual convention in Spokane on December 6, 7, and 8, 1984. The convention theme will discuss the long-term future of mining in the United States. Attendance is expected to exceed 2,500. The approximately 80 speakers will address the technical, management, and environmental

aspects of current concern to the minerals industry.

The NWMA pre-convention short course will be held in Spokane on December 3, 4, and 5. The course will present the anatomy of a mine feasibility study in a workshop course using 10 or more industry experts.

Registration information for the convention and short course is available from the Northwest Mining Association, 633 Peyton Bldg., Spokane, WA 99201, (509) 624-1158.

AAPG PUBLISHES GEOLOGIC MAP OF THE NORTHEAST QUADRANT OF THE CIRCUM–PACIFIC REGION

The Circum-Pacific Map Project is a cooperative international effort designed to show the relationship of known energy and mineral resources to the major geologic features of the Pacific basin and surrounding continental areas. The geologic map of the northeast quadrant is the first to be published in a series of five. Information depicted in color includes geologic units on land, seafloor sediment, Deep Sea Drilling Project (DSDP) sites, stratigraphic columns for selected DSDP boreholes, and age and lithology of the selected bedrock samples. The address where the map may be purchased is listed in the reference below:

Drummond, Kenneth J.; and others, 1983, Geologic map of the Circum-Pacific region, northeast quadrant: American Association of Petroleum Geologists, 1 sheet, scale 1:10 million, with 36 page text. (Available for $12.00 from AAPG, Box 979, Tulsa, OK, 74101.)

DIVISION OF GEOLOGY AND EARTH RESOURCES RELEASES OPEN-FILE REPORTS

The following open-file reports may be purchased from the Department of Natural Resources, Division of Geology and Earth Resources, Olympia, WA 98504; they are also available for inspection in our Division library.

Please send $1 to cover our Handling and Distribution charge for your total publication order.

Manson, Connie J., compiler, 1984, Preliminary bibliography and index of the geology and mineral resources of Washington, 1981-May 15, 1984: Washington Division of Geology and Earth Resources Open-File Report 84-5, 594 p. Price $10.00.

Walsh, Timothy J., 1984, Geology and coal resources of central King County, Washington: Washington Division of Geology and Earth Resources Open-File Report 84-3, 25 p., 3 plates. Price $3.00.

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Banister, D. P.; Barnes, D. J.; Longwill, W. D., 1984, Availability of Federal land for mineral exploration and development in the State of Washington: Washington Division of Geology and Earth Resources Geologic Map GM-30, 4 plates accompanied by 17 pages of text, scale 1:500,000. Prepared in cooperation with the U.S. Bureau of Mines. Free.

Stoffel, K. L., 1984, Geology of the Grande Ronde lignite field, Asotin County, Washington: Washington Division of Geology and Earth Resources Report of Investigation 27, 79 p., 1 plate, scale 1:48,000. Price $4.00.

SUMMARY OF U.S. GEOLOGICAL SURVEY CURRENT ACTIVITIES IN WASHINGTON DURING 1984

These U.S. Geological Survey projects are in progress and the maps and reports mentioned are not yet available. This listing is only for information about the current work of the U.S. Geological Survey in our state.

Frontier Tertiary and Mesozoic hydrocarbon basins of the western United States – Compilation of thermal maturation maps for Oregon and Washington is in progress. [Project chief: T. D. Fouch.]

Volcanogenic manganese deposits – Field investigations in Washington continued. Detailed chemical analyses of ore samples from manganese deposits are underway. Compilation of major and trace element data for resource evaluation will be initiated. Reports on the characteristics of manganese deposits in the western cordillera; manganese deposits in siliceous environments; and the chemistry of volcanogenic manganese deposits in the western United States are being prepared. [Project chief: R. A. Koski.]

Geochronology – Age and isotopic studies in Idaho and northern Washington will continue. Sr isotopic variations will be used to identify major crustal boundaries in these areas. Studies to date demonstrate the ability to identify small differences in amounts of assimilated sialic crust, the geographic variation of these differences, and the difference between upper and lower crustal com-

ponents. The relationship between these variations and mineralization should provide tests of various hypotheses on the origin of the ore deposits. A reconnaissance K-Ar geochronologic study of Mount Adams, Washington, to delineate the age of major volcanic units and reconstruct its eruptive history is also planned. [Project chief: R. J. Fleck.]

Crustal strain — Deformation in Washington is being studied. These studies will include resurveying of trilateration and geodolite networks and the preparation of reports on significant results. [Project chief: W. H. Prescott.]

OFFSHORE

Modern massive sulfides — Samples from the Juan de Fuca Ridge, offshore Washington and Oregon will be acquired for analyses. [Project chief: Robin Brett.]

Geochemistry of stratabound sulfide deposits — Stable isotope studies of samples from the Juan de Fuca Rise and offshore Oregon and Washington is underway. [Project chief: W. C. Shanks.]

Sulfides — Sulfide and basalt samples from the Juan de Fuca Ridge will be analyzed and a report on the results will be prepared. [Project chief: J. A. Philpotts.]

Marine geology and resources of western conterminous United States — Studies are continuing in the collection and analysis of marine geophysical data and sea floor samples from the Exclusive Economic Zone (EEZ) areas off California, Washington, and Oregon. Goals of the project are to describe the geologic framework as a guide to resource assessment, geologic processes, neotectonics, and environmental hazards. [Project chief: David McCulloch.]

Sea floor hydrothermal studies — Two new directions for research have presented themselves. One is the discovery of thermophilic bacteria in the vent waters at 21 degrees north, Eastern Pacific Rise, and the other is the scheduling of the deep submersible Alvin for use of the Geological Survey on the Juan de Fuca vent field, offshore Oregon and Washington. New strains of bacteria have recently been isolated and cultured from the vent waters by John Baross of Oregon State University, and have thrived in laboratory experiments up to an astounding temperature of 250 degree C, the maximum conditions of the experimental equipment. There are minor but systematic differences, particularly with the heavy metals, between the chemistries of the vent waters and those produced in our laboratory experiments using sterilized seawater at 350 degrees C. It is possible that these differences are due to bacterial activity in the sea floor systems. If this is true, then bacteria play a role in metasomatic processses in general, a rather staggering idea. Plans are underway, in collaboration with Baross, to perform tandem experiments progressively heating seawater with basalt. One system will be inoculated with a vent culture of bacteria while the other will be kept sterile. The two experiments will range up to 450 degrees C and paired samples will be analyzed for major and minor dissolved species and gases. The experiments should tell the maximum conditions at which bacteria can live, and the role they play in controlling the metal concentration and other dissolved components of the fluid.

During the summer of 1984, the deep submersible Alvin was tentatively scheduled to dive on the Juan de Fuca massive sulfide mounts discovered by the Geological Survey in 1979. During the dives, actively discharging vents will be located and sampled. Temperature at the vent orifice will be measured, and the pure vent fluids will be sampled. Some of the analyses will be performed immediately on board the support vessel; aliquots will be separated and preserved for numerous analyses at shore-based laboratories. [Project chief: Jim Bischoff.]

Oceanic volcanism — Petrologic studies of the Juan de Fuca Ridge and Gorda Ridge were completed along with geochemical studies of Juan de Fuca sulfides and hydrothermal deposits. [Project chief: D. A. Clague.]

Olympic Peninsula offshore-onshore geologic transect — A structural map of the continental margin of southwest Washington, based upon interpretation of seismic-reflection profiles, magnetic and gravity data, and subsurface information from oil test wells, is being prepared. Reconnaissance geologic studies and sampling for hydrocarbon analyses in the melange terranes along the west side of the Olympic Peninsula, Washington, are also planned. A report on the Tertiary evolution of the continental margin of Oregon and Washington is being prepared for inclusion in an AAPG Memoir. [Project chief: P. D. Snavely.]

Northwest U.S. subduction zone risk assessment — The possible source characteristics and ensuing strong ground motions and tsunami hazards for hypothetical great shallow subduction zone earthquakes off the coast of Washington and Oregon were studied. [Project chief: T. H. Heaton.]

Hydrothermal fluids — Project personnel will participate in investigations of hydrothermal systems at the Juan de Fuca Ridge spreading center. This investigation will include the development of models of the behavior of silica in heated sea water circulating through rock at active spreading centers. [Project chief: R. O. Fournier.]

WESTERN WASHINGTON

Quaternary dating and neotectonics – Preparation of reports and maps on the glacial chronology of the Chehalis River basin, west-central Washington, and on Quaternary and Pliocene faults in the western United States continued. [Project chief: K. L. Pierce.]

Mid-Tertiary chronostratigraphic framework, Pacific Northwest – Primary emphasis will be on the initial drafting or completion of reports on the following topics: new mollusks from the upper Lincoln Creek Formation, Washington, and their correlation with the upper Twin River Group; sequential mineralization in the phragmocone chambers of the Tertiary cephalopod *Aturia*; paleoecologic implications of the Oligocene benthic foraminiferal assemblages at Knappton, Washington; correlation of mid-Tertiary Formations of southwestern Washington; correlation of mid-Tertiary Formations of the northern Olympic Peninsula, Washington (last two reports are dependent on availability of laboratory facilities); and correlation of the Miocene Pillarian and Newportian molluscan stages from Alaska to California. [Project chief: K. A. McDougall.]

Correlation of Tertiary marine basins, Pacific margin, U.S. – Range charts for early and middle Miocene mollusks from Alaska, Washington, Oregon, and California are being prepared. [Project chief: E. J. Moore.]

CASCADE RANGE

Geologic map of the Cascade Range – Compilation of the geology of the Cascade Range is continuing, along with a list of K-Ar ages in the Cascade Range in Washington, and preparation of a map of vent types and ages for the Cascade Range. [Project chief: J. G. Smith.]

Mount St. Helens basement rocks – Geologic mapping of Spirit Lake 15-minute quadrangle will be completed, and mapping of the bedrock in the southern half of Mount St. Helens National Volcanic Monument will be initiated. Fission-track dates for the Spirit Lake pluton and volcanic host rocks and K-Ar dates for the Earl porphyry copper deposits will be determined. [Project chief: R. P. Ashley.]

Beryllium isotope anomaly investigations of lavas from the Cascade Range – A test of the anomalous mantle hypothesis – Existing samples from the Cascade Range will be analyzed to assess the feasibility of using an isotope of beryllium as a geochemical tracer in volcanic arcs to evaluate crustal recycling. A report on these initial investigations will be in preparation. [Project chief: S. E. Church.]

Geomagnetic-telluric array studies of the Cascade Range – Fieldwork is being done in western Washington to fill data gaps and test a recently developed field data processing system. The principal exploration target is a deep-crustal conductor that is interpreted as a subducting sedimentary plate. A preliminary report on the geomagnetic variation field of western Washington is in preparation. [Project chief: J. N. Towle.]

Remote sensing studies of the Cascade Range – The major activity planned is the completion of an open-file report showing the linear-feature data mapped from Landsat images of the Cascade Range. Secondary maps derived from these data and a report summarizing the geologic interpretation of the linear-feature data, with special emphasis on a major west-northwest trending lineament that transects the Cascade Range near the latitude of 44 degrees, will also be prepared. [Project chief: D. H. Knepper.]

Infrared aerial surveillance of volcanoes of Cascade Range – The structural control of heat emission at Cascade Range volcanoes, estimation of high-level heat flow and thermal energy yield of volcanic activity using aerial infrared methods, is being investigated. Calibrated aerial infrared images of selected Cascade Range sites will be acquired. Preparation of reports on the results of these studies will continue. [Project chief: J. D. Friedman.]

Geophysics of the Cascade Range – A series of gravity maps for Oregon and Washington and for the Cascade Range will be completed during 1984. Interpretation of data from the Cascade Range will continue. A report on the Goat Rocks Wilderness will also be prepared. Field work at Mount Baker is planned. [Project chief: D. L. Williams.]

Magnetotelluric sounding for geothermal resource assessment – Processing and interpretation of magnetotelluric data obtained in the Mount Rainier-Mount St. Helens-Mount Adams region during 1983 will continue. The magnetotelluric data, which generally sounds to depths of 30-40 km, will be combined with geomagnetic variation data and interpreted to obtain information on deeper electrical structures related to the subduction of the Juan de Fuca Plate beneath the Cascades. Additional field work of a more detailed nature is planned for the Mount St. Helens region where a northwest-trending conductor associated with an apparent shallow alteration system was found in 1983 field studies. [Project chief: W. D. Stanley]

Aeromagnetic survey of the Cascade Range – During 1984, aeromagnetic data for the Cascade Range, which will include all of Oregon and California, and, if

the data are of sufficient quality, Washington, will be acquired and interpreted. A computer program that will estimate depth to the bottom of a magnetic layer will be developed and tested. [Project chief: R. J. Blakely.]

Snoqualmie Pass quadrangle, Washington – A geologic map of the Snoqualmie Pass (1:100,000 scale) quadrangle will be completed and submitted for review and open-file release prior to its formal full-color publication. The chemistry, petrography, and age of Oligocene and Miocene volcanic rocks of the Cascade arc will continue to be studied. [Project chief: R. W. Tabor.]

Geology of the eastern half of the Doe Mountain quadrangle, Washington – A large number of igneous and sedimentary rock samples were collected; modal analyses and petrographic studies will be conducted on these samples. Compilation of 1:100,000-scale geologic maps of the Robinson Mountain and Twisp quadrangles will continue, along with mapping of the eastern half of the Concrete 2-degree quadrangle. [Project chief: V. R. Todd.]

Sauk River 1-degree quadrangle, Washington – Mineral separation, K-Ar, U-Th-Pb, and fission-track and petrographic studies are being conducted on previously collected samples. Field mapping and collection of additional samples for age dating will continue. [Project chief: R. W. Tabor.]

Volcano monitoring – Short wave length data for Mount St. Helens and Mount Hood, Washington and Oregon, have been received from the Department of Energy and dual-frequency analysis of local thermal features is being conducted. [Project chief: H. H. Kieffer.]

Experimental mapping of liquefaction potential – A report on attenuation of severity of liquefaction effects with distance from the seismic energy source is being prepared. The liquefaction potential of materials in the blockages impounding Spirit Lake, Castle Creek, and Cold Water Creek in the Toutle River valley north of Mount St. Helens was investigated. Instruments were placed in the Spirit Lake and Castle Creek blockages to measure both deep (100 ft) and surficial ground motions and pore-water pressures as they develop during possible future earthquakes. Field tests were conducted and additional field test data were collected from other agencies, such as the Corps of Engineers. Analysis of these data will continue. [Project chief: T. L. Youd.]

Three-dimensional near-field modeling and strong ground-motion prediction in a layered medium – In July and August of 1983, liquefaction arrays (each consisting of two downhole accelerometers, four downhole piezometers, and recording systems) were installed at Spirit Lake and South Fork Castle Creek debris dams, Washington. Three free-field instruments were installed, and monitoring of the arrays will continue. [Project chief: R. J. Archuleta.]

Spirit Lake hazard evaluation liquefaction studies – Instrumentation installed at Spirit Lake will be monitored. [Project chief: A. T. Chen.]

Geothermal tectonic seismic studies – Seismic monitoring of Mount St. Helens and volcanoes in northern Oregon and Washington continued. Seismicity in the Spirit Lake area will be characterized, including a detailed analysis of seismic sources near Elk Lake. A spatial variation of b is observed across the Elk Lake aftershock zone, and we hope to test the hypothesis that the variation is related to changes in physical properties. An analysis of the seismicity and volcanism pattern in Washington and northern Oregon, as it relates to plate-scale subduction geometry, will be completed. The orientation of P-axes, relative to the direction of convergence between the North American and Juan de Fuca Plates in the Puget Sound region, will be compared with P-axes determined in other subduction zones around the Pacific rim. [Project chief: C. S. Weaver.]

Engineering implications of the Mount St. Helens eruptions – Additional funding has been provided for this project to study tributary lakes at Mount St. Helens. Analyses of data from inclinometers at South Fork Castle Creek and Spirit Lake and slope stability (static and dynamic) and piping studies are underway. [Project chief: R. L. Schuster.]

Hydrothermal fluids – Hot-spring waters from Mount St. Helens, Washington, will be collected and analyzed. [Project chief: R. O. Fournier.]

Volcanic hazards – Fieldwork at Mount Rainier to revise the existing volcanic-hazard evaluation and to study blast deposits from Mount St. Helens is continuing. The benefits of a ground-penetrating radar system for studies of pyroclastic-flow phenomena will be evaluated. [Project chief: R. P. Hoblitt.]

Tephra hazards from Cascade Range volcanoes – Efforts will be directed toward completing and field checking a summary report on the principal pre-1980 tephra-fall deposits from Mount St. Helens, and reviewing stratigraphic-petrographic variations in the 1980 tephra-fall deposits and comparing them with similar variations in pre-1980 deposits. [Project chief: D. R. Mullineaux.]

Geochemistry of gas-forming elements – A report on hydrogen monitoring at Mount St. Helens, Washington, is being prepared. [Project chief: Moto Sato.]

Volcanology and petrology of late Cenozoic magmatic systems – Fieldwork at Mount Adams volcano in Washington is planned. [Project chief: R. L. Christiansen.]

Mount St. Helens volcano monitoring – The primary monitoring activities, consisting of seismic, deformation, and volcanic gas measurements, will continue at Mount St. Helens. The apparent change in eruptive behavior of Mount St. Helens will probably require some modifications to these techniques. Another technique that will be incorporated into the monitoring program will be photographic and photogrammetric methods that detect slow dome growth. Deformation measurements on other selected Cascade Range volcanoes, development of continuous recording systems, development and assembly of systems for a quick-response kit for monitoring sudden activities at other volcanoes, and enhancement of techniques for estimating probabilities of various volcanic events for risk assessments will continue. [Project chief: D. W. Peterson.]

Cascade volcanoes observations – Development of a model for Mount St. Helens that includes its mechanism of eruption, its eruptive products, and its relationship to other Cascade Range volcanoes will continue. In addition, the following topics will also be addressed: Chemical and isotopic studies of the gases and solid eruptive products; petrologic studies of the lava; geophysical studies, including gravity, magnetics, electrical, detailed seismic, and heat radiometer studies; and detailed geologic studies of the dome, crater, and nearby air-fall, pyroclastic flow, and avalanche deposits. [Project chief: D. W. Peterston.]

Mineralogy and geochemistry of active hydrothermal and fumarolic alteration processes – A report will be prepared on fumarolic incrustations related to the 1980-1982 eruptive activity of Mount St. Helens, Washington. [Project chief: T. E. C. Keith.]

Geology of interactions among volcanoes, glaciers, and water – Field mapping in the Columbia River Gorge is planned. A report on glaciation of the northeastern Cascade Range is being prepared. [Project chief: R. B. Waitt.]

EASTERN WASHINGTON

NTS-petrophysics – A paleomagnetic study of the Touchet beds in Washington is being undertaken in support of volcano hazards assessments of the Cascade volcanoes. [Project chief: L. A. Anderson.]

Ground failure hazards in the Columbia River valley, Oregon and Washington – At the request of the Bureau of Land Management, a special study was conducted on the stability of slopes below the spoil pile of the Sherwood uranium mine on the Spokane Indian Reservation. The final report to the Bureau of Land Management on the results of this study is being prepared. Final reports will be prepared on irrigation-induced landslides along the middle of the Columbia River and on landslides in the White Bluffs area of the Columbia River. [Project chief: W. H. Hays.]

NORTHEASTERN WASHINGTON

Colville Indian Reservation geophysical studies – A report on electromagnetic soundings on the Colville Indian Reservation, Washington, is being prepared. [Project chief: V. J. Flanigan.]

Uranium source rocks studies – Volcanic rocks – The chemistry of surface, spring, and pore waters at a young uranium deposit in organic-rich sediments in northeastern Washington will be described, and leaching experiments to determine the sites and chemical stability of uranium associated with these organic-rich sediments will be conducted. [Project chief: R. A. Zielinski.]

Uranium in surficial environments – Reconnaissance field work in Washington was initiated in 1983, and detailed studies of samples from the Flodelle Creek deposit in northeastern Washington will continue. Similar deposits are widespread throughout granitic terranes in northeast Washington and northern Idaho. The deposits range in size from a few hundred pounds to over 1 million pounds and occur in clusters along drainages in favorable geomorphic settings. Detailed reconnaissance in northeast Washington and northern Idaho are planned. [Project chief: J. K. Otton.]

Okanogan geologic map, Washington – Geologic mapping is underway in the Omak 7½-minute quadrangle, the southern one-quarter of the Boot Mountain 15-minute quadrangle, and the northeastern one-eighth of the Republic 15-minute quadrangle. [Project chief: K. F. Fox.]

Seismological observatory – The seismologic and geomagnetic observatory continues to operate in Newport, Washington. Data acquired through this observatory will be used in responding to inquires from the public, State and Federal agencies, and the scientific community on geophysical and seismic phenomena. [Project chief: L. E. Kerry.]

RECENT U.S. GEOLOGICAL SURVEY OPEN-FILE REPORTS ADDED TO OUR DIVISION LIBRARY

The following U.S. Geological Survey Open-File Reports are now available for inspection in our Division library. However, if you wish to purchase any of these reports, please write or call:

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Atwater, B. F.; Rinehart, C. D.; Fleck, R. J., 1984, Preliminary geologic map of the Colville Indian Reservation, Ferry and Okanogan Counties, Washington; with a table of potassium-argon ages: U.S. Geological Survey Open-File Report 84-389, 20 p., 4 plates.

Chleborad, A. F.; Schuster, R. L., 1984, Stability of slopes below the Sherwood uranium mine, Spokane Indian Reservation, northeastern Washington: U.S. Geological Survey Open-File Report 84-627, 52 p., 1 plate.

Finn, Carol; Phillips, W. M.; Williams, D. L., 1984, Gravity maps of the State of Washington and adjacent areas: U.S. Geological Survey Open-File Report 84-416, 5 p., 18 plates, scale 1:250,000.

Flanigan, V. J.; Ford, A. B.; Sherrard, Mark, 1983, Geologic interpretation of aeromagnetic survey of Glacier Peak Wilderness, northern Cascades, Washington: U.S. Geological Survey Open-File Report 83-650, 22 p., 2 plates.

Heliker, C. C.; Johnson, Arthur; Hodge, S. M., 1984, The Nisqually Glacier, Mount Rainier, Washington, 1857-1979 — A summary of the long-term observations and a comprehensive bibliography: U.S. Geological Survey Open-File Report 83-541, 20 p., 4 plates.

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, scale 1:740,000.

Miller, F. K.; Frisken, J. G., 1984, Geochemical sampling around the granodiorite of Hall Mountain, northeastern Washington and northern Idaho: U.S. Geological Survey Open-File Report 84-365, 14 p., 1 plate.

Newhall, C. G., 1984, Semiquantitative assessment of changing volcanic risk at Mount St. Helens, Washington: U.S. Geological Survey Open-File Report 84-272, 30 p.

Swift, C. H., III; Kresch, D. L., 1983, Mudflow hazards along the Toutle and Cowlitz Rivers from a hypothetical failure of Spirit Lake blockage: U. S. Geological Survey Water-Resources Investigations Report 82-4125, 10 p., 10 plates, scale 1:24,000.

U.S. Geological Survey, 1984, Aeromagnetic map of part of the North Cascades National Park, Washington: U.S. Geological Survey Open-File Report 84-511, 1 sheet, scale 1:250,000.

U.S. Geological Survey, 1984, Aeromagnetic map of the Olympic Mountains area, Washington: U.S. Geological Survey Open-File Report 84-510, 2 sheets, scale 1:62,500.

RECENT GEOLOGIC REPORTS ADDED TO OUR DIVISION LIBRARY

The following reports have recently been acquired by the Division of Geology and Earth Resources and are now available for reference work in the library:

Cady, J. W.; Fox, K. F., Jr., 1984, Geophysical interpretation of the gneiss terrane of northern Washington and southern British Columbia, and its implications for uranium exploration: U.S. Geological Survey Professional Paper 1260, 29 p., 1 plate.

Church, S. E.; Swanson, D. A.; Williams, D. L.; Clayton, G. A.; Close, T. J.; Peters, T. J., 1983, Mineral resource potential map of the Goat Rocks wilderness and adjacent roadless areas, Lewis and Yakima Counties, Washington: U.S. Geological Survey Miscellaneous Field Studies Map MF-1643-A, 13 p., 1 plate, scale 1:48,000.

Frisken, J. G.; Church, S. E.; Mosier, E. L.; McCollaum, A. D., 1984, Geochemical maps of the Wonder Mountain roadless area, Mason County, Washington: U.S. Geological Survey Miscellaneous Field Studies Map MF-1418-C, 1 sheet.

Klein, J. M., 1984, Some chemical effects of the Mount St. Helens eruption on selected streams in the State of Washington: U.S. Geological Survey Circular 850-E, 26 p.

Williams, D. L.; Finn, Carol; Spydell, D. R.; Danes, Frank, 1984, Gravity and aeromagnetic maps of the Goat Rocks wilderness and adjacent roadless areas, Lewis and Yakima Counties, Washington: U.S. Geological Survey Miscellaneous Field Studies Map MF-1653-C, 2 sheets, scale 1:48,000.

THESES ADDED TO OUR DIVISION LIBRARY

We have recently acquired the following theses in our Division library where they are now available for reference work.

Chou, Gin, 1983, Geochemistry of the Togo metapelites from the Midnite uranium mine, northeastern Washington: Eastern Washington University Master of Science thesis, 84 p.

Dahlgren, Randy, 1984, Impact of tephra perturbations on a forest soil in the *Abies amabilis* zone: University of Washington Master of Science thesis, 147 p.

Donovan, Sean, 1983, A lineament evaluation and structural study of northeastern Washington using Landsat and SLAR imagery and aeromagnetic maps: Eastern Washington University Master of Science thesis, 188 p., 2 plates.

Dunwiddie, P. W., 1983, Holocene forest dynamics on Mount Rainier, Washington: University of Washington Doctor of Philosophy thesis, 129 p.

Johnson, P. E., 1983, The origin of the Chiwaukum graben, Chelan County, Washington: Washington State University Master of Science thesis, 96 p., 1 plate.

Lovett, C. K., 1984, Paleomagnetism of the Touchet beds of the Walla Walla River valley, southeastern Washington: Eastern Washington University Master of Science thesis, 161 p.

Melim, L. A., 1984, The sedimentary petrology and sedimentology of the unnamed middle Eocene sandstones of Scow Bay, Indian and Marrowstone Islands, northwest Washington: Western Washington University Master of Science thesis, 123 p., 1 plate.

Ritzi, R. W., Jr., 1983, The hydrogeologic setting and water resources of Vashon and Maury Islands, King County, Washington: Wright State University Master of Science thesis, 115 p.

Wicklund, M. A., 1984, Geology and genesis of the rocks of the Graeber uranium area, Stevens County, Washington: Eastern Washington University Master of Science thesis, 160 p., 2 plates, geologic map, scale 1:1,200.

Winters, W. J., 1984, Stratigraphy and sedimentology of Paleogene arkosic and volcaniclastic strata, Johnson Creek-Chambers Creek area, southern Cascade Range, Washington: Portland State University Master of Science thesis, 162 p., 2 plates.

RECENT PERMITS FOR OIL AND GAS DRILLING

Operator	Permit no.	County	Well name	Location	Ground elevation (feet)	Estimated total depth (feet)	Spud date	Date permit issued
Oil and Gas Exploratory Wells								
Shell Oil Co. **	340	Grant	BN 1-9	965 ft FWL and 1,869 ft FNL* sec. 9 (15-25E)	2,400	20,000	12-21-82	5-22-81
AMOCO Prod. Co.	354	King	Enumclaw Mill No. 1-34	1,430 ft FNL and 1,370 ft FWL sec. 34 (20-7E)	1,447	2,500	5-16-83	5-16-83
AMOCO Prod. Co.	386	Grays Harbor	Amoco-Weyerhaeuser No. 1-29	2,601 ft FWL and 2,377 ft FSL sec. 29 (19-8W)	390	12,000	6-26-84	5-31-84
Shell Western E & P Inc.	387	Grant	Maughan et al No. 1-5	1,398 ft FSL and 1,822 ft FEL sec. 5 (15-25E)	1,937	15,000		7-11-84
Shell Western E & P Inc.	394	Grant	Maughan et al No. 1-29	221 ft FSL and 2,140 ft FEL sec. 12 (15-24E)	2,241	15,000		8-2-84
Oil and Gas Stratigraphic Tests								
AMOCO Prod. Co.	356	Pierce	Buckley No. 1	1,990 ft FWL and 2,033 ft FSL sec. 11 (19-6E)	755	1,800		7-26-83
AMOCO Prod. Co.	362	King	Snoqualmie Mill Offset No. 1	1,489 ft FNL and 1,297 ft FWL sec. 25 (24-7E)	842	1,500		7-26-83
AMOCO Prod. Co.	363	King	Snoqualmie Mill Twin No. 1	1,779 ft FWL and 601 ft FSL sec. 19 (23-8E)	2,190	1,500		7-26-83
AMOCO Prod. Co.	364	Lewis	Storm King Twin No. 1	2,005 ft FSL and 2,569 ft FEL sec. 23 (14-5E)	1,835	1,500		7-26-83
AMOCO Prod. Co.	365	Lewis	WC-83-12	488 ft FWL and 2,212 ft FSL sec. 7 (14-5E)	1,515	2,000		12-15-83
AMOCO Prod. Co.	366	Pierce	WC-83-11	347 ft FSL and 330 ft FWL sec. 11 (19-6E)	752	2,000		12-29-83
AMOCO Prod. Co.	367	Pierce	WC-83-13	964 ft FNL and 1,015 ft FWL sec. 10 (15-6E)	3,260	2,000		12-29-83
AMOCO Prod. Co.	371	King	WC-83-31	114 ft FSL and 1,194 ft FEL sec. 15 (25-8E)	1,125	2,000		2-2-84
AMOCO Prod. Co.	372	King	WC-83-32	739 ft FNL and 2,032 ft FEL sec. 26 (26-7E)	620	2,000		2-2-84
AMOCO Prod. Co.	373	Pierce	WC-83-26	40 ft FSL and 609 ft FEL sec. 17 (16-4E)	725	2,000		2-2-84
AMOCO Prod. Co.	374	King	WC-83-17	847 ft FSL and 1,460 ft FWL sec. 13 (22-6E)	645	2,000		2-2-84
AMOCO Prod. Co.	375	King	WC-83-16	2,254 ft FNL and 562 ft FEL sec. 4 (20-7E)	1,246	2,000		2-2-84
AMOCO Prod. Co.	377	King	WC-83-20	696 ft FSL and 123 ft FWL sec. 1 (24-6E)	435	2,000		2-22-84
AMOCO Prod. Co.	378	King	WC-83-21	216 ft FSL and 1,131 ft FEL sec. 33 (21-6E)	675	2,000		2-15-84
AMOCO Prod. Co.	379	Pierce	WC-83-23	1,073 ft FSL and 1,130 ft FEL sec. 24 (19-5E)	820	2,000		2-15-84
AMOCO Prod. Co.	380	Lewis	WC-83-24	2,244 ft FSL and 2,356 ft FWL sec. 1 (14-4E)	1,635	2,000		2-15-84
AMOCO Prod. Co.	381	Lewis	WC-83-25	1,023 ft FNL and 752 ft FEL sec. 29 (13-4E)	1,540	2,000		2-15-84
AMOCO Prod. Co.	382	Pierce	WC-83-28	2,335 ft FNL and 661 ft FEL sec. 19 (19-6E)	520	2,000		2-15-84
AMOCO Prod. Co.	384	Lewis	WC-83-33	1,107 ft FNL and 1,243 ft FEL sec. 33 (13-4E)	1,355	2,000		2-15-84

RECENT PERMITS FOR OIL AND GAS DRILLING - Continued

Operator	Permit no.	County	Well name	Location	Ground elevation (feet)	Estimated total depth (feet)	Spud date	Date permit issued
				Oil and Gas Stratigraphic Tests - Continued				
AMOCO Prod. Co.	385	Pierce	WC-83-34	700 ft FNL and 2,346 ft FEL sec. 25 (16-3E)	725	2,000		2-15-84
AMOCO Prod. Co.	388	Pierce	WC-83-35	1,255 ft FSL and 108 ft FEL sec. 36 (20-5E)	810	2,000		8-2-84
AMOCO Prod. Co.	389	Pierce	WC-83-36	99 ft FSL and 2,287 ft FWL sec. 21 (19-5E)	810	2,000		8-2-84
AMOCO Prod. Co.	390	King	WC-83-37	739 ft FSL and 2,838 ft FEL sec. 34 (22-7E)	4,097	2,000		8-2-84
AMOCO Prod. Co.	391	King	WC-83-38	288 ft FSL and 538 ft FEL sec. 14 (21-7E)	1,306	2,000		8-2-84
AMOCO Prod. Co.	392	Pierce	WC-83-39	2,005 ft FWL and 158 ft FNL sec. 16 (19-6E)	702	2,000		8-2-84
AMOCO Prod. Co.	393	Pierce	WC-83-40	160 ft FWL and 2,226 ft FNL sec. 36 (18-6E)	1,540	2,000		8-2-84

* Land description indicates that the location is 965 ft from the west line and 1,869 ft from the north line of sec. 9, township 15 north, range 25 east, Willamette meridian.

** Plugged and abandoned.

Department of Natural Resources
Division of Geology and Earth Resources
Olympia, WA 98504

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