# DEEP NATURAL GAS RESERVOIRS AND CONVENTIONAL PLAYS IN THE UNITED STATES

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## INTRODUCTION

Because of lower worldwide oil prices and a highly mature state of drilling and production in many United States oil provinces, drilling activity in the United States has declined and exploration companies are looking overseas for oil and gas exploration prospects. Concurrently, domestic oil production is declining, and United States reliance on imported oil is increasing. Even if prices were to increase drastically, it would take several years for domestic exploration to reach previous levels of intensity. When the issue of economics is set aside, many drilling frontiers deserve review. One such frontier is natural gas in deep sedimentary basins (fig. 1).

The United States is rapidly exhausting its oil reserves, whereas estimates of resources of natural gas remain high. According to the National Petroleum Council (1992), the United States contains nearly 1,300 trillion cubic feet (TCF) of recoverable natural gas resources. The current U.S. Geological Survey National Petroleum Assessment estimates 480 TCF of conventional natural gas remain to be discovered in the United States or are part of reserve appreciation from known fields. Natural gas is a clean-burning fuel and is more environmentally acceptable than oil. Increased use of domestic natural gas resources would lessen our reliance on foreign-oil imports.

According to Petroleum Information Corporation's Well History Control System (WHCS) (Petroleum Information Corporation, 1991), more than 16,000 wells have been drilled deeper than 15,000 feet in the United States. These deep wells are widely distributed and are drilled into rocks of various ages and lithologies, but they represent a very small percent of the more than 2.2 million United States wells contained in the data file.

Almost one third of the total undiscovered natural gas resources of the onshore and offshore United States are estimated to occur below 15,000 feet (Potential Gas Committee, 1990). For example, one of the most significant new exploration plays in the United States is the deep Norphlet Formation (Upper Jurassic) play of the eastern Gulf Coast Basin region (fig. 1; App. A). Geologic and geochemical studies by Rice and others (1992) indicated significant potential for Norphlet and perhaps Upper Jurassic Smackover Formation natural gas reservoirs in the eastern Gulf region. In other deep basins, only a few deep wells have been drilled, and the natural gas potential of deep horizons remains unknown.

Known deep natural gas accumulations are distributed throughout many United States basins and occur in widely different geologic environments. Two-hundred fifty-six known significant reservoirs, as identified by NRG Associates (1990), produce from depths greater than 15,000 feet and 377 significant reservoirs produce from depths greater than 14,000 ft out of a total of more than 15,000 significant reservoirs in the United States (table 1). Significant reservoirs are defined as those reservoirs with known recoverable production of at least one million barrels of oil (MMBO) or 6 billion cubic feet (BCF) of gas. Nearly three quarters of these reservoirs produce natural gas. These reservoirs occur in the Gulf Coast, Permian, Anadarko, Williston, San Joaquin, Ventura, Cook Inlet, and Rocky Mountain basins (fig. 1; table 1). In addition, 152 conventional deep plays were defined for the 1995 petroleum assessment. One-hundred twenty-three of these plays demonstrate potential for undiscovered non-associated natural gas accumulations (app. A).

Deep natural gas resources have not been evaluated separately for this petroleum assessment; they were included with the overall resources which were assessed. Refer to individual province reports in this CD-ROM for natural gas estimates plays. Deep natural gas resources are an important part of the total resource base of the Nation and should be described for several reasons: (1) Natural gas may form in the deep central portions of basins and migrate into shallower regions where it is conventionally trapped. An understanding of deep basin processes may aid in understanding the occurrence of natural gas in shallow basin environments. (2) The deeper parts of many sedimentary basins have not been adequately drilled, and opportunities for undiscovered accumulations remain good. (3) Many deep undiscovered natural gas accumulations may be part of conventional accumulations or parts of unconventional continuous-type deposits, and economic rather than geologic or technological conditions reduce the number of deep wells presently being drilled. An economic upturn could produce conditions appropriate for immediate exploration.

This report describes both known deep natural gas accumulations and plays based on data from the 1995 U. S. Geological Survey National Petroleum Assessment. It contains (1) a description of geologic conditions or variables favorable for natural gas accumulations in deep sedimentary basins based on published information and unpublished data from computerized files including the NRG Associates Data File

(NRG) and the Well History Control System (WHCS); (2) a summary of the distribution of known significant deep natural gas reservoirs by region in the United States where they are present; and (3) a summary of conventional deep natural gas plays in the United States based on geologic data supplied by province geologists. Deep unconventional plays are discussed briefly at the end of this report. Information in this report on known reservoirs is in part an update of previous work by Dyman and others (1992). Play information was compiled for this report. A descriptive compilation of reservoir and play characteristics can be used to aid future exploration targets in deep sedimentary basins. To our knowledge, no current, detailed data compilations of deep significant natural gas reservoirs and plays exist in the published literature.

Computerized data were taken primarily from the Significant Oil and Gas Fields of the United States, NRG Associates Inc. (NRG Associates, 1990). The NRG data base contains geologic, production, and engineering data for more than 15,000 significant oil and gas reservoirs in the United States. Significant reservoirs only include those with known recoverable production of at least 1 MMBO or 6 BCFG.

Deep reservoirs are defined arbitrarily as those occurring below 15,000 feet. However, a single producing interval may extend both above and below 15,000 feet. For this reason, NRG retrievals were selected for all producing reservoirs below 14,000 feet in order to capture all reservoirs potentially occurring below the 15,000 foot level; therefore, the following reservoir data tables include data in the 14,000 to 15,000 foot depth range as well as deeper. Some fields report only production figures for each field rather than reservoirs within a field (particularly in Oklahoma), and therefore some shallower production is included with the deep. Associated gas in oil reservoirs was not addressed in this report.

Table 1 is a summary of data presented in tables 2 through 8 and in Dyman and others (1992) for the Gulf Coast, Permian, Anadarko, Williston, California, Alaska, and Rocky Mountain basins. Play descriptions were compiled from play summaries supplied by province geologists and are identified in appendix A. Many of these deep plays have a potential for both undiscovered oil and gas accumulations and are identified accordingly. Refer to regional or province reports included in the National Petroleum Assessment for maps illustrating play outlines of all deep plays.

## SUMMARY OF GEOLOGIC CONTROLS

Our analysis of deep natural gas plays and reservoirs has revealed that many geologic factors affect the occurrence and character of natural gas accumulations. Deep natural gas reservoirs are controlled by many of the same geologic factors that influence shallow hydrocarbon reservoirs. These factors are related to the sedimentologic, lithologic, tectonic, and diagenetic history of the reservoir and source rocks and include but are not restricted to the following:

* reservoir rock quality

* trap geometry

* seal characteristics

* preservation of trap integrity

* thermal maturity and proximity of source rocks

* timing of trap formation and hydrocarbon migration

* hydrocarbon and nonhydrocarbon gas compositions

In deep natural gas reservoirs, the relative importance of these factors may vary significantly, and the importance of some factors are difficult to assess due to lack of data from deep reservoir and source rocks. These and other factors are discussed in several of the following sections of this report by region where they play an important role in the formation of deep natural gas accumulations.

**RESERVOIR QUALITY**

Deep gas reservoir rocks are most commonly either sandstones or carbonates. Preservation of original porosity and (or) the creation of secondary porosity is essential for economically viable reservoirs (Wyman, 1993). Mechanisms for preserving and creating porosity in sandstones and carbonates are varied and may be complex.

Under deep burial conditions, sandstones undergo compaction and typically become heavily cemented with quartz overgrowths and other diagenetic cements. Occurrences of good porosity and permeability are unusual (Hefner, 1993; Surdam and others, 1989). However, in some deeply buried, medium- to coarse-grained sandstones, original porosity can be preserved by the occurrence of chlorite rims (Schmoker and Schenk, 1994; Ehrenberg, 1993;) which can inhibit quartz overgrowths during diagenesis. Original porosity can also be preserved by the protective effect of hydrocarbon residues in reservoirs where oil has cracked to natural gas. The presence of bitumen in the pores may prevent the precipitation of cements from formation waters. Secondary porosity can be created by the dissolution of framework grains such as feldspars, calcite and chert, or by dissolution of calcite and other cements. Permeability in "tight" sandstones can be greatly enhanced by both natural and artificially stimulated fractures (Lorenz and Finley, 1991; Hefner, 1993).

Reservoirs may have higher than expected porosities associated with overpressuring due to hydrocarbon generation. Deep overpressured reservoirs with higher-than-normal porosities produce natural gas in Rocky Mountain basins.

Deeply buried carbonate reservoirs can contain excellent porosity and permeability (Hefner, 1993; Brown and Shannon, 1989; Wilson and others, 1994). Dolomite may be diagenetically altered by deep basin diagenetic processes that enhance porosity and permeability due to dissolution and recrystallization. The vuggy "late stage" coarse crystalline and sucrosic dolomites with "baroque" or "saddle" dolomite crystals which occur in high energy, clay-free grainstone beds can form excellent deep gas reservoirs (Prather, 1992; Heydari and Moore, 1989; Qing and Mountjoy, 1994). Fractures in deeply buried dolomites can significantly increase permeability. Under deep burial conditions, limestones typically act in a ductile manner (Handin and others, 1963) and may become effective seals for porosity zones in interbedded dolomites.

## TRAP GEOMETRY

Deep natural gas reservoirs occur in a wide variety of structural and stratigraphic traps. Due to the greater depth of the reservoirs and frequent lack of deep velocity control, seismic definition of traps may involve greater uncertainties than for shallow traps. In addition to conventional structural and stratigraphic trap types, some deep accumulations are of the unconventional "basin-center" type (Masters, 1984)(continuous-type of Schmoker, this CD-ROM), and some traps may be formed by deep pressure compartments that may cut across structural and stratigraphic features (Hunt, 1990; Forbes and others, 1992; Powley, 1987).

## SEAL CHARACTERISTICS

Under deep burial conditions, the brittle-ductile behavior of different rock types becomes increasingly important. Many deep natural gas reservoirs have traditional seals, such as overlying shales or evaporites. However, several important deep gas fields in carbonate reservoirs lack traditional shale or evaporite seal rocks. Thick beds of limestone and calcareous shale are capable of sealing natural gas accumulations due to the ductile behavior of limestone at high temperature and pressure (Wyman, 1993; Handin and others, 1963).

## PRESERVATION OF TRAP INTEGRITY

Natural gas is highly buoyant in subsurface environments and tends to migrate easily through permeable strata and can diffuse through seals that trap oil. The integrity of deep natural gas traps and seals through geologic time is a critical factor, especially considering the ease with which gas can escape through small fractures in seal rocks. Deep reservoirs are often old reservoirs, and may have a long geologic history. Areas which have been tectonically quiet since the traps formed and filled (e.g. Anadarko and Arkoma Basins) are more likely to have undisturbed deep traps than basins with recent tectonic activity which may promote reservoir leaking. An important consideration is the ability, or inability, of source rocks to recharge a "leaky" trap and keep it filled with gas.

## THERMAL MATURITY AND PROXIMITY OF SOURCE ROCKS

Deep natural gas accumulations may be derived from oil-prone source rocks which have passed through the oil and gas windows (Claypool and Mancini, 1989), or may have been derived from gas prone (Type III) source rocks. Some deep natural gas accumulations are former oil-filled reservoirs, sourced by oil-prone source rocks, that have been subjected to deep burial and high temperatures so that the oil has cracked to natural gas and pyrobitumen or graphitic residue. The oil and pyrobitumen accumulations in the reservoir may be important controls on porosity preservation in the reservoirs (Houseknecht and McGilvery, 1990).

Other deep natural gas reservoirs are sourced by gas-prone Type III coals and carbonaceous shaly source rocks. Type III carbonaceous source rocks are evidently capable of generating natural gas at very high levels of vitrinite reflectance (Johnson and others, 1993; Wyman, 1993; Houseknecht and Spotl, 1993). These source rocks may be able to supply gas to recharge deep traps at high levels ($R_o$ >2.0) of thermal maturity.

## TIMING OF TRAP FORMATION AND HYDROCARBON MIGRATION

Timing is an important control on deep natural gas reservoirs, especially due to the long geologic history of many deep traps. Timing of hydrocarbon generation and trap and seal evolution must be understood for these often complex systems. For example, W.J. Perry, Jr., in Dyman and others (1993) identified the sequence of Laramide deformation in the Rocky Mountain foreland and set limits on hydrocarbon entrapment for Rocky Mountain basins with special emphasis on the Hanna Basin. His work was based in part on timing of source-rocks, petroleum migration, and structural development of the Hanna Basin.

### HYDROCARBON AND NONHYDROCARBON GAS COMPOSITIONS

Gas composition in deep gas reservoirs is difficult to predict in frontier areas, due to uncertainties about changes in geothermal gradients over time, uncertainties about deep source rock types, and the possible migration of contaminant gases (hydrogen, helium, nitrogen, carbon dioxide, hydrogen sulfide) from basement fault zones, igneous intrusions, or areas where thermochemical sulfate reduction may have occurred. The cracking of oil to natural gas is fairly well understood. The stability of methane at high temperature has been demonstrated (Houseknecht and Spotl, 1993; Price, 1992). The stabilities of mixtures of methane and contaminant gases in the deep subsurface can be modeled to some extent (Barker and Takach, 1992) but are still difficult to predict. Natural gas and contaminant gases react continuously with minerals in the reservoir during deep burial.

Deep natural gas reservoirs often occur at temperatures greater than the $150^{o}C$ threshold for thermochemical sulfate reduction (Orr, 1982; Heydari and Moore, 1989). Anhydrites and other evaporite rocks containing sulfur may generate considerable amounts of $H_2S$, which may migrate into deep gas reservoirs. However, iron-rich rocks, such as black shales with heavy minerals, or arkosic redbeds with hematite cements, may be capable of buffering $H_2S$: $H_2S$ + Iron -> pyrite.

Carbon dioxide may form from decomposition of carbonates near igneous intrusions, metamorphic belts and deep fault zones, or may be sourced directly from igneous intrusions. Carbon dioxide often occurs in deep, high temperature carbonate reservoirs (Barker and Takach, 1992; Burruss, 1992).

## KNOWN DEEP NATURAL GAS RESERVOIRS

According to Dwights Energy Data (1985), 1,998 producing reservoirs occurred below 15,000 feet in the United States at the end of 1985. Of the total cumulative natural gas production in the United States (698 TCF; Mast and others, 1989), deep reservoirs account for 7 percent (50 TCF) of which deep significant reservoirs (NRG reservoirs) account for nearly half (22.4 TCF; tables 1, 8). When the Nation is taken as a whole, deep natural gas reservoirs account for only a small portion of the total natural gas production. The production percentage rises when only recent production is considered, but the cumulative production to date is still low.

Table 2 lists total fields (329) with deep significant reservoirs (377) for each region of the United States as defined by NRG Associates (1990). Thirteen States contain all of the known deep significant reservoirs in the United States (table 3). Texas has the largest number of such reservoirs of any State (120) reservoirs, including offshore Texas), with most located in the Anadarko, Permian, and Gulf Coast Basins. Alaska and Utah have the least number of deep significant fields and reservoirs.

The 1970's was the most prolific decade for discovery of deep significant fields in the United States. The Gulf Coast Basin led the United States with 72 new deep significant fields discovered during the decade (table 4). Numbers of fields in table 4 should be considered minimum values because deep reservoirs discovered after the original field discovery date are not included.

Most fields containing deep significant reservoirs (203 of 329) are classified as gas producers (62 percent), although data are incomplete for the Anadarko Basin (table 5). An additional 25 reservoirs are classified as oil and gas producers. Classified gas fields and combination oil and gas fields outnumber oil fields in all States and regions except Alabama, Florida, and California. The Permian Basin, the Texas and Louisiana part of the Gulf Coast Basin, and the Offshore Gulf Coast Basin contain predominantly gas fields.

Sixty-seven percent of the reservoirs (253 of 377; table 6) are classified as having structural or combination (combined structural and stratigraphic) traps. Stratigraphic traps outnumber structural traps only in the Anadarko Basin and in California; the Anadarko Basin data are incomplete because of the large number of unknown completion categories. Only two deep significant reservoirs occur in California.

According to NRG Associates (1990), the Harrisville Field in Smith County, Mississippi contains the deepest significant reservoir in the U.S (table 7). At Harrisville Field, the Smackover Formation produces gas from carbonate rocks at an average depth of 23,007 feet. The 618-foot pay zone in the Smackover has produced more than 4.5 BCF of gas and has a known recoverable of 37.5 BCF.

Sixty percent of the deep significant reservoirs (227 of 377 reservoirs; Dyman and others, 1992) produce from deep clastic rocks. Clastic reservoir rocks are most abundant in Rocky Mountain basins, and in the Anadarko, Gulf Coast, California, and

Alaska Basins. Carbonate reservoir rocks are most abundant in the Permian and Williston Basins.

As expected, the number of reservoirs decreases with increasing depth (Dyman and others, 1992), but more than one quarter (26 percent) of the total deep significant reservoirs occur below 17,000 feet.

The 377 deep significant reservoirs have a known recoverable of 33.2 TCF of gas (table 1). They have produced more than 21.4 TCF of gas, more than half of which (12.4 TCF) was produced from the Permian Basin (table 8). Although the Gulf Coast Basin has only produced 6.2 TCF of gas from deep significant reservoirs, an additional 6.6 TCF of gas exists as proven reserves. Only 2.7 TCF of gas is listed as proven reserves in the Permian Basin.

## DEEP CONVENTIONAL NATURAL GAS PLAYS

One-hundred fifty-three deep conventional natural gas plays were defined for the 1995 National Petroleum Assessment. Appendix A contains province and play names, play classification as hypothetical or confirmed, depth ranges, and gas potential as a fractional distribution of total undiscovered accumulations for each play. Plays were identified and described by province geologists responsible for the petroleum geological framework of each province. The number of deep plays in equivalently- ized provinces may vary somewhat based on the manner in which each province geologist interpreted available data and on individual preferences for combining or subdividing geologic attributes. For example, 23 plays were identified for the Western Gulf Basin while only three plays were identified for the Permian Basin. The deep structural gas play in the Permian Basin involves several different reservoirs each of which could be defined also as different stratigraphic plays. Some deep gas plays may extend above and below 15,000 feet, but significant production from such a play may only occur at shallow depths.

The number of deep plays decreases with increasing depth. One hundred-thirteen plays have maximum depths ranging from 15,000 to 20,000 feet, whereas, 26 plays have maximum depths ranging from 20,001 to 25,000 feet, and 13 plays have maximum depths ranging from 25,001 to 30,000+ feet. Three plays exceed 30,000 feet in depth. Ninety-four plays are confirmed (those having known production), whereas, only 58 were defined as hypothetical. Nearly one-half of the confirmed plays (38) occur in the Gulf Coast region, and more than 60 percent of the plays (56) occur in the Gulf Coast and Rocky Mountain regions together. Sixty-three confirmed plays (nearly 70 percent) have a fractional distribution for non-associated gas of 0.5 or greater, whereas only 15 plays have no chance for undiscovered deep non-associated natural gas accumulations. Only in Region 2 (Pacific Coast region) does the number of oil plays (those having no chance for undiscovered nonassociated gas accumulations) exceed the number of plays that have a fractional distribution of 0.5 or greater for such gas. One-hundred of 152 plays have a fractional distribution for non-associated natural gas of 0.5 or more for all regions combined, and 123 plays have at least some minimum potential for natural gas. Thirty-six of these plays are in the Gulf Coast region. Associated gas in oil reservoirs was not addressed in this report.

# *REGION 1--ALASKA*

The petroleum geology of Alaska (Region 1) is complex in part because of the accretion of exotic terranes to the ancestral North American cratonic margin (Bird, this CD-ROM). Numerous sedimentary basins evolved before, during, and after this accretion process. The central Alaska province contains nonmarine rocks in intensely-faulted basins such as the Cook Inlet Basin. The northern Alaska province includes large, deep composite basins such as the North Slope Basin. The southern Alaska province includes forearc basins of the Pacific margin primarily with thick sequences of Tertiary marine rocks. Alaska provinces are relatively frontier areas with respect to deep natural gas drilling.

## SIGNIFICANT FIELDS AND RESERVOIRS

Beaver Creek Field, Cook Inlet area, is the only significant deep field in Alaska and is classified as a gas field According to NRG Associates data file; however, the Alaska Oil and Gas Conservation Commission classified the deep reservoir as oil (Alaska Oil and Gas Conservation Commission, 1992). The Beaver Creek reservoir occurs at 14,800 feet and produces from Tertiary sandstones. The reservoir has an average porosity of 28 percent (fig. 2). Regions 1 and 2 together have a known recoverable of 0.3 TCF of natural gas based only on significant reservoirs from the NRG Associates Data File (table 1).

## DEEP CONVENTIONAL PLAYS

The three Alaska provinces contain 25 conventional plays. Fourteen plays located primarily in central and northern Alaska have at least some non-associated natural gas potential. Northern Alaska has the largest number of plays of the three provinces with 11. Only eight of the 25 plays (32 percent) are confirmed (having known production) indicating that Alaska provinces are relatively frontier areas. For Alaska as a whole, the average maximum depth of deep natural gas plays exceeds 21,000 feet. The deepest plays in the region are the hypothetical western thrust belt, and Lisburne and Endicott plays in northern Alaska which reach 35,000 feet in depth. The Beaver Creek gas pool at Cook Inlet is part of the Cook Inlet Beluga-Sterling Gas Play (303, app. A).

## *REGION 2--PACIFIC COAST*

The Pacific Coast Region includes all of Washington, all but the southeastern quarter of Oregon, and California east of the Sierra Nevada Range (Bird and others, this CD-ROM). The geology of the region is complex because of arc-related volcanism and plutonism, subduction, crustal accretion, eruption of flood basalts, and the development of numerous small deep basins. The region is subdivided into four geologically distinct areas: western Washington and Oregon, eastern Washington and Oregon, Great Valley of California including the San Joaquin Basin, and California coastal basins including the Sonoma-Livermore, and Ventura Basins. Oregon and Washington contain the largest number of deep natural gas plays, while California's fields generally produce oil rather than gas.

### SIGNIFICANT FIELDS AND RESERVOIRS

Only two deep significant reservoirs occur in California, in the Ventura and San Joaquin Basins (Rio Viejo Field--Kern County and Fillmore Field--Ventura County; Dyman and others, 1992). Both of these fields have multiple reservoirs and are classified as oil fields. The deep Rio Viejo reservoir occurs at 14,100 feet and the Fillmore reservoir at 14,250 feet. Both reservoirs produce from Tertiary sandstones and have average reservoir porosities of about 20 percent (fig. 2). Regions 1 and 2 together have a known recoverable volume of 0.26 TCF of natural gas based on data for significant reservoirs from the NRG Associates Data File.

### DEEP CONVENTIONAL PLAYS

Region 2 contains 17 deep plays. Washington and Oregon provinces are generally gas prone, whereas California provinces are oil prone. The Sacramento Basin is gas prone although no deep plays were defined for this assessment. The San Joaquin Basin province has the largest number of deep plays with 6. The Rio Viejo oil Field in the San Joaquin Basin is part of the Neogene oil play (1302, app. A). Ten of 17 plays (59 percent) are confirmed indicating that the region is relatively mature with respect to deep natural gas. For the province as a whole, the average maximum depth of natural gas plays equals about 18,000 feet. The deepest play (app. A) is the hypothetical Deep Overpressured Fractured Rocks--of West Side Fold and Overthrust Belt Play (1011) of the San Joaquin Basin which reaches a depth of 25,000 feet. Other California basins such as the Los Angeles Basin contain deep sedimentary rocks, but no deep plays were assessed for them. The Los Angeles Basin contains one deep oil play but it was not assessed because it is not expected to produce oil fields larger than 1 MMBO.

## *REGION 3--COLORADO PLATEAU AND BASIN AND RANGE*

The Colorado Plateau and Basin and Range Region includes 10 petroleum provinces in Nevada, Idaho, Arizona, eastern California, southeastern Oregon, western and southern Utah, southwestern Colorado, and western New Mexico (Grow and Peterson, this CD-ROM). The geology of the region is typified by Late Precambrian to Early Paleozoic passive continental margin sedimentation dominated by more than 30,000 feet of shallow water carbonate and clastic rocks. This continental margin was subjected to repeated compression and plutonism during the Late Paleozoic and Late Mesozoic culminating in Sevier-style tectonism during the Late Cretaceous. The region was overprinted by Tertiary extension. The Colorado Plateau has remained tectonically stable since the Paleozoic, but the Basin and Range area was tectonically partitioned into numerous Tertiary basins. The region has a fair potential for undiscovered deep natural gas accumulations.

### SIGNIFICANT FIELDS AND RESERVOIRS

No significant fields or reservoirs were identified in the NRG Associates Data File for this region.

### DEEP CONVENTIONAL PLAYS

The Colorado Plateau--Basin and Range region contains 18 plays in 7 provinces (app. A). Fourteen of 18 plays contain some conventional non-associated gas potential, but 9 plays contain a fractional distribution for oil of at least 0.5 or greater. Plays are relatively equally distributed between the provinces with the Idaho Snake River Downwarp Province (017), Western and Eastern Great Basin Provinces (018, 019), and Paradox Basin Province (021) each having 3 deep plays. Only two of the 18 plays, both in the Paradox Basin, are confirmed indicating that the deeper parts of most of the region are relatively frontier areas. For the region as a whole, the average maximum depth equals about 19,000 feet. The deepest plays, each reaching maximum depths of 25,000 feet, are in the Snake River Downwarp Province of Idaho (Older Tertiary Rocks Play, play 1704), western Great Basin Province (1805, Neogene Source Rocks, Northwestern Nevada and Eastern California Play, 1805), and Southern Arizona-Southwestern New Mexico Province (Alamo-Hueco Basin Play, 2501).

## *REGION 4--ROCKY MOUNTAINS AND NORTHERN GREAT PLAINS*

For this assessment, the Rocky Mountains and Northern Great Plains Region is subdivided into 14 provinces, all but one of which (Sioux Arch Province, province 032) currently produce oil and gas (Spencer, this CD-ROM). Region 4 was part of the western United States cratonic margin during much of the Paleozoic. During Mesozoic and Tertiary time, Laramide- and Sevier-style tectonism disrupted the cratonic margin. Laramide structural basins may be very deep (Hanna Basin of the Southwestern Wyoming Province (037) extends to more than 40,000 feet) and are gas prone. Region 4 contains three supergiant fields: Salt Creek in the Powder River Basin, and Oregon Basin and Elk Basin Fields in the Bighorn Basin.

Paleozoic reservoirs are generally marine or eolian sandstone reservoirs and marine carbonate reservoirs; they produce mostly oil and associated gas. Mesozoic reservoirs are commonly marine to fluvial sandstone which produce oil and associated gas and non-associated gas. Tertiary reservoirs are primarily continental clastic rocks which produce nonassociated gas.

**SIGNIFICANT DEEP FIELDS AND RESERVOIRS**

Basins in the Rocky Mountains and Northern Great Plains Region have produced 0.4 TCF of gas from significant Jurassic and Cretaceous clastic reservoirs and Paleozoic mixed clastic-carbonate reservoirs. These NRG Associates reservoirs have a known recoverable resource of 2.2 TCF of gas (tables 1, 8).

Of the 22 significant deep reservoirs in the Rocky Mountains and Northern Great Plains Region, 19 are in Wyoming. The total (22) includes 7 in the Wyoming-Utah-Idaho thrust belt; 2 each in the Wind River Basin, Moxa arch, and Sand Wash Basins; 4 in the Powder River Basin; and 5 in the Washakie Basin (tables 1, 2; Dyman and others, 1992). Deep production in Region 4 is dominantly natural gas and gas condensate. High-gravity oil is produced from Cretaceous (Frontier Formation) and Jurassic (Nugget Sandstone) clastic sequences in the Wyoming-Utah-Idaho Thrust Belt, and from Permian-Pennsylvanian mixed clastic-carbonate sequences (Weber Sandstone and Minnelusa Formation) in primarily structural traps and combination traps there and in the Powder River Basin. Source rocks for deep reservoirs are commonly organic-rich Cretaceous shales in fault contact with older reservoir rocks.

Most deep significant reservoirs in the Rocky Mountains and Northern Great Plains Region are associated with structural or combination structural and stratigraphic trapping mechanisms (table 6).

Methane content ranges from 22.0 to 94.7 percent for significant deep natural gas reservoirs in Region 4 according to the NRG Associates Data File. The lowest value (22.0 percent) occurs at the LaBarge deep Madison Limestone reservoir in Lincoln County, Wyoming (NRG Associates, 1990). All deep Rocky Mountain and Northern Great Plains reservoirs have helium values less than 0.5 percent. Generally the highest hydrogen sulfide values occur in fields with high carbon dioxide content. The highest carbon dioxide values occur in limestone reservoirs.

Only sparse porosity-depth data are available from the NRG Associates Data File for Region 4 (fig. 2). Of the few deep significant reservoirs represented, clastic reservoirs generally exhibit the highest porosities.

## WILLISTON BASIN SIGNIFICANT FIELDS AND RESERVOIRS

Significant fields and reservoirs of the Williston Basin are discussed separately here because they are compiled separately in the NRG Data File (table 1). However, the Williston Basin is considered part of the Rocky Mountains and Northern Great Plains Region for the 1995 petroleum assessment. Only five deep significant fields, each with a single deep reservoir, occur in the Williston Basin, all in McKenzie County in westernmost North Dakota; none exceed 14,200 feet in depth (Dyman and others, 1992). Of the five, Croff and Bear Den are oil fields and North Fork, Cherry Creek, and Poe Fields are classified as oil and gas fields. All reservoirs are located between 14,003 feet and 14,188 feet. Each produces from dolomite in the Ordovician Red River Formation and is part of the Red River (Ordovician) Play (3102) which has a fractional distribution for gas of 0.5. All reservoirs are classified as having structural or combination structural and stratigraphic traps. Only one porosity value (11 percent for Cherry Creek Field--Red River reservoir; fig. 2) was recorded in the NRG Associates Data File for Williston Basin significant reservoirs. The Williston Basin Province (031) has a known recoverable of 38 BCF of natural gas (table 8) from significant reservoirs based on data from the NRG Associates Data File.

## DEEP CONVENTIONAL PLAYS

The Rocky Mountains and Northern Great Plains Region includes Laramide structural basins, the thrust belt, and the Williston Basin, and contains 29 deep plays distributed throughout 8 provinces. Seventeen are predominantly deep gas plays (fractional distribution for non-associated gas greater than 0.5), and only four contain no non-associated gas potential. Two of these four oil plays reside in the Powder River Basin as indicated by significant production from NRG Associates Data File. Deep plays are relatively equally distributed throughout the province, but the Wyoming Thrust Belt Province (036) and Southwestern Wyoming Province (037) each contain the most, with 6 plays each. Eighteen of the 29 plays (64 percent) are confirmed, indicating that the region is relatively mature with respect to deep drilling. The average maximum depth of all plays within the region is about 18,900 feet. The deepest plays (Basin Margin Anticline and Subthrust Plays of Southwestern Wyoming Province, plays 3705, 3706) extend to 30,000 feet. Other Rocky Mountain basins such as the Raton Basin are not included here because deep plays were not defined for the current petroleum assessment. Also not included here are the unconventional continuous-type gas plays which are briefly discussed at the end of this report. Refer to Schmoker (this CD-ROM and Spencer and Rice (this CD-ROM) for details of unconventional plays.

## ADDITIONAL COMMENTS ON GEOLOGIC CONTROLS--ROCKY MOUNTAIN AND NORTHERN GREAT PLAINS REGION

(1) Variations in thermal histories and the Late Cretaceous through Tertiary deformational sequence of Rocky Mountain basins control the distribution of and tendency toward natural gas or oil (Perry, 1992). Significant deep oil production occurs in conventional reservoirs in Rocky Mountain basins (Dyman and others, 1992). Reservoir rocks are primarily Cretaceous sandstones and Permian-Pennsylvanian sandstones and carbonates. These reservoirs are located in areas of abnormally low subsurface temperatures and low thermal maturation, probably caused by cool meteoric water penetrating deep into the basin along bounding faults (Law and Clayton, 1988). The deep western part of the Powder River Basin has below-normal temperatures, possibly as a result of meteoric waters recharged from outcrops along the western margin of the basin.

(2) Deep Mississippian gas production in Region 4 is from limestones and dolomites of the Madison Group (Dyman and others, 1992). These reservoirs have a high productive capacity (> 20 MMCFG per day per well) and commonly contain significant amounts of

non-hydrocarbon gases such as hydrogen sulfide and carbon dioxide. Reservoirs are primarily found in large structural traps.

(3) Structural traps in Rocky Mountain basins are directly related to the tectonic evolution of the Rocky Mountain foreland province. According to Perry (1992), initial progression of uplift and basin development from southwest Montana southeastward during the mid-Cretaceous established timing limits on petroleum migration and trapping trends. Implications of this new model of deformation of the Rocky Mountain foreland include progressive opening and subsequent blockage of migration paths for hydrocarbons generated from Paleozoic source rocks in southeastern Idaho, southwestern Montana, Wyoming, Colorado, and eastern Utah. Deep natural gas, generated during the Tertiary, has likely migrated from the deeper parts of these foreland basins into structural traps formed during Laramide deformation.

## *REGION 5--WEST TEXAS AND EASTERN NEW MEXICO*

Provinces in Region 5 include the Permian Basin (044), Bend Arch-Ft. Worth Basin (045), Marathon Thrust Belt (046), Pedernal Uplift (042), and Palo Duro Basin (043) (Ball and others, this CD-ROM). Although the region has produced hydrocarbons for many years, it includes plays with undiscovered deep natural gas accumulations. During the Early Paleozoic, a thick shallow-water carbonate sequence was deposited in the region. Early Pennsylvanian deformation of the Ouachita Orogeny trapped oil and gas in complex structural and stratigraphic plays. The Late Pennsylvanian through Permian sequence is composed of mixed clastic and carbonate rocks primarily in stratigraphic and combination traps. The region is geographically dominated by the Permian Basin.

### SIGNIFICANT FIELDS AND RESERVOIRS

The Permian Basin contains 24 percent of the deep reservoirs (89 of 377) in the United States with 12.4 TCF of natural gas produced (table 1 ). Forty-five percent of the known recoverable natural gas resources (15.1 TCF; table 8) in the United States occurs in the Permian Basin (Dyman and others, 1992).

Deep production in the Permian Basin is predominantly gas from carbonate reservoirs in the western and southern parts of the greater Permian Basin in what is commonly referred to as the Delaware Basin (see Pre-Pennsylvanian Delaware--Val Verde Basins Play (4401) in app. A). Some deep gas was generated directly from mature source rocks, while additional gas has been generated by the conversion of oil to gas. Presence of oil fields in equivalent rocks on the periphery of the greater Permian Basin, especially on the north and east, supports a thermal conversion process for the formation of natural gas.

Lithologically, relatively shallow reservoirs in the Delaware Basin (14,000 to 17,000 feet) are mixed-carbonate and clastic reservoirs (but mostly carbonate) including some Pennsylvanian- and Permian-aged rocks (table 1). They are located in Lea and Eddy Counties, New Mexico and Loving County, Texas on the margin of the deep basin. The deepest reservoirs are carbonate rocks of early Paleozoic age from the central part of the Delaware-Val Verde Basin (table 7; Dyman and others, 1992). Thirty-three deep reservoirs occur in the Ordovician Ellenburger Group alone. Seventy five percent of the Permian Basin deep reservoirs are developed in Devonian or older rocks (table 1).

All of the stratigraphically trapped deep reservoirs (6) occur at shallower depths (14,000 to 17,000 feet) in strata of Permian age (Dyman and others, 1992). The post-Wolfcampian Permian Basin is a sedimentary rather than a structural basin and traps are facies-controlled in these younger rocks.

Reservoir porosity systematically decreases with depth in the Permian Basin based on data from the NRG Associates Data File (fig. 2). Generally, the significant reservoirs below 16,000 feet are carbonate rocks, mostly dolomite. Matrix porosity is more than 5 percent at depths greater than 19,000 feet (fig. 2). At depths of less than 16,000 feet, clastic reservoirs average higher porosities than carbonate reservoirs. Fractures are common and result in greatly enhanced permeability and increased deliverability. Poor porosities can result at any depth, but the best porosities decrease with depth at a predictable rate. Porosities in limestone reservoirs tend to be lower than in dolomite reservoirs. The highest porosities at these depths occur in dolomite reservoirs (although NRG data are limited).

In the NGR Data File, methane content of natural gas in the deep Permian Basin ranges from 47.0 to 97.7 percent, but averages approximately 90 percent. The three lowest methane values occur in Ellenburger (carbonate) reservoirs (Brown Bassett--Terrell County, Mi Vida--Reeves County, and Moore-Hooper-Vermejo Fields--Loving County) in the southwest Texas part of the deep basin. Each of these reservoirs has high carbon dioxide values (34.8 to 53.8 percent). Helium and hydrogen sulfide values are very low in the deep Permian Basin (NRG Associates, 1990).

**DEEP CONVENTIONAL PLAYS**

Region 5 contains three deep plays in two petroleum provinces. All three plays contain non-associated gas potential, but both the Frontal Zone Oil and Gas Play (4601) of the Marathon Thrust Belt Province (046), and the Pre-Pennsylvanian, Central Basin Platform Play (4402) of the Permian Basin Province (044) have fractional distributions favoring oil accumulations. The Pre-Pennsylvanian, Delaware--Val Verde Basins Play (4401) contains the most deep significant reservoirs. All three plays are confirmed and range from 15,500 to 18,000 feet in maximum depth. These deep plays are primarily structural plays and include many different stratigraphic units, whereas the many shallower plays are stratigraphic and generally based on known stratigraphic subdivisions.

### ADDITIONAL COMMENTS ON GEOLOGIC CONTROLS--PERMIAN BASIN

(1) The volume of available reservoir rocks decreases with depth in the greater Permian Basin because the basin area decreases with depth. As a result, the risk in finding new, good quality, deep gas reservoirs increases with depth. However, increased pressures with depth result in an increase in gas stored within a given volume of reservoir rock.

(2) The deep Ellenburger of the Permian Basin is similar to the Arbuckle of the Anadarko Basin in that it may not be internally sourced (Palacas, 1992). Ellenburger hydrocarbons are predominantly derived from younger rocks including the Woodford Shale where these rocks have been down-faulted during compression or extension. Gas was probably trapped in Ellenburger reservoirs after structures were established during Pennsylvanian and Permian time. These late Paleozoic collisional structures were formed prior to peak gas generation.

(3) The total gas columns in Ellenburger reservoirs can be very thick, for example, more than 3,500 feet in the Gomez Field (Pecos County, southwest Texas). Vertical, interconnected fractures occur in some areas. These fracture systems are associated with huge transpressional structures along the eastern margin of the Delaware Basin (Perry, 1989).

(4) Source-rock type plays a minor role with respect to the presence of oil and (or) gas in deep reservoirs because thermal cracking converts oil to gas and condensate at depth. Normal pressure gradients typify deep reservoirs in large fields in the Permian Basin. Approximately 35 percent of the Permian Basin deep reservoirs in the NRG Associates file are overpressured (Spencer and Wandrey, 1992).

## *REGION 6--GULF COAST REGION*

The Gulf Coast Region includes the States and State waters that border the Gulf of Mexico and extends northward to folded Paleozoic rocks of the inland fold belts (Curtis, 1991; Schenk, this CD-ROM). The region represents the southern passive margin of North America since Triassic time and includes the Western Gulf, East Texas Basin, Louisiana-Mississippi Salt Basins, and Florida Peninsula Provinces (047, 048, 049, and 050). Since an early rifting event during the Triassic, the region has experienced extensive sedimentation, progradation, and subsidence. The region is geologically complex because of rapid facies changes due to marine transgressions and regressions, and gravity and salt tectonism. Mesozoic strata are dominated by mixed carbonate and clastic sequences, while Cenozoic strata are dominated primarily by clastic sequences. The Gulf Coast has been extensively drilled and is the foremost petroleum-producing region of the United States.

**SIGNIFICANT DEEP FIELDS AND RESERVOIRS**

Of the 377 reservoirs occurring below 14,000 feet, 174 (or 46 percent) occur in the Gulf Coast Region (fig. 1). Significant reservoirs in the Gulf Coast Region have produced 6.2 TCF of natural gas (table 8). Reservoirs occur primarily in Tertiary clastic rocks and mixed carbonate-clastic rocks of Mesozoic age. Thirty-nine percent of the known recoverable natural gas resources (12.8 TCF; tables 1, 8) in deep significant reservoirs occurs in the Gulf Coast Basin.

The two oldest fields containing deep reservoirs are the Lake de Cade Field in Terrebonne Parish, near Houma, in southeastern Louisiana, and the Thornwell South Field in Jefferson Davis Parish, in southwestern Louisiana (NRG Associates, 1990). Both fields were discovered in 1942 although some deep reservoirs were discovered later. The deep reservoirs produce from immediately below 14,000 feet in Tertiary sandstones. Generally, the oldest fields were found in Louisiana and Mississippi. Fields in Texas were discovered from the 1940's through the 1980's. Fields in Florida were discovered in the early 1970's, and fields in Alabama were discovered in the 1960's. More fields with deep reservoirs were discovered during the 1970's (72) than in any other decade. The number of deep field discoveries in this category approximately doubled with each succeeding decade (1940's= 5; 1950's= 13; 1960's= 32; 1970's= 72; data for 1980's incomplete) (table 4).

Sixty-five percent of the deep significant reservoirs (116) are classified as gas producing (NRG Associates, 1990); more than 40 percent (49) of these are located in Louisiana. Of the Gulf Coast States, Louisiana, Texas, and Mississippi contain more natural gas than oil reservoirs (table 5). Of the 14 deep significant offshore reservoirs, 11 are gas producers. Of the 110 deep significant Mesozoic reservoirs onshore, 64 are natural gas producers and an additional 9 are classified as producing both oil and gas.

For all States combined, the number of significant deep reservoirs decreases with increasing depth. The deepest reservoirs occur in Alabama and Mississippi (Mancini and Mink, 1985; Curtis, 1991; NRG Associates, 1990). The Jurassic Smackover gas reservoir in the Harrisville Field in Simpson County, south of Jackson, Mississippi (table 7), is the deepest significant reservoir in the Gulf Coast Basin. The reservoir has an average producing depth of 23,007 feet and an average reservoir thickness of 618 feet. Only two other reservoirs listed in the NRG Data File have greater average thicknesses. In the Gulf Coast, the shallower nature of Florida and Texas deep reservoirs is due to the shallow depth of equivalent Mesozoic reservoir rocks. Of the 16 significant reservoirs in offshore Texas and Louisiana, the deepest is 18,895 feet (Dyman and others, 1992). Most offshore reservoirs produce from depths of less than 16,000 feet.

For all depths together, 79 percent of the reservoirs are clastic (Dyman and others, 1992). By depth interval, (1) only 16 percent of the total reservoirs are carbonate reservoirs in the 14,000 to 15,000 feet depth interval, and (2) 29 percent of the total reservoirs are carbonate reservoirs in the 16,000 to 17,000 feet depth interval. Few carbonate reservoirs occur in the 14,000 to 15,000 feet depth interval; correspondingly more clastic lithologies of the Tertiary sequence are present. In both Florida and Texas, all deep significant Mesozoic reservoirs are carbonate rocks. In Louisiana, nearly all deep significant Mesozoic reservoirs are clastic rocks. Alabama and Mississippi display more intermediate reservoir facies. All of the offshore Texas and Louisiana reservoirs are classified as sandstone.

The distribution of reservoirs by geologic age is approximately equal with 65 Tertiary, 53 Cretaceous, and 56 Jurassic reservoirs present (Dyman and others, 1992). The largest numbers of deep significant reservoirs occur in Tertiary Miocene rocks (34), the Jurassic Smackover Formation (29), and the Cretaceous Hosston Formation (20). All Tertiary reservoirs occur in clastic rocks; whereas, 54 percent of Jurassic reservoirs (30 reservoirs of 56 total) occur in carbonate rocks (primarily Smackover Formation). Jurassic reservoirs are generally found deeper than Cretaceous and Tertiary reservoirs in the Gulf Coast Basin. All deep offshore Texas and Louisiana reservoir rocks are Tertiary in age.

Mesozoic reservoirs in the Gulf Coast Basin are primarily structurally trapped (table 6). Only 9 reservoirs are identified as stratigraphically trapped, 5 of which occur in Upper Cretaceous or Tertiary rocks. Stratigraphically trapped reservoirs and reservoirs classified as having combination traps appear to be relatively shallow (less than 20,000 feet). Stratigraphically trapped reservoirs are controlled by facies variations in marine and nonmarine Upper Cretaceous and Tertiary clastic rocks. All offshore Texas and Louisiana reservoirs are structurally trapped.

Methane content ranges from 35-94 percent for Mesozoic gas reservoirs according to the NRG Associates Data File. The lowest value (35 percent) occurs at Flomaton Field, in Escambia County, Alabama near the Florida border, in the Norphlet Formation reservoir, which contains 45 percent carbon dioxide (NRG Associates, 1990). Methane ranges from 79 to 94 percent and averages about 90 percent for Tertiary reservoirs. Carbon dioxide content is low (less than 9 percent) in other reservoirs. The highest hydrogen sulfide value (26 percent) for significant deep Gulf Coast Basin reservoirs occurs at Johns Field, Rankin County, near Jackson, in south-central Mississippi, in the Smackover reservoir.

A systematic decrease in average porosity occurs with increasing depth for all significant deep reservoirs, although the range of porosity values at a particular depth varies significantly (fig. 2). The approximate rate of decrease in porosity with increasing depth appears to change at about 17,000 feet. Although exceptions exist, porosity values below 17,000 feet appear higher than expected based on the distribution of points above 17,000 feet (reservoirs of the Norphlet and Tuscaloosa Formations included here). No significant difference exists between the range of clastic versus carbonate porosities using the NRG Associates Data File.

More than 6.2 TCF of gas have been produced from significant deep reservoirs in the Gulf Coast Basin (table 8). Of this, 2.6 TCF of gas have been produced from Tertiary reservoirs. Clastic reservoirs have produced approximately 5 times as much gas as carbonate reservoirs (Dyman and others, 1992).

## DEEP CONVENTIONAL PLAYS

In the Gulf Coast Region, the distribution of deep plays is very similar to the distribution of known production. Nearly all of the plays have significant reservoirs. The Gulf Coast Region contains 44 deep plays and exceeds all other regions in play frequency because of the extensive areas exceeding 15,000 feet (app. A). Thirty- eight plays are predominantly gas plays (fractional distribution for gas greater than 0.5), and only three plays contain no nonassociated gas potential. These three oil plays are updip equivalents of deeper natural gas plays. The Western Gulf Province (047) contains the most plays with 23, and the Florida Peninsula Province (050) contains the least with one play. Thirty-seven of the 44 plays (86 percent) are confirmed indicating that the region is very mature with respect to deep drilling. The average maximum depth of all plays within the region is nearly 20,000 feet. Average depths for known reservoirs are less than maximum depths for plays suggesting that the resource potential in the deepest parts of the region has not been tested by drilling. The two deepest plays, Norphlet Mobile Bay (4903) and Norphlet Southeast Margin Jackson Dome Flank Deep Gas (4907), extend to 24,000 feet. The 174 deep significant fields and reservoirs in the Gulf Coast Region can be grouped into 44 plays based on the stratigraphic character of most play names. For example, the four deep Smackover plays in the Louisiana--Mississippi Salt Basins Province (049) are defined by their structural origin (such as Jackson Dome).

## *REGION 7--MIDCONTINENT*

The Midcontinent region includes 12 petroleum provinces in the central United States (R.C. Charpentier, this CD-ROM). It includes all or parts of Oklahoma, Kansas, Nebraska, Texas, Arkansas, Missouri, Iowa, Minnesota, Wisconsin, and Colorado. Geologically, the region represents the Paleozoic continental craton. The deepest basins, the Anadarko and Arkoma, are in the southern part of the region and formed as Early Paleozoic aulacogens. They were later altered tectonically by collisional events along the eastern and southern margin of the United States In the northern and central parts of the region, Precambrian rifting led to the development of the Midcontinent rift. The region is mature and has been extensively drilled, but both confirmed and hypothetical deep natural gas plays still possess the potential for undiscovered accumulations.

## SIGNIFICANT DEEP FIELDS AND RESERVOIRS

All of the deep significant fields and reservoirs in the Midcontinent occur in the Anadarko Basin. The Anadarko Basin contains 22 percent of the deep significant reservoirs (84 of 377) in the United States with 2.4 TCF of natural gas produced and a known recovery of 2.8 TCF (fig. 1; table 8). Other Midcontinent petroleum-producing basins, such as the Arkoma Basin, contain deep reservoirs, but significant production as defined in the NRG file (known recoverable of at least one million barrels of oil, or 6 BCF of gas) was lacking as of the end of 1988 (NRG Associates, 1990).

Of 84 deep significant reservoirs, 11 are structurally trapped, 14 are stratigraphically trapped, 16 are combination structural and stratigraphic, and 43 are not classified in the NRG Data File. The largest reservoirs occur in structural and combination traps along the southern margin of the basin in Oklahoma and the Texas panhandle (Dyman and others, 1992). Structural traps in the Anadarko Basin are generally thrust-bounded anticlinal closures in an overall transpressional setting. Anticlines are generally northwest- or west-trending and evolved through time such that updip stratigraphic pinchouts created combination structural and stratigraphic traps (Perry, 1989).

Seventy percent of the deep significant reservoirs in the Anadarko Basin (59) are classed as clastic (table 1). Dominant reservoir lithologies include Pennsylvanian and Mississippian sandstones such as the Morrow, Atoka, and Springer Formations. Subordinate production occurs in Cambrian through Silurian carbonate rocks.

Methane values in the Anadarko Basin are high when compared to other deep basins in the United States according to the NRG and Associates Data File (range 80.4 to 97.3 percent). Helium, carbon dioxide, and hydrogen sulfide values are low (NRG Associates, 1990).

Based on available data from NRG Associates Data File (1990), reservoir porosity ranges from 4 to 15 percent in the Anadarko Basin (fig. 2). The highest porosity values generally occur in clastic reservoirs. All significant reservoirs below 18,000 feet are fractured carbonate reservoirs and have porosities of less than about 12 percent.

## DEEP CONVENTIONAL PLAYS

The Midcontinent Region includes 8 plays distributed in the Superior, Anadarko Basin, Southern Oklahoma, and Arkoma Basin Provinces (051, 058, 061, and 062). All 8 plays are predominantly non-associated gas (fractional distribution of undiscovered gas accumulations greater than 0.5) and 6 of the 8 plays contain no oil potential. The Anadarko and Arkoma Basins Provinces contain the most plays with three each. Six of the 8 plays (75 percent) are confirmed indicating that the region is mature with respect to deep drilling. The average maximum depth of all plays within the region is about 24,000 feet, the deepest maximum average play depth for any region in the United States. Data are strongly influenced by the Deep Structural Gas Play (5801) in the Anadarko Basin which extends to 40,000 feet. The deepest wells drilled in the United States, including the No. 1 Bertha Rogers and No. 1 Ernest Baden wells in the southern Anadarko Basin, are included in this play. The Deep Structural Gas Play (5801) and Deep Stratigraphic Gas Play (5812) in the Anadarko Basin account for most of the significant production carried in the NRG Associates Data File for the Midcontinent.

## ADDITIONAL COMMENTS ON GEOLOGIC CONTROLS--ANADARKO BASIN

(1) Lower than normal thermal gradients may occur locally along the thrust-faulted margins of the Anadarko Basin. Oil might then occur at deeper-than-normal conditions due to inferred downward flow of meteoric water along faults and fracture systems associated with the deep basin margin. Mills Ranch Field, along the Texas-Oklahoma border in Wheeler County, Texas, possibly illustrates these thermal conditions. An analog in the Rocky Mountain region occurs at Bridger Lake Field, located just north of the Uinta Mountains in Utah.

(2) The Morrow-Springer interval in the deep Anadarko Basin is internally sourced and overpressured whereas rocks lower in the stratigraphic column, such as the Hunton Group, are normally pressured (Al-Shaieb and others, 1992). The Morrow-Springer high-pressure compartmentalization is enigmatic. Near maximum burial depths were reached in the basin at the end of the Permian. Thermogenic reactions involving hydrocarbon generation are the most likely cause of overpressuring today.

(3) The Devonian-Mississippian Woodford Shale of the Anadarko Basin is not significantly overpressured, in contrast to the similar Bakken Formation of the Williston Basin. Hydrocarbons are no longer being generated from kerogen at rates which exceed leakage rates in the deeper parts of the Anadarko Basin. If gas is now being generated

in the deep Woodford, and if the Woodford is not overpressured, the natural gas may be migrating into the Hunton.

(4) Two opposing views are presented about the quality of source rocks in the Arbuckle Group:

(a) The Cambrian-Ordovician Arbuckle Group may prove to be disappointing as a major, deep, natural gas producer in the Anadarko Basin because it lacks suitable internal source rocks. Additionally, anhydrite in the Arbuckle reacts with methane to produce significant amounts of non-hydrocarbon gases such as carbon dioxide (which originates from the thermal degradation of carbonates and dilutes methane) and hydrogen sulfide (which originates from thermochemical sulfate reduction of anhydrite and destroys methane). In comparison, the Hunton contains less anhydrite, allowing methane to be stable at depth.

(b) The Arbuckle has undergone high thermal stress and for the most part displays minimum total organic carbon (TOC) values. However, higher TOC values in the geologic past, combined with the oil-prone nature of the organic matter (type II-I), could have enabled at least portions of the Arbuckle to generate petroleum. Smackover carbonates, which are also very mature to overmature in the deeper portions of the Gulf Coast Basin, also exhibit generally low TOC content--an average of 0.5 percent (Palacas, 1992). Yet, these carbonates are known to be the source of giant oil and gas accumulations. Alternatively, the Arbuckle problem may be simply a matter of not locating and analyzing the right organic-rich sections of rock. Palacas (1992), in summarizing Trask and Patnode's (1942) studies, showed that out of 178 subsurface Arbuckle samples from 18 wells in the Anadarko Basin, approximately 46 percent contained TOC contents ranging from 0.4 to 1.4 percent. Carbonate rocks with such values can be considered adequate source beds for petroleum.

(5) Large volumes of gas in Pennsylvanian clastic reservoirs were sourced by Upper Mississippian and Pennsylvanian shales. The high percentage of Pennsylvanian stratigraphic traps in clastic reservoirs suggests generation and entrapment close to source.

(6) The Anadarko Basin is unlike other deep basins in that hydrocarbons have been generated in an unusually long and continuous history that has contributed to the oil and gas productivity in this Paleozoic province. Time-Temperature Index computations indicate that the thermal zone of oil generation has migrated upward

through time (Schmoker, 1986). Oil may have been generated in the deepest parts of the southern Oklahoma aulacogen as long as 350 m.y. ago during the Pennsylvanian and Permian when large volumes of sediment entered the zone of oil generation. Known accumulations of natural gas; however, may have been generated during the last 60 million years.

## *REGION 8--EASTERN*

Most of the eastern United States is in Region 8 including the following provinces: Illinois Basin (064), Michigan Basin (063), Black Warrior Basin (065), Cincinnati Arch (066), Appalachian Basin (067), Blue Ridge Thrust Belt (068), Piedmont (069), Atlantic Coastal Plain (070), Adirondack Uplift (071), and New England (072) (Ryder, this CD-ROM). The Illinois and Michigan Basins are cratonic basins filled with Paleozoic sedimentary rocks and in part underlain by Precambrian rift systems. The Appalachian and Black Warrior Basins are foreland basins recording complex histories of continental rifting, passive margin subsidence, continental collision, and foreland basin subsidence. Up to 40,000 feet of sediments are present in the eastern Pennsylvania part of the Appalachian Basin. The region is very mature and has been extensively drilled, but deep natural gas plays still possess the potential for undiscovered accumulations.

### SIGNIFICANT FIELDS AND RESERVOIRS

No significant fields or reservoirs were identified in the NRG Associates Data File for this region.

### DEEP CONVENTIONAL PLAYS

Region 8 includes 12 deep plays distributed in five provinces including the Michigan Basin, Illinois Basin, Black Warrior Basin, Blue Ridge Thrust Belt, and Appalachian Basin Provinces. All 12 plays are predominantly non-associated gas (fractional distribution of undiscovered gas accumulations greater or equal to 0.5) and 8 of the 12 plays contain no oil potential. The Appalachian Basin Province contains the most plays with 5. The Michigan and Illinois Basins and Blue Ridge Thrust Belt Provinces each contain one play. Six of the 12 plays (50 percent) are confirmed indicating that the region is considered moderate with respect to deep drilling. The Precambrian Rift Play (6315) of the Michigan Basin is the deepest play in the region and extends to 30,000 feet.

### DEEP UNCONVENTIONAL PLAYS

Unconventional continuous-type plays were treated as a separate category in the 1995 National Petroleum Assessment and were assessed using a specialized methodology developed by the U.S. Geological Survey (see Schmoker, this CD-ROM, "Methods for assessing continuous-type (conventional) hydrocarbon accumulations"). These continuous-type plays are geologically diverse and fall into the following categories: coal-bed gas, biogenic gas, Bakken-Woodford Shales and equivalent fractured shales, heavy oil and bitumen, natural gas hydrates, and basin-centered natural gas accumulations. Biogenic gas, coal-bed gas, and gas hydrate plays do not exceed 15,000 feet in depth due to a variety of geologic factors. Only continuous-type basin-centered natural gas plays could comprise future significant undiscovered resources in many deep sedimentary basins.

In many deep sedimentary basins, it is difficult to differentiate between discrete conventionally-trapped and continuous-type accumulations. Continuous-type basin-centered gas accumulations may grade into discrete accumulations along basin margins and may occur above and below 15,000 feet in depth.

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Table 1. Summary of significant reservoirs in major deep basin areas of U.S. Based on data from NRG Associates Significant Field file (NRG Associates, 1990). Significant fields contain ultimate recoverable resources greater than 6 BCF of gas (equals 1 MMBO). Rec.= recoverable; res.= reservoirs; total of of 377 reservoirs used for U.S. Cumulative and known recoverable natural gas production in trillions of cubic feet (Tcf). Cumulative gas= cumulative natural gas production through 1988; known rec= known recoverable natural gas production; strat= stratigraphically trapped reservoirs. Percentages do not always add up to 100 percent due to rounding of numbers.

| Location | Number of reservoirs and percent of total number(377) | Cumulative ga and percent of total gas (21.4 TCF) | Known rec. gas and percent of total gas (33.2TCF) | Stratigraphic and Lithologic informatior | Number fields and % of total discovered prior to 1970 | Comments |
|---|---|---|---|---|---|---|
| Rocky Mts | 22, 6 % | 0.4, 2 % | 2.2, 7 % | Jurassic and Cretaceous clastic res. and Paleozoic mixed carb/clastic res | 9/22= 41 % | Deep gas mostly from Utah-Wyoming thrust belt. Potential from Hanna and Wind River basins |
| Anadarko Basin | 84, 22 % | 2.4, 11 % | 2.8, 8 % | Mostly a clastic basin. Some Cambrian-Silurian carbonate production | 25/84= 30% | 65% of res. produce from Pennsylvanian strata |
| Permian Basin | 89, 24 % | 12.4, 58 % | 15.1, 45 % | Middle Paleozoic mixed clastic/carb. reservoirs and Silurian/Devonian mostly carbonate res | 32/89= 36% | 67/89 res occur in Devonian or older rocks. Permian res strat trapped |
| Gulf Coast Basin | 174, 46 % | 6.2, 29 % | 12.8, 39 % | Tertiary reservoirs mostly clastic; Jurassic and Cretaceous reservoirs mixed carbonate/clastic | 64/174= 37% | 37% of deep reservoirs are Tertiary |
| Williston Basin | 5, 1 % | 0.1, <1 % | <0.1, <1 % | Ordovician Red River dolomitic reservoirs | 3/5= 60% | Structurally trapped |
| California/ Alaska | 3, <1 % | <0.1, <1 % | 0.3, 1 % | Tertiary clastic reservoirs | 2/3= 67% | Structural and stratigraphic traps |

Table 2. Numbers of significant fields with deep significant reservoirs in the U.S. Data from NRG Associates (1990) for all reservoirs below 14,000 feet (4,270 m) producing either natural gas, oil, or both. Res= reservoirs. West Coast includes California and Alaska fields and reservoirs. Gulf Coast includes 16 State and Federal offshore fields and reservoirs.

| Region | Fields | Res |
|---|---|---|
| Rocky Mountains-- | 19 | 22 |
| Permian basin-- | 68 | 89 |
| Anadarko-- | 76 | 84 |
| West Coast-- | 3 | 3 |
| Gulf Coast-- | 158 | 174 |
| Williston basin-- | 5 | 5 |
| Total | 329 | 377 |

Table 3. Numbers of deep significant fields and reservoirs by state. Data from NRG Associates (1990) for all reservoirs below 14,000 feet (4,270 m) producing either natural gas, oil, or both.

| State | Location | Fields | Reservoirs |
|---|---|---|---|
| Oklahoma | Anadarko basin | 58 | 63 |
| Texas | Anadarko basin | 18 | 21 |
| Texas | Permian basin | 56 | 77 |
| New Mexico | Permian basin | 12 | 12 |
| Wyoming | Rocky Mountains | 16 | 19 |
| Utah | Rocky Mountains | 1 | 1 |
| Colorado | Rocky Mountains | 2 | 2 |
| California | W. Coast/ Alaska | 2 | 2 |
| Alaska | W. Coast/ Alaska | 1 | 1 |
| North Dakota | Williston basin | 5 | 5 |
| Texas-Louisiana | Offshore | 14 | 16 |
| Louisiana | Gulf Coast | 49 | 50 |
| Florida | Gulf Coast | 3 | 3 |
| Mississippi | Gulf Coast | 53 | 64 |
| Alabama | Gulf Coast | 19 | 19 |
| Texas | Gulf Coast | 20 | 22 |
| TOTAL | | 329 | 377 |

Table 4. Numbers of deep significant fields by discovery year. Data from NRG Associates (1990) for all reservoirs below 14,000 feet (4,270 m) producing either natural gas, oil, or both. For fields with multiple reservoirs, first discovered reservoir indicates age of field discovery. Data combined for 1926 through 1959. Rocky Mts.= Rocky Mountain basins; W. Coast/Alaska= California and Alaska basins.

| Year | Anadarko Basin | Rocky Mts. | Permian Basin | Gulf Coast | W.Coast/ Alaska | Williston Basin |
|---|---|---|---|---|---|---|
| 1923-1949 | 2 | 3 | 1 | 5 | | |
| | | | | | | |
| 1950 | | | | | | |
| 1951 | 1 | | | 1 | | |
| 1952 | | | | 1 | | 1 |
| 1953 | 1 | | | | | |
| 1954 | 2 | | | 2 | 1 | |
| 1955 | | 1 | 1 | | | |
| 1956 | | | 1 | 1 | | |
| 1957 | | | | 3 | | 1 |
| 1958 | | | 2 | 2 | | 1 |
| 1959 | 1 | 1 | | 3 | | |
| | | | | | | |
| 1960 | 1 | | 4 | 2 | | |
| 1961 | 1 | | 2 | 2 | | |
| 1962 | 4 | | 2 | 2 | | |
| 1963 | 1 | | 1 | | | |
| 1964 | 2 | | 1 | 2 | | |
| 1965 | | 1 | 2 | 3 | | |
| 1966 | 2 | 3 | 4 | 5 | | |
| 1967 | 2 | | 1 | 2 | 1 | |
| 1968 | | | 5 | 6 | | |
| 1969 | 2 | | 3 | 8 | | |
| 1970 | 4 | | 2 | 12 | | |
| 1971 | 2 | | 3 | 5 | | |
| 1972 | 2 | 1 | 2 | 7 | | |
| 1973 | 2 | | 7 | 4 | | |
| 1974 | 5 | | 1 | 4 | | |
| 1975 | 3 | | 6 | 4 | 1 | |
| 1976 | 4 | | 1 | 8 | | |
| 1977 | 7 | 1 | 5 | 8 | | |
| 1978 | 3 | | 1 | 8 | | 1 |
| 1979 | 5 | 2 | 4 | 12 | | |
| | | | | | | |
| 1980 | 7 | 1 | 1 | 7 | | |
| 1981 | 10 | 1 | 3 | 8 | | 1 |
| 1982 | | 3 | 1 | 6 | | |
| 1983 | | | 1 | 4 | | |
| 1984 | | | | 10 | | |
| 1985 | | 1 | | 1 | | |
| Total (= 329) | 76 | 19 | 68 | 158 | 3 | 5 |

Table 5. Field completion classification for 329 deep significant fields by location. Data from NRG Associates (1990) for all reservoirs below 14,000 feet (4,270 m) producing either natural gas, oil, or both.

| Region | Oil | Gas | Oil and Gas | Unknown | Total |
|---|---|---|---|---|---|
| Anadarko basin | | 22 | | 54 | 76 |
| Rocky Mountains basins | 6 | 10 | 3 | | 19 |
| New Mexico (Permian basin) | | 11 | 1 | | 12 |
| Texas (Permian basin) | | 56 | | | 56 |
| California | 2 | | | | 2 |
| Alaska | | 1 | | | 1 |
| Williston basin | 2 | | 3 | | 5 |
| Gulf Coast Offshore | 1 | 11 | 2 | | 14 |
| Gulf Coast Louisiana | 4 | 36 | 9 | | 49 |
| Gulf Coast Texas | | 19 | 1 | | 20 |
| Gulf Coast Mississippi | 18 | 32 | 3 | | 53 |
| Gulf Coast Florida | 3 | | | | 3 |
| Gulf Coast Alabama | 11 | 5 | 3 | | 19 |
| TOTAL | 47 | 203 | 25 | 54 | 329 |

Table 6. Trapping mechanisms for deep significant reservoirs by State and/or basin. Data from NRG Associates (1990) for all reservoirs below 14,000 feet (4,270 m) producing either natural gas, oil, or both. Strat= stratigraphically trapped; Comb= combination structural and stratigraphic trap; unknown= trap type unknown. Texas and Louisiana rows include State and Federal offshore reservoirs.

| Region or area | Structural | Strat-igraphic | Comb-ination | Unknown | Total |
|---|---|---|---|---|---|
| Anadarko basin | 11 | 14 | 16 | 43 | 84 |
| Rocky Mountains basins | 8 | | 9 | 5 | 22 |
| Permian basin | 40 | 5 | 30 | 14 | 89 |
| California | | 2 | | | 2 |
| Alaska | 1 | | | | 1 |
| Williston basin | 2 | | 2 | 1 | 5 |
| Gulf Coast Louisiana | 41 | | 4 | 18 | 63 |
| Gulf Coast Texas | 8 | 7 | 4 | 6 | 25 |
| Gulf Coast Mississippi | 49 | 2 | 11 | 2 | 64 |
| Gulf Coast Florida | 2 | | 1 | | 3 |
| Gulf Coast Alabama | 9 | | 5 | 5 | 19 |
| TOTAL | 171 | 30 | 82 | 95 | 377 |

Table 7. Field and reservoir name, location, average depth to production, discovery year, and cumulative production for deepest significant reservoir by region. Data from NRG Associates (1990) for all reservoirs below 14,000 feet (4,270 m) producing either natural gas, oil, or both. Depth equals average depth to production as listed in NRG. Depth in feet. Not rep= data not reported; (field) = production totals by field only; Cum prod= cumulative production of natural gas in billions of cubic feet (Bcf). Reservoir names taken directly from NRG Associates Inc. (1988). One meter equals 3.28 feet.

| Basin | Field/Reservoir | Depth | Discovery year | Cummulative Production |
|---|---|---|---|---|
| Anadarko | New Liberty SW/Hunton | 23,920 | 1979 | not rep |
| Rocky Mountain | Bull Frog/Frontier | 18,792 | 1979 | 3.7 |
| Gulf Coast Off. | Eugene Island/Pliocene | 18,895 | 1977 | 3.3 |
| Permian Basin (field) | Cheyenne/Ellenburger | 21,699 | 1960 | 51.6 |
| Gulf Coast | Harrisville/Smackover | 23,007 | 1984 | 4.5 |
| California basins | Fillmore/Pico | 14,250 | 1954 | oil only |
| Alaska | Beaver Creek/Tyonek | 14,800 | 1967 | 63.0 |

Table 8. Total cumulative production, proven reserves, and known recoverable natural gas for deep significant reservoirs in all basins and areas in U.S. Data from NRG Associates (1990) for all reservoirs below 14,000 feet (4,270 m) producing natural gas. Data represent maximum values for Oklahoma because production totals are only available for fields. Some fields contain no data. Gas in millions of cubic feet. Data vary in significant figures; rounding taken from NRG data file.

| Basin or area | cumulative production | proven reserves | known recoverable |
|---|---|---|---|
| Anadarko | 2,358,260 | 416,490 | 2,774,750 |
| Rocky Mountain | 436,400 | 1,782,900 | 2,219,300 |
| Permian | 12,413,306 | 2,713,874 | 15,127,180 |
| Gulf Coast | 6,192,094 | 6,628,587 | 12,820,681 |
| West Coast/Alaska | 84,998 | 179,912 | 264,910 |
| Williston | 12,808 | 25,334 | 38,142 |
| TOTAL | 21,497,866 | 11,747,097 | 33,244,963 |

Appendix A. Conventional petroleum plays extending to depths of 15,000 feet or more in the U.S. In some cases, only a small part of the play occurs below 15,000 feet. Play definitions compiled from data by province geologists. C= confirmed play with known production; H= hypothetical play; min= minimum depth of play; med= median depth of play; max= maximum depth of play; Prob= the probability of undiscovered accumulations of at least 6 BCF of gas or 1 MMBOE in play where the play is hypothetical; Gas fraction= fractional distribution of undiscovered non-associated gas accumulations expected in this play where 0.0 indicates that play is entirely an oil play and 1.0 indicates that play is entirely a gas play. Blank indicates no data available. Unconventional plays not included. Question mark indicates highly interpretive or speculative data. Play numbers correspond to play numbrs in other parts of this CD-ROM.

| Region and Province | Play number and name | Status C/H | Prob | Depth (feet) min | med | max | Gas fraction |
|---|---|---|---|---|---|---|---|
| **Region 1- Alaska** | | | | | | | |
| Northern Alaska | 102 Turbidite | C | | 500 | 8000 | 25000 | 0.2 |
| | 103 Barrow Arch Beaufortian | C | | 1500 | 7000 | 15000 | 0.3 |
| | 104 Barrow Arch Ellesmerian | C | | 2200 | 10000 | 15300 | 0.0 |
| | 105 Ellesmereian-Beaufortian Clastics | C | | 2000 | 10000 | 26000 | 1.0 |
| | 106 Lisburne | H | 0.5 | 9000 | 25000 | 30000 | 1.0 |
| | 107 Lisburne Unconformity | H | 0.6 | 8500 | 25000 | 30000 | gas |
| | 108 Endicott | H | | 9500 | 25000 | 30000 | gas |
| | 109 Fold Belt | C | | 100 | 4000 | 25000 | 0.8 |
| | 110 Western Thrust Belt | H | 0.2 | 1000 | 10000 | 35000 | 0.6 |
| | 111 Eastern Thrust Belt | C | | 2000 | 13000 | 25000 | 0.7 |
| Central Alaska | 201 Central Alaska Cenozoic Gas | H | 0.1 | | | 15000? | gas |
| | 203 Central Alaska Paleozoic Oil | H | 0.1 | | | 15000+ | oil |
| | 204 Kandik Pre-Mid Cretaceous Strata | H | 0.1 | | | 15000+ | gas? |
| Southern Alaska | 301 Alaska Peninsula Mesozoic | H | low | 2000 | | 20000 | gas |
| | 302 Alaska Peninsula Tertiary | H | low | 5000 | | 15000+ | gas |
| | 303 Cook Inlet-Beluga-Sterling Gas | C | | 2000 | 4000 | 20000 | 1.0 |
| | 304 Cook Inlet Hemlock-Tyonek Oil | C | | 5000 | 10000 | 18000 | 0.0 |
| | 305 Cook Inlet Late Mesozoic Oil | H | low | | | 15000 | oil |
| | 307 Copper River Mesozoic Oil | H | low | | | 15000 | oil |
| | 308 Gulf of Alaska Yakataga Fold Belt | H | | 0 | | 28000+ | oil |
| | 309 Gulf of Alaska Yakutat Foreland | H | | 1600 | | 28000+ | oil |
| **Region 2- Pacific** | | | | | | | |
| Western Oregon and Washington | 403 Puget Lowland Deep Gas | H | 0.1 | 10000 | 15000 | 20000 | 1.0 |
| | 404 Tofino-Fuca Basin Gas | H | 0.2 | 500 | 6000 | 20000 | 1.0 |
| | 405 Western Washington Melange | H | 0.5 | 100 | 9000 | 18000 | 0.0 |
| | 410 Southwest Oregon Eocene Gas | H | 0.1 | 500 | 3000 | 15000 | 1.0 |
| Eastern Washington and Washington | 501 NW Columbia Plateau Gas | H | 0.6 | 500 | 8000 | 15000 | 1.0 |
| Northern California Coastal | 703 Sargent/Hollister Oil and Gas | C | | 1000 | 2000 | 15000 | 0.5 |
| Sonoma-Livermore Basin | 801 Sonoma-Livermore | C | | 1000 | 6000 | 16000 | 0.5 |
| San Joaquin Basin | 1003 Lower Bakersfield Arch | C | | 5600 | 8500 | 18000 | 0.0 |
| | 1004 West Side Fold Belt Sourced by Post-Lower Miocene rocks | C | | 800 | 9000 | 18000 | 0.0 |
| | 1005 West Side Fold Belt Sourced by Pre- | | | | | | |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | Middle Miocene Rocks | C | | 300 | 9000 | 22000 | 0.0 |

| Region and Province | Play number and name | Status | Prob | Depth (feet) | | | Gas |
|---|---|---|---|---|---|---|---|
| | C/H | | | min | med | max | fraction |
| San Joaquin Basin | 1008 Tejon Platform | C | | 500 | 6000 | 15000 | 0.0 |
| (Continued) | 1009 Southern End Thrust Salient | C | | 2000 | 9000 | 16000 | 0.0 |
| | 1011 Deep Overpressured Fractured Rocks of West Side Fold and Overthrust Belt | H | | 18000 | | 25000 | gas |
| Central coastal Basins | 1104 La Honda Oil | C | | 0 | 1800 | 15000 | 0.0 |
| Ventura Basin | 1301 Paleogene | C | | 1000 | 7000 | 20000 | 0.4 |
| | 1302 Neogene | C | | 500 | 8000 | 20000 | 0.0 |
| | 1313 Cretaceous | H | | | | 15000+ | gas? |
| **Region 3- Colorado Plateau and Basin and Range** | | | | | | | |
| Idaho Snake River | 1701 Miocene Lacustrine (Lake Bruneau) | H | 0.2 | 5000 | 7000 | 15000 | 0.6 |
| Downwarp | 1703 Pre-Miocene | H | 0.1 | 4000 | 6000 | 15000 | 0.6 |
| | 1704 Older Tertiary | H | 0.1 | 10000 | 15000 | 25000 | 0.9 |
| Western Great Basin | 1801 Hornbrook Basin--Modoc Plateau | H | 0.1 | 4500 | 9000 | 15000 | 0.9 |
| | 1804 Cretaceous Source Rocks--Northwest Nevada | H | 0.1 | 4500 | 9000 | 15000 | 0.1 |
| | 1805 Neogene Source Rocks--Northwest Nevada and Eastern California | H | 0.1 | 4500 | 12000 | 25000 | gas? |
| Eastern Great Basin | 1902 Late Paleozoic | H | 0.2 | 3000 | 8000 | 20000 | 0.2 |
| | 1906 Late Paleozoic-Mesozoic Thrust Belt | H | 0.2 | 3000 | 12000 | 20000 | 0.0 |
| | 1907 Sevier Frontal Zone | H | 0.4 | 6500 | 12000 | 20000 | gas |
| Paradox Basin | 2101 Buried Older Paleozoic Fault Blocks | C | | 6000 | 9000 | 15000 | 0.4 |
| | 2104 Marginal Permian-Pennsylvanian Clastic Rocks | H | | 3000 | 7000 | 20000 | 0.8 |
| | 2105 Salt Anticline Flank | C | | 3000 | 5000 | 15000 | 0.7 |
| Albuquerque Basin-- Sante Fe Rift | 2301 Albuquerque Basin | H | 0.5 | 8000 | 12000 | 20000 | 0.8 |
| | 2305 San Juan Sag | H | 0.6 | 3000 | 7000 | 15000 | 0.0 |
| Southern Arizona-- SW New Mexico | 2501 Alamo Hueco Basin | H | 0.1 | 1500 | 12000 | 25000 | 0.4 |
| | 2502 Pedregosa Basin | H | 0.1 | 5000 | 10000 | 17000 | 0.4 |
| South-Central New Mexico | 2602 Orogrande Basin | H | <0.1 | 2000 | 10000 | 24000 | 0.5 |
| | 2603 Mesilla--Mimbres Basins | H | <0.1 | 5000 | 14000 | 24000 | 0.4 |
| **Region 4- Rocky Mountains** | | | | | | | |
| Montana Thrust Belt | 2701 Imbricate Thrust Gas | C | 0.3 | 3000 | 12000 | 19000 | 0.95 |
| | 2704 Helena Salient Gas | H | 0.5 | 500 | 9000 | 20000 | 1.0 |
| | 2706 Tertiary Basins Oil and Gas | H | 0.3 | 2000 | 8000 | 16000 | 0.8 |
| Southwest Montana | 2901 Crazy Mountains and Lake Basins Cretaceous Gas | C | | 1000 | 5000 | 20000 | 1.0 |
| | 2904 Beartooth Frontal Oil and Gas | H | 0.4 | 4000 | 12000 | 20000 | 0.4 |
| | 2907 Tertiary Basins Oil and Gas | H | 0.2 | 200 | 12000 | 18000 | 0.8 |
| Williston Basin | 3102 Red River (Ordovician) | C | | 7000 | 13000 | 16000 | 0.5 |
| | 3106 Post Madison to Triassic Clastic | | | | | | |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | Rocks | C | | 10000 | 13000 | 16000 | 1.0 |
| | 3107 Pre-Red River Gas | C | | 12000 | | 16000+ | 1.0 |

| Region and Province | Play number and name | Status | Prob | Depth (feet) | | | Gas |
|---|---|---|---|---|---|---|---|
| | C/H | | | min | med | max | fraction |
| Powder River Basin | 3301 Basin Margin Subthrust | H | 0.4 | 5000 | 12000 | 15000 | 0.0 |
| | 3304 Upper Minnelusa Sandstone | C | | 5000 | 85000 | 15000 | 0.0 |
| Big Horn Basin | 3401 Basin Margin Subthrrust | H | 0.5 | 5000 | 12000 | 20000 | 0.3 |
| | 3403 Deep Basin Structure | C | | 8000 | 14000 | 20000 | 1.0 |
| Wind River Basin | 3501 Basin Margin Subthrust | C | | 5000 | 12000 | 20000 | 0.3 |
| | 3503 Deep Basin Structure | C | | 1300 | 85000 | 24000 | 0.9 |
| | 3504 Muddy Sandstone Stratigraphic | C | | 5000 | 12000 | 16000 | 0.3 |
| | 3506 Phosphoria Satratigraphic | H | | 2000 | 11000 | 20000 | 0.0 |
| Wyoming Thrust Belt | 3601 Moxa Arch Extension | C | | 10000 | 14000 | 18000 | 1.0 |
| | 3602 Crawford--Meade Thrusts | H | | 4500 | 11000 | 17500 | 1.0 |
| | 3603 Northern Thrusts | H | | 4500 | 10000 | 15000 | 0.7 |
| | 3604 Absaroka Thrust | C | | 5000 | 10000 | 18000 | 0.8 |
| | 3606 Hogsback Thrust | C | | 6000 | 10000 | 17000 | 0.6 |
| | 3607 Cretaceous Stratigraphic | C | | 1000 | 8000 | 17000 | 0.0 |
| Southwestern Wyoming | 3701 Rock Springs Uplift | C | | 1500 | 6000 | 18000 | 0.8 |
| | 3702 Cherokee Arch | C | | 1500 | 5000 | 20000 | 0.3 |
| | 3703 Axial Uplift | C | | 2000 | 6000 | 15000 | 0.3 |
| | 3704 Moxa Arch--LaBarge Platform | C | | 1200 | 10000 | 18000 | 0.7 |
| | 3705 Basin Margin Anticline | C | | 4000 | 14000 | 30000 | 0.6 |
| | 3706 Subthrust | H | 0.8 | 5000 | 12000 | 30000 | 0.4 |
| **Region 5- West Texas and Eastern New Mexico** | | | | | | | |
| Permian Basin | 4401 Pre-Pennsylvanian, Delaware/ Val Verde Basins | C | | 8400 | 16000 | 24000 | 1.0 |
| | 4402 Pre-Pennsylvanian, Central Basin Platform | C | | 4000 | 10000 | 15500 | 0.2 |
| Marathon Thrust Belt | 4601 Frontal Zone Oil and Gas | C | | 3500 | 9000 | 18000 | 0.4 |
| **Region 6- Gulf Coast** | | | | | | | |
| Western Gulf Basin | 4701 Houston Salt Dome Flank Oil and Gas | C | | 250 | | 16000 | 0.6 |
| | 4702 Norphlet South Texas Deep Gas | H | 0.8 | 14000 | 18000 | 22000 | 1.0 |
| | 4703 Smackover South Texas Gas | C | | 10000 | 16000 | 22000 | 1.0 |
| | 4704 Cotton Valley Western Gulf Gas and Oil | C | | 3000 | 12000 | 20000 | 0.7 |
| | 4705 Lower Cretaceous Carbonate Shelf Edge Gas and Oil | C | | 6000 | 14000 | 20000 | 0.7 |
| | 4709 Tuscaloosa Deep Sandstone Gas | C | | 12000 | 17000 | 22000 | 1.0 |
| | 4710 Woodbine South Angelina Flexure Oil and Gas | C | | 7000 | 14000 | 20000 | 0.3 |
| | 4720 Lower Wilcox Downdip Over-pressured Gas | C | | 8000 | 16000 | 20000 | 1.0 |
| | 4723 Upper Wilcox Downdip Over-presured Gas | C | | 8000 | 16000 | 22000 | 1.0 |
| | 4724 Middle Eocene Sandstones Downdip Gas | C | | 8000 | 12000 | 18000 | 0.9 |
| | 4727 Yegua Downdip Gas | C | | 8000 | 14000 | 22000 | 1.0 |
| | 4729 Jackson Downdip Gas | H | 0.5 | 6000 | 14000 | 22000 | 1.0 |

| Region and Province | Play number and name C/H | Status | Prob | Depth (feet) min | med | max | Gas fraction |
|---|---|---|---|---|---|---|---|
| | 4731 Vicksburg Downdip Gas | C | | 7000 | 14000 | 22000 | 1.0 |
| | 4732 Frio South Texas Downdip Gas | C | | 6000 | 12000 | 18000 | 1.0 |
| Western Gulf Basin (Continued) | 4735 Frio SE Texas/ South Louisiana Mid-dip Gas and Oil | C | | 6000 | 12000 | 16000 | 0.6 |
| | 4736 Frio SE Texas/South Louisiana Downdip Gas | C | | 8000 | 14000 | 20000 | 1.0 |
| | 4738 Anahuac Sandstone Gas and Oil | C | | 8000 | 15000 | 20000 | 0.7 |
| | 4740 Lower Miocene Deltaic Sandstone Gas and Oil | C | | 3000 | 10000 | 16000 | 0.7 |
| | 4741 Lower Miocene Slope and Fan Sand-stone Gas | C | | 8000 | 14000 | 20000 | 1.0 |
| | 4742 Middle Miocene Fluvial Sandstone Gas and Oil | C | | 1000 | 10000 | 17000 | 0.8 |
| | 4743 Middle Miocene Deltaic Sandstone Gas and Oil | C | | 8000 | 14000 | 20000 | 0.8 |
| | 4744 Upper Miocene Fluvial Sandstone Gas and Oil | C | | 1000 | 8000 | 16000 | 0.4 |
| | 4745 Upper Miocene Deltaic Sandstone Gas and Oil | C | | 4000 | 14000 | 20000 | 0.6 |
| Louisiana--Mississippi Salt Basins | 4901 Piercement Salt Dome Flanks Oil and Gas | C | | 4000 | 10000 | 16000 | 0.7 |
| | 4903 Norphlet Mobile Bay Deep Gas | C | | 17000 | 20000 | 24000 | 1.0 |
| | 4904 Norphlet Wiggins--Hancock Arch Gas | H | 0.6 | 13000 | 17000 | 21000 | 1.0 |
| | 4905 Norphlet Salt Basin Oil and Gas | C | | 8000 | 12000 | 17000 | 0.0 |
| | 4906 Norphlet Alabama Updip Oil | H | 0.5 | 8000 | 12000 | 16000 | 0.0 |
| | 4907 Norphlet SE Margin Jackson Dome Flank Deep Gas | H | 0.5 | 20000 | 22000 | 24000 | 1.0 |
| | 4909 Smackover Wiggins--Baldwin Flanks Gas | C | | 12000 | 16000 | 20000 | 1.0 |
| | 4910 Smackover Alabama/Florida Fault Zone Oil and Gas | C | | 10000 | 15000 | 20000 | 0.3 |
| | 4912 Smackover Salt Basins Gas and Oil | C | | 8000 | 12000 | 18000 | 0.6 |
| | 4913 Smackover Jackson Dome Deep Gas | C | | 20000 | 21000 | 23000 | 1.0 |
| | 4918 Haynesville Salt Basins Gas and Oil | C | | 6000 | 14000 | 20000 | 0.9 |
| | 4920 Gilmer Limestone Gas | C | | 10000 | 14000 | 18000 | 1.0 |
| | 4921 Cotton Valley Updip Oil | C | | 2000 | 10000 | 18000 | 0.0 |
| | 4922 Cotton Valley Salt Basins Gas | C | | 8000 | 14000 | 20000 | 1.0 |
| | 4925 Hosston Updip Oil | C | | 4000 | 9000 | 16000 | 0.0 |
| | 4926 Hosston/Travis Peak Salt Basins gas | C | | 4000 | 12000 | 18000 | 1.0 |
| | 4929 Sligo/Pettet Salt Basins Gas | C | | 5000 | 11000 | 16000 | 1.0 |
| | 4931 James Limestone Gas | C | | 8000 | 11000 | 16000 | gas? |
| | 4933 Glen Rose/Rodessa Salt Basins Gas | C | | 3000 | 10000 | 16000 | 1.0 |
| | 4935 Paluxy Downdip Gas | C | | 4000 | 10000 | 16000 | 1.0 |
| Florida Peninsula | 5006 Wood River Dolomite Deep Gas | H | 0.1 | 14000 | 16000 | 19000 | gas? |
| **Region 7- Midcontinent** | | | | | | | |
| Superior | 5101 Precambrian Midcontinent Rift System | H | 0.4 | 5000 | 10000 | 25000 | 0.6 |
| Anadarko Basin | 5801 Deep Structural Gas | C | | 13000 | 17000 | 40000 | 1.0 |
| | 5812 Deep Stratigraphic Gas | C | | 13000 | 15000 | 30000 | 1.0 |

| Region and Province | Play number and name | Status C/H | Prob | Depth (feet) min | med | max | Gas fraction |
|---|---|---|---|---|---|---|---|
| | 5827 Washes | C | | 500 | 9400 | 15000+ | 0.8 |
| Southern Oklahoma | 6101 Deep Gas | C | | 13000 | 15000 | 40000 | 1.0 |
| Arkoma Basin | 6205 Arbuckle Through Misner Basement Fault Shelf Gas | C | | 4000 | 8000 | 15000 | 1.0 |
| | 6206 Cromwell--Spiro--Wapanucka Sub-Choctaw Thrust Gas | C | | 7000 | 12000 | 15000 | 1.0 |
| | 6207 Carboniferous Turbidite Thrust Belt Gas | H | 0.2 | 6000 | 13000 | 20000 | 1.0 |
| **Region 8- Eastern** | | | | | | | |
| Michigan Basin | 6315 Precambrian Rift | H | 0.1 | 10000 | 20000 | 30000 | 1.0 |
| Illinois Basin | 6405 Rough Creek Graben | H | 1.0 | 4500 | 12000 | 19000 | 1.0 |
| Black Warrior Basin | 6501 Cambrian and Ordovician Carbonate | H | ? | 1000 | 10000 | 25000 | 0.8 |
| | 6502 Upper Mississippian Sandstone | C | | 2500 | 8000 | 16000 | 0.8 |
| | 6503 Pennsylvanian Sandstone | C | | 1500 | 7000 | 15000 | 1.0 |
| | 6505 Devonian Chert and Carbonate | H | 0.8 | 2000 | 8000 | 18000 | 1.0 |
| Appalachian Basin | 6701 Rome Trough | H | 0.8 | 6000 | 10000 | 25000 | 1.0 |
| | 6702 Upper Cambrian, Ordovician, and Lower/Middle Sulurian Thrust Belt | C | | 1000 | 10000 | 20000 | 1.0 |
| | 6703 Beekmantown/Knox Carbonate Oil and Gas | C | | 2500 | 10000 | 18000 | 0.5 |
| | 6704 Rose Run/Gatesburg/Theresa Sand-stone Gas | C | | 5000 | 9000 | 20000 | 1.0 |
| | 6707 Trenton/Black River Carbonate Oil and Gas | C | | 1000 | 8000 | 15000 | 0.5 |
| Blue Ridge Thrust Belt | 6801 Southern Appalachians Subthrust Sheet | H | | | <0.1 | >15000 | 1.0 |