ESTIMATES OF GAS RESOURCES IN OVERPRESSURED LOW-PERMEABILITY CRETACEOUS AND TERTIARY SANDSTONE RESERVOIRS, GREATER GREEN RIVER BASIN, WYOMING, COLORADO, AND UTAH[1]

B. E. Law, C. W. Spencer, R. R. Charpentier, R. A. Crovelli, R. F. Mast, G. L. Dolton, and C. J. Wandrey[2]

[1]Prepared by the U.S. Geological Survey in cooperation with the U.S. Department of Energy's Western Gas Sands Subprogram, Morgantown Energy Technology Center, Morgantown, West Virginia.

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ABSTRACT

The Greater Green River basin of Wyoming, Colorado, and Utah contains large amounts of gas in overpressured low-permeability Cretaceous and Tertiary reservoirs. The stratigraphic sequence in which these reservoirs occur is as much as 14,000-ft (4,267-m) thick and includes the Lower Cretaceous Cloverly Formation through the lower Tertiary Fort Union Formation.

The accumulation of thermogenic gas in these low-permeability reservoirs, at rates greater than it is lost, causes fluid (gas) pressure to rise above regional hydrostatic pressure. Thus, in the study area, all overpressured reservoirs are gas bearing. The gas-bearing overpressured sandstone reservoirs occupy the deeper parts of the basin, down-dip from water-bearing normal-pressured reservoirs. Structural and stratigraphic trapping aspects in these unconventional reservoirs are not as important

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as in conventional reservoirs; the top of overpressuring cuts across structural and stratigraphic boundaries. The source of the gas is predominantly type III organic matter in the interbedded coal and carbonaceous lithologies and type II and III organic matter in the interbedded marine shales.

For resource appraisal purposes, the gas-bearing interval was subdivided into five stratigraphic plays and the volume of gas-in-place for each play was estimated using a probabilistic analysis. Not included were normally-pressured "transition zones" where interbedded gas and water-bearing reservoirs occur shallower than and/or updip of the overpressured rocks. The estimate of the total gas-in-place resource of these plays ranges from 3,611 to 6,837 tcf (trillion cubic feet) with 5,063 tcf as the mean estimate.

Because of additional uncertainty related to economic recovery factors, estimation of recoverable volumes is inherently less precise than estimation of in-place volumes. Two of the most important factors influencing the volume of recoverable gas are price and technology. Therefore, recoverable gas was estimated for each play under two cases: (1) current technology, with a gas price of five dollars per thousand cubic feet, and (2) future technology, with no dollar limit. For the current technology case, the estimate of total recoverable gas ranges from 27 to 148 tcf, with 73 tcf as the mean estimate. For the future technology case, the estimate of total recoverable gas ranges from 189 to 816 tcf, with 433 tcf as the mean estimate.

INTRODUCTION

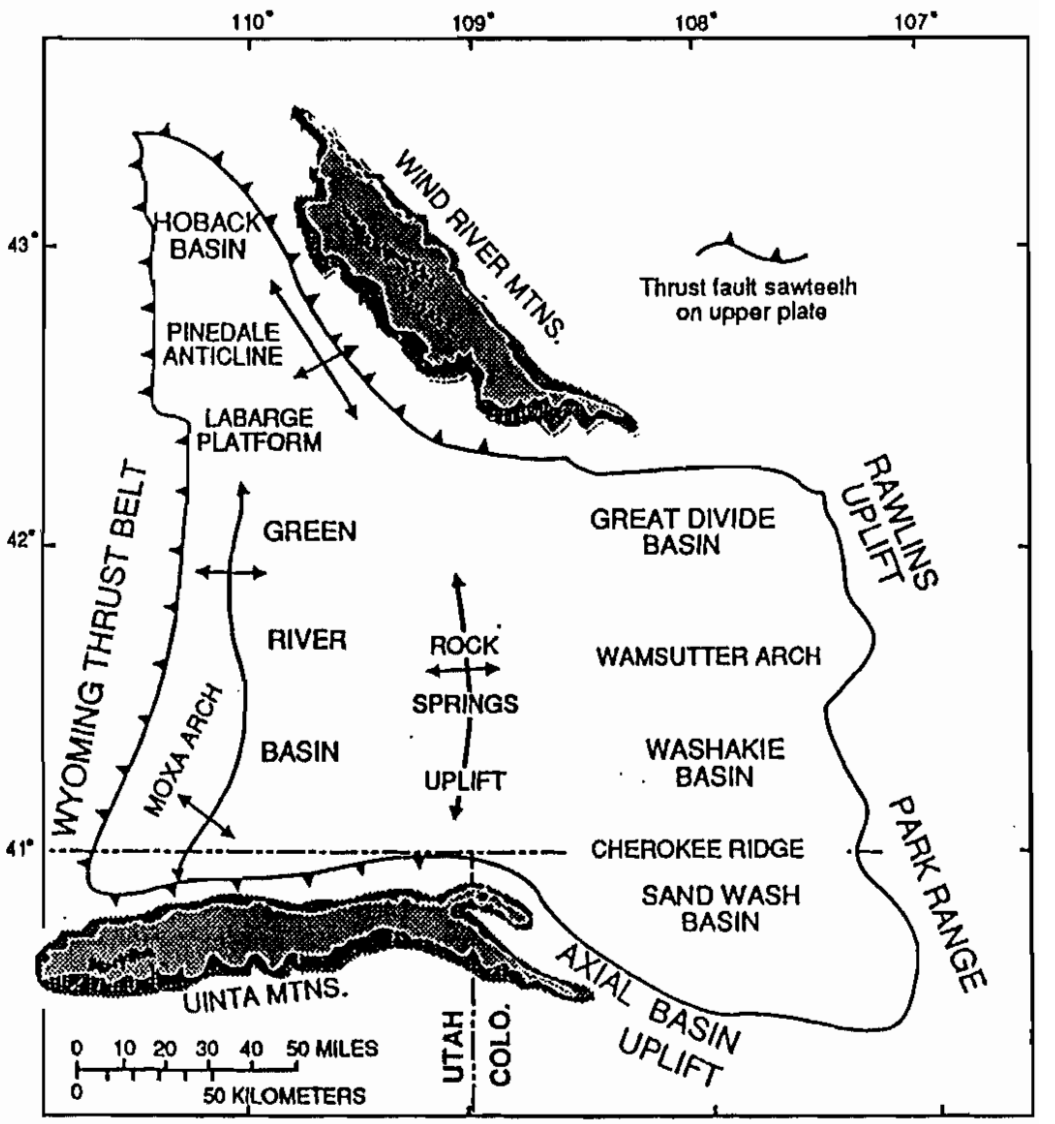
The Greater Green River basin of Wyoming, Colorado, and Utah (Figure 1) contains large amounts of gas in overpressured low-permeability Cretaceous and Tertiary reservoirs. The stratigraphic sequence in which these reservoirs occur is as much as 14,000-ft (4,267-m) thick and includes the Lower Cretaceous Cloverly Formation through the lower Tertiary Fort Union Formation.

Figure 1--Near Here

The Supply-Technical Advisory Task Force (1973) estimated the gas-in-place in the Greater Green River basin at 240 trillion cubic feet (tcf). Kuuskraa and others (1978) estimated 91 tcf of gas-in-place and the National Petroleum Council (1980) estimated 136 tcf. In the eastern part of the Greater Green River basin, McPeek (1981) estimated the gas-in-place resource of selected Upper Cretaceous reservoirs at 20.4 tcf. These estimates only evaluated selected reservoirs and areas ("sweet spots"), and did not include the entire gas-bearing sequence.

The U.S. Geological Survey (USGS) has conducted multidisciplinary research for several years on behalf of the U.S. Department of Energy. More than 200 research papers have been published as a result of this work. This cooperative work has greatly improved our understanding of the occurrence of gas-bearing low-permeability reservoirs. Geologic criteria have been identified that greatly facilitate identifying the vertical and lateral distribution of these unconventional gas accumulations.

The purpose of this study is to re-evaluate the gas resources contained in low-permeability overpressured Cretaceous and lower Tertiary sandstone reservoirs in the Greater Green River basin of Wyoming, Colorado, and Utah by using some existing, and largely unpublished,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109°
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HOBACK BASIN
WIND RIVER MTNS.
Thrust fault sawteeth on upper plate
PINEDALE ANTICLINE
LABARGE PLATFORM
WYOMING THRUST BELT
GREEN RIVER BASIN
MOXA ARCH
ROCK SPRINGS UPLIFT
GREAT DIVIDE BASIN
RAWLINS UPLIFT
WAMSUTTER ARCH
WASHAKIE BASIN
CHEROKEE RIDGE
SAND WASH BASIN
PARK RANGE
AXIAL BASIN UPLIFT
UINTA MTNS.
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geologic information that, we believe, lead to a more accurate estimate of gas-in-place. Early in this study, it was decided to make an estimate of gas-in-place in all overpressured sandstones more than 10-ft (3-m) thick in intervals where most of the reservoirs were known to be gas saturated. We knew that these gas-in-place figures would be very large because we were also aware of areas, formations, and thicknesses of reservoirs excluded from previous studies.

We believe that our estimates of gas-in-place, as large as they may be, are actually conservative. For example, they do not include gas in sandstones thinner than 10 ft (3 m), do not include gas in coals, nor gas in shales and siltstones. Also, the assessment does not include gas in strata with many water reservoirs interbedded with normally-pressured gas reservoirs. These intervals with mixed gas and water reservoirs are called "transition zones" and generally occur above and/or updip of the overpressured, gas-saturated intervals that we did assess. These transition zones can be evaluated locally in this basin and also in other basins with fairly close well control such as the Piceance basin in Colorado (Johnson and others, 1987).

OVERVIEW OF TIGHT GAS RESERVOIRS

Tight gas reservoirs are gas-bearing rocks that usually have an in-situ permeability to gas of less than 0.1 md. Artificial stimulation, such as hydraulic fracturing, is almost always needed in order to produce the gas. We estimate that approximately 500 to 800 billion cubic feet of gas has been produced from tight gas reservoirs to date in the basin.

In the United States, there are many lithologies that can be considered as tight gas reservoirs, such as sandstones, siltstones,

shales, limestones, dolomites, and chalks. However, in the subject basin, sandstones are the dominant tight reservoir rocks, and only gas in these rocks is assessed. Furthermore, only gas in overpressured individual sandstones thicker than 10 ft (3 m) is included.

Spencer (1985) describes the characteristics of various types of tight reservoirs in the Rocky Mountain region. These reservoirs usually do not have discrete gas/water contacts; most of the gas occurs in stratigraphic traps. Well-log analysis is difficult, and formation damage may occur during drilling and completion. In the Greater Green River basin, sandstone reservoir geometry is both lenticular and blanket. The definition of blanket reservoirs is based more on engineering characteristics than geologic criteria, although most "blanket" reservoirs in the basin were deposited in marginal-marine environments. Blanket reservoirs respond to artificial hydraulic fracturing in a somewhat predictable way; that is, if the volume of proppant is increased, there usually is a corresponding increase in well productivity up to certain limits. Conversely, lenticular reservoirs, which were mostly deposited in fluvial environments, generally do not respond to hydraulic fracturing in a predictable manner.

The sandstones in the basin are of the low-porosity type (Spencer, 1985) and originally were conventional reservoirs. They subsequently were altered by deep burial cementation and other factors. Most of the porosity is secondary and is caused by the dissolution of mineral grains, rock fragments, and cements (usually carbonate). The pores are poorly connected by sheet-like capillaries. Most of these sheets or ribbons are less than 2-μm thick and often are less than 1-μm thick. Because of their small size, they usually have very high capillary pressures.

The Cretaceous sandstones are mostly lithic sandstones and quartz sandstones and the Tertiary reservoirs are mostly lithic arkoses (Law and others, 1986; Pollastro, in press). The sandstones usually have authigenic clays in the pore spaces. This clay is an additional factor decreasing effective permeability to gas.

Because the rock permeabilities are very low, natural fracturing is a very important factor controlling well productivity. The best well completions usually are those wells where the most natural fractures are intersected by the well bore or where the artificial stimulation connects the wellbore to the natural fracture system in the least damaging manner.

STRUCTURE

The Greater Green River basin is located in the Rocky Mountains foreland and encompasses an area of about 19,700 mi^2 (51,000 km^2) (Figure 1). It is a composite of five smaller basins in Wyoming, Colorado, and Utah that include the Hoback, Green River, Great Divide, Washakie, and Sand Wash basins. The basin is bounded on the west by the Wyoming thrust belt, on the north by the Wind River Mountains uplift and thrust fault, on the east by the Rawlins and Park Range uplifts, and on the south by the Axial basin uplift and the Uinta Mountains uplift and thrust fault.

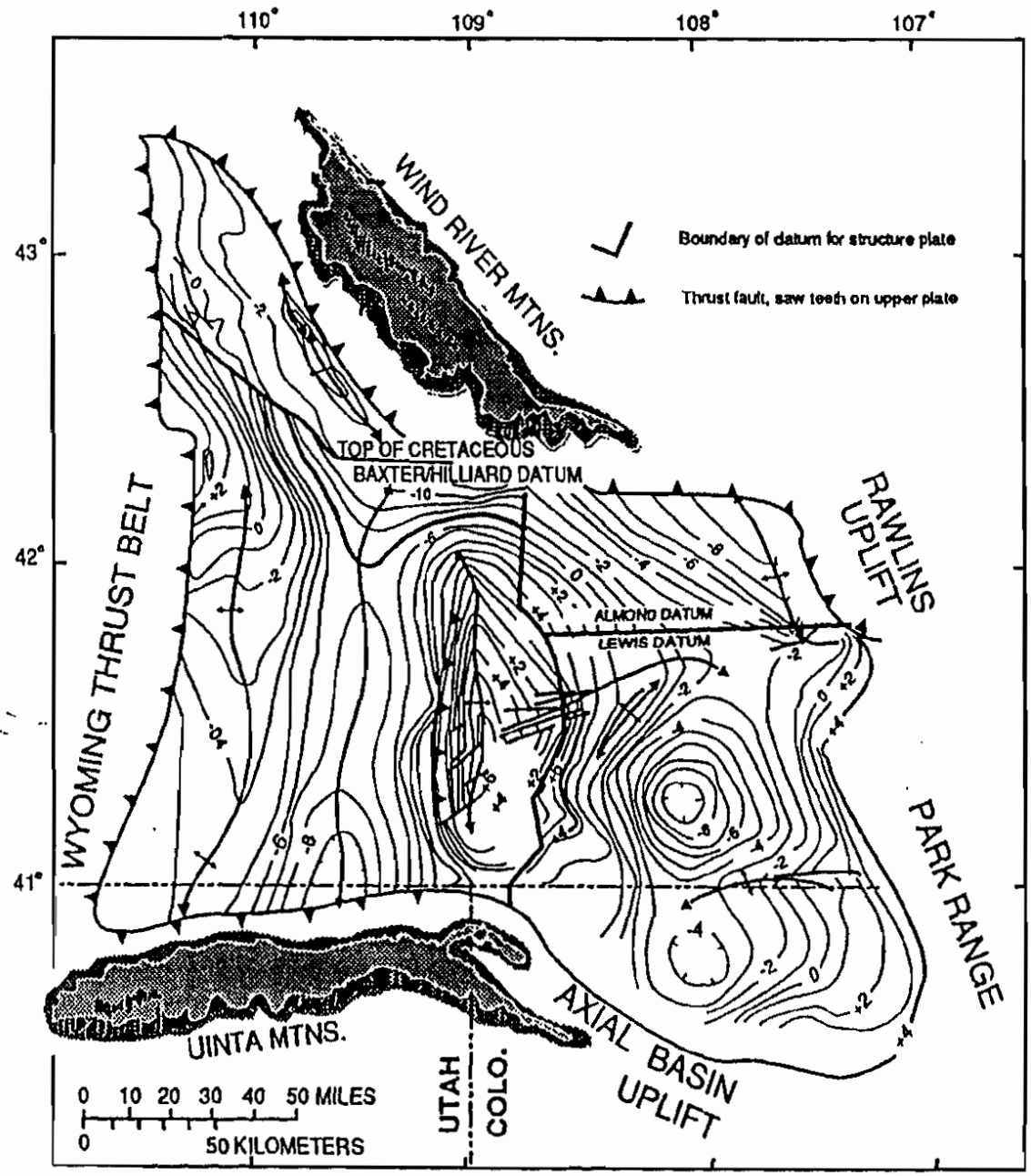
The area is characterized by basement-involved uplifts and adjacent basins. Figure 2 is a structure contour map of the Greater Green River basin showing the major structural features. The edges of the basins are typically thrust margins, and have been the subject of several investigations (Berg, 1961, 1962, 1963; Smithson and others, 1978; Royce and others, 1975; Gries, 1983; Garing and Tainter, 1985). For the most part, the structural features in and adjacent to the basin are the result

of compressional deformation that occurred during the Laramide orogeny (Campanian through late Eocene); however, there is evidence that some of these features may have undergone structural deformation prior to Laramide deformation. For example, in the Lost Soldier area, located along the northeast edge of the Great Divide basin, Reynolds (1976) noted structural and stratigraphic evidence of pre-Laramide structural growth. Pre-Laramide structural growth has also been noted by Wach (1977) along the Moxa arch, and by Stone (1986) on the Axial basin uplift. Merewether and Cobban (1986) presented stratigraphic evidence for the presence of structural swells in southwestern Wyoming during deposition of the Upper Cretaceous Frontier Formation. Post-Laramide deformation (late Eocene to Pliocene) in southwestern Wyoming is characterized by extensional faulting and partial to complete collapse of the basement uplifts surrounding the basin in Miocene and Pliocene time (Hansen, 1965; Love, 1970; Reynolds, 1976; Sales, 1983; Ryder, 1988).

Figure 2---Near Here

STRATIGRAPHY

A maximum of about 32,000 ft (9,750 m) of Cambrian through Tertiary sedimentary rocks are present in the Greater Green River basin. For the purposes of this investigation, we are primarily concerned with Cretaceous through lower Tertiary rocks. The stratigraphic correlations of these rocks within the basin are shown in Figure 3. Some of the more notable stratigraphic studies that have been conducted on these rocks are those by Hale (1950, 1955, 1961), Douglas and Blazzard (1961), Keith (1965), Weimer (1960, 1961, 1962), Smith (1961), Reynolds (1976), McGookey (1972), Dorr and others (1977), Miller (1977), Bader and others (1983), Kiteley (1983),


110°
109°
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43°
42°
41°
WIND RIVER MTNS.
Boundary of datum for structure plate
Thrust fault, saw teeth on upper plate
TOP OF CRETACEOUS
BAXTER/HILLIARD DATUM
ALMOND DATUM
LEWIS DATUM
WYOMING THRUST BELT
RAWLINS UPLIFT
PARK RANGE
AXIAL BASIN UPLIFT
UINTA MTNS.
UTAH
COLO.
0 10 20 30 40 50 MILES
0 50 KILOMETERS

Merewether and others (1984), Merewether and Cobban (1986), and Ryder (1988).

Figure 3 Near Here

Lower Cretaceous Rocks

Lower Cretaceous rocks in the Greater Green River basin are composed of interbedded conglomerate, sandstone, siltstone, shale, and coal that were deposited in marine and nonmarine environments. Throughout the region they unconformably overlie the Upper Jurassic Morrison Formation (McGookey, 1972). The stratigraphic relationships of Lower Cretaceous rocks in southwestern Wyoming are poorly known, primarily because of a paucity of biostratigraphic data, uncertainties regarding unconformities, and limited subsurface data. The generalized stratigraphic correlations of these rocks in the Greater Green River basin are shown in Figure 3.

Along the western edge of the basin, in the vicinity of the La Barge platform and the Moxa arch (Figure 1), Lower Cretaceous rocks include, in ascending order, the Cloverly Formation and Bear River Formation. The Cloverly and Bear River Formations are composed of conglomerate, sandstone, siltstone, and shale that were derived from highlands, located west of the Greater Green River basin, in eastern Idaho and north-central Utah. These rocks were deposited in predominantly non-marine environments and range in thickness from 300 to 500 ft (91-152 m). Further east, in the Great Divide, Washakie, and Sand Wash basins, correlative Lower Cretaceous rocks are 100- to 250-ft (30-76-m) thick and intertongue with non-marine, marginal marine, and marine sandstone, siltstone, and shale (Figure 3).

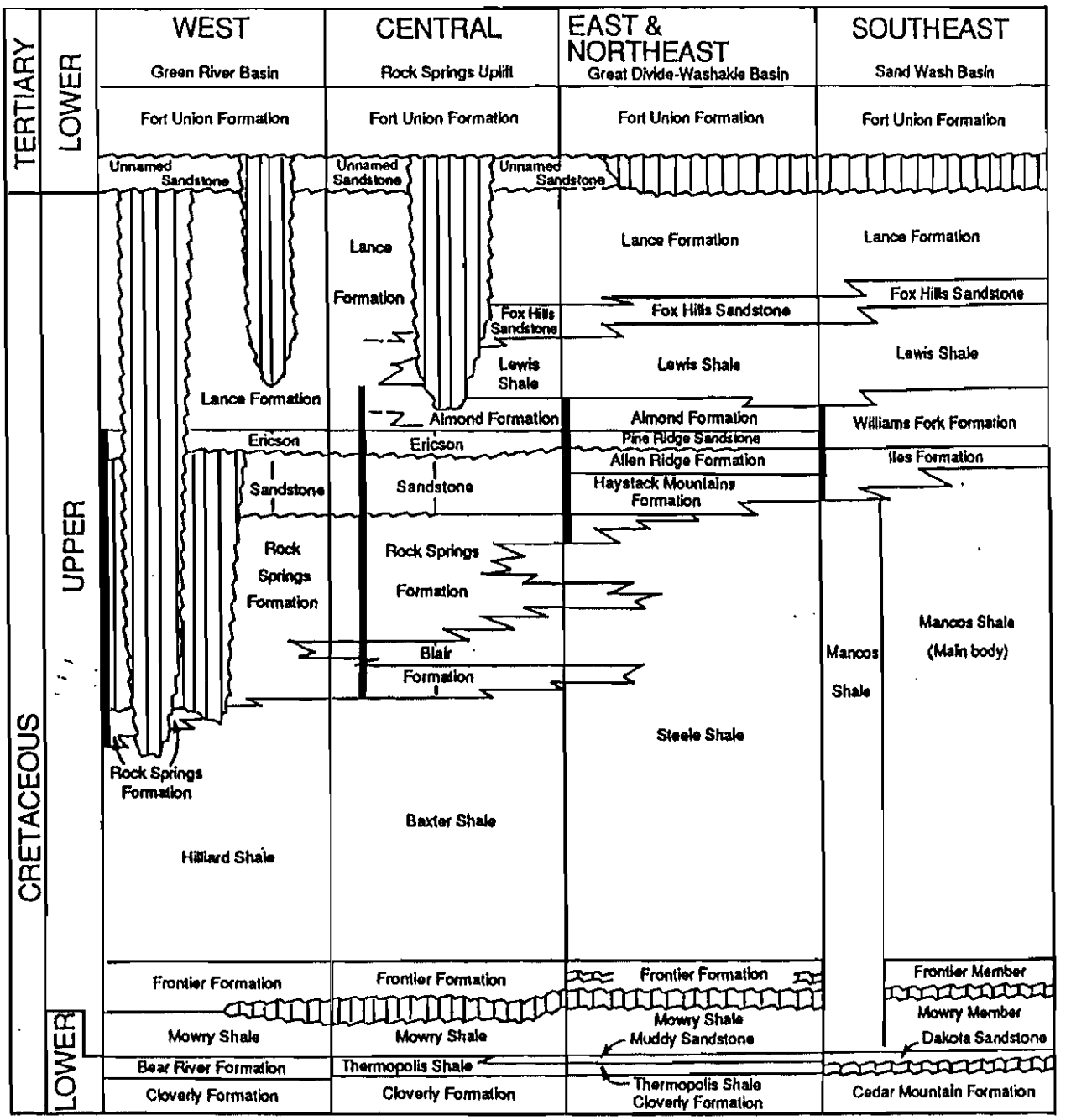


Figure 3.-- Generalized correlation chart of Cretaceous and lower Tertiary stratigraphic units in the Greater Green River basin. Heavy black bar shows limits of Mesaverde Group in various areas. Diagram represents general age and facies relationships and not relative rock thickness.

Upper Cretaceous Rocks

Upper Cretaceous rocks in the Greater Green River basin are lithologically similar to Lower Cretaceous rocks. They are composed of interbedded sandstones, siltstones, shales, and carbonaceous lithologies, including coal, that were deposited in marine and nonmarine environments. Upper Cretaceous rocks, in contrast to Lower Cretaceous rocks, have been extensively studied and for the most part are well understood.

The stratigraphic correlations of Upper Cretaceous rocks within the Greater Green River basin are shown in Figure 3. With reference to the stratigraphic sequence in the western part of the basin (Figure 3), the sequence, from oldest to youngest, includes the Mowry Shale, Frontier Formation, Hilliard Shale, Rock Springs Formation, Ericson Sandstone, and Lance Formation. The sources of the clastic sediments in these rocks were highlands and volcanic areas in eastern Idaho and north-central Utah, west of the Greater Green River basin. The sequence is composed of thick intervals of siliciclastic rocks deposited during marine transgressions and regressions. The cycles of transgressions and regressions are, in some cases, incomplete due to extensive erosion marked by regional unconformities. For example, erosion associated with unconformities in the Frontier Formation (Merewether and Cobban, 1986) has, in some cases, obscured parts of the transgressive or regressive cycles. Erosion at unconformities associated with the Ericson Sandstone and equivalent rocks and at the Cretaceous-Tertiary boundary has removed parts of the depositional cycle and poses problems for the establishment of a reliable stratigraphic framework in the region.

The Upper Cretaceous Mowry Shale (Figure 3) conformably overlies Lower Cretaceous rocks and is a siliceous, organic-rich shale that was deposited during a southward marine transgression (McGookey, 1972). The Mowry ranges in thickness from 300-to 500-ft (91-152-m) thick in the western part of the region and thins to 100- to 200-ft (30-60-m) in the eastern and southeastern part of the region. Recent work by Cobban and Kennedy (in press) has shown that the age of the Mowry Shale is early Cenomanian.

The Frontier Formation unconformably overlies the Mowry Shale through most of the area. It is thickest in the west-central part of the area where it is 800- to 1,600-ft (244-488-m) thick. To the south and east, along the north flank of the Uinta Mountains and in the vicinity of the Rawlins uplift, the Frontier thins to 100 to 200 ft (30-60 m). The Frontier is composed of marine and nonmarine sandstones, siltstones, and shales that were deposited in marine and nonmarine environments during periodic transgressions and regressions of the Western Interior seaway. The source area of sediments for the Frontier was west of the Greater Green River basin, in the Sevier orogenic belt. Detailed discussions of the environments of deposition for various parts of the Frontier are given by De Chadenedes (1975), Hale (1962), Winn and Smithwick (1980), Merewether (1983), Merewether and others (1984), and Merewether and Cobban (1986).

The Hilliard Shale and equivalent rocks conformably overlie the Frontier Formation (Figure 3). The Hilliard Shale is equivalent to the Baxter Shale in the vicinity of the Rock Springs uplift, the Steele Shale in the eastern part of the region, and the main body of the Mancos Shale in the Sand Wash basin. It is composed of shale and silty shale that were

deposited in shallow-water neritic environments. The Hilliard Shale and equivalent rocks range in thickness from 2,800 to 4,100 ft (853-1,250 m) in the western part of the area, and 4,900 to 5,200 ft (1,494-1,585 m) in the eastern part of the area.

The overlying Mesaverde Group and younger Cretaceous rocks consist of an eastward-prograding wedge of siliciclastics derived primarily from western sources during the Sevier and Laramide orogenies. This rock sequence attains a maximum thickness of about 10,500 ft (3,200 m) in the northern part of the Green River basin and consists of interbedded sandstone, siltstone, shale, mudstone, carbonaceous shale, and coal. In the western part of the region, the entire section, with the exception of the lowest few hundred feet, is nonmarine and was deposited in fluvial-dominated environments. Further east and southeast, in the Washakie and Sand Wash basins, this sequence grades into and intertongues with marine, marginal marine, and fluvial deposits of the Upper Cretaceous Steele and Mancos Shales (upper part); the Iles and Williams Fork Formations of the Mesaverde Group; and the Lewis Shale, Fox Hills Sandstone, and Lance Formation (Figure 3). In the Great Divide basin, correlative rock units include the Upper Cretaceous Steele Shale (upper part); the Haystack Mountains Formation, Allen Ridge Formation, Pine Ridge Sandstone, and Almond Formation of the Mesaverde Group; and the Lewis Shale, Fox Hills Sandstone, and Lance Formation (Figure 3). The age of these siliciclastic rocks ranges from about middle Santonian to late Maastrichtian in the northern Green River basin and early middle Campanian to late Maastrichtian in the southeastern part of the Sand Wash basin.

Tertiary Rocks

The discussion of Tertiary rocks is limited to the lower Tertiary sequence, inasmuch as upper Tertiary rocks within the Greater Green River basin have mostly conventional reservoir characteristics.

The base of the Tertiary in the Greater Green River basin is marked by a regional unconformity (Ritzma, 1965; Roehler, 1961; Dorr and others, 1977; Winterfeld, 1979; Beaumont, 1979). Throughout most of the region, the oldest Tertiary unit is the Paleocene Fort Union Formation or equivalent units. However, in the subsurface of the northern Green River basin and Great Divide basin, an older unnamed Tertiary interval has been identified on the basis of well-log correlations and palynology (Law, 1979; Law and Nichols, 1982). The lateral extent of this unit is uncertain. The interval does not crop out due to truncation in the subsurface, at the base of the Fort Union Formation. This unnamed lower Tertiary rock interval attains a maximum thickness of about 1,600 ft (488 m) and consists of interbedded conglomerate, sandstone, siltstone, and shale. The environment of deposition is interpreted as fluvial, based on the examination of well logs and a few cores.

The Paleocene Fort Union Formation and equivalent units unconformably overly the unnamed Tertiary sequence (locally) and Upper Cretaceous rocks in most of the Greater Green River basin. The Fort Union consists of interbedded conglomerate, sandstone, siltstone, mudstone, carbonaceous shale, coal, and limestone that represent depositional features commonly associated with fluvial-dominated systems.

SOURCE ROCKS

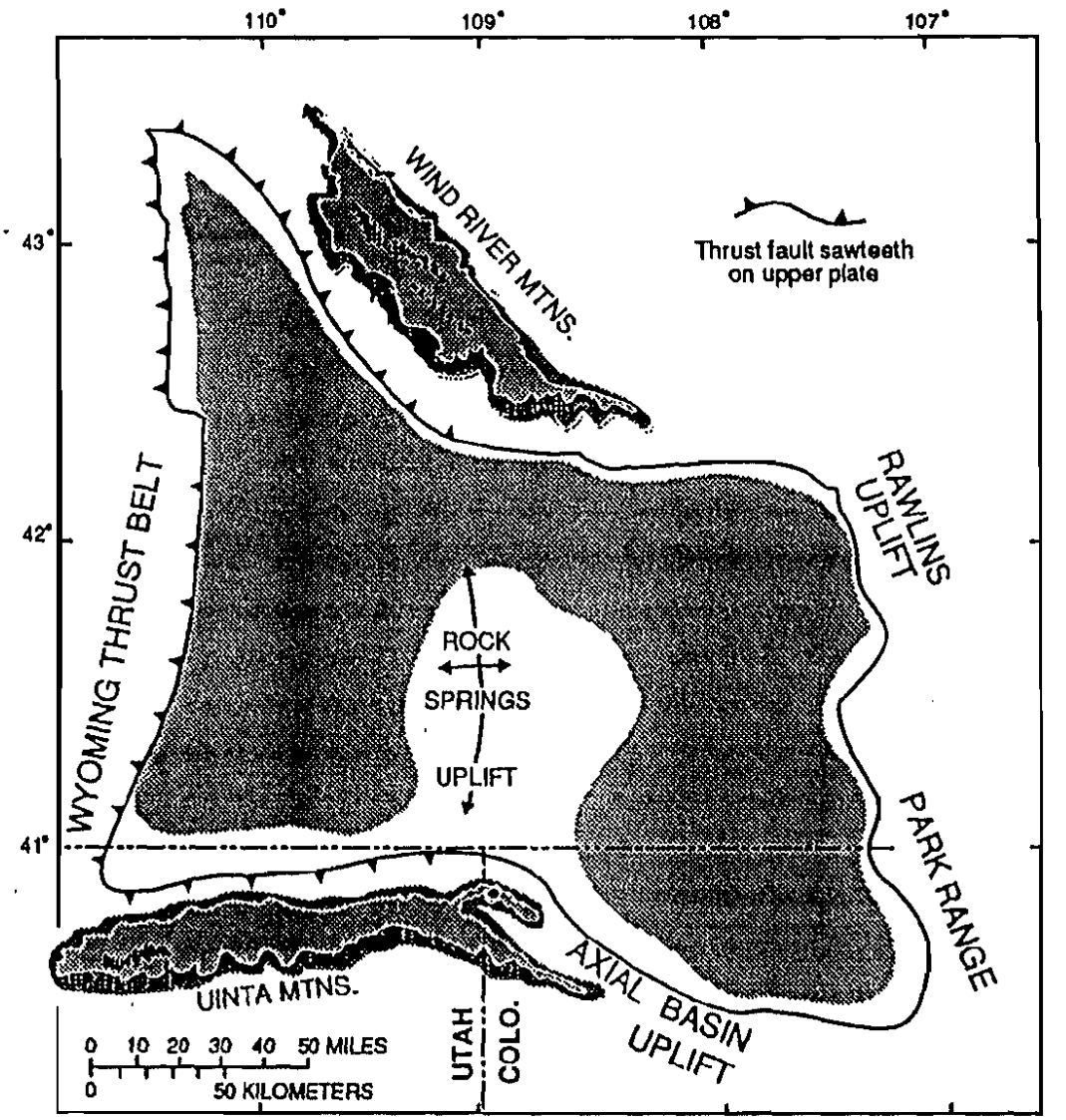
A source rock evaluation of interbedded coalbeds, carbonaceous shales, siltstones, and sandstones in the Mesaverde through the Fort Union and equivalent rocks (Law and others, 1979, 1980; Law, 1984) indicates that they contain humic, type III organic matter with a hydrocarbon generative potential of primarily gas. A source bed should contain at least 0.5% organic carbon to be considered a favorable source for economic oil and gas accumulations. Excluding coal, the average organic carbon content of these rocks is 2.04%. Total organic carbon content of a few samples of the marine Baxter Shale and equivalent rocks range from 0.20 to 2.71%. There are insufficient data to determine the quality of organic matter in these marine shales but it most likely consists of types II and III organic matter. The Upper Cretaceous Mowry Shale contains types II and III organic matter and the organic carbon content ranges from 1.5 to 2.5% (Burtner and Warner, 1984). Source rock analyses of a few samples from the Frontier Formation along the Moxa arch (Merewether and others, 1984) and the Pacific Creek area in the northeastern part of the Green River Basin (Law and others, 1979, 1980) show total organic carbon values ranging from 0.25 to 2.0%. The coal and carbonaceous lithologies in the Cloverly Formation and Frontier Formation probably contain type III organic matter, similar to that in the Mesaverde and younger Cretaceous rocks. Thermal maturity maps of the Greater Green River basin by Pawlewicz and others (1986) and Merewether and others (1987) indicate that Cretaceous and lower Tertiary rocks are thermally mature throughout most of the basin.

ABNORMALLY HIGH FORMATION PRESSURES

Extensive research has shown that abnormally high formation pressures (overpressuring) in the Greater Green River basin are always associated with gas-bearing low-permeability strata. Consequently, recognition of overpressured rocks in this region is of considerable value to economic evaluation and resource assessment. Figure 4 shows the approximate area of overpressured Cretaceous and Tertiary rocks in the Greater Green River basin. Overpressured gas-bearing rocks occur in the deeper parts of the basin, down-dip from normally pressured water-bearing rocks (Law, 1984; Spencer, 1985, 1987). There is no recognizable lithologic seal for these accumulations and structural and stratigraphic trapping aspects are not as important as in more conventional accumulations; the top of overpressuring cuts across structural and stratigraphic boundaries as shown in cross sections A-A′ through D-D′ (Figures 5-8).

Figures 4-8---Near Here

Overpressuring in the basin was first recognized by Rathbun (1968) and Rathbun and Dickey (1969). They concluded that tectonism was the cause of overpressuring. Later work by Law and others (1979, 1980), McPeek (1981), Law (1984), Law and Dickinson (1985), Law and others, 1986, and Spencer (1987) attributed overpressuring to the accumulation of thermogenic gas in low-permeability reservoirs. The generation of large amounts of thermogenic gas and the initiation of overpressuring occurs at temperatures of 190 to 200°F (88-93°C) (Law, 1984; Spencer, 1987). Initially, formation water becomes saturated with gas, and as additional gas enters the pore system, bubbles of free gas form. With continued gas generation, free and weakly bound waters are forced out of the gas generation zone into overlying and updip lower-pressured rocks. In the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WIND RIVER MTNS.
Thrust fault sawteeth on upper plate
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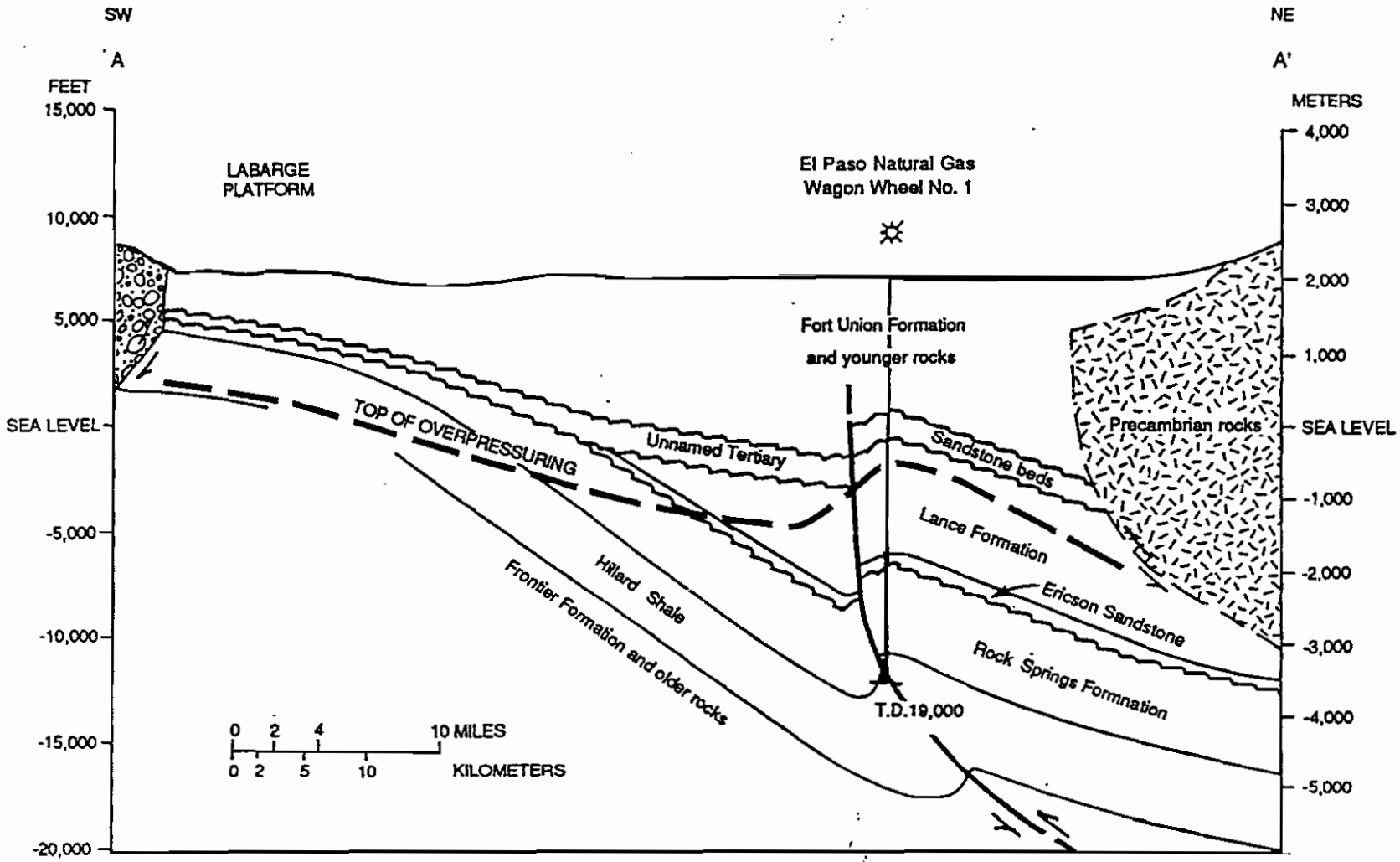
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LABARGE
PLATFORM
El Paso Natural Gas
Wagon Wheel No. 1
Fort Union Formation
and younger rocks
Precambrian rocks
TOP OF OVERPRESSURING
Unnamed Tertiary
Sandstone beds
Lance Formation
Ericson Sandstone
Rock Springs Formation
Hilard Shale
Frontier Formation and older rocks
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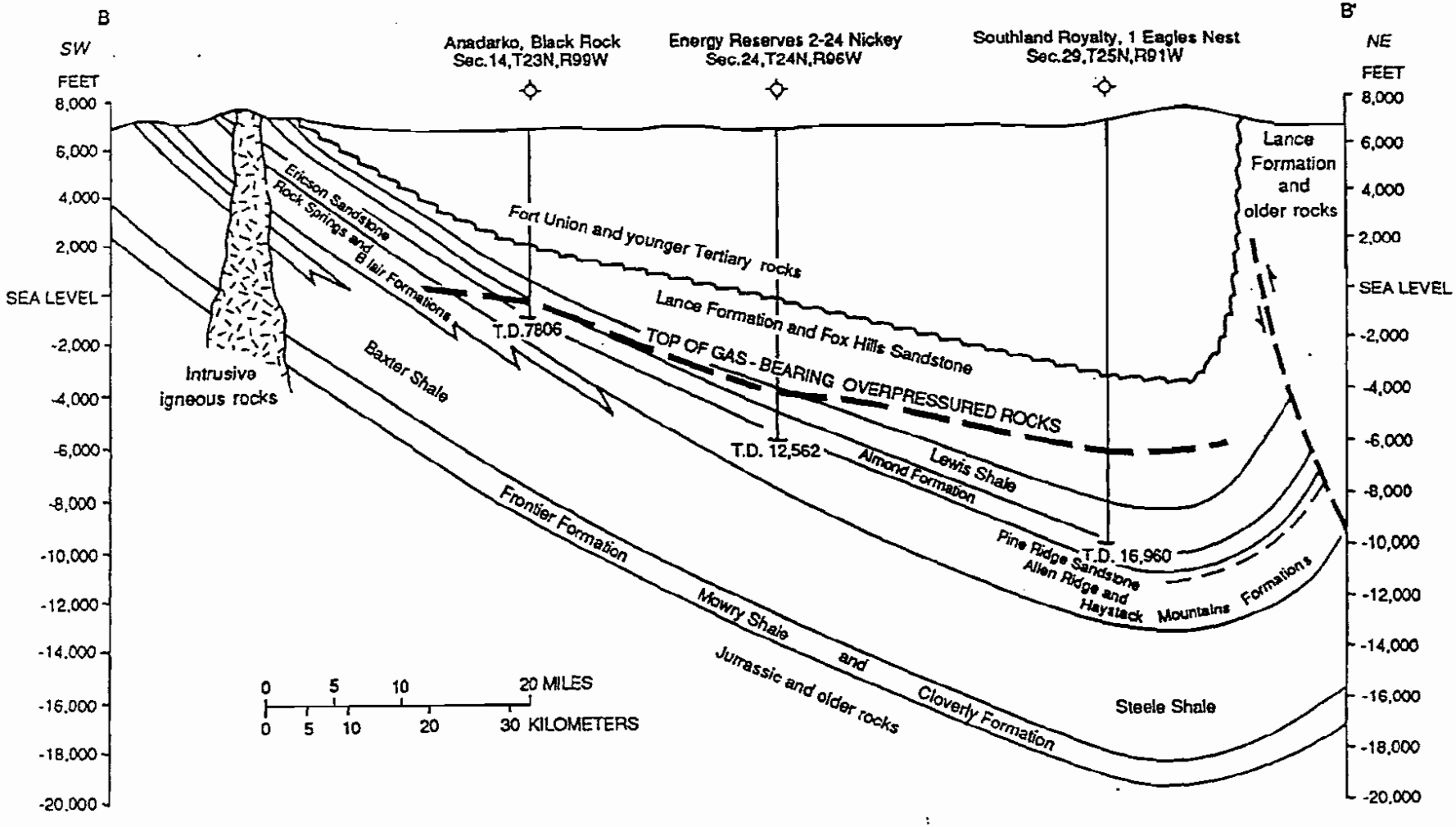
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Anadarko, Black Rock
Sec.14,T23N,R99W
Energy Reserves 2-24 Nickey
Sec.24,T24N,R96W
Southland Royalty, 1 Eagles Nest
Sec.29,T25N,R91W
B'
NE
FEET
Lance Formation and older rocks
Ericson Sandstone
Rock Springs and Blair Formations
Fort Union and younger Tertiary rocks
Lance Formation and Fox Hills Sandstone
T.D.7806
TOP OF GAS - BEARING OVERPRESSURED ROCKS
Intrusive igneous rocks
Baxter Shale
T.D. 12,562
Lewis Shale
Almond Formation
Pine Ridge Sandstone
T.D. 16,960
Allen Ridge and Haystack Mountains Formations
Frontier Formation
Mowry Shale and Cloverly Formation
Jurassic and older rocks
Steele Shale
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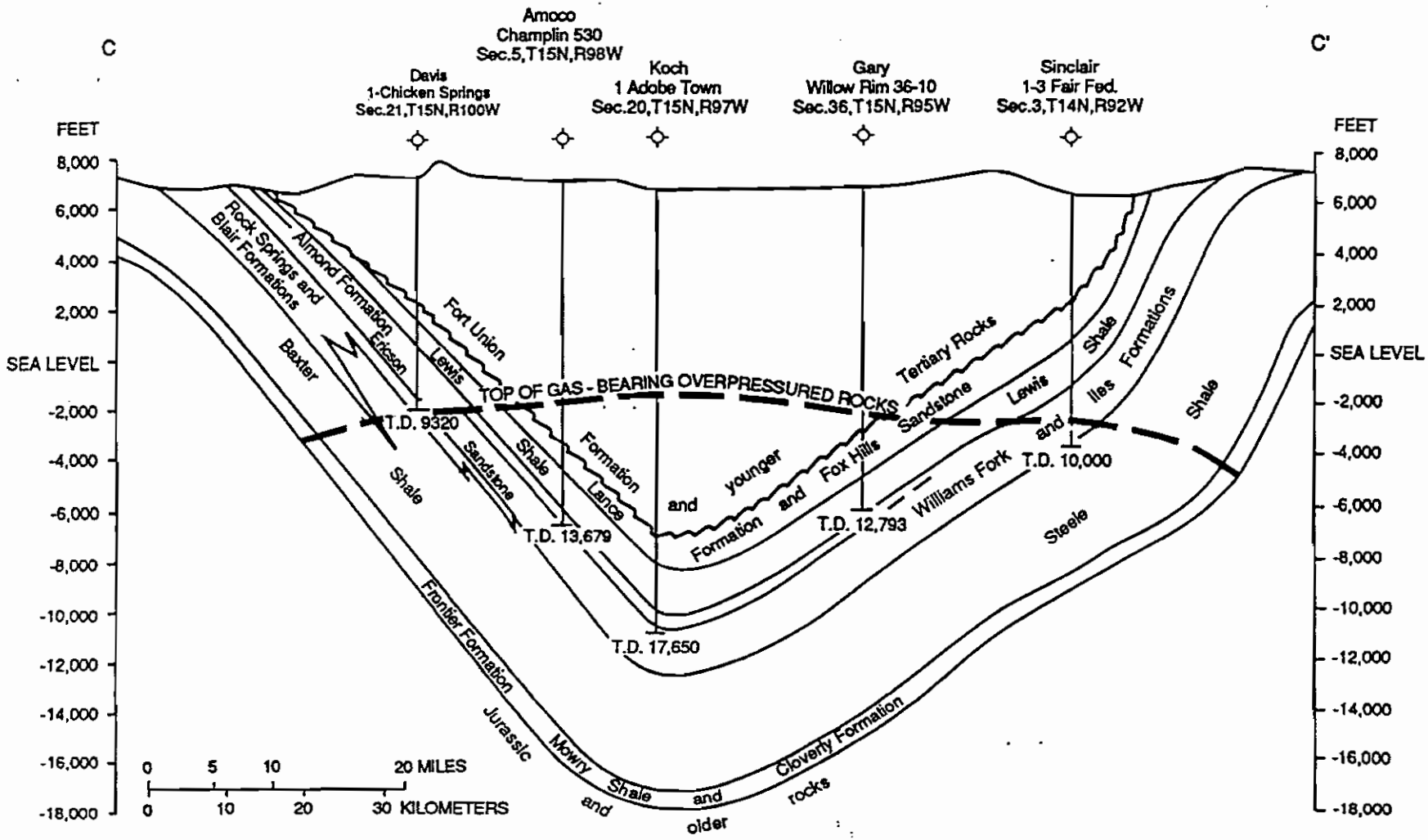
C
C'
Amoco
Champlin 530
Sec.5,T15N,R98W
Davis
1-Chicken Springs
Sec.21,T15N,R100W
Koch
1 Adobe Town
Sec.20,T15N,R97W
Gary
Willow Rim 36-10
Sec.36,T15N,R95W
Sinclair
1-3 Fair Fed.
Sec.3,T14N,R92W
FEET
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Rock Springs and Blair Formations
Almond Formation
Ericson
Fort Union
Lewis
Shale
Sandstone
Shale
Baxter
Frontier Formation
Jurassic
Mowry Shale and older rocks
TOP OF GAS - BEARING OVERPRESSURED ROCKS
T.D. 9320
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Formation
Lance
and younger
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Tertiary Rocks
Fox Hills
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Lewis
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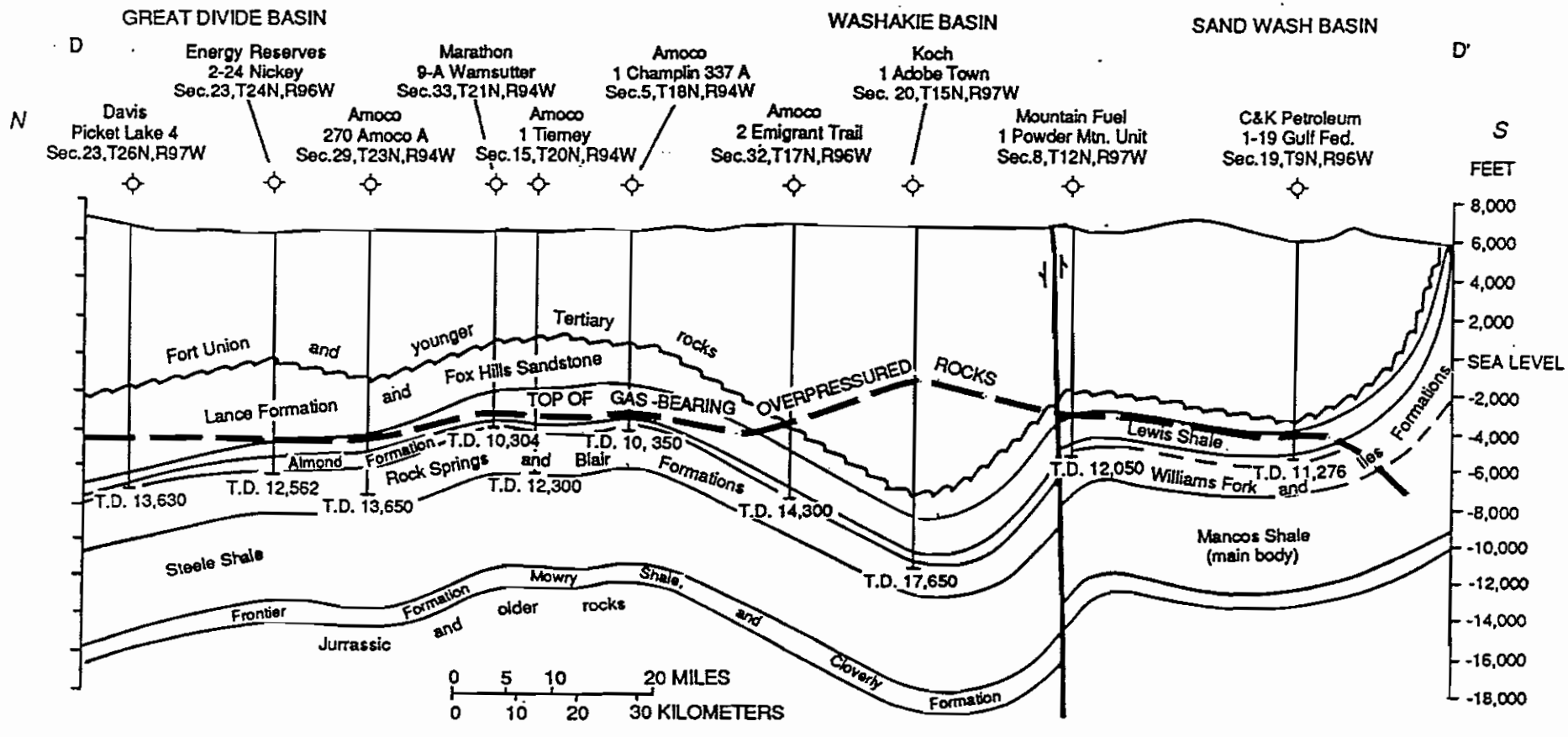
Shale
Cloverly Formation
0 5 10 20 MILES
0 10 20 30 KILOMETERS


GREAT DIVIDE BASIN
WASHAKIE BASIN
SAND WASH BASIN
D
D'
N
S
Davis
Picket Lake 4
Sec.23,T26N,R97W
Energy Reserves
2-24 Nickey
Sec.23,T24N,R96W
Amoco
270 Amoco A
Sec.29,T23N,R94W
Marathon
9-A Wamsutter
Sec.33,T21N,R94W
Amoco
1 Tierney
Sec.15,T20N,R94W
Amoco
1 Champlin 337 A
Sec.5,T18N,R94W
Amoco
2 Emigrant Trail
Sec.32,T17N,R96W
Koch
1 Adobe Town
Sec. 20,T15N,R97W
Mountain Fuel
1 Powder Mtn. Unit
Sec.8,T12N,R97W
C&K Petroleum
1-19 Gulf Fed.
Sec.19,T9N,R96W
FEET
8,000
6,000
4,000
2,000
SEA LEVEL
-2,000
-4,000
-6,000
-8,000
-10,000
-12,000
-14,000
-16,000
-18,000
Fort Union and younger Tertiary rocks
Lance Formation and Fox Hills Sandstone
TOP OF GAS-BEARING OVERPRESSURED ROCKS
Almond Formation and Rock Springs and Blair Formations
Lewis Shale
Williams Fork and Iles Formations
Steele Shale
Frontier Formation
Mowry Shale,
Jurrassic and older rocks
Cloverly Formation
Mancos Shale
(main body)
T.D. 13,630
T.D. 12,562
T.D. 13,650
T.D. 10,304
T.D. 12,300
T.D. 10, 350
T.D. 14,300
T.D. 17,650
T.D. 12,050
T.D. 11,276
0 5 10 20 MILES
0 10 20 30 KILOMETERS

pore system of the overpressured rocks the remaining irreducible water is present as thin films of water coating grain boundaries and filling small capillaries.

The position of the top of overpressuring in the Greater Green River basin has been shown to be related to the level of thermal maturity, organic-richness of the gas source rocks, and present-day temperature (Law, 1984). The top of overpressuring commonly occurs at a vitrinite reflectance of 0.8% (ranging from 0.74 to 0.94%) and an uncorrected bottom-hole temperature of about 180°F (82°C) (corrected to 190 to 200°F). However, because overpressuring is a transient condition these criteria should be used in conjunction with other data, such as drillstem tests, drilling mud weights, and gas-mud logs in order to identify the top of overpressuring. Figure 9 shows a map of the subsurface elevation of the 0.80% R_m in the Greater Green River basin and Figure 10 shows a map of the depth to 180°F (82°C) (uncorrected).

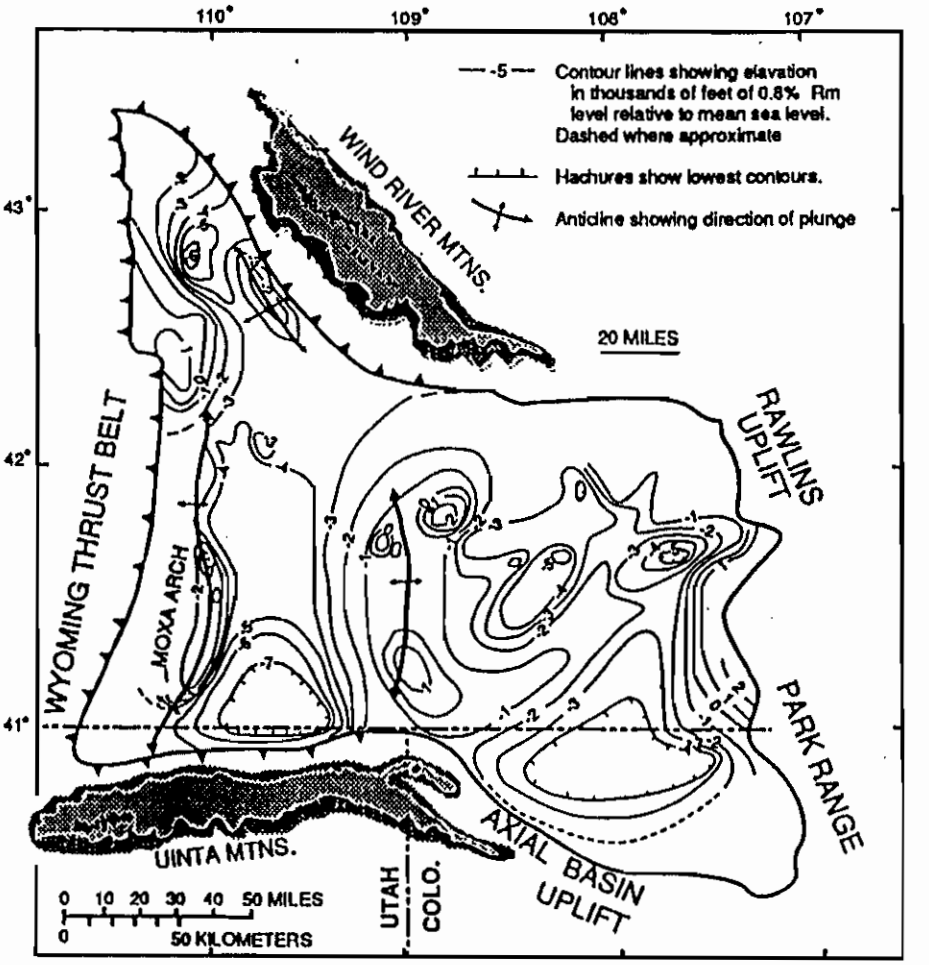
Figures 9-10 ---Near Here

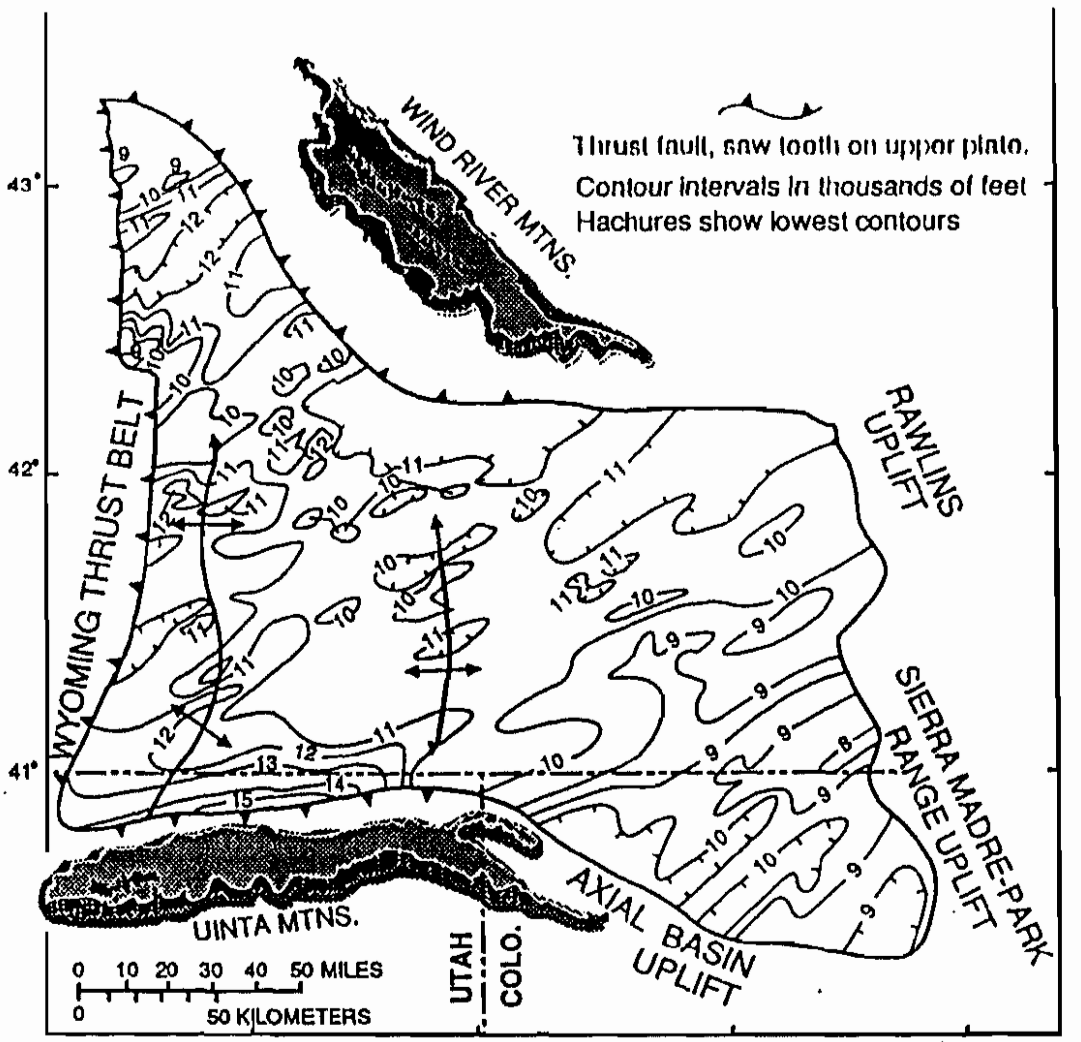
GAS PRODUCTION

The Greater Green River basin produces oil and gas from both conventional and unconventional reservoirs. Cumulative oil and gas production, through 1987, was approximately 216 million barrels of oil and 5.4 trillion cubic feet of gas. The oil and gas fields in the Greater Green River basin are shown in Figure 11. Cumulative production statistics for the principal oil and gas fields are listed in Table 1.

Figure 11 and Table 1--Near Here

The Greater Green River basin is primarily a gas-prone area and has produced gas from Mississippian through Tertiary reservoirs. The oil


110°
109°
108°
107°
43°
42°
41°
-5-
Contour lines showing elevation in thousands of feet of 0.8% Rm level relative to mean sea level. Dashed where approximate
Hachures show lowest contours.
Anticline showing direction of plunge
WIND RIVER MTNS.
20 MILES
WYOMING THRUST BELT
MOXA ARCH
RAWLINS UPLIFT
PARK RANGE
AXIAL BASIN UPLIFT
UINTA MTNS.
UTAH
COLO.
0 10 20 30 40 50 MILES
0 50 KILOMETERS


Thrust fault, saw tooth on upper plate.
Contour intervals in thousands of feet
Hachures show lowest contours
WIND RIVER MTNS.
WYOMING THRUST BELT
RAWLINS UPLIFT
SIERRA MADRE-PARK RANGE UPLIFT
AXIAL BASIN UPLIFT
UINTA MTNS.
UTAH
COLO.
43°
42°
41°
0 10 20 30 40 50 MILES
0 50 KILOMETERS

K_F K_{Be} designated tight ->

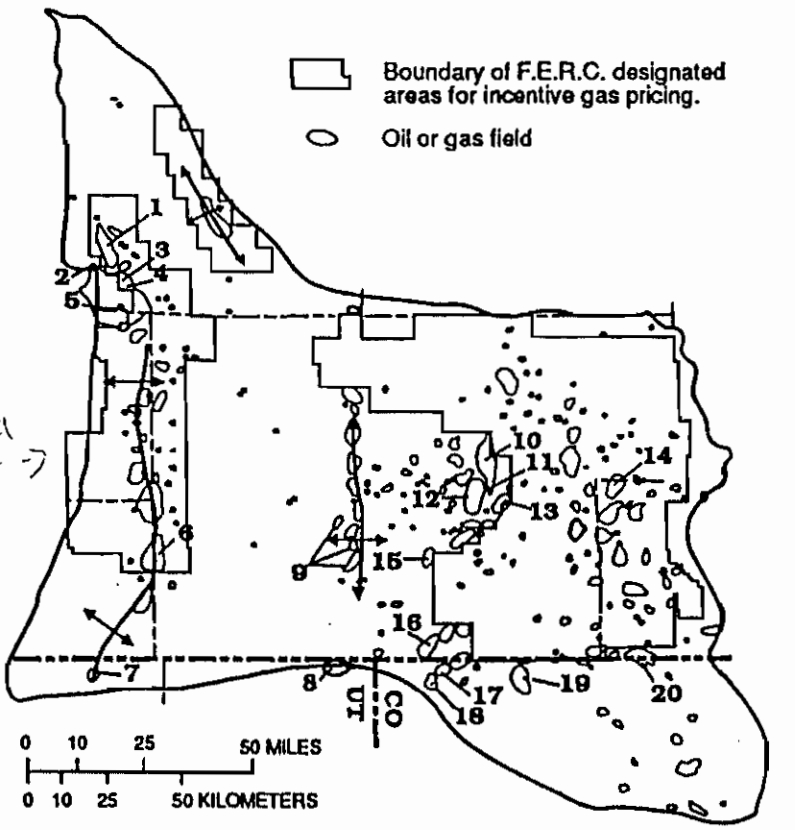


Table 1. Cumulative oil and gas production from selected fields in the Greater Green River basin, Wyoming, Colorado, and Utah. Most of these fields have conventional reservoirs. Field numbers refer to locations shown in Figure 11. From Wyoming Oil and Gas Commission (1987); Utah Division of Oil, Gas, and Mining (1987); and Colorado Oil and Gas Conservation Commission (1986).

Field No.	Field Name	Oil (BBLS)	Gas (MCF)
1	Big Piney	6,820,874	164,738,603
2	Tip Top	5,137,746	327,332,099
3	McDonald Draw	8,245,672	33,655,173
4	Birch Creek	10,484,551	163,159,137
5	Green River Bend	9,835,310	180,006,890
6	Church Buttes	222,394	346,130,838
7	Bridger Lake	11,687,021	59,750,754
8	Clay Basin	326,502	151,326,778
9	Baxter Basin South	5,934	131,621,113
10	Desert Springs	1,984,109	247,238,690
11	Arch	18,252,845	82,300,866
12	Patrick Draw	41,898,085	143,473,983
13	Table Rock	4,091,818	414,509,389
14	Echo Springs	3,232,445	129,060,179
15	Brady	52,982,741	263,042,308
16	Canyon Creek	1,208,106	237,926,860
17	Hiawatha	3,860,796	131,499,039
18	Hiawatha West	224,623	139,208,472
19	Powder Wash	6,994,288	214,844,003
20	West Side Canal	2,728	125,841,169

production is primarily from Cretaceous reservoirs in conventional structural and stratigraphic traps located on the Moxa arch and the east flank of the Rock Springs uplift.

An estimated 500 to 800 billion cubic feet of gas have been produced in the basin from low-permeability reservoirs, as defined by the Federal Energy Regulatory Commission (FERC). The areas designated by FERC for incentive gas pricing are shown in Figure 11. Gas production from low-permeability reservoirs in the Greater Green River basin is mainly from overpressured sandstones in the upper part of the Almond Formation and the Lewis Shale in the Great Divide and Washakie basins. A minor amount is also produced from the Lance Formation in the Pinedale anticline area.

Not all of the low permeability reservoirs in the Greater Green River basin are included in this assessment. As much as possible, only overpressured low-permeability reservoirs were included. A large part of the area in the vicinity of the Moxa arch and La Barge platform, though designated by FERC for incentive gas pricing in the Bear River and Frontier Formations (Figure 11), was excluded because the areas appear to be a mixture of conventional and low-permeability reservoirs for which there is no convenient method to regionally separate the reservoir types. Separation is possible only on a field or individual well basis. The volume of gas thus excluded does not significantly affect the overall estimate of gas-in-place volume. The exclusion, however, does tend to cause the gas-in-place estimate to be slightly conservative.

GAS RESOURCE ESTIMATES

Methodology

The overpressured gas-bearing rocks of the Greater Green River basin were subdivided into five stratigraphic plays, each having individually homogeneous geologic characteristics. In ascending order, the plays are 1) Cloverly-Frontier, 2) Mesaverde, 3) Lewis, 4) Fox Hills-Lance, and 5) Fort Union. Because the overpressured gas accumulation has been already shown to exist in these rocks, each of the five plays was considered to have all the basic attributes required for a gas accumulation: 1) an appropriate source rock or rocks which have undergone a suitable thermal history to produce gas, 2) migration paths during the appropriate time in geologic history to serve as conduits between the source(s) and reservoir, 3) reservoir rocks (the sandstones) with effective porosity to hold the gas, and 4) a trapping mechanism to retain the gas in the reservoir. Thus, the existence of a gas resource in each play was not at issue, only the size of the resource in each.

The assessment of the gas resource in these low-permeability plays is based on assessment of reservoir characteristics of each play. The equation used expresses gas volume as a function of the areal extent of the gas-bearing reservoir, the average total thickness of reservoir sandstones at least 10-ft (3-m) thick, the average porosity, the average gas saturation, the average reservoir temperature and pressure, and the average gas compressibility. Probabilistic methods are used to estimate the uncertainty of the resource value based on the uncertainty about the geologic variables. The geologic variables are expressed as probability distributions in order to show their uncertainty.

The volume of in-place gas (in trillion cubic feet) was calculated by the reservoir equation:

$$V = \left(\frac{1}{10^9}\right)\left(A\right)\left(H\right)\left(\frac{43560\ ft^3}{acre\text{-}foot}\right)\left(P\right)\left(S_h\right)\left(\frac{P_e}{14.73\ lb/in^2}\right)\left(\frac{520°R}{T}\right)\left(\frac{1}{Z}\right)$$

where

V = volume of in-place gas (tcf)

A = areal extent of gas-bearing reservoir (thousands of acres)

H = average total thickness of reservoir sandstones at least 10-ft thick

P = average effective porosity (decimal fraction)

S_h = average hydrocarbon saturation (decimal fraction)

P_e = average reservoir pressure (pounds per square inch)

T = average reservoir temperature (degrees Rankine)

Z = average gas compressibility factor (no units)

The input variables were treated as continuous independent random variables, with the exception of effective porosity which was treated as perfectly positively correlated with hydrocarbon saturation. The probability distribution for a variable was determined by consensus of subjective judgments based on geological and geophysical data, and on analog data and geologic extrapolations. The probability distribution for each attribute was described by a complementary cumulative distribution function determined from seven estimated fractiles (100th, 95th, 75th, 50th, 25th, 5th, 0th). The 5th fractile, for example, is a value such that there is a 5% chance of at least that value.

The probability model was originally designed to be used with conventional oil and gas accumulations, and was subsequently modified in order to be used for unconventional low-permeability gas reservoirs. The probabilistic methodology used to process the data is an analytic method derived from probability theory. The analytic methodology was developed by conditional probability theory and the application of the laws of expectation and variance. The methodology systematically tracks through the probability model, computes all of the means and variances of the appropriate random variables, and calculates all of the probabilities of occurrence. The lognormal distribution is used as a probability distribution in order to arrive at probability fractiles.

On the basis of this methodology, a computer program was designed and called the Fast Appraisal System for Petroleum (FASP). A separate methodology was developed for estimating the aggregation of a set of plays. In this method, the resource estimates of the individual plays from the FASP program are aggregated by means of probability theory in a computer program called the Fast Appraisal System for Petroleum Aggregation (FASPA). FASPA can aggregate a set of plays under a dependency assumption. Any degree of dependency is possible between 0 and 1, where 0 corresponds to independence and 1 denotes perfect positive correlation. The computer package, consisting of FASP and FASPA is described in Crovelli and Balay (1986) and Crovelli (1987, 1988). A microcomputer version is available on diskette, ready to run (Crovelli and Balay, 1989). For a metric version, the reader should see Crovelli and Balay (1987).

Hydrocarbon-Volume Input Data

The geologic and engineering data needed to assess the gas-in-place resources include 1) accumulation area, 2) average total thickness of reservoir rock more than 10-ft (3-m) thick, 3) average porosity, 4) average depth of the play, 5) average hydrocarbon saturation, 6) average reservoir pressure, 7) average reservoir temperature, and 8) average gas compressibility factor. The methods used to determine these data for each play vary from objective measurements to the extrapolation of geologic analogs. The input data for each play are shown in tables 2-6.

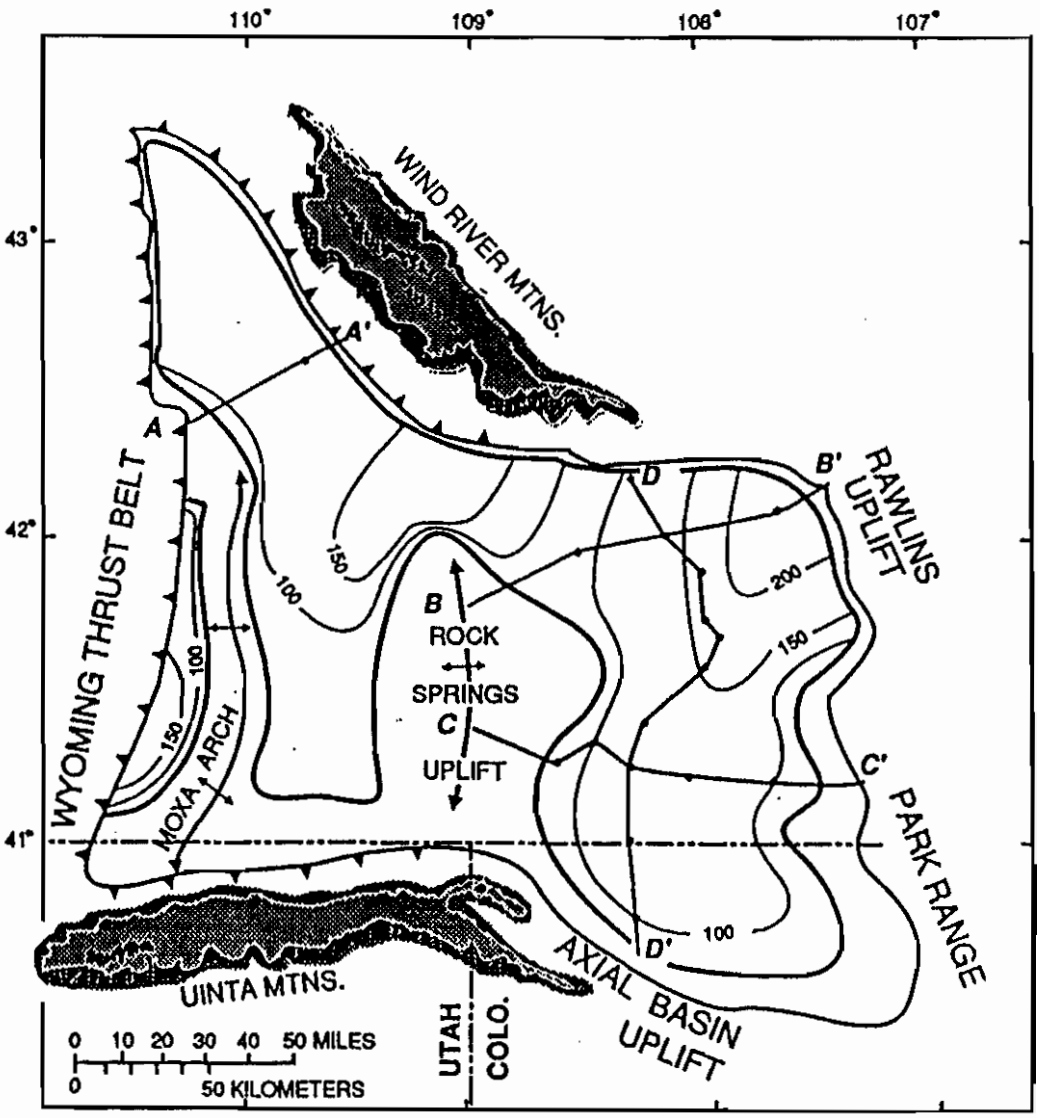
The assessment relies heavily on the ability to identify the vertical and horizontal distribution of overpressured gas-bearing reservoirs. Figure 4 shows the areal extent of overpressured Cretaceous and Tertiary rocks in the Greater Green River basin. Overpressuring, as previously discussed, was determined by using a combination of different types of data that included drillstem tests (DST's), mud weights, mud logs, vitrinite reflectance, and bottom-hole temperatures. The most reliable pressure data are obtained from DST's and long-term, shut-in, cased-hole pressures; however, for reasons outlined by Spencer (1987), good extrapolatable pressure data are frequently not available. The most commonly used method of detecting overpressuring in this region is drilling mud weights and gas-mud logs. In places where these data are lacking, we have utilized vitrinite reflectance data in combination with temperature data. Vitrinite values of about 0.8% and uncorrected subsurface temperatures of about 180°F (82°C) are commonly associated with the top of overpressuring (Law, 1984). Using these criteria, the top of overpressuring was determined in several wells. Cross sections A-A' through D-D' (Figures 5-8) show the interpreted top of overpressuring with

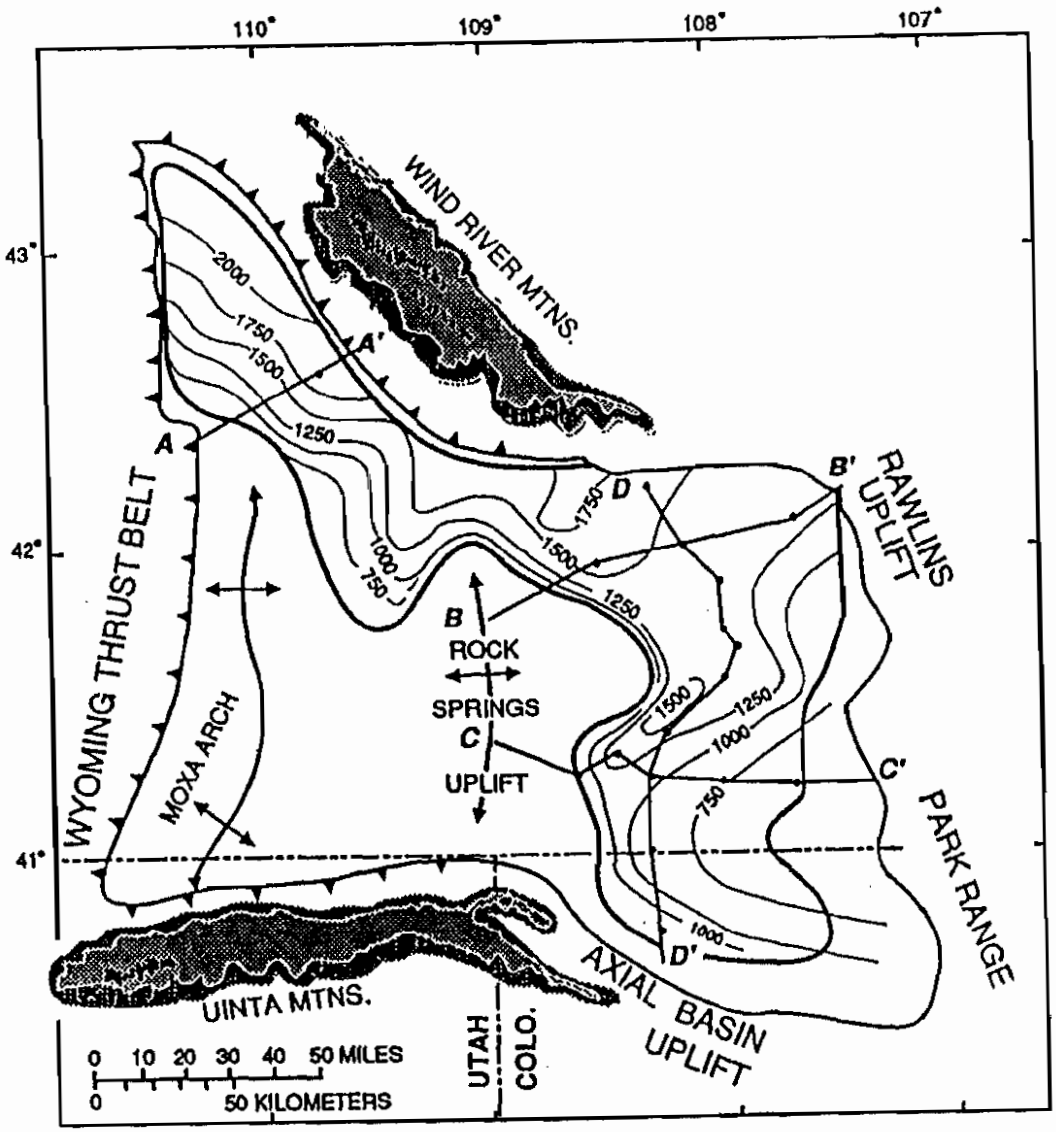
respect to structure and stratigraphy. In addition to wells used in these cross sections, other wells were examined in order to define the vertical and horizontal limits of overpressuring. The size of the overpressured area for each play was then measured with a planimeter. Figures 12-16 show the outlines for each play.

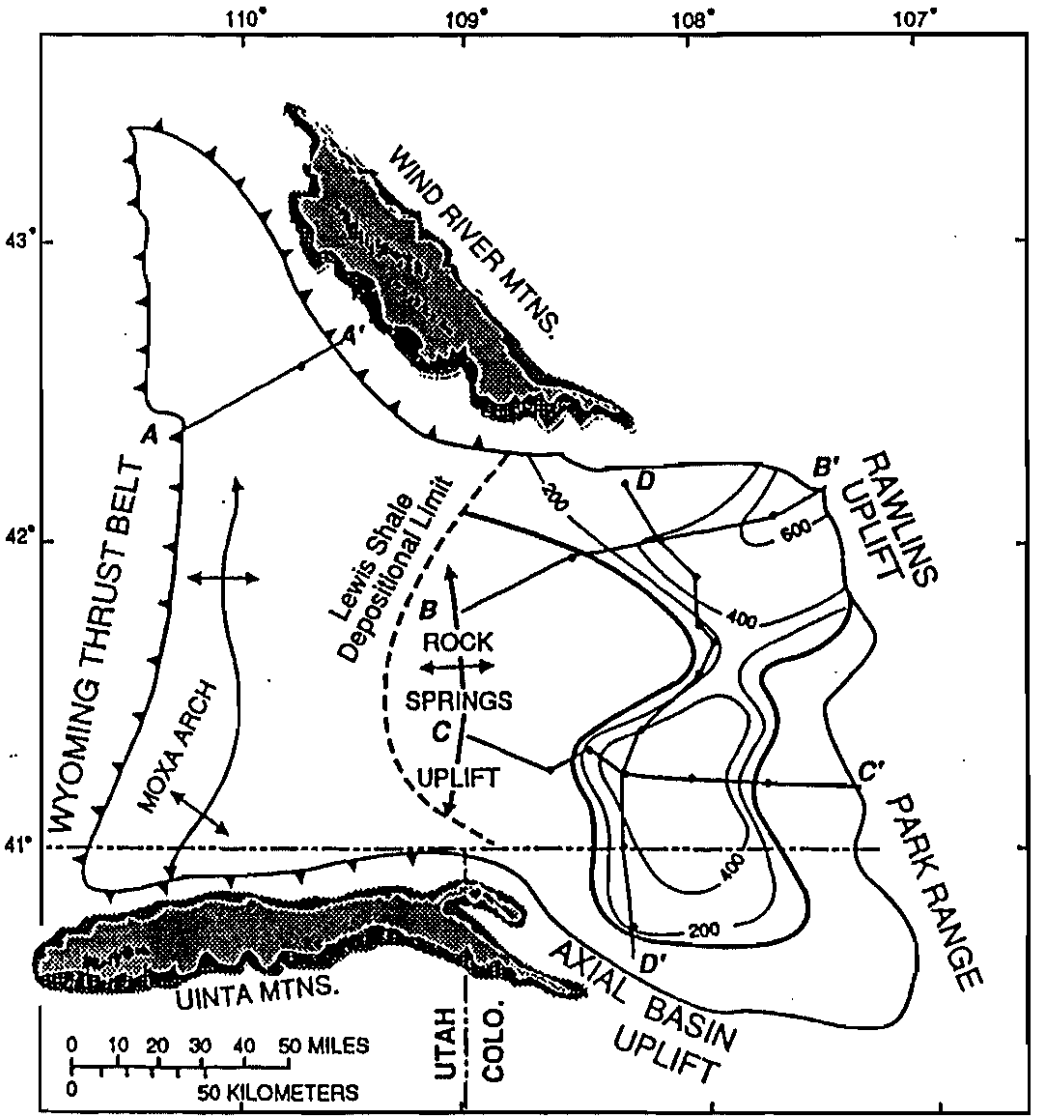
Figures 12 -16---Near Here

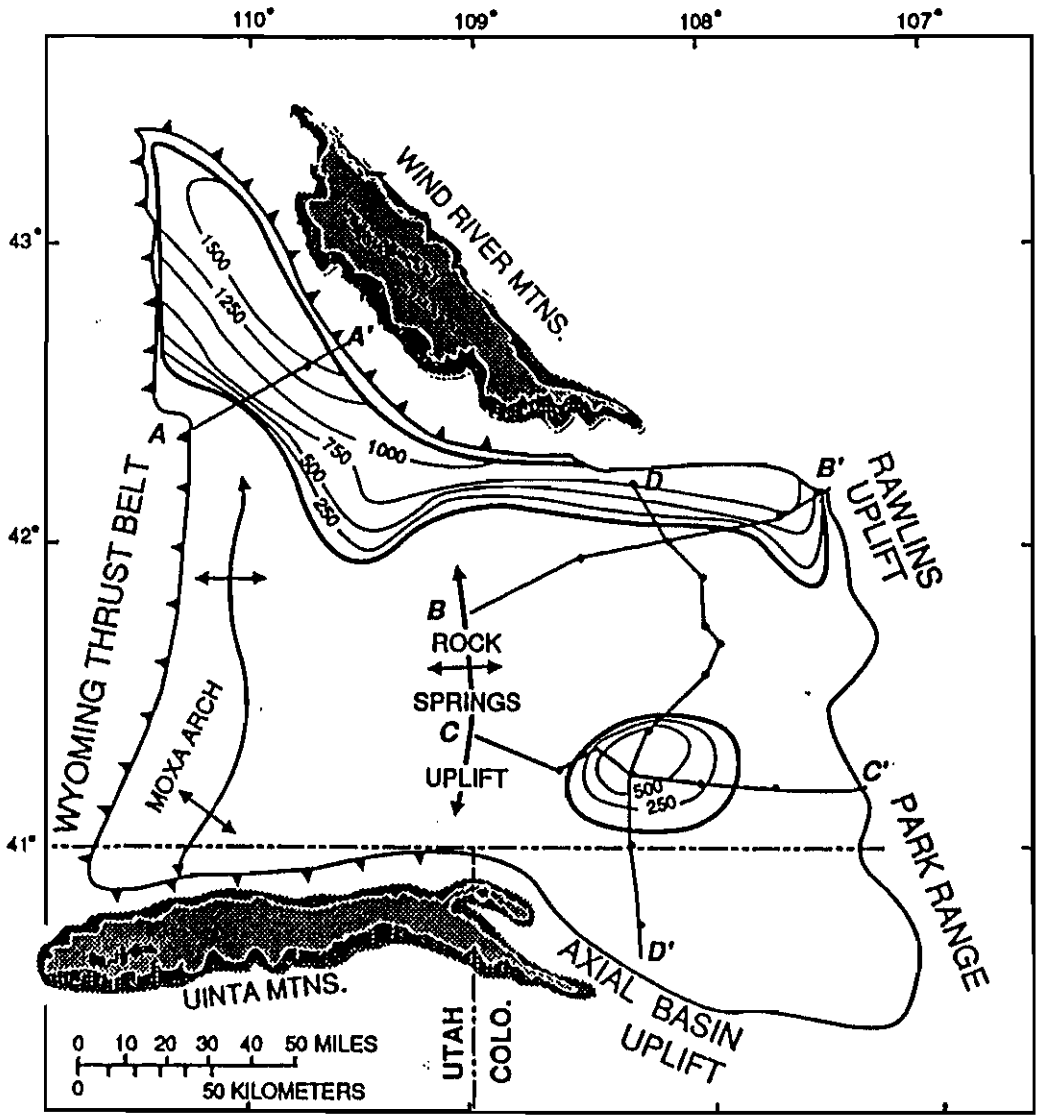
Only sandstone reservoirs greater than 10-ft (3-m) thick were included in the assessment. The thickness of reservoirs in each play was determined by examining well logs and summing the thickness of sandstones greater than 10-ft (3-m) thick. Figures 12-16 show the reservoir thickness variations in each play. Porosity values were based on a general knowledge of the relationships between porosity and depth of burial in the region (Markochick and others, 1982; Law and others, 1986; Charpentier and others, 1987; Keighin and others, in press) and core-derived data from several wells distributed throughout the basin. The determination of hydrocarbon saturation is largely based on direct and indirect evidence that the pore system in overpressured tight gas reservoirs in Rocky Mountain basins are gas saturated and water is usually present only at irreducible levels (Law, 1984; Law and Dickinson, 1985). Local water-bearing sandstones may occur in the overall gas-saturated interval.

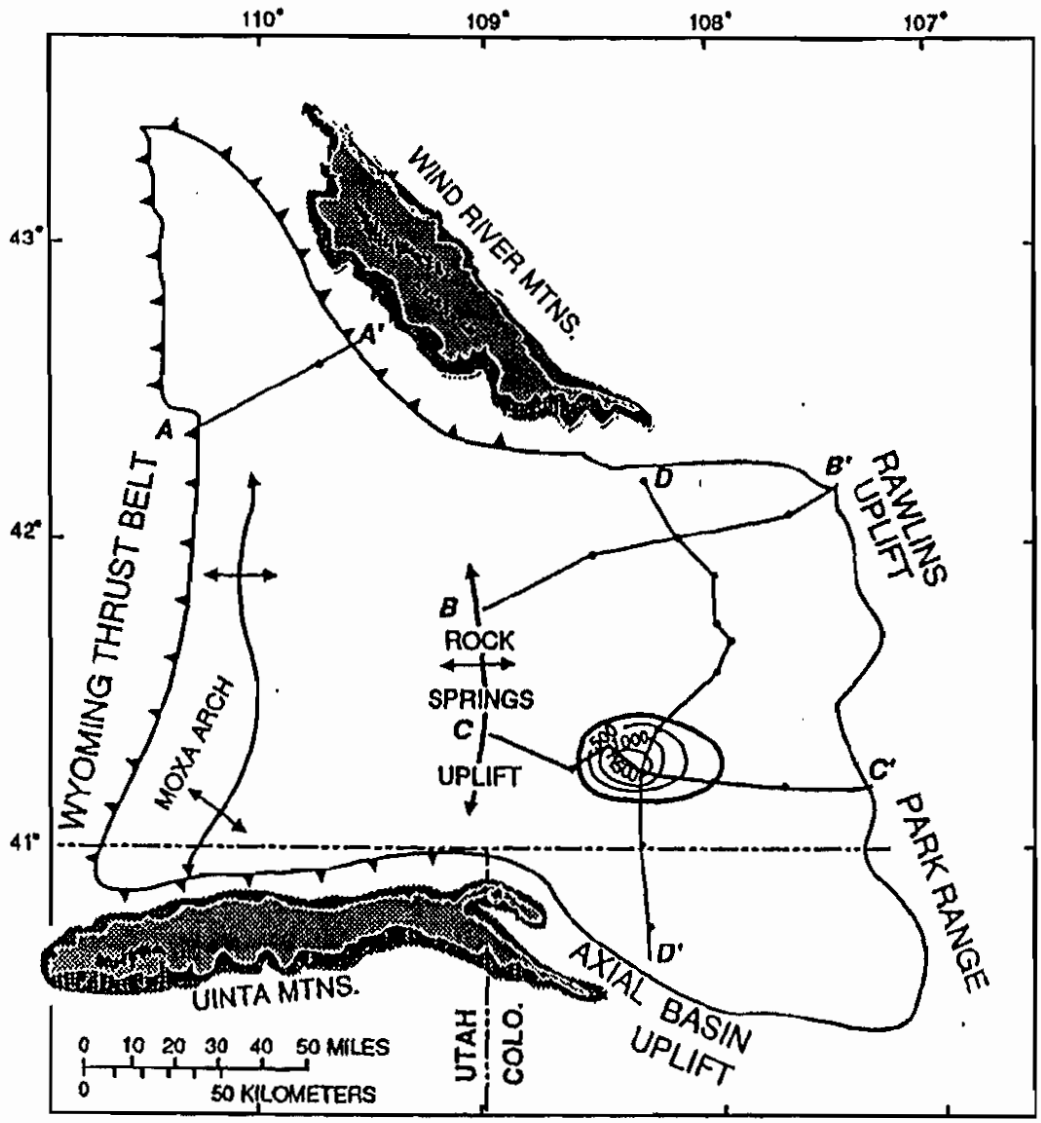
Geothermal gradients were, in most cases, determined from bottom-hole temperature data (Figure 10), and pressure gradient data were derived from pressure profiles of a few wells (Law and others, 1979, 1980; Law, 1984; Spencer, 1987) and unpublished data. Specific reservoir temperatures and pressures used in the gas-volume equation represent values determined for the average reservoir depth. Gas compressibility (Z factor) for each play


110°
109°
108°
107°
43°
42°
41°
WIND RIVER MTNS.
A
A'
B
B'
C
C'
D
D'
WYOMING THRUST BELT
MOXA ARCH
ROCK SPRINGS UPLIFT
RAWLINS UPLIFT
PARK RANGE
AXIAL BASIN UPLIFT
UINTA MTNS.
UTAH
COLO.
100
150
200
0 10 20 30 40 50 MILES
0 50 KILOMETERS


110°
109°
108°
107°
43°
42°
41°
WIND RIVER MTNS.
2000
1750
1500
1250
1000
750
A
A'
B
B'
C
C'
D
D'
WYOMING THRUST BELT
MOXA ARCH
ROCK SPRINGS UPLIFT
RAWLINS UPLIFT
PARK RANGE
AXIAL BASIN UPLIFT
UINTA MTNS.
UTAH
COLO.
0 10 20 30 40 50 MILES
0 50 KILOMETERS


110°
109°
108°
107°
43°
42°
41°
WIND RIVER MTNS.
A
A'
WYOMING THRUST BELT
MOXA ARCH
Lewis Shale Depositional Limit
B
B'
ROCK SPRINGS UPLIFT
C
C'
D
D'
200
400
600
RAWLINS UPLIFT
PARK RANGE
AXIAL BASIN UPLIFT
UINTA MTNS.
UTAH
COLO.
0 10 20 30 40 50 MILES
0 50 KILOMETERS


110°
109°
108°
107°
43°
42°
41°
WIND RIVER MTNS.
1500
1250
1000
750
500
250
A
A'
B
B'
C
C'
D
D'
WYOMING THRUST BELT
MOXA ARCH
ROCK SPRINGS UPLIFT
RAWLINS UPLIFT
PARK RANGE
AXIAL BASIN UPLIFT
UINTA MTNS.
0 10 20 30 40 50 MILES
0 50 KILOMETERS
UTAH
COLO.


110°
109°
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WIND RIVER MTNS.
A
A'
B
B'
C
C'
D
D'
WYOMING THRUST BELT
MOXA ARCH
ROCK SPRINGS UPLIFT
RAWLINS UPLIFT
PARK RANGE
AXIAL BASIN UPLIFT
UINTA MTNS.
UTAH
COLO.
0 10 20 30 40 50 MILES
0 50 KILOMETERS

was determined by the pseudocritical method as outlined in several reservoir engineering texts (e.g. Metcalfe, 1987). In each play, we attempted to use representative gas analyses in order to obtain the mole fraction; however, that was not always possible. In such cases, we used gas analyses that were from stratigraphically adjacent plays.

Plays

The overpressured gas-bearing rocks were subdivided into five stratigraphic plays, which in ascending order are 1) Cloverly-Frontier, 2) Mesaverde, 3) Lewis, 4) Fox Hills-Lance, and 5) Fort Union. The stratigraphic boundaries of these plays coincide with the formation boundaries shown in Figure 3 and the areal distribution of the plays are shown in Figures 12-16.

Cloverly-Frontier:

The Cloverly-Frontier play includes the strata in the interval from the base of the Cloverly and equivalents to the top of the Frontier Formation. This play encompasses an area of about 12,160 mi^2 (31,223 km^2) (Figure 12). The play area includes all of the overpressured deeper parts of the basin. Although the Cloverly and Frontier Formations along the crest of the Moxa arch are overpressured and gas-bearing, the area was excluded because the trend contains both conventional and tight sandstones (Merewether and others, 1984), and we do not have a way of separating them on a regional basis. The thickness of reservoirs in the play ranges from less than 100 ft (30 m) to over 200 ft (60 m) (Figure 12), with an estimated median thickness (50th fractile) of 110 ft (34 m) (Table 2). The other play input data are listed in Table 2. The gas in-place

Table 2. Estimates of gas-in-place and recoverable gas for the Cloverly-Frontier play, Greater Green River basin, Wyoming, Colorado, and Utah

GAS-IN-PLACE RESOURCE INPUT DATA

Geologic Variables	Fractile Distribution F100	F95	F75	F50	F25	F05	F0
Area (thousand acres)	7366	7505	7644	7783	7922	8061	8200
Ave. thickness (feet)	80	90	100	110	120	130	140
Ave. porosity (percent)	3.0	3.8	4.5	5.0	5.3	5.7	6.0
Ave. depth (thousand feet)	16.5	16.8	17.2	17.5	17.8	18.2	18.5
Ave. HC saturation (percent)	40	41	43	45	47	49	50

Pressure gradient = 0.7 psi/ft; Temperature gradient = 1.5°F/100 ft; Gas Compressibility Factor = 1.54

GAS-IN-PLACE RESOURCE ESTIMATES

	Mean	Standard Deviation	Fractile Distribution F95	F75	F50	F25	F05
Resource Size (tcf)	304	66	208	256	296	343	423

CURRENT TECHNOLOGY CASE RECOVERY FACTORS

	Fractile Distribution F100	F95	F75	F50	F25	F05	F0
Recovery (percent)	0.25	0.50	0.75	1.00	1.50	2.50	3.00

CURRENT TECHNOLOGY CASE RECOVERABLE GAS ESTIMATES

	Mean	Standard Deviation	Fractile Distribution F95	F75	F50	F25	F05
Resource Size (tcf)	3.7	2.1	1.3	2.2	3.2	4.6	7.7

FUTURE TECHNOLOGY CASE RECOVERY FACTORS

	Fractile Distribution F100	F95	F75	F50	F25	F05	F0
Recovery (percent)	2.00	3.00	4.00	5.00	6.50	9.00	10.00

FUTURE TECHNOLOGY CASE RECOVERABLE GAS ESTIMATES

	Mean	Standard Deviation	Fractile Distribution F95	F75	F50	F25	F05
Resource Size (tcf)	16.4	6.8	7.9	11.6	15.2	19.9	29.3

estimates for the Cloverly-Frontier play range from 208 to 423 tcf, with a mean estimate of about 304 tcf (Table 2).

Mesaverde:

The Mesaverde play includes the stratigraphic interval from the base of the Rock Springs Formation and equivalent rocks to the top of the Almond Formation in the Great Divide, Washakie, and Sand Wash basins. West of the Rock Springs uplift, in the Green River basin, the Mesaverde play includes the stratigraphic interval from the base of the Rock Springs Formation and equivalent rocks to the top of the Ericson Sandstone (Figure 3). The play encompasses an area of about 8,125 mi^2 (21,044 km^2) (Figure 13). The thickness of the stratigraphic interval ranges up to 5,000 ft (1,524 m), and the thickness of reservoirs in the play ranges from less than 750 ft (229 m) to greater than 2,000 ft (610 m) (Figure 13). The median thickness (50th fractile) is 1,350 ft (411 m) (Table 3). The play input data are shown in Table 3. The gas in-place estimates for the Mesaverde play range from 2,329 to 4,607 tcf, with a mean estimate of 3,347 tcf (Table 3).

Some difficulty was experienced in defining the limits of gas-saturated Mesaverde reservoirs adjacent to the Rock Springs uplift and other areas. This accounts for the apparent truncation of the isopach lines. Potentially gas-productive overpressured and normally pressured tight reservoirs are present outside the play area but were not included in the resource estimate in order to maintain a somewhat conservative and justifiable play area.

Table 3. Estimates of gas-in-place and recoverable gas for the Mesaverde play, Greater Green River basin, Wyoming, Colorado, and Utah

GAS-IN-PLACE RESOURCE INPUT DATA

Geologic Variables	Fractile Distribution F100	F95	F75	F50	F25	F05	F0
Area (thousand acres)	4800	5000	5100	5200	5350	5500	5700
Ave. thickness (feet)	1200	1250	1310	1350	1390	1450	1500
Ave. porosity (percent)	4.5	5.0	5.8	6.5	7.2	8.0	8.5
Ave. depth (thousand feet)	14.5	14.8	15.2	15.5	15.8	16.2	16.5
Ave. HC saturation (percent)	40	41	43	45	47	49	50

Pressure gradient = 0.75 psi/ft; Temperature gradient = 1.5°/100 ft; Gas Compressibility Factor = 1.52

GAS-IN-PLACE RESOURCE ESTIMATES

	Mean	Standard Deviation	Fractile Distribution F95	F75	F50	F25	F05
Resource Size (tcf)	3347	701	2329	2848	3276	3767	4607

CURRENT TECHNOLOGY CASE RECOVERY FACTORS

	Fractile Distribution F100	F95	F75	F50	F25	F05	F0
Recovery (percent)	0.25	0.50	0.75	1.00	1.50	2.50	4.00

CURRENT TECHNOLOGY CASE RECOVERABLE GAS ESTIMATES

	Mean	Standard Deviation	Fractile Distribution F95	F75	F50	F25	F05
Resource Size (tcf)	41.4	25.6	13.8	24.0	35.2	51.7	89.9

FUTURE TECHNOLOGY CASE RECOVERY FACTORS

	Fractile Distribution F100	F95	F75	F50	F25	F05	F0
Recovery (percent)	2.0	3.0	5.0	7.0	10.0	15.0	20.0

FUTURE TECHNOLOGY CASE RECOVERABLE GAS ESTIMATES

	Mean	Standard Deviation	Fractile Distribution F95	F75	F50	F25	F05
Resource Size (tcf)	265.2	144.4	100.8	165.2	232.9	328.5	538.6

Lewis:

The Lewis play includes the stratigraphic interval of the Lewis Shale (Figure 3). The play area (Figure 14) encompasses an area of about 3,906 mi^2 (10,117 km^2) and is restricted to the eastern half of the Greater Green River basin. The western limit of the play coincides with the western edge of the Lewis Shale transgression (Figure 14). Reservoirs in the Lewis occur as isolated sandstones bounded above and below by shale. The thickness of reservoirs in the play ranges from less than 200 ft (60 m) to over 600 ft (183 m) (Figure 14) and the median thickness (50th fractile) is 400 ft (122 m) (Table 4). Within the play area, there may be some conventional reservoirs; we estimate that the volume of conventional reservoirs in the play is less than 5%. The other Lewis play input data are shown in Table 4. The gas-in-place estimates for the play range from 428 to 835 tcf, with a mean estimate of 610 tcf (Table 4).

Fox Hills-Lance:

The Fox Hills-Lance play includes the stratigraphic interval from the base of the Fox Hills Sandstone to the top of the Lance Formation (Figure 3). The play area encompasses an area of about 4,062 mi^2 (10,521 km^2) (Figure 15). The thickness of reservoirs in the play ranges from less than 250 ft (76 m) to greater than 1,500 ft (457 m) (Figure 15), with a median thickness (50th fractile) of 675 ft (206 m) (Table 5). The other play input data are shown in Table 5. The gas-in-place estimates for the Fox Hills-Lance play range from 470 to 1,009 tcf, with a mean estimate of 707 tcf (Table 5).

Table 4. Estimates of gas-in-place and recoverable gas for the Lewis play, Greater Green River basin, Wyoming, Colorado, and Utah

GAS-IN-PLACE RESOURCE INPUT DATA

Geologic Variables	Fractile Distribution F100	F95	F75	F50	F25	F05	F0
Area (thousand acres)	2300	2350	2400	2500	2600	2650	2700
Ave. thickness (feet)	350	360	380	400	430	470	500
Ave. porosity (percent)	6.0	6.6	7.4	8.0	8.6	9.4	10.0
Ave. depth (thousand feet)	11.5	11.6	11.8	12.0	12.2	12.7	13.0
Ave. HC saturation (percent)	45	46	48	50	53	57	60

Pressure gradient = 0.65 psi/ft; Temperature gradient = 1.5°F/100 ft; Gas Compressibility Factor = 1.21

GAS-IN-PLACE RESOURCE ESTIMATES

	Mean	Standard Deviation	Fractile Distribution F95	F75	F50	F25	F05
Resource Size (tcf)	610	125	428	521	598	686	835

CURRENT TECHNOLOGY CASE RECOVERY FACTORS

	Fractile Distribution F100	F95	F75	F50	F25	F05	F0
Recovery (percent)	0.50	1.00	1.75	2.50	3.75	6.00	8.00

CURRENT TECHNOLOGY CASE RECOVERABLE GAS ESTIMATES

	Mean	Standard Deviation	Fractile Distribution F95	F75	F50	F25	F05
Resource Size (tcf)	18.0	10.8	6.2	10.6	15.5	22.4	38.4

FUTURE TECHNOLOGY CASE RECOVERY FACTORS

	Fractile Distribution F100	F95	F75	F50	F25	F05	F0
Recovery (percent)	6.0	8.0	10.0	12.0	15.0	23.0	30.0

FUTURE TECHNOLOGY CASE RECOVERABLE GAS ESTIMATES

	Mean	Standard Deviation	Fractile Distribution F95	F75	F50	F25	F05
Resource Size (tcf)	81.8	34.8	38.5	57.2	75.3	99.1	147.1

Table 5. Estimates of gas-in-place and recoverable gas for the Fox Hills-Lance play, Greater Green River basin, Wyoming, Colorado, and Utah

GAS-IN-PLACE RESOURCE INPUT DATA

Geologic Variables	Fractile Distribution F100	F95	F75	F50	F25	F05	F0
Area (thousand acres)	2300	2400	2500	2600	2700	2800	2900
Ave. thickness (feet)	500	550	600	675	750	800	850
Ave. porosity (percent)	6.0	6.4	7.0	7.5	8.0	8.8	9.5
Ave. depth (thousand feet)	9.5	9.6	9.8	10.0	10.3	10.7	11.0
Ave. HC saturation (percent)	35	36	38	40	43	47	50

Pressure gradient = 0.6 psi/ft; Temperature gradient = 1.5°/100 ft; Gas Compressibility Factor = 1.1

GAS-IN-PLACE RESOURCE ESTIMATES

	Mean	Standard Deviation	Fractile Distribution F95	F75	F50	F25	F05
Resource Size (tcf)	707	167	470	588	688	805	1009

CURRENT TECHNOLOGY CASE RECOVERY FACTORS

	Fractile Distribution F100	F95	F75	F50	F25	F05	F0
Recovery (percent)	0.25	0.50	0.75	1.00	1.50	2.25	3.00

CURRENT TECHNOLOGY CASE RECOVERABLE GAS ESTIMATES

	Mean	Standard Deviation	Fractile Distribution F95	F75	F50	F25	F05
Resource Size (tcf)	8.4	4.7	3.1	5.1	7.3	10.4	17.2

FUTURE TECHNOLOGY CASE RECOVERY FACTORS

	Fractile Distribution F100	F95	F75	F50	F25	F05	F0
Recovery (percent)	2.0	4.0	6.0	8.0	11.0	15.0	18.0

FUTURE TECHNOLOGY CASE RECOVERABLE GAS ESTIMATES

	Mean	Standard Deviation	Fractile Distribution F95	F75	F50	F25	F05
Resource Size (tcf)	61.5	29.6	26.2	40.7	55.4	75.4	117.5

Fort Union:

Low-permeability, overpressured, gas-bearing Tertiary reservoirs in the Greater Green River basin occur only in the deeper part of the Washakie basin (Figure 16) at an average depth of 10,200 ft (3,109 m). The stratigraphic interval of the play includes the Paleocene Fort Union Formation and locally younger Tertiary rocks. The play encompasses an area of about 517 mi^2 (1,339 km^2). Cross sections C-C′ and D-D′ (Figures 7-8) show the top of overpressuring occurring in the Fort Union Formation in the Washakie basin. The thickness of reservoirs in the play ranges from less than 500 ft (152 m) to greater than 1,500 ft (457 m) (Figure 16), and the median thickness is 600 ft (183 m) (Table 6). The other play input data are shown in Table 6. The gas-in-place estimates for the Fort Union play range from 70 to 127 tcf, with a mean estimate of 96 tcf (Table 6).

Aggregation of Plays

In order to determine the total gas-in-place resource for all five plays, the aggregation program FASPA was used. The plays were aggregated with a degree of dependency of 0.75. Two gas resource aggregations were calculated; one for all five plays, and one that excluded the Cloverly-Frontier play. Two aggregations were calculated because, with the exception of the Moxa arch, Rock Springs uplift, and the margins of the Greater Green River basin where the Cloverly and Frontier outcrop or occur at shallow depths, there is very little data available for these stratigraphic units. Consequently, we consider the estimates of gas-in-place for the Cloverly-Frontier play to be less reliable than those for the other plays.

Table 6. Estimates of gas-in-place and recoverable gas for the Fort Union play, Greater Green River basin, Wyoming, Colorado, and Utah

GAS-IN-PLACE RESOURCE INPUT DATA

Geologic Variables	Fractile Distribution F100	F95	F75	F50	F25	F05	F0
Area (thousand acres)	278	291	311	331	351	371	384
Ave. thickness (feet)	500	550	575	600	625	650	700
Ave. porosity (percent)	7.0	7.3	7.7	8.0	8.5	9.0	9.5
Ave. depth (thousand feet)	9.9	10.0	10.1	10.2	10.3	10.4	10.5
Ave. HC saturation (percent)	35	36	38	40	43	47	50

Pressure gradient = 0.6 psi/ft; Temperature gradient = 1.6°F/100 ft; Gas Compressibility Factor = 0.98

GAS-IN-PLACE RESOURCE ESTIMATES

	Mean	Standard Deviation	Fractile Distribution F95	F75	F50	F25	F05
Resource Size (tcf)	96	18	70	83	94	106	127

CURRENT TECHNOLOGY CASE RECOVERY FACTORS

	Fractile Distribution F100	F95	F75	F50	F25	F05	F0
Recovery (percent)	0.25	0.50	0.75	1.00	1.50	2.25	3.00

CURRENT TECHNOLOGY CASE RECOVERABLE GAS ESTIMATES

	Mean	Standard Deviation	Fractile Distribution F95	F75	F50	F25	F05
Resource Size (tcf)	1.1	0.6	0.4	0.7	1.0	1.4	2.3

FUTURE TECHNOLOGY CASE RECOVERY FACTORS

	Fractile Distribution F100	F95	F75	F50	F25	F05	F0
Recovery (percent)	2.0	4.0	6.0	8.0	11.0	15.0	18.0

FUTURE TECHNOLOGY CASE RECOVERABLE GAS ESTIMATES

	Mean	Standard Deviation	Fractile Distribution F95	F75	F50	F25	F05
Resource Size (tcf)	8.3	3.8	3.7	5.7	7.6	10.2	15.5

A summary of the gas-in-place resources for each play and the aggregation of all plays are shown in Table 7. The aggregation of gas-in-place resources for all five plays ranges from 3,611 to 6,837 tcf, with a mean estimate of 5,063 tcf.

Recoverable Gas Resources

Permeability is a critical factor in gas production rates and estimates of ultimate gas recovery. It is not critical in the assessment of gas-in-place resources. We have extensively used drillstem test (DST) data in our pressure analyses. However, only a small (<10%) percentage of DSTs can be used to calculate a true, original-reservoir pressure. Because most of the tight reservoir in-situ permeabilities to gas are in the micro- and nannodarcy range, only DSTs testing an areally large natural-fracture system can be used to determine true pressure.

Some workers mistakenly believe that these extrapolatable DSTs can be used to measure the matrix transmissibility of a given tight rock interval. But, owing to the very low rock-matrix permeability, the test results are dominated by the permeability of the fracture system.

One way to measure transmissibility in conventional reservoirs is to perform a carefully conducted pressure drawdown-buildup test in a cased hole. In tight rocks that are gas productive, the test evaluates the fracture system permeability plus the matrix permeability.

Another method to approach the permeability question is to extensively core and perform restored-state laboratory tests on the core. Restored state would include reapplication of in-situ stress, water saturation, pressure, temperature, etc. This method, rarely used, was employed at the DOE Multiwell Experiment site. This research was able to

Table 7.--Greater Green River basin estimates of tight gas resources in trillions of cubic feet

Play	In-Place			Recoverable					
				Current Technology[1]			Future Technology[2]		
	Low F_{95}	High F_5	Mean	Low F_{95}	High F_5	Mean	Low F_{95}	High F_5	Mean
Fort Union	70	127	96	0.4	2.3	1.1	3.7	15.5	8.3
Lance-Fox Hills	470	1009	707	3.1	17.2	8.4	26.2	117.5	61.5
Lewis	428	835	610	6.2	38.4	18.0	38.5	147.1	81.8
Mesaverde	2329	4607	3347	13.8	89.9	41.4	100.8	538.6	265.2
Cloverly-Frontier	208	423	304	1.3	7.7	3.7	7.9	29.3	16.4
Aggregation of all five plays	3611	6837	5063	27	148	73	189	816	433
Aggregation of first four plays	3383	6445	4760	26	141	69	180	789	417

[1]Current technology assumes present-day, state-of-the-art drilling and completion methods and existing well spacing and $5 per MCF (1987 dollars). The price was selected based on the assumption that this price would presently encourage economic development of the resource.

[2]Future technology assumes exotic drilling and completion methods that will maximize well and stimulation contact with the greatest feasible number of reservoirs. It assumes nondamaging communication can be made between the wellbore and the natural fractures. It also assumes very high gas prices on a par or higher than other future energy sources.

Fractiles are not additive; means are additive within round-off error.

document the extremely low-matrix permeabilities and the dominant influence of natural fractures on gas flow rates (Branagan and others, 1987).

Although permeability was not used in the computation of gas-in-place resources, our knowledge of the relationships among fracture and matrix permeability was an important consideration in the assumptions used to estimate recoverable gas.

The recovery factors used in the estimate of recoverable gas are shown in Tables 2-6. The recovery factors were subjectively determined because of the absence of analogs and the problem of evaluating multiple stacked reservoirs. For example, in the Mesaverde play there are as many as 25 sandstone reservoirs, 10-ft (3-m) thick or greater, distributed through an interval as thick as 4,000 ft (1,219 m). It is not realistic to believe that every sandstone will be perforated and effectively stimulated; therefore, the recovery factors represent an estimated mean recovery percentage for the whole section.

Two of the most important factors influencing the volume of recoverable gas are price and technology. For the purposes of our recovery estimates, therefore, we used two cases: 1) a current technology case, and 2) a future technology case. The current technology case assumes a gas price of five dollars per thousand cubic feet of gas in 1987 dollars, no pipeline constraints, and the application of present-day, state-of-the-art drilling and completion practices. The future technology case assumes exotic drilling and completion methods that will maximize well and stimulation contact with the greatest feasible number of reservoirs. It assumes nondamaging communication can be made between the

wellbore and the natural fractures. It also assumes very high gas prices on a par or higher than other future energy sources.

The recovery factors and the recoverable gas resources for each play are shown in Tables 2-6. For the current technology scenario, the aggregated recoverable gas for all five plays ranges from 27 to 148 tcf, with 73 tcf as the mean estimate (Table 7). For the future technology scenario, the aggregated recoverable gas for all five plays ranges from 189 to 816 tcf, with 433 tcf as the mean estimate (Table 7).

Tables 2-7--Near Here

Because the estimation of future recovery factors for such unconventional resources is necessarily very imprecise compared to estimation of purely geologic factors, the estimates of recoverable resources consequently show less precision than the estimates of in-place resources. Thus, whereas the high and low estimates for in-place resources differ by about a factor of two, the high and low estimates for recoverable resources differ by a factor of about four or five.

DISCUSSION

The Supply-Technical Advisory Task Force (1973) estimated a gas-in-place resource of 240 tcf. Kuuskraa and others (1978) estimated 91 tcf and the National Petroleum Council (1980) estimated 136 tcf. These estimates are substantially less than our mean estimate of 5,063 tcf; however, they only included selected formations and areas and did not assess total gas-in-place. Even though our in-place estimates are large, especially when compared to previous work, the assessment does not include gas in coal, siltstone, shale, or fractures. Nor does it include gas in sandstones less than 10-ft (3-m) thick. We believe the play boundaries

are conservative in area and vertical extent. Thus, in many respects, our estimates of the gas-in-place in overpressured reservoirs in the basin are conservative.

There are several reasons for the differences between our estimates and previous estimates. Some of the reasons have been discussed by Spencer and Law (1988). They noted that earlier estimates did not include reservoirs deeper than 15,000 ft (4,572 m), only evaluated one or two sandstone reservoirs from each stratigraphic unit, and essentially were evaluating "sweet spots." The earlier assessments were also very conservative in terms of the areal extent of reservoirs included in their assessments. In particular, they excluded gas in reservoirs underneath or near existing production. They also excluded all or most of the gas in sparsely drilled areas such as the northern Green River and the Sand Wash basins. The primary reason for the contrasting resource estimates, however, is that previous estimates apparently did not recognize the relationship between the occurrence of gas-bearing rocks and overpressuring, and the fact that there are great thicknesses of strata where essentially all the reservoirs are gas saturated.

SUMMARY

The Greater Green River basin of Wyoming, Colorado, and Utah contains an estimated (mean) 5,063 tcf of gas-in-place in low-permeability overpressured Cretaceous and lower Tertiary sandstone reservoirs. These reservoirs are distributed through an overpressured gas-bearing sequence that ranges up to 14,000 ft (4,267 m) thick.

The gas-bearing interval was subdivided into five stratigraphic plays and the gas-in-place resource and recoverable gas were estimated for each

play using a probabilistic analysis. The aggregate gas-in-place resource of these plays ranges from 3,611 to 6,837 tcf, with 5,063 tcf as the mean estimate.

Because of additional uncertainty related to economic recovery factors, estimation of recoverable volumes is inherently less precise than estimation of in-place volumes. Two of the most important factors influencing the volume of recoverable gas are price and technology. Therefore, recoverable gas was estimated for each play under the following cases: 1) current technology, with a gas price of five dollars per thousand cubic feet in 1987 dollars, and 2) future technology, with no dollar or technology constraints. For the current technology case, the aggregated recoverable gas ranges from 27 to 148 tcf, with 73 tcf as the mean estimate. For the future technology case, the aggregated recoverable gas ranges from 189 to 816 tcf, with 433 tcf as the mean estimate.

We believe a team effort, involving geologic and engineering experts, is needed to further refine the volume of gas expected to be recovered from this important unconventional energy resource. We encourage creative geologic and engineering thinking to develop methods to access this vast and valuable energy resource.

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