DEPARTMENT OF THE INTERIOR

U.S. GEOLOGICAL SURVEY

Petroleum Geology and Principal Exploration Plays in the Uinta-Piceance-Eagle Basins Province, Utah and Colorado

By

Charles W. Spencer[1] and Robert J. Wilson[2]

Open-File Report 88-450-G

[1]U.S. Geological Survey, Box 25046, Denver Federal Center, Denver, Colorado 80225

[2]Consultant, 8345 W. 8th Ave., Lakewood, Colorado, 80215

1988

CONTENTS

ILLUSTRATIONS

TABLES

PETROLEUM GEOLOGY AND PRINCIPAL EXPLORATION PLAYS IN THE UINTA-PICEANCE-EAGLE BASINS PROVINCE, UTAH AND COLORADO

By
Charles W. Spencer and Robert J. Wilson

INTRODUCTION

The Uinta-Piceance-Eagle geologic province (fig. 1) is within the overall Colorado Plateau and Basin and Range Petroleum Region (Dolton and others, 1981). The province covers about 40,000 mi² and the volume of sedimentary rocks is about 116,000 mi³ (Varnes and Dolton, 1982a). The geology and recoverable oil and gas resource potential of this province was reanalyzed in 1987 as part of a nationwide assessment of conventional resources (USGS-MMS, 1988). The Federal Government and Indian Tribes own about 75 percent of mineral leases within the potentially productive areas of the subject province (Varnes and Dolton, 1982b). As a result of this review, six petroleum plays were identified that had sufficient undiscovered resource potential on a national basis to be worthy of individual study. Four plays are conventional and two involve unconventional (tight) reservoirs. However, only the conventional plays are discussed in detail in the present report because the subject national assessment is made for conventional resources only. These plays are located in the Uinta basin of northeast Utah and the Piceance basin of northwest Colorado. A play is a group of discovered and/or undiscovered oil and gas accumulations that have similar geologic attributes. Individual plays usually have a similar range of geologic age but not always.

The Eagle basin (fig. 1) is primarily a Pennsylvanian-age depositional basin (Peterson and Hite, 1969) located in a structurally complex area east of the southern Piceance basin (Sanborn, 1981). The Eagle basin has a relatively low potential for the discovery of significant gas (on a national scale) based on surface data and present subsurface control. The basin has very low potential for discovery of economic oil accumulations because of the very high thermal maturity of most Paleozoic source rocks (Nuccio and Schenk, 1986) and presence of only small areas containing younger rocks with oil source beds. Therefore, the emphasis of this report is on the Uinta and Piceance basins.

ACKNOWLEDGMENTS

The authors would like to thank Richard B. Powers, Gregory F. Ulmishek, and Katharine L. Varnes for reviewing this paper and their constructive comments. R.C. Johnson, V.F. Nuccio, and W.J. Perry, Jr., provided important unpublished data.

GENERAL STRUCTURAL SETTING

The Uinta and Piceance basins are both asymmetrical and formed mostly during Tertiary time. The basins are separated by the Douglas Creek arch (fig. 2). The Uinta basin trends about east-west and is deepest on the north side, where Phanerozoic sediments may be more than 30,000 ft thick. The Piceance basin is deepest on the east side where more than 20,000 ft of Phanerozoic sediments may be present.

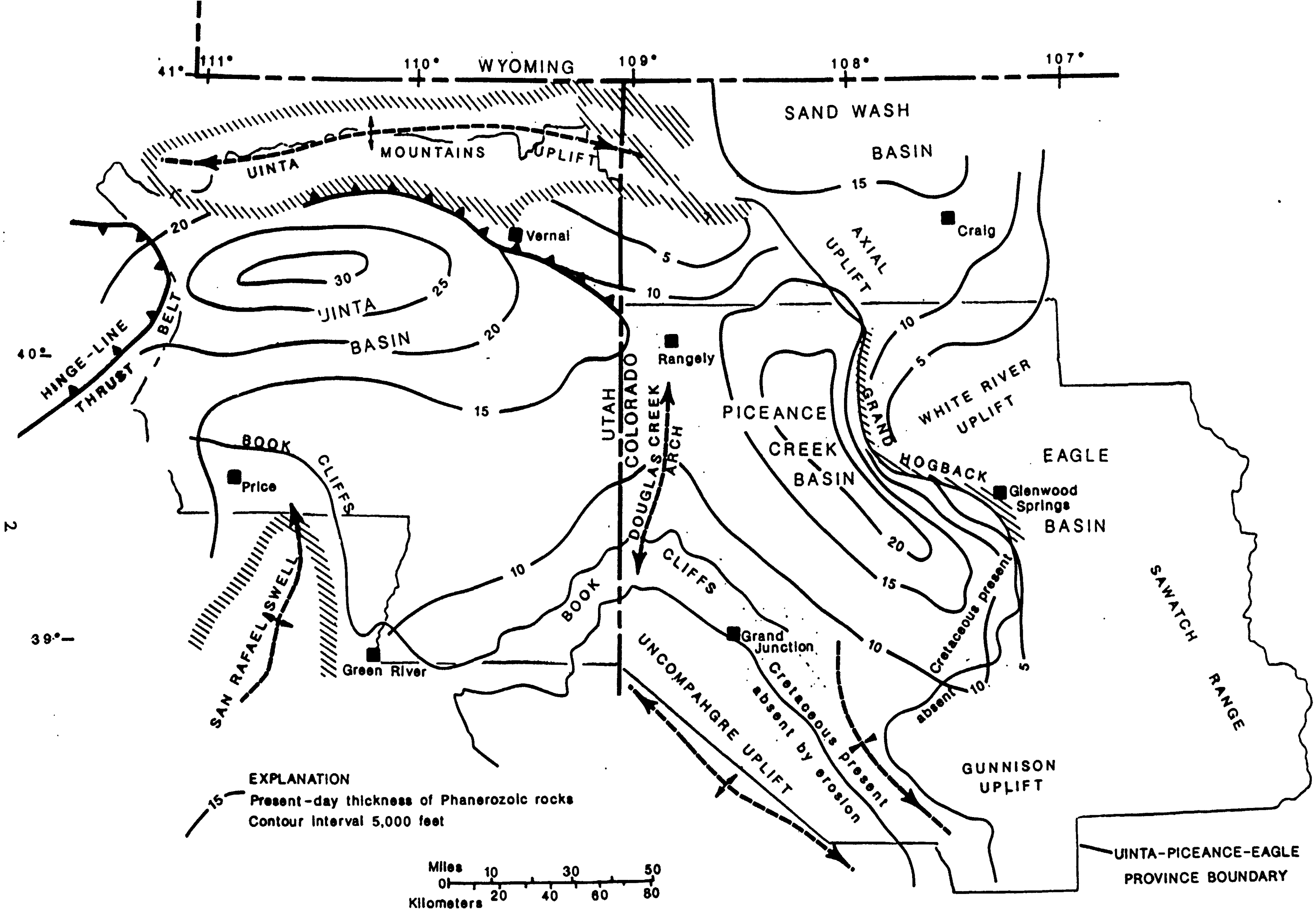

Figure 1.--Map showing thickness of Phanerozoic rocks and major tectonic elements within and adjacent to the Uinta-Piceance-Eagle basins province. Province outline slightly modified from Dolton and others (1981). The Phanerozoic thicknesses are modified from Jensen (1972).

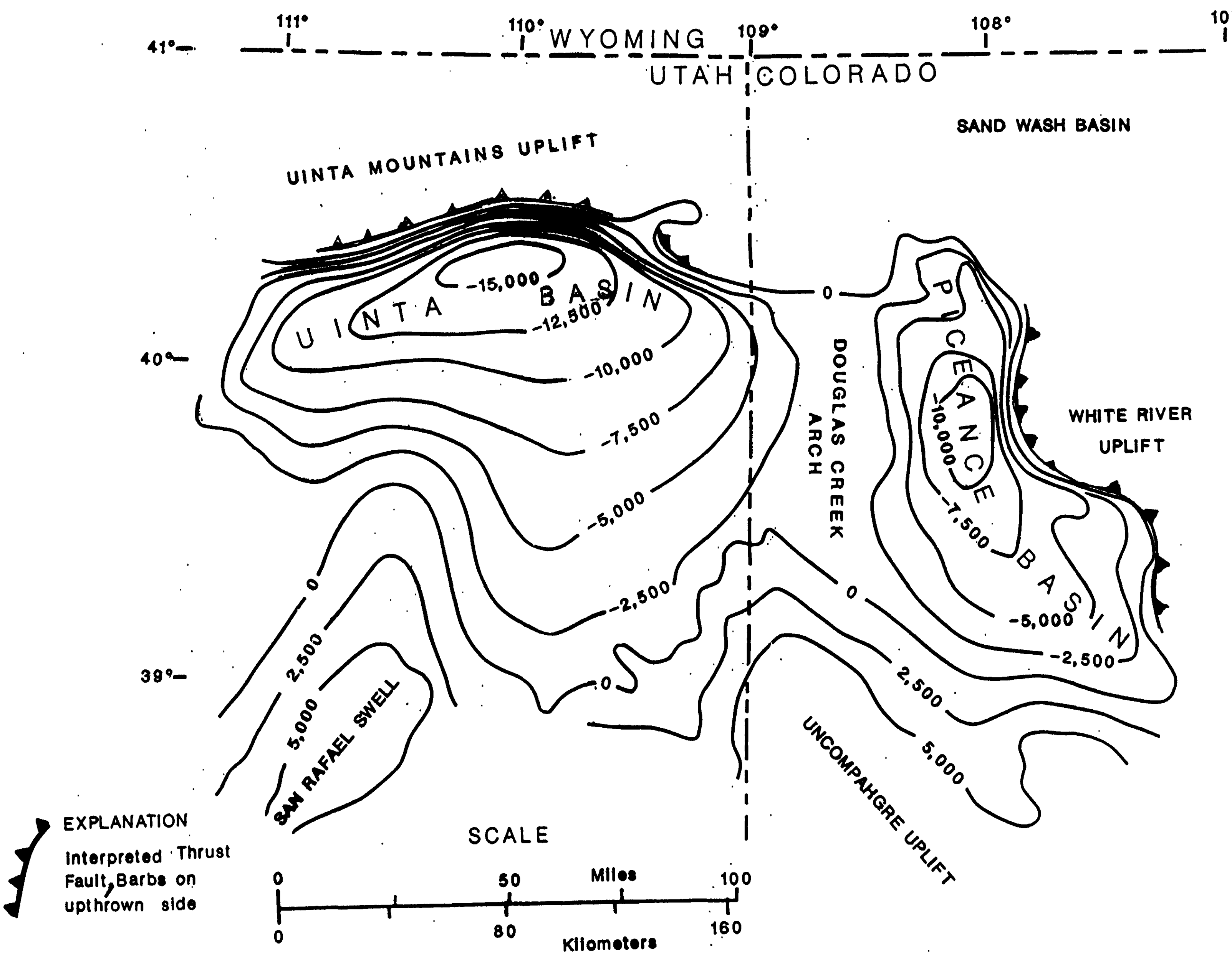

Figure 2.--Structure contour map of the Uinta and Piceance basins. Contours on the top of the Triassic Chinle Formation modified from the Tectonic Map of the United States (U.S. Geological Survey and American Association of Petroleum Geologists, 1962). Contour interval 2,500 ft.

The Uinta basin is about 120 miles long and is bounded on the west by the Hingeline thrust belt and on the east by the Douglas Creek arch. Its maximum width is nearly 100 miles as measured from the Book Cliffs on the south to the southern edge of the Uinta Mountains uplift. The southern flank of the Uinta Mountains uplift is probably bounded by a reverse fault (Lucas and Drexler, 1976; Hansen, 1984; Powers, 1986).

The Piceance basin is kidney shaped and oriented somewhat north-south. It is about 100 miles long and about 40 to 50 miles wide. It is bounded on the south by the Uncompahgre and Gunnison uplifts, on the west by the Douglas Creek arch, on the northeast by the Axial uplift, and on the east by the White River uplift. The steep dip in outcrop along the Grand Hogback changes to a reverse fault at depth (W.J. Perry, Jr., oral commun., 1987; Gries, 1983; Stone, 1986a).

GENERAL STRATIGRAPHY

The general stratigraphy of the Uinta and Piceance basins are discussed in Mallory (1972) and Sanborn (1971, 1981). Figure 3 shows the sequence of rock units. Also shown are intervals or formations with hydrocarbon source-rock potential and significant oil and or gas production. The oldest preserved rocks are Cambrian. Most rocks of Ordovician to Middle Devonian age are absent by erosion and/or lack of deposition. Marine rocks of Late Devonian to Mississippian age were deposited on a shallow shelf east of the main depocenter in western Utah and eastern Nevada. Pennsylvanian rocks are mostly continental and marine clastics with some marine carbonates. A relatively thin (1,000 to <500 ft) sequence of marine and continental Permian age rocks was deposited over much of the Uinta and Piceance province. Triassic and Jurassic continental siliciclastics were deposited over much of the area and are separated by a few tongues of marine shale and carbonate. The Triassic and Jurassic marine invasions came from the west. Lower Cretaceous sandstones, conglomerates, and shales are thin (generally <500 ft) and are overlain by a thick (6,000 to >8,000 ft) section of Upper Cretaceous marine shale and continental and marine sandstone, mudstone, shale, and siltstone with some coal. The Uinta and Piceance basins, as they are known today, began to form in Paleocene time (Johnson, 1985). During Paleocene and Eocene time the basins subsided relatively rapidly. The greatest subsidence occurred in the Uinta basin where more than 15,000 ft of fluvial and lacustrine deposits accumulated. The most distinctive aspect of Tertiary sedimentation was the development of Lake Uinta. This lake covered large parts of both basins during maximum lake development in Eocene time and resulted in the deposition of Green River Formation oil shales (fig. 3) (kerogenous dolomitic marls) with some limestones, evaporites, and intertonguing lacustrine and fluvial sandstones, siltstones, and mudstones (Fouch, 1975, 1981).

SOURCE ROCKS

There are probably no good hydrocarbon source rocks in Cambrian to Devonian age rocks in the Uinta and Piceance basins. The Mississippian may have some potential source rocks in the western part of the Uinta basin. According to Britt and Howard (1982) 44 outcrop samples of the Mississippian Manning Canyon Shale and Chainman Shale in the central

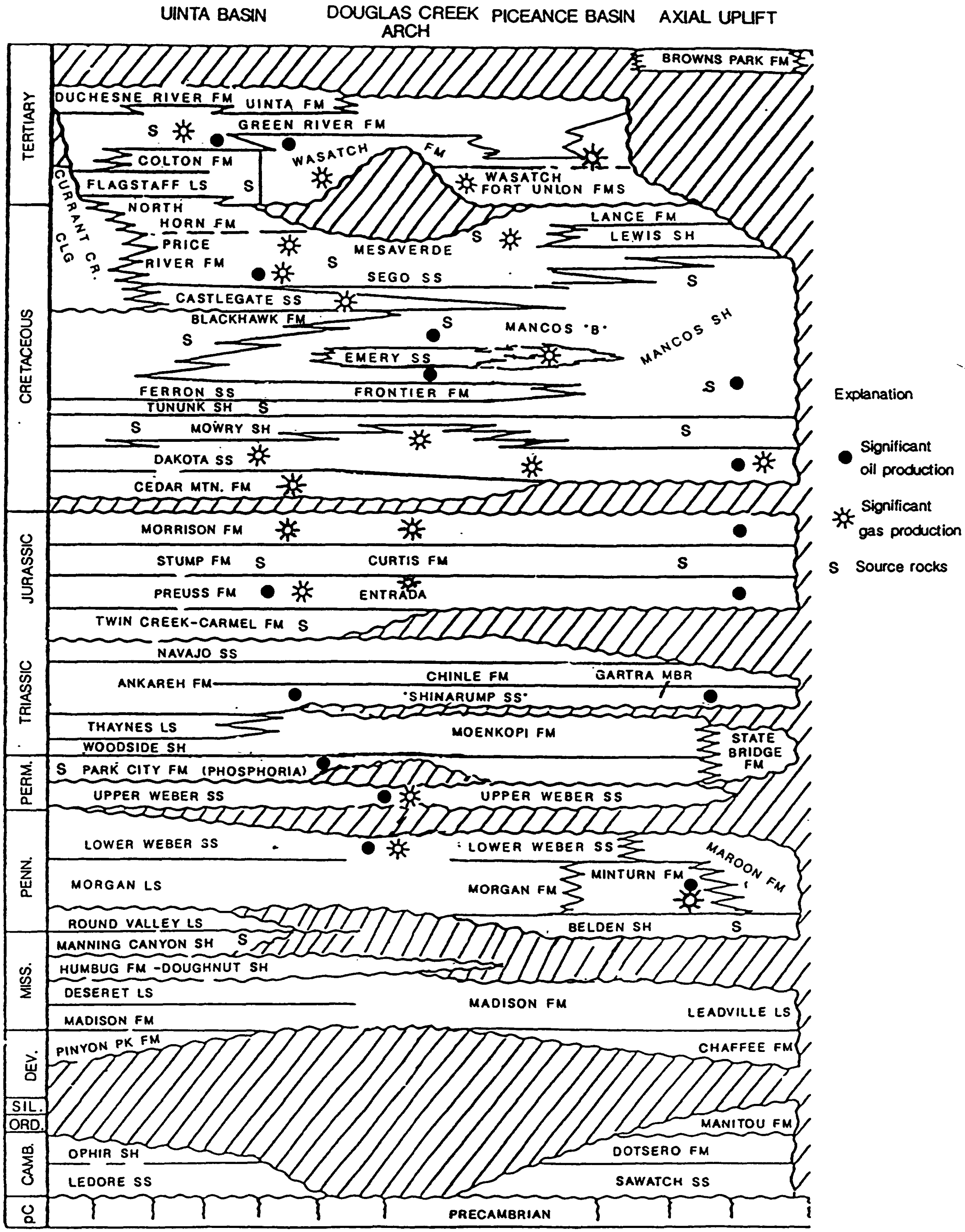

Figure 3.--Diagram showing general correlation of rock units from the Uinta basin, Utah, to the Axial uplift, Colorado. Diagram modified from Sanborn (1971, 1981).

Utah-Hingeline thrust belt region have an average of 0.98 percent total organic carbon (TOC) with a range of TOC of 0.07 to 3.32 percent. There is no production from Mississippian age rocks in the study area but relatively few Mississippian prospects have been drilled. There are no obvious major source rocks of Pennsylvanian age in the immediate Uinta-Piceance area but the Belden Shale, in the nearby Eagle basin, could have been a good source rock (Waechter and Johnson, 1986; Nuccio and Schenk, 1986).

The Rangely field produces oil from the Permo-Pennsylvanian Weber Sandstone and is one of the largest fields in the Rocky Mountain region. It is located on the northern part of the Douglas Creek arch. This field has an ultimate recovery of about 850 million barrels of oil (Powers, 1986). The source of this oil has been controversial, but the most likely interpretation is that the field was initially the site of a large stratigraphic trap that was later deformed by an asymmetrical, northwest-trending anticline during Laramide deformation which caused remigration into a structural trap (Hoffman, 1957). The most likely source of the Weber oil is organic-rich, oil-prone shales in the Permian Park City (Phosphoria) Formation (Hoffman, 1957; Stone, 1986b; Fryberger and Koelmel, 1986). Waechter and Johnson (1986) believe that the oil at Rangely migrated from the Pennsylvanian Belden Shale which was deposited in the Eagle basin. The Belden was a good source bed in the Eagle basin area (Nuccio and Schenk, 1986; Nuccio and Johnson, 1988) but it is not a likely source for the Rangely oil. Migration would have had to occur vertically and horizontally through very discontinuous reservoirs. The best Belden Shale source beds are nearly 100 miles southeast of Rangely field. However, some thin Belden Shale equivalent dark shales are present in a few wells north of Rangely (R.B. Powers, oral commun., 1988)

The best Permian age source rocks occur in the Park City Formation. Britt and Howard (1982) analyzed nine Park City (Phosphoria Formation) outcrop samples in Utah and determined they had an average TOC of 1.26 percent. Study of Permian outcrops and subsurface data indicate that the Park City equivalent rocks in Colorado are probably not good hydrocarbon source rocks. The Park City is probably now postmature for oil in the deeper parts of the Uinta basin.

Some possible source rocks may be present in Triassic and Jurassic marine tongues although they probably are relatively organically lean. Excellent hydrocarbon source beds are present in marine and continental shales and mudstones of Cretaceous age throughout the Uinta and Piceance basins. Coals are also present in most of the area. These Mesozoic source rocks are postmature with respect to oil in the deeper parts of both basins.

The Tertiary Green River Formation lacustrine oil shales are excellent source rocks where they are thermally mature in the deeper parts of the Uinta basin. The oil shales range from mostly immature to only marginally mature over most of the Piceance basin. Some source rocks for gas are present in coaly shales and low-quality coals in the Wasatch in the Piceance and Uinta basins (V.F. Nuccio, personal commun., 1987).

THERMAL MATURATION AND BURIAL HISTORY

It is now generally accepted that oil and gas are generated from source rock kerogen by the combined effects of both time and temperature. Because increased burial usually causes an increase in rock temperature, it is possible to construct Lopatin-type, burial-maturation diagrams to help estimate the times of the onset of oil and gas generation and destruction of oil (Waples, 1980). There are various potential sources of error involved in the assumptions made relative to oil and gas generation and destruction using burial curves; however, they can provide some approximations of thermal maturity. Lopatin maturation diagrams (Waples, 1980) were constructed for a location in the Uinta basin and a location in the Piceance basin.

Uinta Basin

The Shell No. 1-11B4 Brotherson well is located in the Greater Altamont field (fig. 4) and produces oil from the Tertiary Wasatch and Green River Formations. The stratigraphy of the Tertiary rocks penetrated by this well is shown by Fouch (1981). Figure 5 is an interpreted burial curve for the well showing the position of the oil window through geologic time using the time-temperature index (TTI) methods of Lopatin (Waples, 1980). A geothermal gradient of 1.5°F per 100 ft was assumed. The assumed top of the oil window is at a TTI of 10, and the base was assumed to be TTI 180. The burial diagram suggests that Cambrian and Devonian rocks entered the oil window about 210 m.y. ago and subsided below the oil window at about 90 m.y. Below the oil window, previously accumulated oil would have been destroyed and probably converted to natural gas. But, because neither the Cambrian or Devonian here are believed to contain good oil-source beds, this observation is somewhat academic. The Permian Phosphoria Formation contains about 1 percent organic carbon in the outcrops north and northwest of the 1-11B4 Brotherson (Maughan, 1984; Britt and Howard, 1982). There are good source beds in the Cretaceous (mostly gas prone) and Tertiary (oil prone). At the present time the interpreted top of the oil window occurs in the Wasatch Formation-Green River Formation interval at about 7,500 ft, and the burial diagram (fig. 5) shows the interpreted base is at about 12,500 ft in the Wasatch-Green River Formation. These depths agree fairly closely with an oil window of 8,500 ft to 12,500 ft as proposed by Anders and Gerrild (1984) using geochemical and other analyses. However, on the basis of oil- and gas-producing depths in Altamont wells, large volumes of gas <u>and</u> oil are being produced at depths below 14,500 ft. At the present time we do not fully understand how significant volumes of liquid oil can be preserved at depths deeper than the <u>estimated</u> oil window. The strata are highly overpressured (Lucas and Drexler, 1976; Spencer, 1987) and possibly high levels of overpressuring over long periods of time can suppress, or retard, the thermochemical reactions that usually destroy liquid oil. More research on this discrepancy needs to be done. Some regional thermal maturity analyses have been made (Nuccio and Johnson, 1986, 1988). Sweeney and others (1987) and Tissot and others (1978) provide additional thermal maturity information.

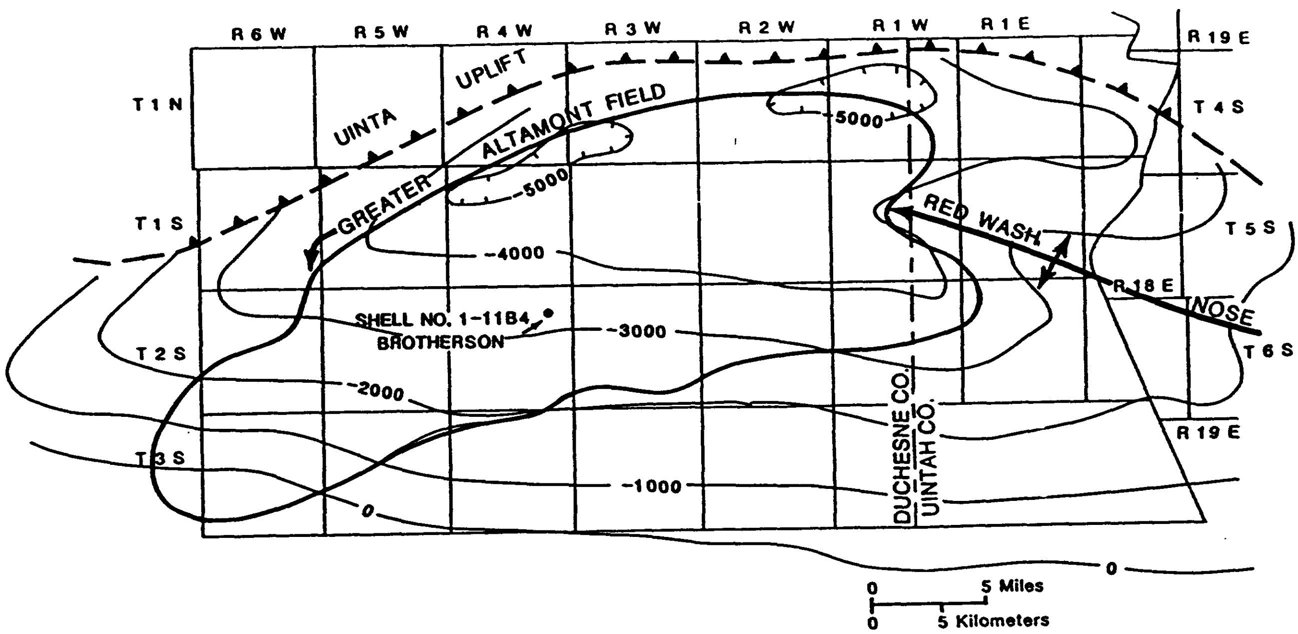

Figure 4.--Structure map of the greater Altamont field area. Structure contours on the top of a lower Green River Formation marker from Lucas and Drexler (1976).

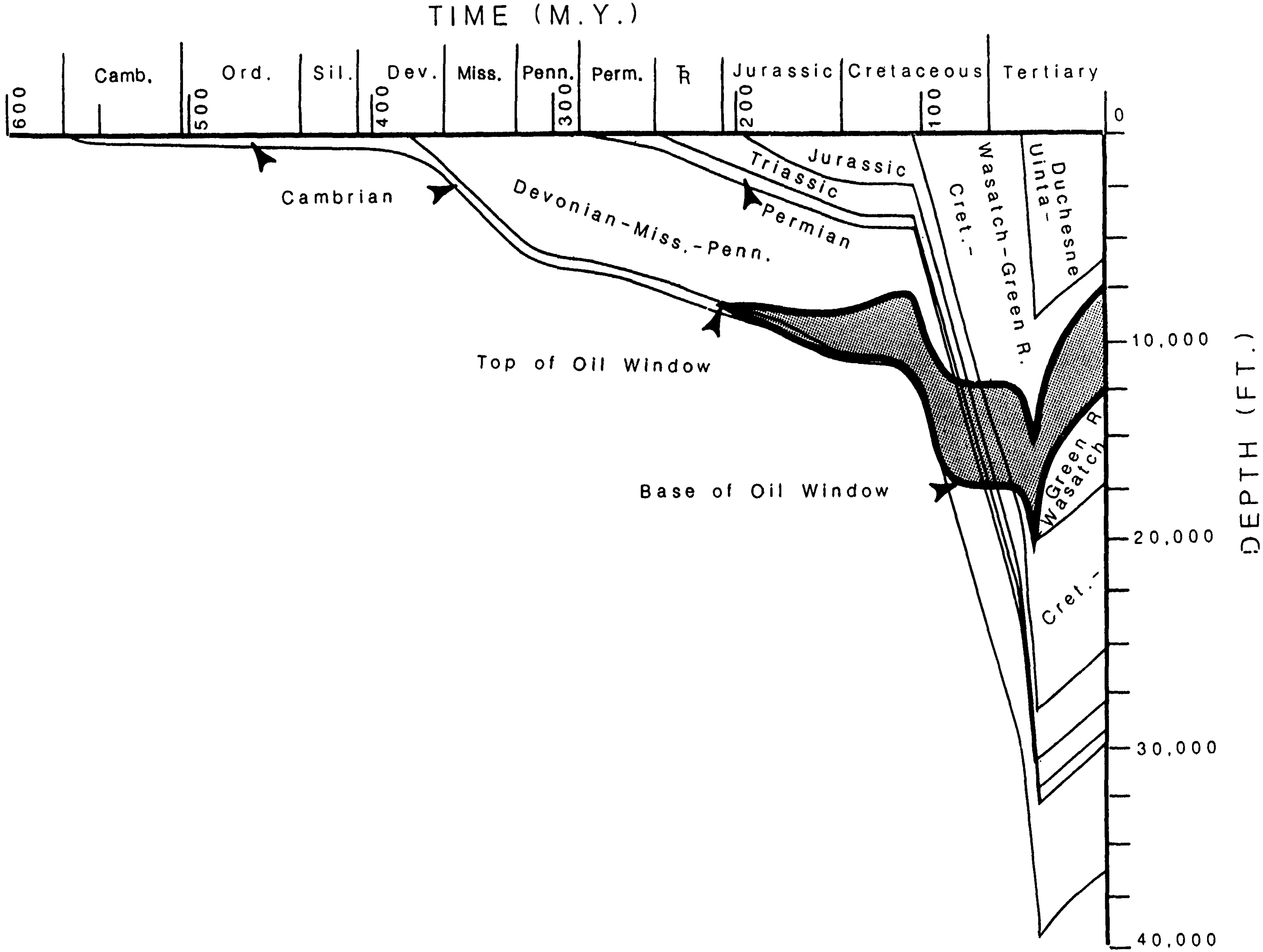

Figure 5.--Lopatin thermal maturation time-temperature burial curve (Waples, 1980) for Shell No. 1-11B4 Brotherson. See figure 4 for well location in Uinta basin, Utah. This well was drilled to a total depth of 17,776 ft in the Upper Cretaceous. Below total depth, the formation thickness and geologic history are estimated from various sources in Mallory (1972).

Piceance Basin

A Lopatin-type (Waples, 1980) burial curve was constructed for the U.S. Department of Energy's Multiwell Experiment (MWX) site located in sec. 34, T. 6 S., R. 94 W., Garfield County, Colorado (fig. 6). Three closely spaced wells were drilled at this location in order to advance the state-of-the-art of recovery of gas from very low-permeability (tight) reservoirs (Spencer and Keighin, 1984). The wells were extensively cored at depths deeper than 4,000 ft and therefore provide an excellent set of samples for the determination of vitrinite reflectance. There is some variation of vitrinite reflectance (Bostick and Freeman, 1984; Nuccio and Johnson, in press) in spite of the large amount of cores and MWX well cuttings and surface data.

The burial curve shows the present top of the oil window (TTI-10) at about 2,500 ft in the Wasatch. The present base of the oil window (TTI-180) is at about 6,000 ft in the middle of the Upper Cretaceous Mesaverde Group. Figure 7 is a plot of vitrinite reflectance from Nuccio and Johnson (in press) showing a range of depths for >1.35 R_o (base of oil window) from about 5,700 ft to 6,100 ft with a best fit of about 6,000 ft. Even though there is a lot of scatter in these data, oil production would not be expected from rocks older than the Mesaverde in the vicinity of the MWX site and at other locations in the basin, where the base of the Mesaverde is at depths of about 12,000 ft or deeper. Oil is expected in pre-Mesaverde rocks in other parts of the Piceance basin that are shallower and, therefore, thermally less mature.

HYDROCARBON OCCURRENCE

Both basins and the Douglas Creek arch have significant oil and gas production (fig. 8). Cumulative production from all fields in the province area is about 1,164 million barrels of oil (MMBO) and 2.29 trillion cubic feet (TCF) of gas to January 1, 1986. Sanborn (1981) speculated that the Uinta and Piceance basins and vicinity will ultimately produce 3 billion barrels of oil (BBO) and 5 TCF of gas.

Uinta Basin

The Uinta basin has a surface area of about 12,000 mi^2 and has yielded a cumulative production of about 378 million barrels (MMBO) and 733 billion cubic feet (BCF) of natural gas to January 1, 1986 (Utah Division of Oil, Gas, and Mining, 1985). Data for selected fields are shown in table 1. About 50 oil and gas fields have been discovered since 1925. Twelve of these fields have been abandoned and 4 fields are presently shut-in. Only about 12 fields have cumulative gas production of more than 6 BCF, and only 4 fields have produced more than 60 MMBO.

Most of the oil and gas production comes from Tertiary stratigraphic and diagenetic traps at a depth of less than 5,000 ft to more than 16,000 ft; however, one large oil field (Red Wash) produces from a combination structural-stratigraphic trap. In the Altamont area, the dominant Tertiary reservoirs are low-porosity, naturally fractured sandstones with lesser production from limestones, fractured shales, and mudstones. The porosity of sandstone reservoirs deeper than 10,000 ft ranges from 3 to 10 percent with an average of 5 percent (Lucas and Drexler, 1976).

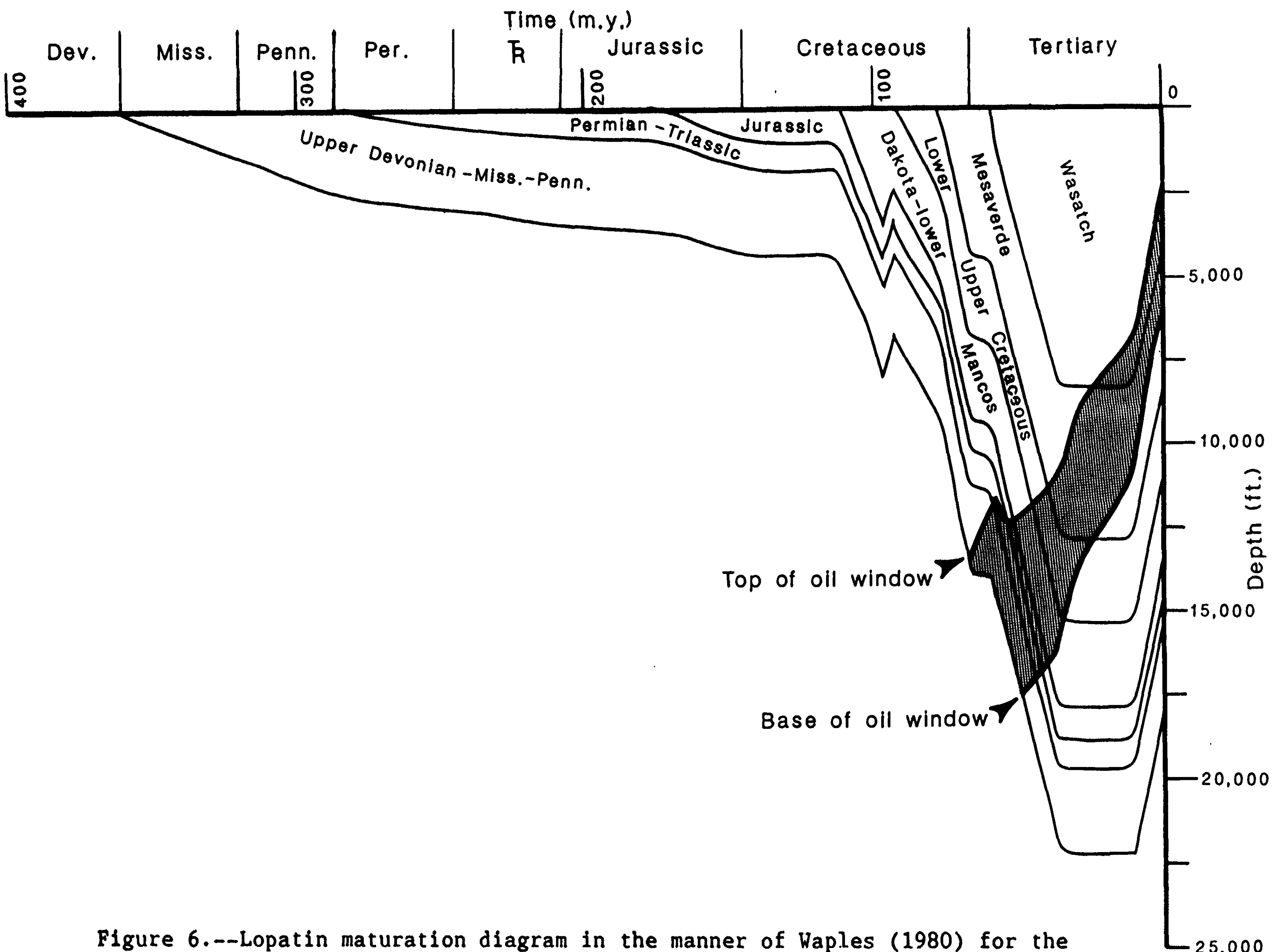

Figure 6.--Lopatin maturation diagram in the manner of Waples (1980) for the MWX site wells in sec. 34, T. 6 S., R. 94 W., Garfield County, Colorado. The deepest well at this site was drilled to 8,350 ft and reached total depth at the base of the Upper Cretaceous Mesaverde Group and the top of the Mancos Shale. Formation thickness below this depth were estimated from various sources in Mallory (1972).

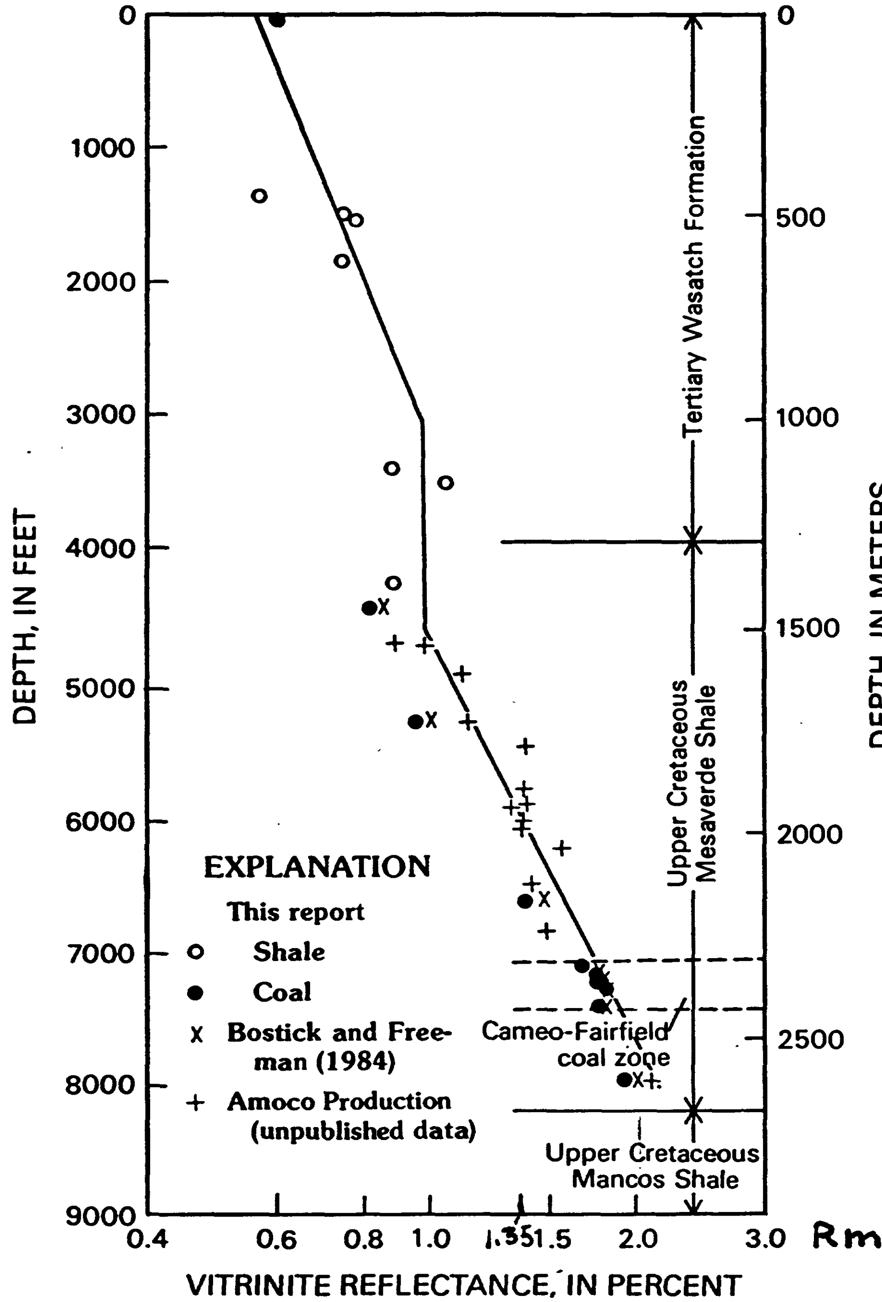

Figure 7.--Random vitrinite reflectance (Rm) measured in oil for subsurface core samples below 4,000 ft and cuttings samples above 4,000 ft. One surface sample measured. From Nuccio and Johnson (in press).

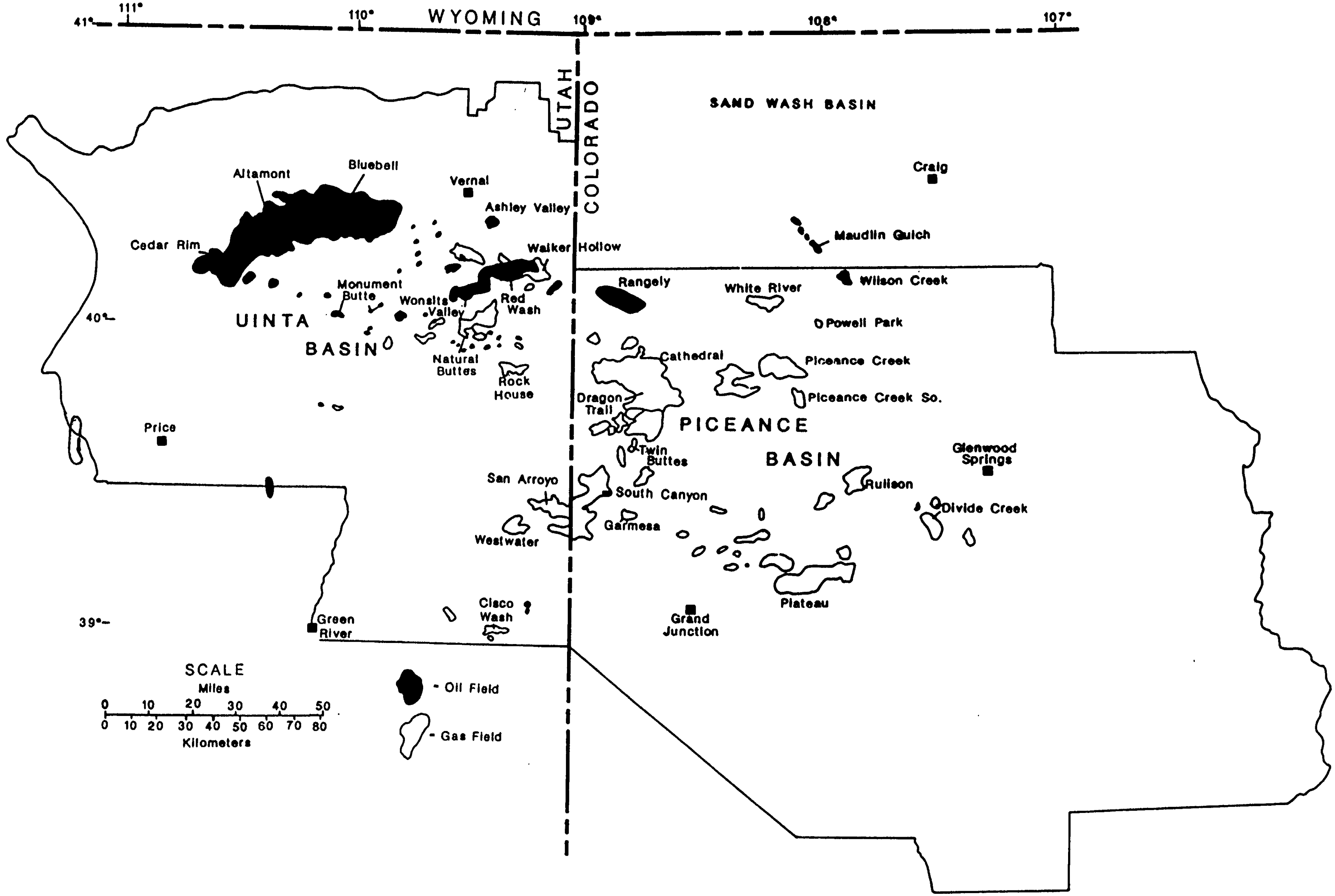

Figure 8.--Oil and gas fields of the Uinta and Piceance basins and vicinity modified from Scanlon (1983) and Utah Geological and Mineral Survey (1983). Many small fields not shown.

Table 1.—Uinta basin production from selected fields in the Uinta-Piceance-Eagle basins province to January 1, 1986 (data source Utah Division of Oil, Gas and Mining, 1985)

Field	Discovery date	Number of producing wells	Producing formations[1]	Oil (MMBO)	Gas (MMCFG)	Water (MMBW)
Ashley Valley	1925	31	Weber, Park City, Phosphoria, Entrada, Frontier, Morrison	8.3	–	518.1
Altamont	1970	325	Green River, Wasatch, Flagstaff, North Horn	77.3	116,983.1	119.5
Blue Bell	1955	288	Green River, Wasatch	92.7	97,704.4	59.2
Cedar Rim	1969	38	Green River, Wasatch	9.05	17,853.8	10.9
Monument Butte	1964	126	Green River	3.1	6,420.3	0.15
Natural Butte	1952	485	Green River, Wasatch, Mesaverde	1.4	188,407.6	0.76
Red Wash	1951	217	Uinta, Green River, Wasatch, Mesaverde	66.0	244,664.1	174.5
Walker Hollow	1963	74	Green River	10.0	18,920.6	19.0
Wonsits Valley	1962	104	Green River	32.8	18,386.8	81.1
Total other Fields				77.1	23,659.3	
Total All Fields				377.75	733,000.0	

[1]For complete formation names and ages of producing formations see figure 3.

The Tertiary sandstones in shallow fields have porosities from 12 to more than 18 percent. Cretaceous sandstones are the second most prolific reservoirs, but the production is dominantly gas. The Cretaceous produces from stratigraphic and structural-stratigraphic traps in the deeper (>8,000 ft) parts of the basin and from structural and structural-stratigraphic traps in the southern, shallower (<5,000 ft) part of the basin.

The oldest field is Ashley Valley, which was discovered in 1925. The largest field area is the Greater Altamont field, which includes Altamont, Bluebell, Cedar Rim, and Roosevelt. The fields produce mostly from naturally fractured sandstones in the Tertiary Green River and Wasatch Formations. Producing reservoirs deeper than about 11,000 ft are overpressured (Lucas and Drexler, 1976; Spencer, 1987). Figure 9 shows a typical pressure profile for an oil well in the main part of the Altamont field. The Greater Altamont trend is about 48 mi long and covers more than 400 mi^2. Lucas and Drexler (1976) estimated the trend may ultimately produce more than 250 MMBO. Altamont has both conventional and unconventional (tight) reservoirs. They can not be separated. Red Wash is the second largest field in the basin and has 217 wells producing from several reservoir sequences. The majority of the production at Red Wash comes from conventional sandstone reservoirs in the Wasatch and Green River Formations.

There are many small fields producing from Tertiary through Jurassic age rocks not shown in figure 8 nor listed in table 1. Also, low BTU gas is produced from sandstones of Cretaceous and Jurassic age in the southern part of the province in both Utah and Colorado.

Piceance Basin and Douglas Creek Arch

The Piceance basin proper covers approximately 8,000 mi^2. It is separated from the Uinta basin by the Douglas Creek arch (fig. 2). For the purposes of this discussion, the Douglas Creek arch fields are included in the Piceance basin. The total cumulative production for the combined area outlined by the Colorado portion of the province (fig. 7) is about 786 MMBO and 1.56 TCF to January 1, 1986 (Colorado Oil and Gas Conservation Commission, 1985). The first discovery was made at the White River field in 1890. A total of 2,097 producing and shut-in wells have been identified. Of these wells, 511 are shut-in or depleted.

Only two fields have produced more than 1 MMBO, and neither of these fields are in the Piceance basin proper, but they are within the overall basin province. Six fields have produced more than 45 BCF (table 2). Thirteen fields have produced from 6 BCFG to 45 BCFG. There are substantial opportunities awaiting the exploration geologist in the Uinta and Piceance basins.

Gas is the dominant hydrocarbon produced from Cretaceous and Tertiary reservoirs. The early gas discoveries were located by mapping surface structures, but most of the recently discovered fields are producing from stratigraphic traps. In fact, the Piceance basin proper is probably the site of a large, unconventional basin-center gas accumulation that will eventually be one large producing area (Johnson, 1987) similar to the San

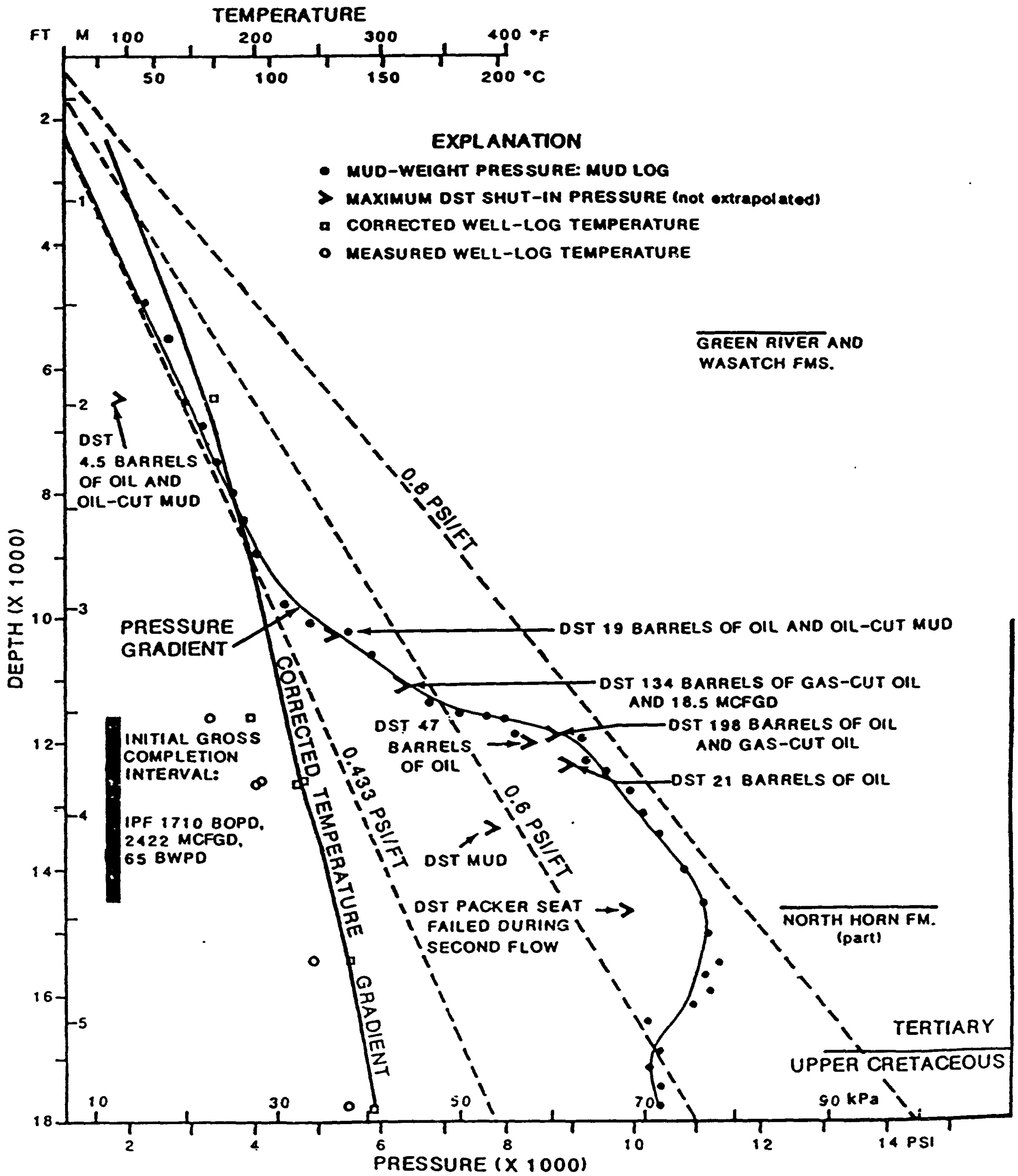

Figure 9.--Pressure profile for Shell No. 1-11B Brotherson well in the Altamont field. (See fig. 4 for well location.)

Table 2.—Piceance basin production from selected fields in the Uinta-Piceance-Eagle basins province to January 1, 1986 [data source Colorado Oil and Gas Conservation Commission, 1985]

Field	Discovery date	Number of producing wells	Producing formations[1]	Oil (MBO)	Gas (MMCFG)
Divide Creek	1956	7	Mesaverde	–	47,612.8
Dragon Trail	1959	107	Mancos	9.9	122,655.2
Piceance Creek	1930	38	Wasatch*, Green River, Mesaverde	127.7	200,915.6
Rangely	1902	488	Weber*, Shinarump, Entrada, Morrison, Dakota, Mancos*	703,099.7	698,678.6
Twin Buttes	1951	157	Morrison*, Dakota*, Mancos	39.8	83,371.2
Wilson Creek	1938	19	Minturn-Weber, Entrada*, Morrison*	82,701.4	61,274.3
Total other fields				310.4	341,530.7
Province total all fields				786,288.8	1,556,039.4

[1]For complete formation names and ages of producing formations, see figure 3.

*Most significant producing reservoirs in field.

Juan basin. However, improved prices and completion methods will be needed in order to facilitate exploitation of this extensive unconventional resource. The present study is mainly concerned with conventional resources.

Two significant oil fields occur within the Colorado part of the province but outside the Piceance basin proper. The Rangely field, located on the north end of the Douglas Creek arch, is a giant field (ultimate recoverable production of about 850 MMBO). It originally was a Permian-Pennsylvanian age sandstone stratigraphic trap that was folded into an asymmetrical anticline during the Laramide orogeny (Hoffman, 1957). Rangely has also produced oil from shallow fractured Upper Cretaceous Mancos Shale and a small amount of oil from the Triassic.

The second field is Wilson Creek located on a domal closure on the southeast end of the Danforth Hills anticlinal trend just northeast of the northern end of the Piceance basin proper. Wilson Creek produces from a Jurassic Entrada Sandstone pool and sandstones within the Jurassic Morrison Formation (Stone, 1986a). Wilson Creek has also recently produced a small amount of gas and condensate from the Weber Sandstone-Minturn Formation interval. This field has an estimated ultimate production of about 100 MMBO.

PRINCIPAL PLAYS

There are many exploration plays within the province; however, for the purposes of a national assessment it was necessary to focus in on plays that have significant undiscovered conventional resources.

Regional Permian-Pennsylvanian Sandstone Pinchouts

There are several major Permian and Pennsylvanian blanket sandstone reservoirs that pinchout within and adjacent to the province. The most prospective of these regional pinchouts involve wedge-edge traps within the Permian-Pennsylvanian Weber Sandstone and the Permian White Rim Sandstone member of the Cutler Formation. This play is relatively unexplored. These sandstones are dominantly eolian but include some marginal-marine deposits. They both comprise quartz arenites (very quartz-rich sandstones) and were transported in a generally southerly direction. The sandstones are enclosed in locally derived redbeds and pinchout into relatively impermeable redbed sequences.

The reservoirs mostly have good intergranular sandstone porosity ranging from less than 12 percent to higher than 18 percent. Because these reservoirs are relatively pure quartz sandstones, they tend to lose porosity and permeability at shallower depths than impure sandstones. The reason for this is that the clean quartz sandstones become cemented by quartz overgrowths; whereas, the diagenetic clay coats of clayey sandstones (especially chloritic sandstones) inhibit quartz overgrowths (Pittman, 1972; Wilson and Pittman, 1977). We do not expect either the Weber or the White Rim to have conventional (>11 percent porosity) reservoirs at present-day depths greater than about 10,000 ft. In fact, on the basis of limited deep well penetrations in the province and the authors' experience elsewhere in the Rockies, we expect most of these

Paleozoic sandstones will have 8 percent porosity or less at burial depths greater than 10,000 ft. Naturally, exceptions will occur, especially in those areas where early diagenetic carbonate cements and the like were subsequently dissolved during or prior to oil generation and subsequent entrapment. Also, porosity decrease could be minimized by early, oil or gas saturation of pore spaces. Drilling depths to potential traps within the play range from about 10,000 ft to less than 5,000 ft.

Two giant accumulations have been discovered in this play. They are the Rangely field (Weber Sandstone) on the north plunge at the Douglas Creek arch and the Tar Sand Triangle (White Rim Sandstone member of the Cutler Formation) (Ritzma, 1973) in the western Paradox basin just south of the subject province (see fig. 11). Figure 10 shows the stratigraphic relationships of the White Rim and other rocks in the Tar Sand Triangle area.

The Rangely field has an ultimate recovery of more than 850 million barrels of oil. The field has already produced over 700 million barrels (table 2) from depths of about 5,200 ft to 6,600 ft. The Tar Sand Triangle may have as much as 16 billion barrels of tar (heavy oil) in-place (Campbell and Ritzma, 1979). The Tar Sand Triangle accumulation has been breached by the downcutting of the Colorado and Green Rivers. The trap is now well exposed in various localities within the Canyonlands Park and the Glen Canyon Recreation Area. This accumulation is an exhumed stratigraphic trap overlain by marine Triassic Moenkopi Formation red, red-brown, green, purple, and buff mudstone, shale, siltstone, and sandstone. The eastward updip seal for this fossil oil field are tight argillaceous rocks in the Moenkopi and Permian. The bottom seal to the accumulation is Permian redbeds (fig. 10).

The White Rim Sandstone is a blanket sandstone and presumably could have had the capability of being sourced by contact with a low-quality source bed over a large gathering area and the oil then secondarily migrated and concentrated into a major accumulation. Certainly the entrapment of 16 billion barrels of tar (heavy oil) necessitates the bringing together of a unique set of conditions. In fact, studies by J.G. Palacas (oral commun., 1988) indicate the oil is heavily biodegraded and, therefore, he concludes that the trap probably contained in excess of 20 billion barrels of oil prior to being exhumed.

Baars (1970) speculated that the Moenkopi Formation could be one of several possible source beds for the tar. Mitchell (1984) estimated that the Triassic Moenkopi Formation in central Utah contains over 1 billion barrels of oil and that the oil was sourced by the Moenkopi. Possibly in excess of 1 billion barrels of tar is present in siltstones and sandstones in the lower part of the Moenkopi Formation on the flanks of the Circle Cliffs uplift of southwest Utah (Ritzma, 1973).

Palacas and others (1988) analyzed tar samples from Tar Sand Triangle and samples from Vermillion Creek in northwest Colorado. They concluded that the tars have similar "maturity" signatures indicating a similar level of thermal maturity in the respective source rocks. But, similar maturity levels do not necessarily mean that they share a common hydrocarbon source rock. We believe the Moenkopi is a likely source of

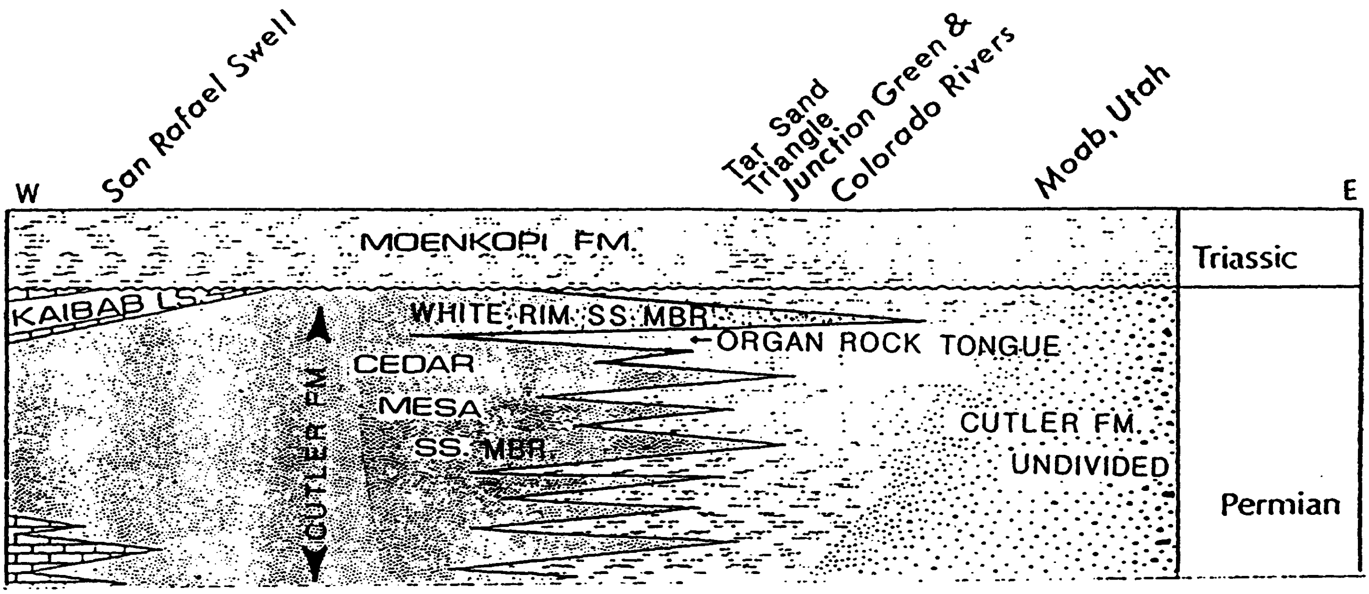

Figure 10.--Diagrammatic stratigraphic sections through the Tar Sand Triangle area, Utah. Modified from Baars (1970).

the oils at the Tar Sand Triangle, Circle Cliffs uplift, and other accumulations in contact with the marine part of the Moenkopi Formation. It would be very important to type the tars back to various possible source rocks. We encourage this research effort.

Other potential sources of White Rim oil are source beds in the Permian Toroweap and Kaibab Limestones in western Utah (Baars, 1970). R.J. Hite (oral commun., 1975) believes that the Tar Sand Triangle oil migrated vertically from the underlying Pennsylvanian Paradox Member of the Hermosa Formation (USGS terminology). Further geochemical research could aid exploration and improve assessments of oil and gas resources.

An additional aspect of the play involves the occurrence of tar in the Permian Schoolhouse tongue of the Weber Sandstone along the Grand Hogback (Waechter and Johnson, 1986). As noted earlier, Waechter and Johnson believe that the tar here and the oil at Rangely were both sourced by the Pennsylvanian Belden Shale in the Eagle basin area. We agree that the Hogback tar is probably from oil sourced by the Belden but for reasons noted earlier, the Belden is an unlikely source bed for the Rangely oil. However, more geochemical research is needed in order to resolve these problems and aid exploration and resource assessment.

Figure 11 shows the interpreted limits of the play. No single sandstone pinchout is readily identifiable on a regional basis but the limits of the play on the east and south sides are mostly controlled by absence of blanket-like orthoquartzite sandstone reservoirs. In these areas, the sandstones pinch out into a tight redbed sequence shed off the Uncompahgre uplift and the ancestral Rockies. The play is limited on the northwest by a general lack of conventional porosity and permeability caused by deep burial and reservoir cementation.

There is a 5 percent probability of discovering 10 fields with recoverable oil in excess of 1 million barrels of oil in the play, and a 50 percent probability of four fields, and a 95 percent probability of two fields in excess of 1 million barrels of oil being found. This is primarily an oil play. Some nonassociated gas is expected where thermal maturities are higher than the stability of oil, but poor reservoir quality is expected under these conditions. Therefore, some gas fields will be found but none as large as 6 BCF are expected. Therefore, the gas potential of this play is grouped with resource estimates (not accompanying this report) of all gas in less than 6 BCF accumulations.

Wasatch-Green River Shallow Uinta Basin Oil Play

The Tertiary Wasatch and Green River Formations produce major amounts of oil with associated gas in the Uinta basin (table 1). These same strata are not significant oil-producing rocks in the Piceance basin because the Tertiary Green River oil shales here are only marginally thermally mature to mostly immature. The lower Wasatch does produce some gas in the Piceance basin.

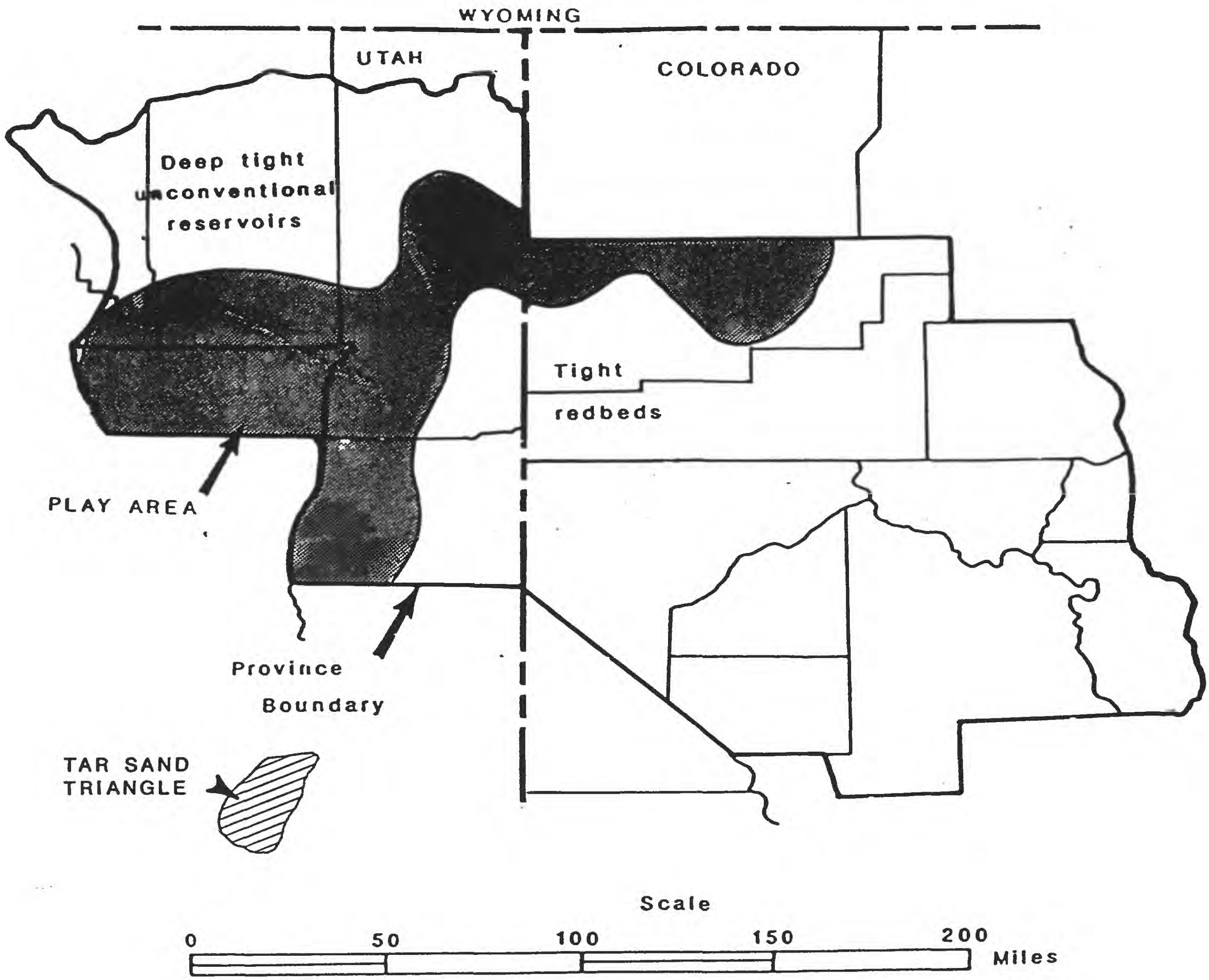

Figure 11.--Regional Permian Pennsylvanian sandstone play.

A large part of the oil in the north and northeast central part of the Uinta basin is classified as discovered or inferred resources. The production comes from both conventional and unconventional reservoirs. The principal remaining undiscovered potential exists in sandstone stratigraphic traps in the areas to the south, southwest, and southeast of this production but some small fields will also be found to the north of existing production and as extensions to existing production. Figure 12 shows the overall outline of the play. The play is moderately well explored. Included within the overall outline are known fields and areas of field extensions (inferred resources) but this discovered oil is not included in undiscovered resource estimates. Because of the high pourpoint of most of the oil (±100°F), shallow prospects will only produce oil with great difficulty and at low rates. Some low-maturity, black asphaltic oils with lower pourpoints will be found but these oils are fairly viscous and may require enhanced oil recovery methods to be produced. Drilling depths to this shallow conventional oil play are about 5,000 ft to 10,000 ft.

Input data to the National resource assessment (USGS-MMS, 1988) includes a 95 percent probability of the occurrence of finding 6 oil fields with more than 1 million barrels of recoverable oil. It is estimated that there is a 5 percent probability of 14 such accumulations being present.

Uinta-Piceance Tertiary Conventional Gas Play

Major resources of gas are present in tight unconventional reservoirs in the Tertiary and Cretaceous in the province. However, this assessment is only concerned with conventional resources. There is fair potential for discovery of more small conventional gas accumulations in sandstone stratigraphic and structural traps but this play is moderately well explored by drilling. These fields will be found at depths of less than 3,000 ft to more than 7,000 ft. Deeper than 7,000 ft, most of the reservoirs are unconventional (tight). Figure 13 shows the general play areas. The Tertiary source rocks are thermally mature in the deeper parts of the Uinta basin. In the southern part of the Uinta play area, the Tertiary is immature and gas accumulations in this part may be sourced from downdip Tertiary rocks or vertical migration from deeper, mature Cretaceous source rocks.

In the Piceance basin, almost all the Tertiary rocks are immature. Limited gas analyses from producing fields suggest most or all Tertiary gas in this play area is gas that migrated (mostly vertically) from mature, deeper Upper Cretaceous Mesaverde source beds (D.D. Rice and R.C. Johnson, oral commun., 1988).

Data used as input to the National resource assessment (USGS-MMS, 1988) resulted in an estimation of a 95 percent probability of 9 accumulations with recoverable gas in excess of 6 BCF occurring in the play area. There was an estimation of a 5 percent probability of 35 such accumulations being present.

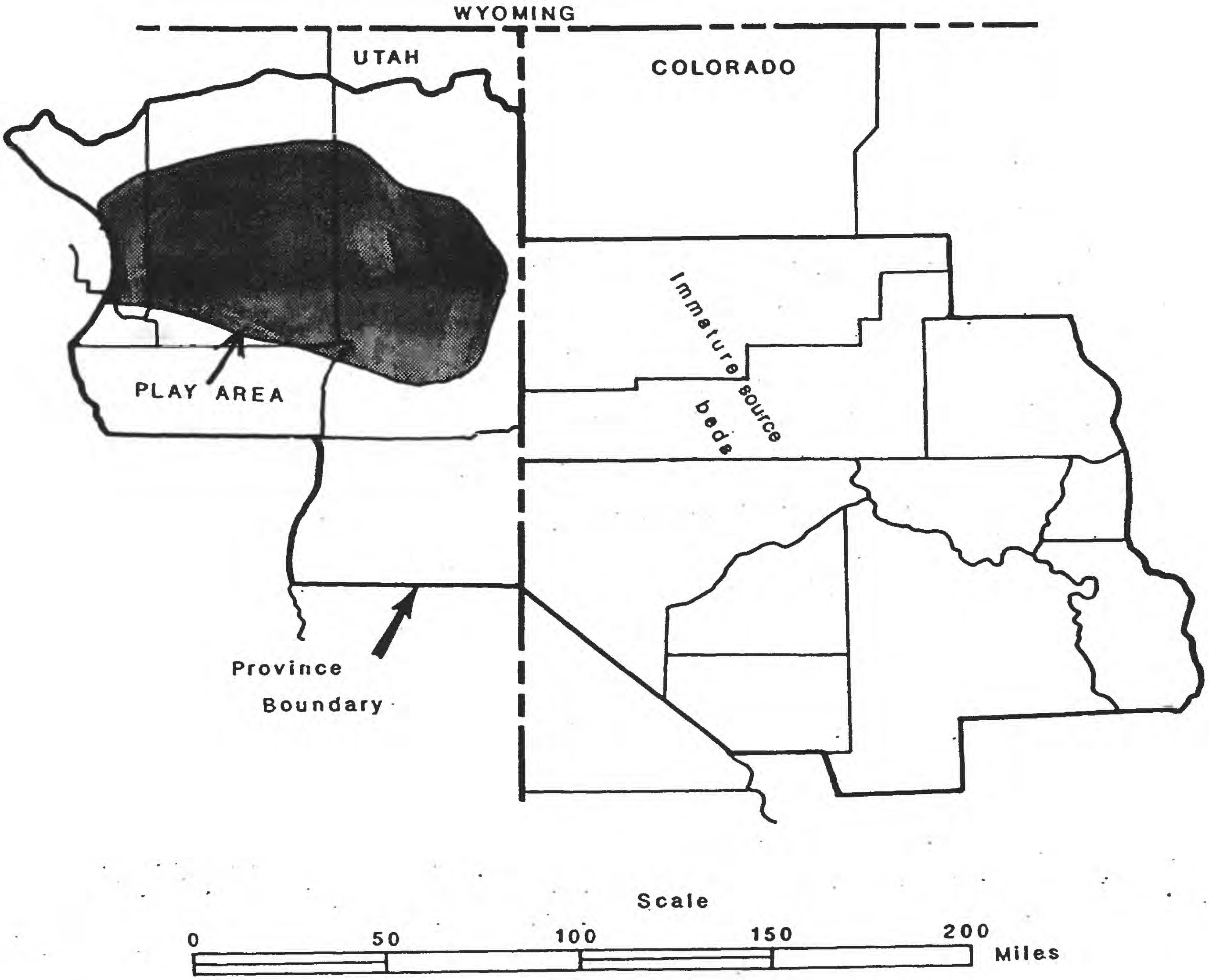

Figure 12.--Regional Uinta basin shallow Tertiary undiscovered oil play. Discovered fields and areas of inferred resources are included within overall outline but not included in estimates (USGS-MMS, 1988) of undiscovered resources.

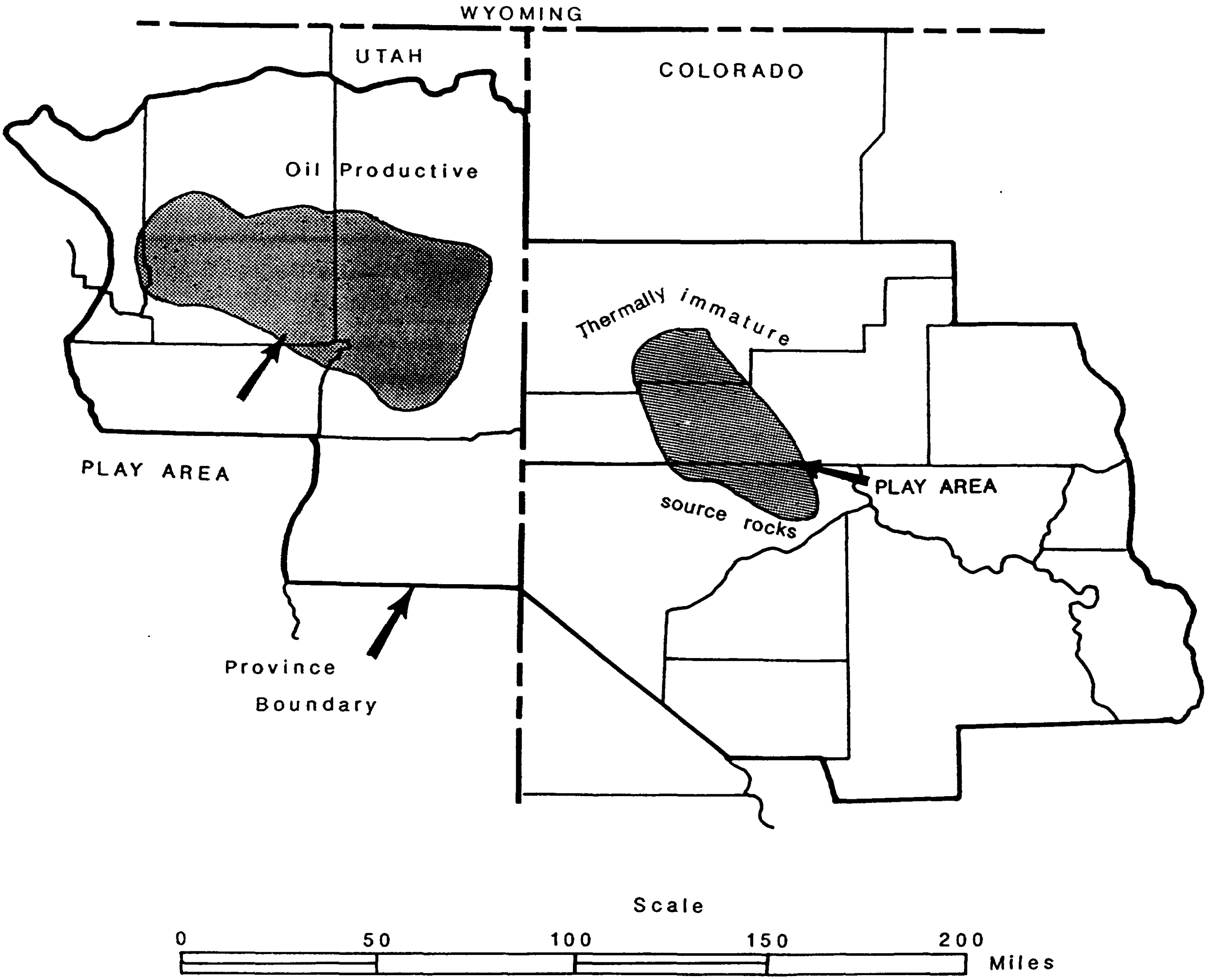

Figure 13.--Uinta-Piceance Tertiary conventional gas play. Includes some areas with discovered and inferred resources. Some unconventional reservoirs are present among and below conventional reservoirs. The Tertiary reservoirs in the northern part of the Uinta basin are mostly tight and oil productive. The Tertiary gas play in the Piceance basin is in an area of generally thermally immature source rocks; however, available gas analyses indicate most Tertiary gas migrated vertically from the Upper Cretaceous Mesaverde Group (D.D. Rice and R.C. Johnson, oral commun., 1988).

Uinta-Piceance Upper Cretaceous Gas Play

The Uinta and Piceance basins both produce significant volumes of gas from Upper Cretaceous fluvial, marginal-marine, and marine sandstones and some siltstones. The most potentially prolific reservoirs in this play (fig. 14) are sandstones in the Mesaverde Group and its equivalents.

Shelf siltstones and very fine-grained sandstones in the Mancos Shale produce gas over a large part of the Douglas Creek arch area at depths of about 2,000 to 4,000 ft. These reservoirs are called Mancos "B" by subsurface workers (Kellogg, 1977). At the time of the 1981 USGS resource assessment (Dolton and others, 1981), these reservoirs were considered mostly conventional. They have subsequently been mostly classified as unconventional by the Federal Energy Regulatory Commission (FERC). Figure 15 from Finley (1984, his fig. 74) shows the FERC-designated tight gas areas. These designations cover most of the Mancos "B" and some of the Mesaverde on the Douglas Creek arch and vicinity.

The gas resources on the Douglas Creek arch are either (1) designated as unconventional, (2) developed (discovered), (3) included in field extensions (inferred resources), or (4) in reservoirs that are expected to have recoveries of less than 6 BCF per field, such as the Dakota Sandstone, Morrison Formation, and Entrada Sandstone. For this reason, the Douglas Creek arch reservoirs are excluded from the assessment of conventional gas resources in the Upper Cretaceous play. The expected accumulations of less than 6 BCF are included in the overall resource assessment of undiscovered province gas in this resource size (USGS-MMS, 1988).

The Mesaverde Group conventional sandstones have been fairly well explored in the Piceance basin but only moderately explored in the Uinta basin. This exploration has shown that the conventional reservoir production comes mostly from fluvial and marginal-marine sandstones in structural and structural-stratigraphic traps at depths from about 2,000 ft to about 5,000 ft. The high-topographic relief in the basin causes variation in producing depths. Most Mesaverde reservoirs are tight where they have experienced paleoburial depths of more than about 7,000 ft.

During the course of the National resource assessment (USGS-MMS, 1988), it was estimated that there is a 95 percent probability of 25 accumulations of more than 6 BCF recoverable gas occurring and a 5 percent probability of 55 such accumulations being present.

Other Plays

As noted earlier, only the most significant plays, on a national resource basis, were individually described. However, we recognize that a number of other smaller plays exist. For example, figure 3 shows the ages of various source beds and production in the province.

Additional small Phosphoria and Triassic oil and gas fields will be found. Small oil fields have been found in Jurassic sandstones in Utah and more will be discovered.

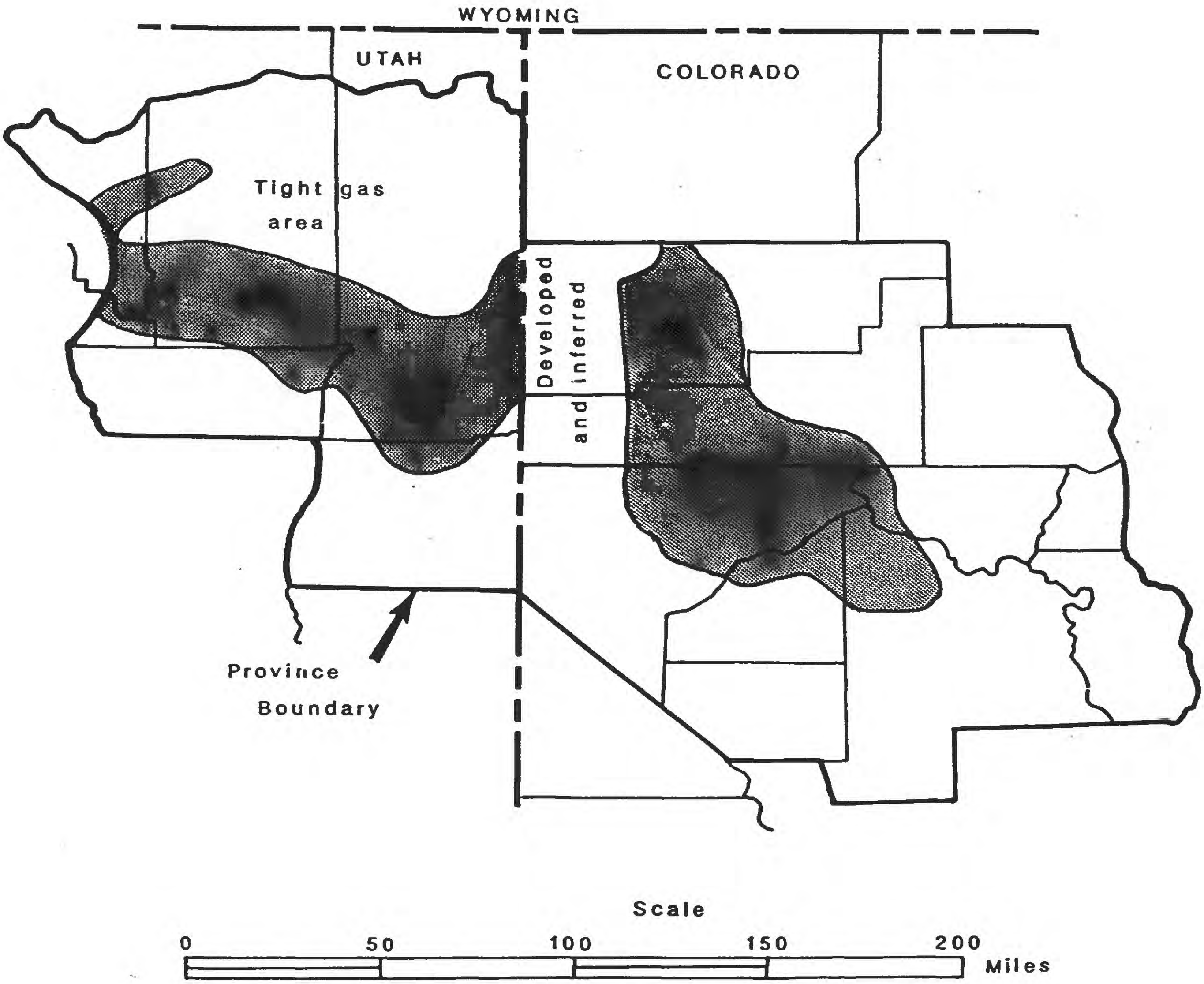

Figure 14.--Uinta-Piceance Upper Cretaceous sandstone conventional gas play. Includes some areas with discovered and inferred resources. Significant tight gas reservoirs are also present in much of the play areas.

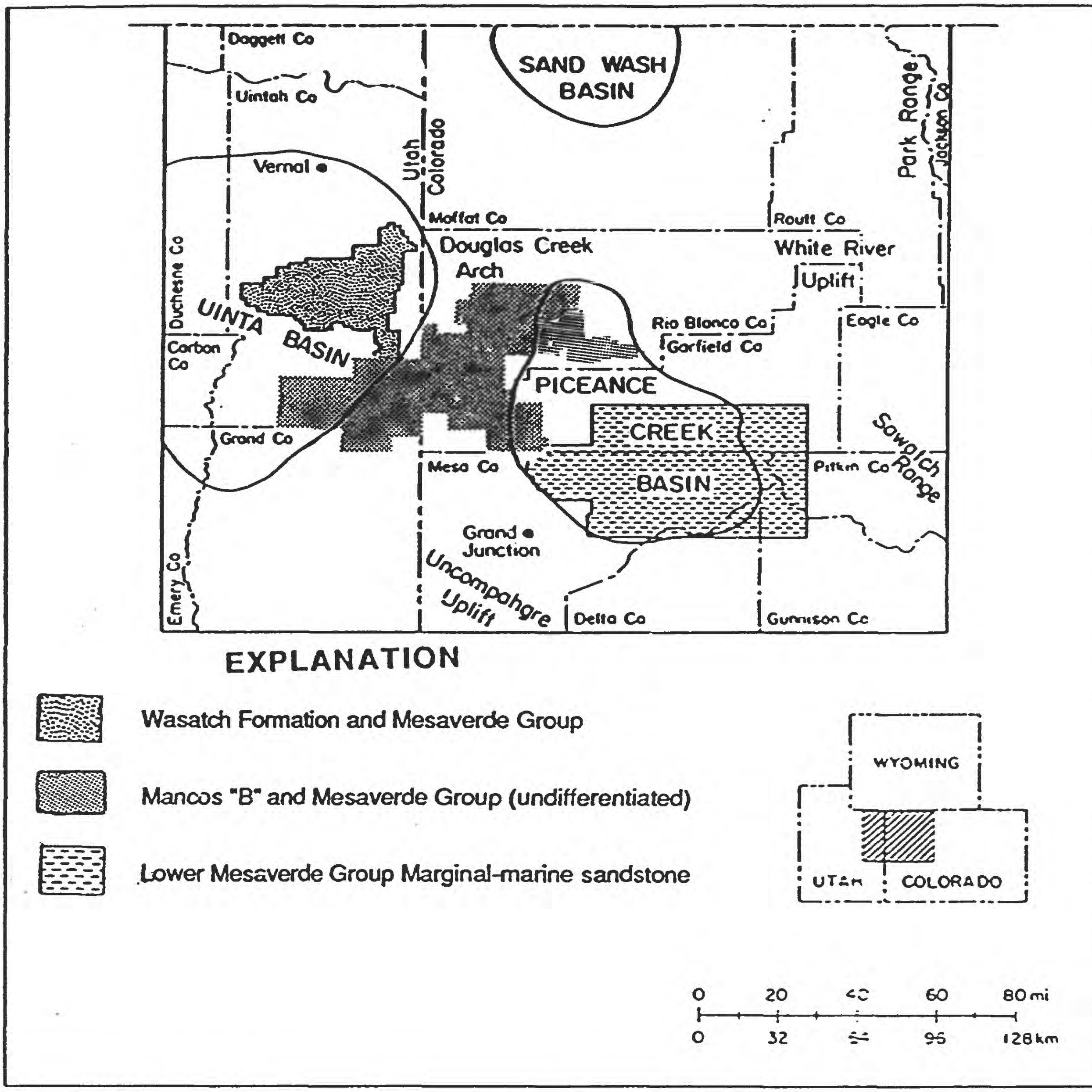

Figure 15.--Areas in the Uinta and Piceance basins designated as eligible for receiving tight gas production incentive prices by the Federal Energy Regulatory Commission (Modified from Finley, 1984, his fig. 74).

Jurassic and Lower Cretaceous sandstones produce gas from a number of fields in the province. Most of this gas is being produced from structural traps. At shallow depth, this gas is usually low BTU. The shallow, large structures mostly are discovered, and the deep prospects will contain dominantly tight, unconventional reservoirs.

Major oil-reserve additions will result from presently on-going infill drilling in the Altamont field trend. Also, additional oil will be recovered from these Tertiary reservoirs as a result of application of secondary and enhanced oil recovery methods. As noted earlier, these reservoirs are enhanced by natural fractures. Inclined or horizontal drilling should intersect many of these vertical fractures and increase recovery. These reserve additions are significant but not part of the undiscovered resource.

The Eagle (structural) basin as noted earlier has potential for discovery of mostly gas resources. However, present data suggest that the relative volume of conventional reservoirs will be low. The Eagle basin has been compared stratigraphically to the prolific Paradox basin to the south (Peterson and Hite, 1969). This comparison is justified but the oil and gas potential of each area is totally different when important aspects of the tectonic and thermal histories are considered.

Pennsylvanian Minturn reservoirs associated with the Eagle depositional basin produce a small amount of oil, gas, and condensate outside of the Eagle structural basin. Most of this production and undiscovered potential are outside of the subject province.

A subthrust basin-margin play is present along the southern margin of the Uinta Mountains uplift and adjacent areas (Gries, 1983; Hansen, 1984; Powers, 1986). A similar play is present along the east side of the White River uplift and vicinity (Gries, 1983; W.J. Perry, Jr., written commun., 1988).

Neither of the two thrust plays are considered by us to have significant resource potential on a national basis, although discoveries may be made. Of the two, the thrusts on the east side of the Piceance basin may have the better potential because of the tar saturation in the Schoolhouse tongue, noted earlier, along the upthrusted part of the play. Small occurrences of tar in Triassic and Jurassic rocks also occur in this area.

On the basis of studies by Nuccio and Schenk (1986) and Nuccio and Johnson (1988), the thermal maturity of subthrust rocks will be quite high. Some gas potential may be present but the oil potential appears to be quite low.

Unconventional Gas

Although this report is concerned with only undiscovered conventional resources, some comment should be made relative to two unconventional (tight) gas plays in Upper Cretaceous and Tertiary rocks. Gas from tight reservoirs is currently being produced from both basins, and major resources are yet to be developed.

The National Petroleum Council (1980) estimated that the Uinta basin might ultimately produce 15.27 TCF with advanced technology and wellhead prices of $9.00 per thousand cubic feet of gas (MCF) from Tertiary and Cretaceous rocks. Under the same conditions, they estimated the Piceance basin might produce as much as 29.71 TCF.

The USGS modified the NPC data and estimated the Uinta basin Tertiary and Cretaceous tight reservoirs might produce between 5.28 and 13.92 TCF using current technology and $5.00 per MCF (Spencer and Law, 1988). Johnson and others (1987) estimated that the Piceance basin Mesaverde Group tight reservoirs may produce between 8.75 and 19.41 TCF with state-of-the-art current technology and $5.00 per MCF gas prices.

Methane in Cretaceous coal beds is another major source of unconventional gas. The coalbed methane resource in the Uinta basin is not well known but much research has been conducted on this resource in the Piceance basin, mostly by the Colorado Geological Survey and the Gas Research Institute. McFall and others (1986) estimated an in-place Piceance coalbed resource of 84 TCF. Tremain (1984) estimated in-place resources of 77 TCF.

CONCLUSIONS

The Uinta-Piceance-Eagle basins province has significant established oil and gas production in the Uinta and Piceance basins. The Eagle basin is small, presently nonproductive, and relatively unexplored but appears to have limited resource potential when viewed from a total United States oil and gas potential perspective.

By January 1, 1986, the two basins had produced about 1.16 billion barrels of oil and about 2.3 trillion cubic feet of gas. Most of this production came from Permian-Pennsylvanian, Tertiary, and Cretaceous sandstone reservoirs.

Four significant conventional plays were identified. One play comprises regional, wedge-edge sandstone stratigraphic traps in eolian and marine rocks of Permian-Pennsylvanian age. This play is mostly prospective for oil production. A second play involves shallow Tertiary oil potential in Wasatch-Green River Formation stratigraphic traps in the southern part of the Uinta basin. The third play is a Tertiary conventional reservoir gas play in stratigraphic traps in both the Uinta and Piceance basins. The fourth play comprises Upper Cretaceous sandstone stratigraphic and diagenetic traps in the Uinta and Piceance basins. These traps will be primarily gas bearing. Very high-potential unconventional gas reservoirs are present in Upper Cretaceous Mesaverde and Mesaverde-equivalent rocks in the Uinta and Piceance basins. However, the present report is only concerned with conventional reservoirs.

REFERENCES CITED

Anders, D.E., and Gerrild, P.M., 1984, Hydrocarbon generation in lacustrine rocks of Tertiary age, Uinta basin, Utah--Organic carbon, pyrolysis yield, and light hydrocarbons, in Woodward, J., Meissner, F.F., and Clayton, J.L., Hydrocarbon source rocks of the greater Rocky Mountain region: Rocky Mountain Association of Geologists, p. 513-529.

Baars, D.L., 1970, Stratigraphic control of petroleum in White Rim Sandstone (Permian) in and near Canyonlands National Park, Utah; American Association of Petroleum Geologists Bulletin v. 54, no. 5, p. 709-718.

Bostick, N.H., and Freeman, V. L., 1984, Tests of vitrinite reflectance and paleotemperature models at the Multiwell Experiment Site, Piceance Creek basin, Colorado, in Spencer, C.W., and Keighin, C.W., eds., Geologic studies in support of the U.S. Department of Energy Multiwell Experiment, Garfield County, Colorado: U.S. Geological Survey Open-File Report 84-757, p. 110-120.

Britt, T.L., and Howard, E.D., 1982, Oil and gas potential of the central Utah hingeline-thrust belt region, in Powers, R.B., ed., Geologic studies of the Cordilleran thrust belt: Rocky Mountain Association of Geologists, p. 475-505.

Campbell, J.A., Ritzma, H.R., 1979, Geology and petroleum resources of the major oil-impregnated sandstone deposits of Utah: Utah Geological and Mineral Survey Special Studies 50, 24 p.

Colorado Oil and Gas Conservation Commission, 1985, Colorado oil and gas statistics: State of Colorado Oil and Gas Conservation Commission, 530 p.

Dolton, G.L., Carlson, K.H., Charpentier, R.R., Coury A.B., Crovelli, R.A., Frezon, S.E., Khan, A.S., Lister, J.H., McMullin, R.H., Pike, R.S., Powers, R.B., Scott, E.W., and Varnes, K.L., 1981, Estimates of undiscovered recoverable conventional resources of oil and gas in the United States: U.S. Geological Survey Circular 860, 87 p.

Finley, R.J., 1984, Geology and engineering characteristics of selected low-permeability gas sandstones: A national survey: Texas Bureau of Economic Geology, Report of Investigations, no. 138, 220 p.

Fouch, T.D., 1975, Lithofacies and related hydrocarbon accumulations in Tertiary strata of the western and central Uinta basin, Utah, in Bolyard, D.W., ed., Symposium on deep drilling frontiers in the central Rocky Mountains: Rocky Mountain Association of Geologists, p. 163-173.

Fouch, T.D., 1981, Distribution of rock types, lithologic groups and interpreted depositional environments for some lower Tertiary and Upper Cretaceous rocks from outcrops at Willow Creek-Indian Canyon through the subsurface of Duchesne and Altamont oil fields, southwest to north central parts of the Uinta basin, Utah: U.S. Geological Survey Oil and Gas investigation OC-81, 2 sheets.

Fryberger, S.G., and Koelmel, M.H., 1986, Rangely field--Eolian system-boundary trap in the Permo-Pennsylvanian Weber Sandstone of northwest Colorado, in Stone, D.S., ed., New interpretations of northwest Colorado geology: Rocky Mountain Association of Geologists, p. 129-149.

Gries, Robbie, 1983, Oil and gas prospecting beneath Precambrian of foreland thrust plates in Rocky Mountains: American Association of Petroleum Geologists Bulletin, v. 67, no. 1, p. 1-28.

Hansen, W.R., 1984, Post-Laramide tectonic history of the eastern Uinta Mountains, Utah, Colorado, and Wyoming: The Mountain Geologist, v. 21, no. 1, p. 5-29.

Hoffman, F.H., 1957, Possibilities of Weber stratigraphic traps, Rangely area, northwest Colorado: American Association of Petroleum Geologists Bulletin, v. 41, no. 5, p. 894-905.

Jensen, F.S., 1972, Thickness of Phanerozoic rocks, in Mallory, W.W., ed., Geologic atlas of the Rocky Mountain region: Rocky Mountain Association of Geologists, p. 56.

Johnson, R.C., 1985, Early Cenozoic history of the Uinta and Piceance Creek basins, Utah and Colorado, with special reference to the development of Eocene Lake Uinta, in Flores, R.M., and Kaplan, S.S., eds., Cenozoic paleogeography of west-central United States: Rocky Mountain Section, Society of Economic Paleontologists and Mineralogists, Rocky Mountain Paleogeography Symposium 3, p. 247-276.

Johnson, R.C., 1987, Geologic history and hydrocarbon potential of Late Cretaceous age, low-permeability reservoirs, Piceance basin, western Colorado: U.S. Department of Energy, DOE/MC/20422-2337, 97 p.

Johnson, R.C., Crovelli, R.A., Spencer, C.W., and Mast, R.F., 1987, An assessment of gas resources in low-permeability sandstones of the Upper Cretaceous Mesaverde Group, Piceance basin, Colorado: U.S. Geological Survey Open-File Report 87-357, 165 p.

Kellogg, H.E., 1977, Geology and petroleum potential of the Mancos B Formation, Douglas Creek arch area, Colorado and Utah, in Veal, H.V., eds., Exploration frontiers of the central and southern Rockies: Rocky Mountain Association of Geologists, p. 167-179.

Lucas, P.T., and Drexler, J.M., 1976, Altamont-Bluebell--A major, naturally fractured stratigraphic trap, Uinta basin, Utah, in Braunstein, Jules, ed., North American oil and gas fields: American Association of Petroleum Geologist Memoir 24, p. 121-135.

Mallory, W.W., ed., 1972, Geologic atlas of the Rocky Mountain region: Rocky Mountain Association of Geologists, 331 p.

Maughan, E.K., 1984, Geological setting and some geochemistry of petroleum source rocks in the Permian Phosphoria Formation, in Woodward, Jane, Meissner, F.F., and Clayton, J.L., eds., Hydrocarbon source rocks of the greater Rocky Mountain region: Rocky Mountain Association of Geologists, P. 281-294.

McFall, K.S., Wicks, D.E., Kuuskraa, V.A., and Sedwick, K.B., 1986, A geologic assessment of natural gas from coal seams in the Piceance basin, Colorado--Topical report September 1985-September 1986: Gas Research Institute GRI 87/0060, 75 p.

Mitchell, Gary C., 1984, Permo-Triassic of northwestern Paradox basin area, Utah [abs.]: American Association of Petroleum Geologists Bulletin, v. 68, no. 7, p. 943.

National Petroleum Council, 1980, Tight gas reservoirs; part I, in National Petroleum Council Unconventional Gas Resource: Washington, D.C., 222 p. with appendices.

Nuccio, V.F., and Johnson, R.C., 1986, Thermal maturity of the lower part of the Upper Cretaceous Mesaverde Group, Uinta basin, Utah: U.S. Geological Survey Miscellaneous Field Study Map, MF-1842.

Nuccio, V.F., and Johnson, R.C., 1988, Surface vitrinite reflectance map of the Uinta, Piceance, and Eagle basins area, Utah and Colorado: U.S. Geological Survey Miscellaneous Field Study Map, MF-2008-B, one plate, 19 p.

Nuccio, V.F., and Schenk, C.J., 1986, Thermal maturity and hydrocarbon source-rock potential of the Eagle basin, northwestern Colorado, in Stone, D.S., ed., New interpretations of northwest Colorado geology: Rocky Mountain Association of Geologists, p. 259-264.

Nuccio, V.F., and Johnson, R.C., in press, Thermal history of selected coal beds in the Upper Cretaceous Mesaverde Group and Tertiary Wasatch Formation, in relation to hydrocarbon generation, in Law, B.E., and Spencer, C.W., eds., Geology of tight gas reservoirs in the Pinedale anticline area, Wyoming and the Multiwell Experiment site, Colorado: U.S. Geological Survey Bulletin.

Palacas, J.G., Anders, D.E., and King, J.D., 1988, Applying aromatic steroids to determinations of thermal maturity of biodegraded heavy oils, tar sands, and bitumens (abs.], in Carter, L.M.H., ed., USGS Research on Energy Resources--1988, program and abstracts: U.S. Geological Survey Circular 1025, p. 44.

Peterson, J.A., and Hite, R.J., 1969, Pennsylvanian evaporite-carbonate cycles and their relation to petroleum occurrence, southern Rocky Mountains: American Association of Petroleum Geologists Bulletin, v. 53, no. 4, p. 884-908.

Pittman, E.D., 1972, Diagenesis of quartz in sandstones as revealed by scanning electron microscopy: Journal of Sedimentary Petrology, v. 42, p. 507-519.

Powers, R.B., 1986, The Willow Creek thrust fault, eastern Uinta Mountains--Geologic analysis of a foreland subthrust play, in Stone, D.S., ed., New interpretations of northwest Colorado geology: Rocky Mountain Association of Geologists, p. 183-190.

Ritzma, H.R., 1973, Oil-impregnated rock deposits at Utah: Utah Geological and Mineral Survey Map 33, 2 sheets.

Sanborn, A.F., 1971, Possible future petroleum of the Uinta and Piceance basins and vicinity, northeast Utah and northwest Colorado, in Cram, I.H., ed., Future petroleum provinces of the United States--Their geology and potential: American Association of Petroleum Geologists Memoir 15, v. 1, p. 489-537.

Sanborn, A.F., 1981, Potential petroleum resources of northeastern Utah and northwestern Colorado, in 32nd Field Conference Western Slope Colorado Guidebook, 1981: New Mexico Geological Society, p. 255-265.

Scanlon, A.H., 1983, Oil and gas fields map of Colorado: Colorado Geological Survey Map Series 22, scale 1:500,000.

Spencer, C.W., 1987, Hydrocarbon generation as a mechanism for overpressuring in the Rocky Mountain region: American Association of Petroleum Geologists Bulletin, v. 71, no. 4. p. 368-388.

Spencer, C.W., and Keighin, C.W., editors, 1984, Geologic studies in support of the U.S. Department of Energy Multiwell Experiment, Garfield County, Colorado: U.S. Geological Survey Open-File Report 84-757, 134 p.

Spencer, C.W., and Law, B.E., 1988, Unconventional resources--Western tight gas reservoirs, in USGS-MMS working paper--National assessment of undiscovered conventional oil and gas resources: U.S. Geological Survey Open-File Report 88-373, p. 480-500.

Stone, D.S., 1986a, Geology of the Wilson Creek field, Rio Blanco County, Colorado, in Stone, D.S., ed., New interpretations of northwest Colorado geology: Rocky Mountain Association of Geologists, p. 229-246.

Stone, D.S., 1986b, Rangely field summary: 2. Seismic profile, structural cross section, and geochemical comparisons, in Stone, D.S., ed., New interpretations of northwest Colorado geology: Rocky Mountain Association of Geologists, p. 226-228.

Sweeney, A.K., Burnham, A.K., Braun, A.L., 1987, A model of hydrocarbon generation from Type I kerogen--Application to Uinta Basin, Utah: American Association of Petroleum Geologists Bulletin, v. 71, no. 8, p. 967-985.

Tissot, B., Deroo, G., and Hood, A., 1978, Geochemical study of the Uinta basin--Formation of petroleum from the Green River Formation: Geochemica et Cosmochimica Acta, v. 42, p. 1469-1486.

Tremain, C.M., 1984, Coalbed methane resources of Colorado: Colorado Geological Survey Map Series 19, scale 500,000.

U.S. Geological Survey and American Association of Petroleum Geologists, 1962, Tectonic map of the United States--U.S. Geological Survey, scale 1:2,500,000.

USGS-MMS, 1988, Working paper--National assessment of undiscovered conventional oil and gas resources: U.S. Geological Survey Open-File Report 88-373, 522+ p.

Utah Geological and Mineral Survey, 1983, Energy resources map of Utah: Utah Geological and Mineral Survey Map 68, scale 1:500,000.

Utah Division of Oil, Gas and Mining, 1985, Production report, December 1985: State of Utah Natural Resources, 203 p.

Varnes, K.L., and Dolton, G.L., 1982a, Estimated areas and volumes of sedimentary rock in the United States by province--Statistical background data for U.S. Geological Survey Circular 860: U.S. Geological Survey Open-File Report 82-666C, 11 p.

Varnes, K.L., and Dolton, G.L., 1982b, Estimates of Federal ownership of undiscovered oil and gas resources by province--Statistical background data for U.S. Geological Survey Circular 860: U.S. Geological Survey Open-File Report 82-666b, 14 p.

Waechter, N.B., and Johnson, W.E., 1986, Pennsylvanian-Permian paleostructure and stratigraphy as interpreted from seismic data in the Piceance basin, northwest Colorado, in Stone, D.S., ed., New interpretations of northwest Colorado geology: Rocky Mountain Association of Geologists, p. 51-64.

Waples, D.W., 1980, Time and temperature in petroleum formation--Application of Lopatin's methods to petroleum exploration: American Association of Petroleum Geologists Bulletin, v. 64, no. 6, p. 919-926.

Wilson, M.D., and Pittman, E.D., 1977, Authigenic clays in sandstones: Recognition and influence on reservoir properties and paleoenvironmental analysis: Journal of Sedimentary Petrology, v. 47, p. 3-31.