Geologic and Production Characteristics of Deep Natural Gas Resources Based on Data From Significant Fields and Reservoirs

By T.S. Dyman, C.W. Spencer, J.K. Baird, R.C. Obuch, *and*
D.T. Nielsen

GEOLOGIC CONTROLS OF DEEP NATURAL GAS RESOURCES IN THE UNITED STATES

U.S. GEOLOGICAL SURVEY BULLETIN 2146–C

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1997

CONTENTS

FIGURES

TABLES

CONTENTS

Geologic and Production Characteristics of Deep Natural Gas Resources Based on Data From Significant Fields and Reservoirs

By T.S. Dyman, C.W. Spencer, J.K. Baird, R.C. Obuch, *and* D.T. Nielsen

ABSTRACT

Known deep natural gas accumulations are present in many basins in the United States in various geologic settings. Of more than 15,000 significant reservoirs in the United States, 377 significant oil and gas reservoirs (reservoirs having known recoverable production of at least 6 BCFG or 1 MMBO) produce from depths greater than 14,000 ft (4,267 m), and 256 reservoirs produce from depths greater than 15,000 ft (4,572 m). Almost 75 percent of all reservoirs below 14,000 ft produce natural gas and are in the Gulf Coast, Permian, Anadarko, Williston, San Joaquin, Ventura, Rocky Mountains, and Cook Inlet basins.

Thirteen States contain all of the deep significant oil and gas reservoirs below 14,000 ft (4,267 m) in the United States. Texas has the largest number (121), in the Anadarko, Permian, and Gulf Coast basins. The most prolific decade for deep discoveries in the United States was the 1970's; during that decade 72 new deep significant oil and gas fields were discovered in the Gulf Coast Basin. Most fields containing deep significant reservoirs (203 of 329 below 14,000 ft) are gas producers (62 percent), although data are incomplete for the Anadarko Basin. Twenty-five reservoirs are classified as oil and gas producers. Gas and oil and gas reservoirs outnumber oil reservoirs in all States except Alabama, Florida, and California.

Sixty-seven percent of all significant reservoirs below 14,000 ft (4,267 m) (253 of 377) have structural or combination traps, and stratigraphic traps outnumber structural traps only in the Anadarko and California basins. Sixty percent of all deep significant reservoirs below 14,000 ft (227 of 377) produce from clastic rocks. Clastic reservoir rocks are most abundant in Rocky Mountain basins and in the Anadarko, Gulf Coast, California, and Alaska basins, whereas carbonate reservoirs are most abundant in the Permian and Williston basins. The number of reservoirs in a basin decreases with increasing depth, but 26 percent of the total significant reservoirs are below 17,000 ft.

Reservoirs deeper than 15,000 ft (4,572 m) account for 7 percent (50 TCF) of the total cumulative natural gas production in the United States (698 TCF; U.S. Geological Survey), and deep significant reservoirs (NRG reservoirs) account for almost half (22.4 TCF) of the deep reservoir total. More than half of the gas from deep significant reservoirs (12.4 TCF) has been produced from the Permian Basin. Significant reservoirs below 14,000 ft (4,267 m) have known recoverable production of 36.4 TCFG. Although the Gulf Coast Basin has only produced 6.2 TCF of gas from these reservoirs, an additional 6.6 TCF of gas is proven reserves. In the entire United States, deep natural gas reservoirs account for a small, but important, part of total natural gas production.

Of the total U.S. natural gas resource (almost 1,300 TCF), 519 TCF is considered unconventional including coalbed methane, gas in low-permeability shale and sandstone reservoirs, and deep-basin gas accumulations. The need for new geologic research dealing with all aspects of natural gas exploration and production is obvious.

INTRODUCTION

Deep natural gas accumulations are present in many basins of the United States in various geologic settings. Of a total of more than 15,000 significant reservoirs in the United States, 256 significant reservoirs produce from depths greater than 15,000 ft (4,572 m), and 377 produce from depths greater than 14,000 ft (4,267 m) (NRG Associates, 1990). A significant reservoir is defined as a reservoir having known recoverable production of at least 1 MMBO or 6 BCFG. Almost three-quarters of the significant reservoirs produce natural gas. These reservoirs are in the Gulf Coast, Permian, Anadarko, Williston, San Joaquin, Ventura, and Rocky Mountain basins and the Cook Inlet area of Alaska (fig. 1, table 1).

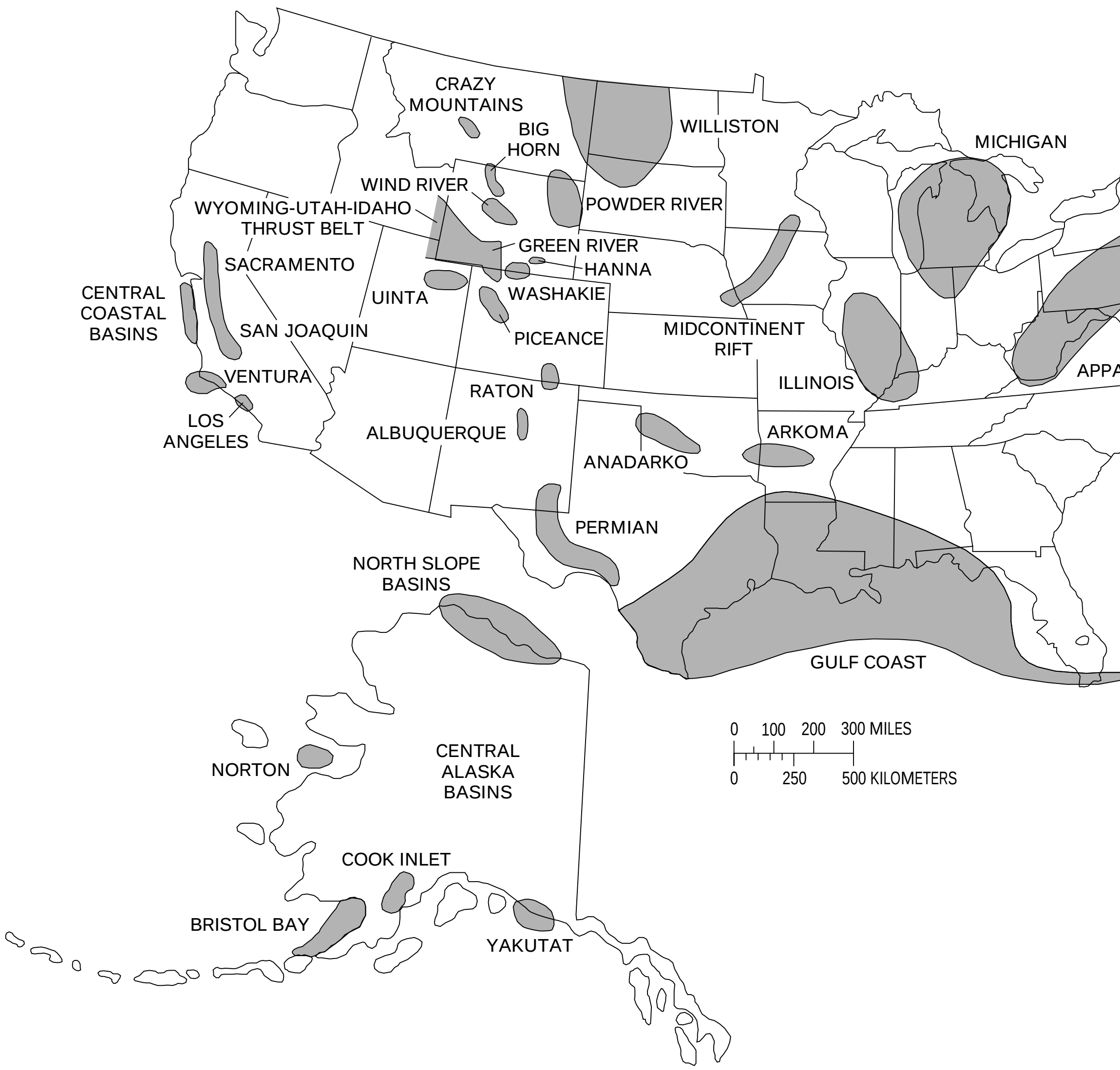

Figure 1. Map of the United States showing basins containing sedimentary rocks more than 15,000 ft (4,572 m) deep. Shading indicates entire basin area, in which some of the sedimentary rocks are at shallow depths.

This report updates and summarizes the work of Dyman and others (1992), who compiled preliminary tables of deep reservoir data and identified geologic conditions or variables favorable for natural gas accumulations in deep sedimentary basins based on work by Takahashi and Cunningham (1987) and Wandrey and Vaughan (this volume) and on published information and supporting unpublished data from computerized data files including the NRG Associates data file and the Well History Control System (WHCS). We hope that the descriptive compilation of reservoir characteristics can be used as a tool for future exploration targets in deep sedimentary basins. To our knowledge, no recent, detailed data compilations of deep significant natural gas reservoirs are available. Our data compilations are organized as data tables by region in the United States, and each regional presentation includes a brief discussion of geologic characteristics related to natural gas accumulations.

The deep basins are described in terms of their geologic characteristics, and comparisons are made between basins. Computerized data are primarily from the NRG Associates Inc. Significant Field File (NRG Associates, 1990), which contains geologic, production, and engineering data for more than 15,000 significant oil and gas reservoirs in the United States.

For this study, a deep reservoir is defined as a reservoir below 15,000 ft (4,572 m); however, because a single producing horizon can extend both above and below 15,000 ft, NRG retrievals were selected for all reservoirs below 14,000 ft (4,267 m) in order to retrieve all potential reservoirs in the 15,000-foot range. Therefore, the data tables include data in the 14,000–15,000-foot depth range. Also, many fields contain separate reservoirs above and

Table 1. Summary of significant reservoirs in major deep basins of the United States.

[Cumulative and known recoverable natural gas production is in trillions of cubic feet (TCF). Cumulative natural gas production is through 1988. Percentages do not always sum to 100 because of rounding of numbers. Based on data from NRG Associates (1990) significant oil and gas field file]

Basin region	Number of reservoirs and percentage of total number	Cumulative gas and percentage of total gas produced in basin	Known recoverable gas and percentage of total gas produced in basin	Stratigraphic and lithologic information	Number of fields discovered prior to 1970 and percentage of total number of reservoirs in basin	Comments
Rocky Mountain basins	22/377 6 percent	0.4/21.4 2 percent	2.2/33.2 7 percent	Jurassic and Cretaceous clastic reservoirs and Paleozoic mixed carbonate-clastic reservoirs	9/22 41 percent	Deep gas mostly from Utah-Wyoming thrust belt; potential for gas from Hanna and Wind River Basins.
Anadarko	84/377 22 percent	2.4/21.4 11 percent	2.8/33.2 8 percent	Mostly a clastic basin; some Cambrian-Silurian carbonate production	25/84 30 percent	65 percent of reservoirs produce from Pennsylvanian strata.
Permian	89/377 24 percent	12.4/21.4 58 percent	15.1/33.2 45 percent	Middle Paleozoic mixed clastic-carbonate reservoirs and Silurian-Devonian, mostly carbonate reservoirs	32/89 36 percent	67 of 89 reservoirs are in Devonian or older rocks; Permian reservoirs are stratigraphically trapped.
Gulf Coast	174/377 46 percent	6.2/21.4 29 percent	12.8/33.2 39 percent	Mostly clastic Tertiary reservoirs; mixed carbonate-clastic Jurassic and Cretaceous reservoirs	64/174 37 percent	37 percent of deep reservoirs are Tertiary.
Williston	5/377 1 percent	0.1/21.4 <1 percent	<0.1/33.2 <1 percent	Ordovician Red River dolomitic reservoirs	3/5 60 percent	Structurally trapped.
California, Alaska	3/377 <1 percent	<0.1/21.4 <1 percent	0.3/33.2 1 percent	Tertiary clastic reservoirs	2/3 67 percent	Structurally and stratigraphically trapped.

below 14,000 ft. Production figures tabulated by field in the following tables may include some reservoirs above 14,000 ft. Areas in which production is reported only by field rather than by reservoir, such as Oklahoma, are identified where appropriate.

Tables 2–32 were prepared using NRG data through 1988 (NRG Associates, 1990) and contain geologic and production data summaries for the entire United States or for each basin or region in the United States containing deep significant reservoirs. Table 1 is a summary of data presented in tables 2–32 for the Gulf Coast, Permian, Anadarko, Williston, California, and Rocky Mountain basins.

KNOWN DEEP NATURAL GAS RESOURCES

According to Dwights Energy Data (1985) 1,998 reservoirs below 15,000 ft (4,572 m) in the United States were producing hydrocarbons at the end of 1985. Of the total cumulative natural gas production in the United States (698 TCFG) (Mast and others, 1989), deep reservoirs account for 7 percent (50 TCFG) of the total, and deep significant reservoirs (NRG reservoirs) account for almost half (22.4 TCFG) (fig. 2, tables 1, 8) of the deep reservoir total (Dyman and others, 1992). If the Nation is taken as a whole, deep natural gas reservoirs account for only a small part of total natural gas production. The percentage of production from deep reservoirs is greater if only recent production is considered, but the total cumulative production is still low.

Table 2 lists total fields (329) containing deep significant reservoirs (377) for each region of the United States. Thirteen States contain all of the deep significant reservoirs (table 3). Texas has the most reservoirs of any State (121 reservoirs, including one in offshore Texas) and has reservoirs in the Anadarko, Permian, and Gulf Coast Basins. Alaska and Utah have the fewest fields and reservoirs.

The most prolific decade for discovery of deep significant fields in the United States was the 1970's; in the Gulf

Table 2. Deep significant fields and reservoirs in the United States.

[Data from NRG Associates (1990) for all reservoirs below 14,000 ft (4,270 m) producing either natural gas or oil, or both. Gulf Coast Basin region includes 16 offshore fields and reservoirs]

Region	Number of fields	Number of reservoirs
Rocky Mountains	19	22
Permian Basin	68	89
Anadarko Basin	76	84
California, Alaska	3	3
Gulf Coast Basin	158	174
Williston Basin	5	5
Total	329	377

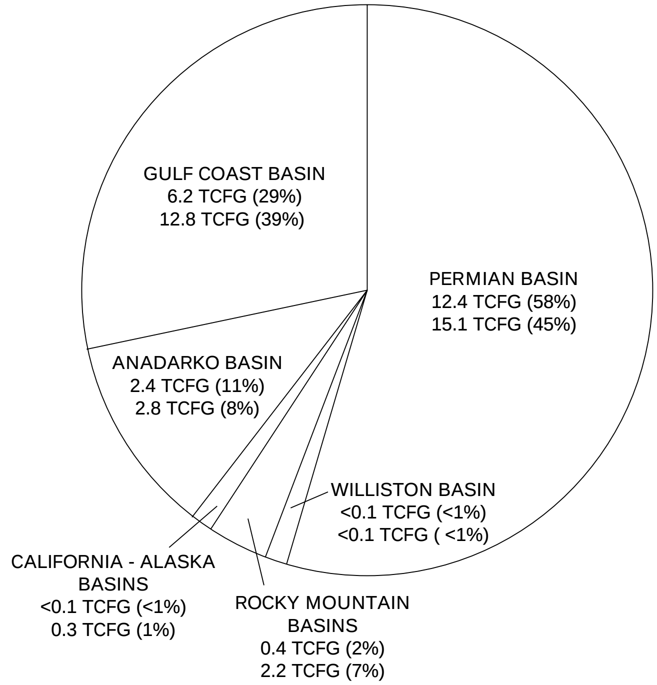

Figure 2. Pie chart illustrating distribution of total cumulative production of natural gas from deep significant reservoirs (those containing more than 6 BCFG and deeper than 14,000 ft, 4,267 m) in the United States by region. Total deep significant production is 21.4 TCFG, and ultimate recoverable production is 33.2 TCFG. Data from NRG Associates Inc. (1990).

Table 3. Deep significant fields and reservoirs in the United States by State.

[Data from NRG Associates (1990) for all reservoirs below 14,000 ft (4,270 m) producing either natural gas or oil, or both]

State	Region	Number of fields	Number of 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	West Coast and Alaska	2	2
Alaska	West Coast and 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. Deep significant fields in the United States by discovery year.

[Data from NRG Associates (1990) for all reservoirs below 14,000 ft (4,270 m) producing either natural gas or oil, or both. For fields containing multiple reservoirs, first discovered reservoir indicates age of field discovery. Data are combined for 1923–1950]

Year	Anadarko Basin	Rocky Mountains	Permian Basin	Gulf Coast Basin	California-Alaska basins	Williston Basin
1923–1950		2	3	1	5	
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 (*n*=329)	76	19	68	158	3	5

Coast Basin, 72 new deep significant fields were discovered (table 4). The numbers of fields given in table 4 should be considered minimum values because for older fields 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. Gas and 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

Table 5. Field completion classification for deep significant fields in the United States by region.
[Data from NRG Associates (1990) for all reservoirs below 14,000 ft (4,270 m) producing either natural gas or 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 in the United States by State and (or) basin.
[Data from NRG Associates (1990) for all reservoirs below 14,000 ft (4,270 m) producing either natural gas or oil, or both. Texas and Louisiana include offshore reservoirs]

Region	Structural traps	Stratigraphic traps	Combination traps	Unknown traps	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 in the United States by region.
[Data from NRG Associates (1990) for all reservoirs below 14,000 ft (4,270 m) producing either natural gas or oil, or both. Production totals are by field only; cumulative production of natural gas is in billions of cubic feet (BCF). Reservoir names are directly from NRG Associates Inc. (1988)]

Basin	Field/reservoir	Average depth (feet) to production	Discovery year	Cumulative production of natural gas (BCF)
Anadarko Basin	New Liberty SW/Hunton	23,920	1979	Not reported
Rocky Mountain basins	Bull Frog/Frontier	18,792	1979	3.7
Gulf Coast offshore	Eugene Island/Pliocene	18,895	1977	3.3
Permian Basin	Cheyenne/Ellenburger	21,699	1960	51.6(field)
Gulf Coast Basin	Harrisville/Smackover	23,007	1984	4.5
California basins	Fillmore/Pico	14,250	1954	Oil only
Alaska basins	Beaver Creek/Tyonek	14,800	1967	63.0

outnumber structural traps only in the Anadarko Basin and in California; data for the Anadarko Basin are incomplete because of the large number of unknown completion categories. In California, there are only two deep significant reservoirs.

According to NRG Associates (1990), the Harrisville Field in Smith County, Mississippi, contains the deepest significant reservoir in the United States (table 7). In the Harrisville field, the Smackover Formation produces gas from carbonate rocks at an average depth of 23,007 ft

Table 8. Total cumulative production, proven reserves, and known recoverable natural gas for deep significant reservoirs in all basins and areas in United States.

[Data from NRG Associates (1990) for all reservoirs below 14,000 ft (4,270 m) producing natural gas. Data represent maximum values for Oklahoma because production totals only are available for fields, and for some fields no data are available. Data vary in significant figures; rounding taken from NRG data file]

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

(7,013 m). The 618-foot (188 m)-thick pay zone in the Smackover has produced more than 4.5 BCFG (table 7) and has a known recoverable resource of 37.5 BCFG .

Sixty percent of the deep significant reservoirs (227 of 377 reservoirs, tables 11, 15, 19, 25, 29, 30, 31) produce from 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 (tables 12, 16, 18, 24), but more than one-quarter (26 percent) of the total significant deep reservoirs are below 17,000 ft (5,180 m).

The 377 deep significant reservoirs have a known recoverable resource of 33.6 TCFG. They have produced more than 22.4 TCFG, more than half of which (12.4 TCFG) is from the Permian Basin (fig. 2, table 8). Although the Gulf Coast Basin has only produced 6.2 TCFG from deep significant reservoirs, an additional 6.6 TCFG is present as proven reserves. Only 2.7 TCFG is listed as proven reserves in the Permian Basin (table 8).

ROCKY MOUNTAIN BASINS

The Rocky Mountain basins are grouped on the basis of geography and origin. These basins have produced 0.4 TCFG from Jurassic and Cretaceous clastic reservoirs and Paleozoic mixed clastic-carbonate reservoirs. They have a known recoverable resource of 2.2 TCFG (tables 1, 8, 13, fig. 3) (Dyman and others, 1992).

Of the 22 significant reservoirs in the Rocky Mountain region, 19 are in Wyoming. Seven are in the Wyoming-Utah-Idaho thrust belt, two each in the Wind River Basin, Moxa arch, and Sand Wash Basin, four in the Powder River Basin, and five in the Washakie Basin (tables 9, 10). Of these 22 reservoirs, only five are below 17,000 ft (5,182 m). Deep production in the Rocky Mountain region is dominantly natural gas, gas condensate, and high-gravity oil in the Wyoming-Utah-Idaho thrust belt (tables 9, 10). Significant reservoirs in the thrust belt produce primarily from Cretaceous (Frontier Formation) and Jurassic (Nugget Sandstone) clastic sequences and from Permian-Pennsylvanian mixed

Table 9. Structurally trapped deep significant reservoirs in the Rocky Mountain region.

[Data from NRG Associates (1990) for all reservoirs below 14,000 ft (4,270 m) producing either natural gas or oil, or both. Nine reservoirs that have combination traps are not listed. No stratigraphically trapped reservoirs are listed in the NRG data file]

Reservoir name	Classification	Basin or area
Johnson County, Wyoming		
Reno	Oil	Powder River Basin.
Reno East	Oil	Powder River Basin.
Natrona County, Wyoming		
Poison Spider West	Oil	Wind River Basin.
Uinta County, Wyoming		
Butcher Knife Springs	Gas	Thrust belt.
Whitney Canyon	Gas	Thrust belt.
Anschutz Ranch East	Gas and oil	Thrust belt.
Session Mountain	Gas	Thrust belt.
Chicken Creek	Gas and oil	Thrust belt.

Table 10. Geographic distribution, reservoir classification, and API gravity for deep significant reservoirs in the Rocky Mountain region.

[Data from NRG Associates (1990) for all reservoirs below 14,000 ft (4,270 m) producing either natural gas or oil, or both. Leaders (--) indicate no data are available]

Basin or area	Number of reservoirs	Completion classification	Average API gravity
Powder River Basin	4	Oil	35
Moxa arch	2	Oil and gas	40
Wind River Basin	2	Oil and gas	46
Sand Wash Basin	2	Gas	--
Wyoming-Utah-Idaho thrust belt	7	Oil and gas	51
Washakie Basin	5	Gas	--

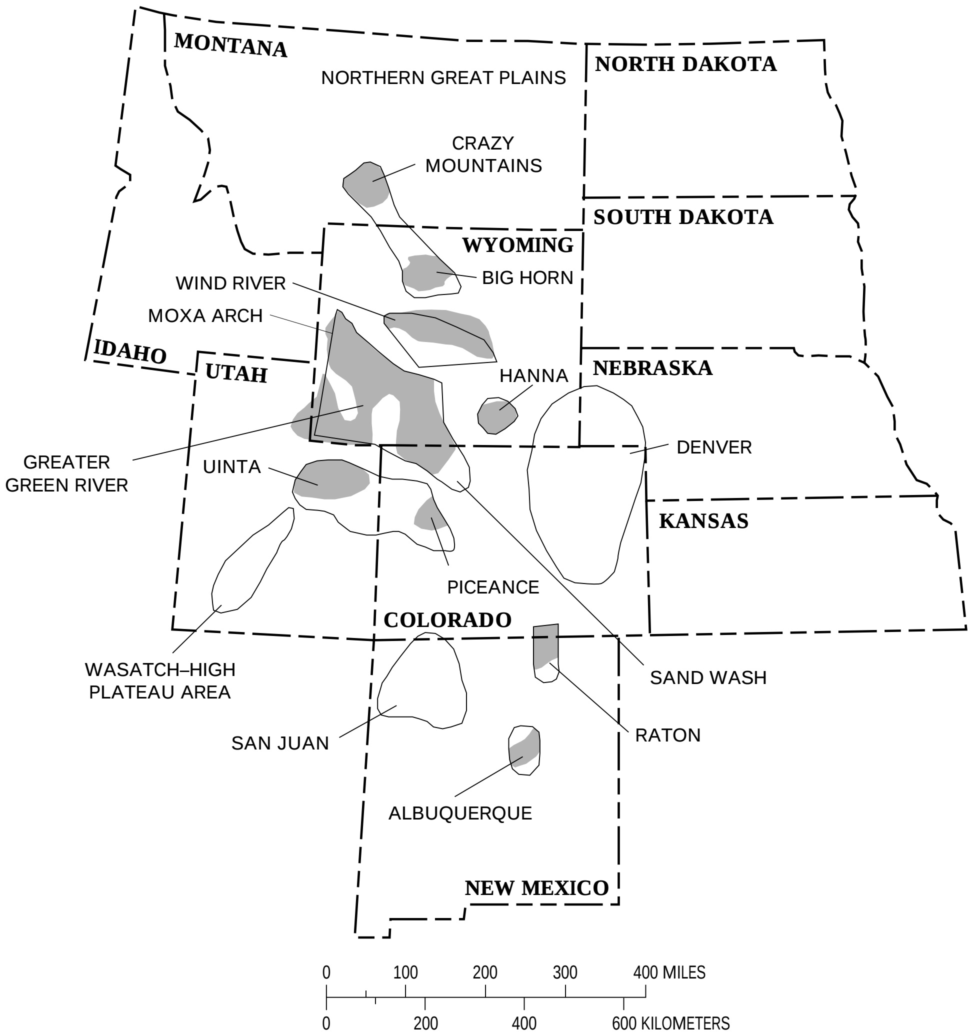

Figure 3. Map of Rocky Mountain region showing basins (outlined areas) in which deep (greater than 15,000 ft, 4,572 m) natural gas is presumed to be present on the basis of gas shows, formation tests, geology, and known production (shaded areas). Deep gas is being produced in the Wind River Basin and from a few structural traps in the Greater Green River Basin and the thrust belt in southwestern Wyoming and northern Utah.

clastic-carbonate sequences (Weber Sandstone and Minnelusa Formation) in primarily structural traps (table 11). Source rocks for deep reservoirs are primarily organic-rich Cretaceous shale in fault contact with older reservoir rocks.

Variations in thermal history and in the Late Cretaceous through Tertiary deformational sequence of Rocky Mountain basins control the distribution of and tendency toward natural gas or oil (Perry and Flores, this volume). Significant deep oil production occurs in conventional reservoirs in Rocky Mountain basins (tables 9, 10). Reservoir rocks are primarily Cretaceous sandstones and Permian-Pennsylvanian sandstones and carbonate rocks. Reservoirs are in deep 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 (table 9) has below normal temperatures, possibly as a result of meteoric waters recharged from outcrops along the western margin of the basin.

Deep significant Mississippian production in the Rocky Mountain region is from limestone and dolomite of the Madison Group (or Limestone) (table 11). These reservoirs have a high productive capacity (> 20 MMCFG per day per well) and commonly contain significant amounts of nonhydrocarbon gases such as hydrogen sulfide and carbon dioxide. Reservoirs are primarily in large structures.

Methane content ranges from 22.0 to 94.7 percent. The lowest value (22.0 percent) is at the LaBarge deep Madison Limestone reservoir in Lincoln County, Wyoming (NRG Associates, 1990). All Rocky Mountain reservoirs have helium values of less than 0.5 percent. Generally, the highest hydrogen sulfide values are in fields having high carbon dioxide content. The highest carbon dioxide values are in limestone reservoirs.

Only limited porosity-depth data are available from the NRG data file for the Rocky Mountain region (fig. 4). Of the few deep significant reservoirs represented, clastic reservoirs generally exhibit the highest porosities.

Most deep significant reservoirs in the Rocky Mountain region are associated with structural or combination structural (table 9) and stratigraphic trapping mechanisms. Structural traps in Rocky Mountain basins are directly related to the tectonic evolution of the Rocky Mountain fore-

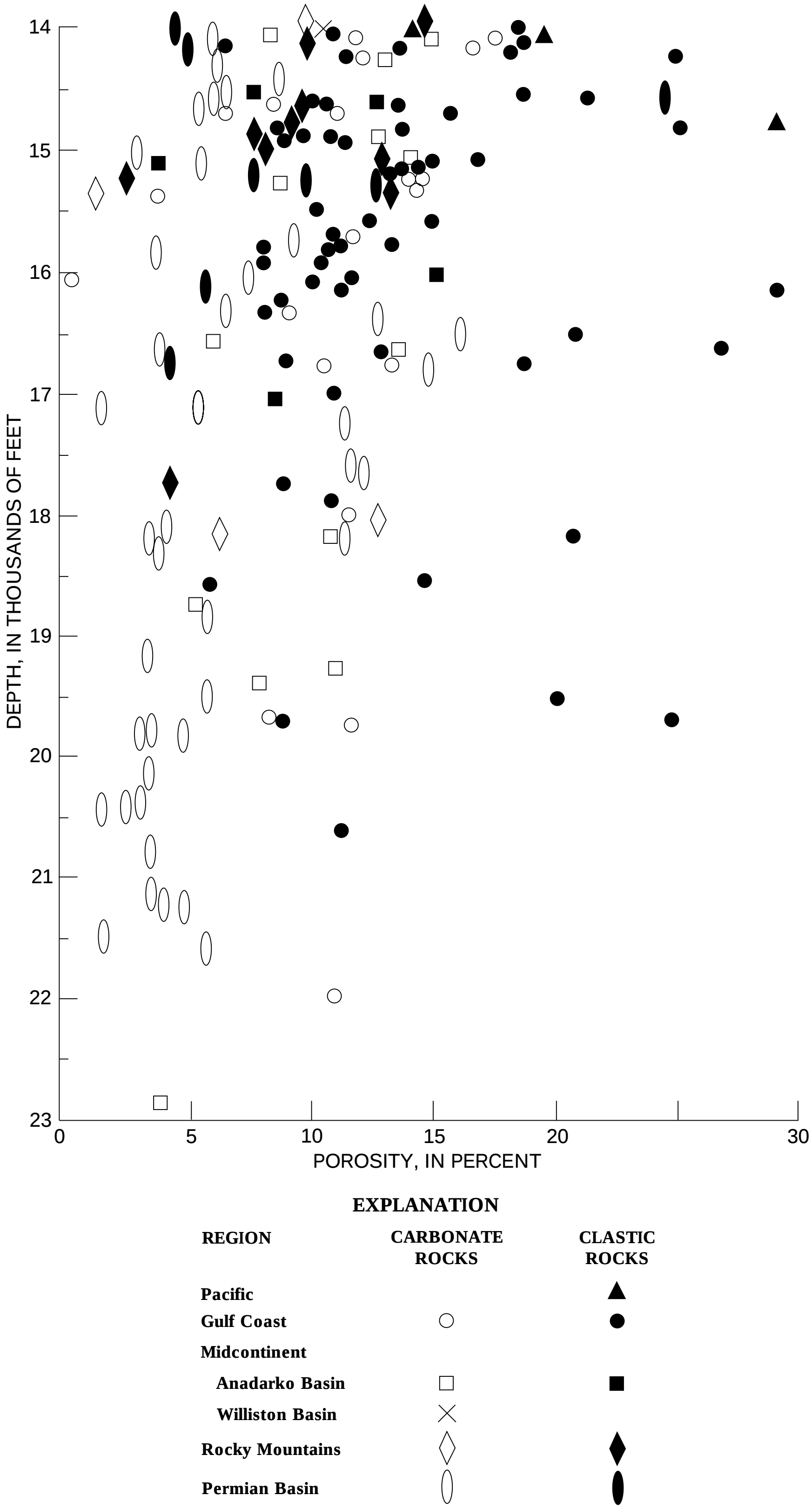

Figure 4. Porosity versus depth for deep significant reservoirs of the United States. Pacific region includes California and Alaska. Data points represent actual porosity values. Data from NRG Associates (1990).

land province. According to Perry and Flores (this volume), initial progression of uplift and basin development from southwest Montana southeastward during the mid-Cretaceous established timing limits on petroleum migration and trapping trends. Economic 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

Table 11. Producing formation, number of reservoirs, geologic age, and lithology of deep significant reservoirs in the Rocky Mountain region.

[Data from NRG Associates (1990) for all reservoirs below 14,000 ft (4,270 m) producing either natural gas or oil, or both. Names of producing formations are from NRG Associates data file]

Producing formation	Geologic age	Lithology	No. of reservoirs
Minnelusa	Penn.-Permian	Mixed carbonate and clastic	4
Madison	Mississippi	Carbonate	2
Nugget	Jurassic	Clastic	6
Bighorn	Ordovician	Carbonate	3
Dakota	Cretaceous.	Clastic	3
Weber	Penn-Permian	Clastic	1
Frontier	Cretaceous	Clastic	2
Morgan	Pennsylvanian	Carbonate	1
Total			22

Table 12. Deep significant reservoirs in the Rocky Mountain region by depth.

[Data from NRG Associates (1990) for all reservoirs below 14,000 ft (4,270 m) producing either natural gas or oil, or both]

Depth interval (feet)	Number of reservoirs
14,000–15,000	9
15,000–16,000	8
16,000–17,000	0
17,000–18,000	2
18,000–19,000	3
Total	22

Table 13. Total cumulative production, proven reserves, and known recoverable gas and oil for deep significant reservoirs in the Rocky Mountain region.

[Data from NRG Associates (1990) for all reservoirs below 14,000 ft (4,270 m) producing either natural gas or oil, or both. Oil in is thousands of barrels; gas is in MMCF. Leaders (--) indicate no data available. Data represent minimum values, and for some fields there are no data]

	Total	Major reservoir lithology Clastic	Carbonate
Oil			
Known recoverable	45,100	45,100	--
Proven reserves	14,400	14,400	--
Cumulative production	30,400	30,400	--
Gas			
Known recoverable	2,192,600	836,000	1,356,600
Proven reserves	1,782,900	595,200	1,187,700
Cumulative production	436,400	300,600	135,800

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 that formed during Laramide deformation.

ANADARKO BASIN

The Anadarko Basin contains 22 percent of the deep significant reservoirs (84 of 377) in the United States; it has produced 2.4 TCFG and has a known recoverable resource of 2.8 TCFG (figs. 1, 2; table 2) (NRG Associates, 1990). The Anadarko Basin accounts for all of the deep significant natural gas (and oil) production in the Midcontinent region. Other Midcontinent petroleum-producing basins such as the Arkoma Basin contain deep reservoirs, but significant production as defined in the NRG file (known recoverable resource of at least 1 MMBO or 6 BCFG) was lacking as of the end of 1988 (NRG Associates, 1990). The deep Anadarko Basin contains significant reserves of natural gas (tables 8, 17). Of 84 deep significant reservoirs, 11 are structurally trapped, 14 are stratigraphically trapped, and 16 are a combination of the two types (data are not available for 43 reservoirs). The largest reservoirs are in structural and combination traps along the southern margin of the basin in Oklahoma and the Texas Panhandle (tables 14, 16). Structural traps in the Anadarko Basin generally are thrust-bounded anticlinal closures in a transpressional setting. Anticlines generally trend northwest or west 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 15). Dominant reservoir lithologies include Pennsylvanian and Mississippian sandstone such as the Morrow, Atoka, and Springer Formations. Subordinate production is from Cambrian through Silurian carbonate rocks.

Lower than normal thermal gradients may be present locally along the thrust-faulted margins of the Anadarko Basin. In these areas, oil may be present at deeper than normal conditions due to inferred downward flow of meteoric water along faults and fracture systems associated with the deep basin margin. The Mills Ranch field, along the Texas-Oklahoma State line in Wheeler County, Texas, possibly illustrates these thermal conditions. An analog in the Rocky Mountain region is Bridger Lake field, just north of the Uinta Mountains in Utah.

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. It seemingly could not be due to undercompaction as a result of burial. Burial depths in the basin were near maximum at the end of the Permian. Thermogenic reactions involving hydrocarbon generation are the most likely cause of overpressuring today.

The 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 that

Table 14. Deep significant reservoirs in the Anadarko Basin by location and depth.
[Data from NRG Associates (1990) for all reservoirs below 14,000 ft (4,270 m) producing either natural gas or oil, or both]

Location	Depth (in intervals of 1,000 ft)									
	14	15	16	17	18	19	20	21	22	23
Texas										
Cooke County	1									
Hemphill County	2	2	1	1		2	1			
Wheeler County	4	2	2		2		1		1	
Oklahoma										
Ellis County	1									
Carter County			1							
Comanche County					1	1				
Grady County	1	3	3							
Beckham County	1	2	3	3	2			1	1	1
Caddo County	1	2	1	4	1		1			
Custer County	5	4	1							
Washita County	1	1	2							
Roger Mills County	3	3	2	2					1	
Dewey County		1	1							

Table 15. Deep significant reservoirs in the Anadarko Basin by producing stratigraphic unit, geologic age, and lithology.
[Data from NRG Associates (1990) for all reservoirs below 14,000 ft (4,270 m) producing either natural gas or oil, or both. Stratigraphic names are from the NRG data file and may not represent formal stratigraphic units. Leaders (--) indicate data are not available]

Formation or unit	Geologic age	Lithology	No. of reservoirs
Morrow	Pennsylvanian	Clastic	29
Cottingham	Pennsylvanian	Clastic	2
Atoka	Pennsylvanian	Clastic	8
Red Fork	Pennsylvanian	Clastic	1
Boatwright	Pennsylvanian	--	1
Puryear	Pennsylvanian	--	1
Morrow-Springer	Miss-Pennsylvanian	Clastic	1
Goddard	Mississippian	Clastic	2
Springer	Miss.-Pennsylvanian	Clastic	13
Meramec	Mississippian	Carbonate	1
Hunton	Silurian-Devonian	Carbonate	18
Henryhouse	Silurian	Carbonate	1
Oil Creek	Ordovician	Clastic	1
Simpson	Ordovician	Clastic	1
Bromide	Ordovician	Clastic	1
Ellenburger	Ordovician	Carbonate	1
Arbuckle	Cambrian-Ordovician	Carbonate	2
Total			84

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.

Two opposing views are presented about the quality of source rocks in the Arbuckle Group.

1. The 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 nonhydrocarbon 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. By comparison, the Hunton contains less anhydrite, thus allowing methane to be stable at depth.

2. The Arbuckle has undergone high thermal stress and for the most part has low total organic carbon values; however, higher total organic carbon values in the geologic past, combined with the oil-prone nature of the organic matter (type II–I), could have enabled at least parts of the Arbuckle to generate petroleum. Smackover carbonate rocks, which are also very mature to overmature in the deeper parts of the Gulf Coast Basin, also have generally low total organic carbon contents (average 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 studies of Trask and Patnode (1942), showed that, of 178 subsurface Arbuckle samples from 18 wells in the Anadarko Basin, approximately 46 percent had total organic carbon contents ranging from 0.4 to 1.4 percent. Carbonate rocks having such values are considered adequate source beds for petroleum.

Large volumes of gas in Pennsylvanian clastic reservoirs (table 17) were sourced by Upper Mississippian and Pennsylvanian shale. The high percentage of Pennsylvanian stratigraphic traps in clastic reservoirs (tables 15, 16) suggests generation and entrapment close to source.

Table 16. Deep significant reservoirs in the Anadarko Basin by depth and trap type.

[Data from NRG Associates (1990) for all reservoirs below 14,000 ft (4,267 m) producing either natural gas or oil, or both. Total does not include 43 reservoirs in the Anadarko Basin for which trap type is not identified in NRG data file]

	Trap type		
Depth interval (feet)	Stratigraphic	Structural	Combination
14,000–15,000	5	3	5
15,000–16,000	4	3	4
16,000–17,000	1	2	3
17,000–18,000	2		
18,000–19,000	1	3	1
19,000–20,000	1		2
20,000–21,000			
21,000–22,000			
22,000–23,000			1
23,000–24,000			
Total	14	11	16

Table 17. Total cumulative production, proven reserves, and known recoverable gas and oil for deep significant reservoirs in the Anadarko Basin.

[Data from NRG Associates (1990) for all reservoirs below 14,000 ft (4,270 m) producing either natural gas or oil, or both. Data represent approximate values because production totals are available only for fields in the State of Oklahoma. Oil is in thousands of barrels; gas is in millions of cubic feet]

	Major reservoir lithology		
	Total	Clastic	Carbonate
Gas			
Known recoverable	2,774,750	1,176,050	1,598,600
Proven reserves	416,490	274,433	142,057
Cumulative production	2,358,260	901,617	1,456,643
Oil			
Known recoverable	2,385	165	2,420
Proven reserves	253	61	192
Cumulative production	2,132	104	2,028

Methane values in the Anadarko Basin are high, ranging from 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. 4). The highest porosity values generally are in clastic reservoirs. All significant reservoirs below 18,000 ft (5,486 m) are fractured carbonate reservoirs and have porosities of less than about 12 percent.

The Anadarko Basin is unlike other deep basins in that the hydrocarbons in the basin 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 oil window has migrated upward through time (Schmoker, 1986). Oil may have been generated in the deepest parts of the southern Oklahoma aulacogen during the Pennsylvanian and Permian when large volumes of sediment entered the zone of oil generation. Known discoveries of natural gas may have been generated, however, during the last 60 m.y.

PERMIAN BASIN

The Permian Basin contains 24 percent of the deep reservoirs (89 of 377) in the United States and has produced 12.4 TCFG (fig. 2, tables 1, 22). Forty-five percent of the known recoverable natural gas resource (15.1 TCFG, tables 8, 22) in the United States is in the Permian Basin.

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. Some deep gas was generated directly from mature source rocks, and additional gas has been generated by the conversion of oil to gas. Most oil fields in equivalent rocks are on the periphery of the greater Permian Basin, on the northern and eastern margins, supporting this theory of a thermal conversion process.

Table 18. Deep significant reservoirs in the Permian Basin by depth and county.

[Data from NRG Associates (1990) for all reservoirs below 14,000 ft (4,270 m) producing either natural gas or oil, or both]

	Depth (in intervals of 1,000 ft)							
Location	14	15	16	17	18	19	20	21
New Mexico								
Eddy County	3							
Lea County	8	1						
Texas								
Culberson County		1						
Loving County	1	4	2		1		1	2
Pecos County	2	5		1	2	1	2	3
Reeves County	1	1	6	1	2	1	2	
Terrel County	1							
Ward County	2	2	3	6	3	4		
Winkler County	3	1	1	2	2	2	1	2
Total (*n*=89)	21	15	12	10	10	8	6	7

Table 19. Deep significant reservoirs in the Permian Basin by stratigraphic unit, geologic age, and lithology.
[Data from NRG Associates (1990) for all reservoirs below 14,000 ft (4,270 m) producing either natural gas or oil, or both. Leaders (--) indicate no data are available. Information in column labeled stratigraphic unit is from NRG Associates data file; in some cases, formation name is not available, and only epoch is given]

Stratigraphic unit or geologic age	Geologic age	Lithology	No. of reservoirs
Wolfcampian	Permian	--	2
--	Pennsylvanian	--	1
Strawn	Pennsylvanian	Carbonate	3
Atoka	Pennsylvanian	Clastic and carbonate	5
Morrow	Pennsylvanian	Clastic	10
--	Mississippian	Carbonate	1
Lower Devonian	Devonian	Chert	5
--	Silurian-Devonian	Carbonate	3
--	Silurian	Carbonate	4
Fusselman	Silurian	Carbonate	22
Ellenburger	Ordovician	Carbonate	33
Total			89

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 chances of finding new, good-quality, deep gas reservoirs decreases with depth; however, increased pressure as a result of increased depth results in an increase in the amount of gas stored within a given volume of reservoir rock.

Lithologically, relatively shallow reservoirs in the Delaware Basin (14,000–17,000 ft, 4,267–5,181 m) are mixed-carbonate and clastic reservoirs (mostly carbonate) including some Pennsylvanian and Permian rocks (tables 18–20). The reservoirs are in Lea and Eddie Counties, New Mexico, and Loving County, Texas, on the margin of the deep basin. The deepest reservoirs are carbonate rocks of early Paleozoic age in the central part of the Delaware Basin (tables 19, 20). Thirty-three deep reservoirs are in the Ordovician Ellenburger Group alone. Seventy-five percent of Permian Basin reservoirs are in Devonian or older rocks.

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). Hydrocarbons of the Ellenburger are predominantly derived from younger rocks, including the Woodford Shale, where these rocks have been downfaulted during compression or extension. Gas was probably placed in Ellenburger reservoirs after structures were established during Pennsylvanian and Permian time. These late Paleozoic collisional structures formed prior to peak gas generation.

All of the stratigraphically trapped deep reservoirs (6) are at shallower depths (14,000–17,000 ft, 4,267–5,181 m, table 21) in the youngest reservoir strata of Permian age. The post-Wolfcampian Permian Basin is a sedimentary rather than a structural basin, and traps are facies controlled in these younger rocks.

The total gas column in Ellenburger reservoirs is very thick, more than 3,500 ft (1,066 m) in the Gomez field (Pecos County, southwestern Texas). Vertical, interconnected fractures are present in some areas. These fracture systems are associated with huge transpressional structures along the eastern margin of the Delaware Basin (Perry, this volume).

Reservoir porosity systematically decreases with depth in the Permian Basin (fig. 4). Generally, significant reservoirs below 16,000 ft (4,876 m) are carbonate reservoirs. Matrix porosity is more than 5 percent at depths greater than 19,000 ft (5,791 m) (fig. 4) in the deep Permian Basin. At shallower depths (less than 16,000 ft), clastic reservoirs have higher porosities than carbonate reservoirs.

Fractures are common and result in greatly enhanced permeability and increased deliverability. Porosities can be poor at any depth, but the best porosities decrease with depth at a predictable rate. Limestone reservoirs tend to produce economic volumes of hydrocarbons at lower porosities than do dolomite reservoirs. The highest porosities at these depths are in dolomite reservoirs, although NRG data are limited.

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

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. Pressure gradients are normal in deep reservoirs in large fields in the Permian Basin. No evidence exists for overpressurized compartments in the significant fields of the NRG data file (Spencer and Wandrey, this volume).

Table 20. Deep significant reservoirs in the Permian Basin by location, reservoir lithology, and depth.
[Data from NRG Associates (1990) for all reservoirs below 14,000 ft (4,270 m) producing either natural gas or oil, or both. Lithology: c, carbonate; cl, clastic; ch, chert; b, unknown. Leader (--) indicates no data are available]

	Depth (in intervals of 1,000 ft)																															
	14				15				16				17				18				19				20				21			
Location	c	cl	ch	b	c	cl	ch	b	c	cl	ch	b	c	cl	ch	b	c	cl	ch	b	c	cl	ch	b	c	cl	ch	b	c	cl	ch	b
New Mexico																																
Eddy County	3	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Lea County	4	3	1	--	1	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Texas																																
Culberson County	--	--	--	--	1	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Loving County	1	--	--	--	1	1	--	2	--	--	--	2	--	--	--	--	1	--	--	--	--	--	--	--	1	--	--	--	2	--	--	--
Pecos County	--	--	2	--3	1	--	1	--	--	--	--	--	--	1	--	2	--	--	--	1	--	--	--	2	--	--	--	3	--	--	--	
Reeves County	1	--	--	--	1	--	--	--	4	2	--	--	1	--	--	--	2	--	--	--	1	--	--	--	2	--	--	--	--	--	--	--
Terrell County	1	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Ward County	2	--	--	--	2	--	--	--	3	--	--	--	6	--	--	--	3	--	--	--	4	--	--	--	--	--	--	--	--	--	--	--
Winkler County	1	1	--	1	1	--	--	--	1	--	--	--	2	--	--	--	2	--	--	--	2	--	--	--	1	--	--	--	2	--	--	--
Total (*n*=89)			21				15				12				10				10				8				6				7	

Table 21. Deep significant reservoirs in the Permian Basin by trap type and depth.
[Data from NRG Associates (1990) for all reservoirs below 14,000 ft (4,270 m) producing either natural gas or oil, or both. For reservoirs listed in column labeled "Blank," no trap type was identified in NRG file]

Depth	Trap type			
interval (feet)	Stratigraphic	Structural	Combination	Blank
14,000–15,000	4	6	8	3
15,000–16,000	1	6	4	4
16,000–17,000	1	7	3	1
17,000–18,000	0	5	5	
18,000–19,000	0	6	2	2
19,000–20,000	0	2	4	2
20,000–21,000	0	4	1	1
21,000–22,000	0	3	3	1
Total (*n*=89)	6	39	30	14

GULF COAST BASIN

Of the 377 reservoirs below 14,000 ft (4,267 m), 174 (or 46 percent) are in the Gulf Coast Basin (fig. 1). Significant reservoirs in the Gulf Coast Basin have produced 6.2 TCFG (fig. 2, tables 8, 28). Reservoirs are primarily in Tertiary clastic rocks and deeper mixed carbonate-clastic rocks of Mesozoic age. Forty percent of the known recoverable natural gas resource (13.3 TCFG, tables 1, 8, 28) in deep significant reservoirs is 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 ft (4,267 m) in Tertiary sandstone. Generally, the oldest fields are in Louisiana and Mississippi. Fields in Texas were discovered from the 1940's through the 1980's. Fields in Alabama were discovered in the 1960's, and fields in Florida were discovered in the early 1970's. More fields containing deep reservoirs were discovered during the 1970's (72) than during any other decade. The number of deep field discoveries approximately doubled with each succeeding decade (1940's, 5 discoveries; 1950's, 13; 1960's, 32; 1970's, 72; 1980's, data incomplete) (table 4).

Sixty-five percent of the deep significant reservoirs (116) are classified as gas producing (tables 23, 24), and more than 40 percent (49) of these gas producers are in Louisiana. Of all of the Gulf Coast States, Louisiana, Texas, and Mississippi have more natural gas reservoirs than oil reservoirs (tables 23, 24). Of the 16 deep significant offshore reservoirs, 15 are gas producers (table 23). Of the 110 deep significant Mesozoic reservoirs onshore, 64 are natural gas producers and an additional 9 are classified as oil and gas producing.

Table 22. Total cumulative production, proven reserves, and known recoverable gas and oil for deep significant reservoirs in the Permian Basin.

[Data from NRG Associates (1990) for all reservoirs below 14,000 ft (4,270 m) producing either natural gas or oil, or both. Data represent minimum values. Oil is in thousands of barrels; gas is in millions of cubic feet. Leaders (--) indicate no production in category]

	Major reservoir lithology				
	Total	Clastic	Carbonate	Chert	Blank
Oil					
Known recoverable	8,075	--	8,075	--	--
Proven reserves	939	--	939	--	--
Cumulative production	7,136	--	7,136	--	--
Gas					
Known recoverable	15,127,180	566,030	13,766,982	709,530	84,638
Proven reserves	2,713,874	157,053	2,481,937	49,970	24,914
Cumulative production	12,413,306	408,977	11,285,045	659,560	59,724

Table 23. Deep significant reservoirs in the Gulf Coast Basin by State.

[Data from NRG Associates (1988) for all reservoirs below 14,000 ft (4,267 m) producing either natural gas or oil, or both. Data for Texas and Louisiana include 16 offshore reservoirs. Leaders (--) indicate no reservoirs in category]

State	Oil	Gas	Oil and gas
Louisiana	5	49	11
Texas	--	22	1
Mississippi	21	40	3
Alabama	11	5	3
Florida	3	--	--
Total (*n*=174)	40	116	18

For all States combined, the number of significant deep reservoirs decreases with increasing depth (table 25). The deepest reservoirs are in Alabama and Mississippi (Mancini and Mink, 1985; NRG Associates, 1990; Curtis, 1991). The Jurassic Smackover gas reservoir in the Harrisville field in Simpson County, south of Jackson in southern Mississippi, is the deepest significant reservoir in the Gulf Coast Basin. The reservoir has an average producing depth of 23,007 ft (7,012 m) and an average reservoir thickness of 618 ft (188 m). Only two other reservoirs listed in the NRG data file for the Gulf Coast Basin have greater average thicknesses. 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 ft (5,759 m). Most offshore reservoirs produce from depths of less than 16,000 ft (4,877 m).

For all depths together, 79 percent of the reservoirs in the Gulf Coast Basin are clastic (table 26). By depth interval, (1) only 16 percent of the total reservoirs are carbonate reservoirs in the 14,000–15,000-foot (4,267–4,572 m) depth interval, and (2) 29 percent of the total reservoirs are carbonate reservoirs in the 16,000–17,000-foot (4,877–5,182 m) depth interval. Few carbonate reservoirs are in the 14,000–15,000-foot 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, whereas in Louisiana almost all deep significant Mesozoic reservoirs are clastic rocks. Reservoirs in Alabama and Mississippi are more intermediate facies rocks, and all offshore Texas and Louisiana reservoirs are classified as sandstone.

Table 24. Deep significant reservoirs in the Gulf Coast Basin by depth and State.

[Data from NRG Associates (1990) for all reservoirs below 14,000 ft (4,267 m) producing either natural gas or oil, or both. LA, Louisiana; TX, Texas; MS, Mississippi; AL, Alabama; FL, Florida]

Depth	Oil					Gas					Oil and gas				
interval (feet)	LA	TX	MS	AL	FL	LA	TX	MS	AL	FL	LA	TX	MS	AL	FL
14,000–15,000	1		12	2		19	12	14			2	1	1		
15,000–16,000			3	4	3	13	5	13	1		4	2	2		
16,000–17,000	2		3	2		7	4	6	1		4			1	
17,000–18,000	1		1			4	1	2			1				
18,000–19,000	1		1	3		3		1							
19,000–20,000		1				3		2							
20,000–21,000									2						
21,000–22,000									1						
22,000–23,000								1							
23,000–24,000								1							
Total (*n* =174)	5		21	11	3	49	22	40	5		11	3	3	1	

Table 25. Deep significant reservoirs in the Gulf Coast Basin by primary reservoir lithology and depth, for each State.

[Data from NRG Associates (1990) for all reservoirs below 14,000 ft (4,267 m) producing either natural gas or oil, or both. Reservoir lithology: C, carbonate reservoirs; Cl, clastic reservoirs]

Depth	Louisiana		Texas		Mississippi		Alabama		Florida	
interval (feet)	C	Cl	C	Cl	C	Cl	C	Cl	C	Cl
14,000–15,000		22	3	10	6	20	1	1		
15,000–16,000		17	2	3	2	16	5	2	2	1
16,000–17,000	1	12	3	1	1	8	4			
17,000–18,000		6		1	1	3				
18,000–19,000		4				2	3			
19,000–20,000		3			2	1				
20,000–21,000								2		
21,000–22,000								1		
22,000–23,000					1					
23,000–24,000					1					
Total (*n*=174)	1	64	8	15	14	50	13	6	2	1

Table 26. Deep significant reservoirs in the Gulf Coast Basin by producing stratigraphic unit, geologic age of producing unit, and lithology of producing unit.

[Lithology may vary locally due to facies and depositional variations. Stratigraphic names are taken directly from the NRG Associates (1990) data file; names may be formal or informal stratigraphic units or may be biostratigraphic names applied to intervals; biostratigraphic units are given in italics. Lithology of producing stratigraphic unit: c, carbonate; c-cl, mixed carbonate and clastic; cl, clastic]

		Depth (in intervals of 1,000 ft)										
Stratigraphic unit	Lithology	14	15	16	17	18	19	20	21	22	23	24
Tertiary												
Robulus	cl	2										
Fri	cl	7										
Miocene	cl	15	10	6	3							
Anahuac	cl		3	1								
Bolivina mex.	cl	1										
Discorbis B	cl	1										
Wilcox	cl	2	2		1							
Textularia	cl	2										
Yegua	cl	1										
Planulina	cl		1									
Camerina	cl		1									
Woodburn	cl		1									
Pliocene	cl			1	1	1						
Pleistocene	cl	1										
Bigerina hum.	cl			1								
Cretaceous												
Austin	c	1										
Tuscaloosa	cl	1	2	3	2	3	3					
Edwards	c	1		1								
Hosston	cl	3	12	5								
Sligo	c-cl	4	5	1								
James	c	1										
Mooringsport	cl	1										
Paluxy	cl	1										
Red	cl	3										
Jurassic												
Buckner	c	1										
Black River	cl					1						
Cotton Valley	cl	8	1	3	1		1					
Norphlet	cl	3	3		2			2	1			
Smackover	c	5	9	6	1	4	2			1	1	
Total (*n*=174)		65	50	28	11	9	6	2	1	1	1	

Table 27. Deep significant reservoirs in the Gulf Coast Basin by trap type and depth, for each State.

[Data from NRG Associates (1990) for all reservoirs below 14,000 ft (4,267 m) producing either natural gas or oil, or both. Trap type: R, structural; S, stratigraphic; C, combination structural and stratigraphic; B, no trap type identified in NRG file]

Depth	Mississippi				Florida				Texas				Louisiana				Alabama			
interval (feet)	R	S	C	B	R	S	C	B	R	S	C	B	R	S	C	B	R	S	C	B
14,000–15,000	21	1	3	1					4	4	3	4	18			2	1		1	
15,000–16,000	13		4	1	2		1		2	3		1	9		1	7	2		2	3
16,000–17,000	6		3						1		1	1	7		1	5	3			1
17,000–18,000	3		1						1				4			2				
18,000–19,000	2												2		1	1			2	1
19,000–20,000	2	1											1		1	1				
20,000–21,000																	2			
21,000–22,000																	1			
22,000–23,000	1																			
23,000–24,000	1																			
24,000–25,000																				
Total (*n*=174)	49	2	11	2	2		1		8	7	4	6	41		4	18	9		5	5

The distribution of reservoirs by geologic age is approximately equal in that 65 Tertiary, 53 Cretaceous, and 56 Jurassic reservoirs are present (table 26). The largest number of deep significant reservoirs is in Tertiary Miocene rocks (34), the Jurassic Smackover Formation (29), and the Cretaceous Hosston Formation (20). All Tertiary reservoirs are in clastic rocks, whereas 54 percent of Jurassic reservoirs (30 reservoirs of 56 total) are in carbonate rocks (primarily Smackover Formation). Although not identified in this table, approximately 50 percent of the carbonate reservoirs are defined as dolomite (NRG Associates, 1990). Jurassic reservoirs are generally deeper than Cretaceous and Tertiary reservoirs. All offshore Texas and Louisiana reservoir rocks are Tertiary in age.

Reservoirs in the Mesozoic Gulf Coast Basin are primarily structurally trapped (table 27). Only nine reservoirs are stratigraphically trapped, and five of these are in Upper Cretaceous or Tertiary rocks. Stratigraphically trapped reservoirs and reservoirs classified as having combination traps are relatively shallow (less than 20,000 ft, 6,096 m). 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 to 94 percent for Mesozoic gas reservoirs. The lowest value (35 percent) is at Flomation 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) for other reservoirs. The highest hydrogen sulfide value (26 percent) for significant deep Gulf Coast Basin reservoirs is in Johns Field, Rankin County, near Jackson in south-central Mississippi, in the Smackover reservoir.

Average porosity decreases systematically with increasing depth for all significant deep reservoirs, although the range of porosity values at a particular depth varies significantly (fig. 4). The approximate rate of decrease in porosity with increasing depth changes at about 17,000 ft (5,182 m). For the most part, porosity values below 17,000 ft are higher than expected based on the distribution of points above 17,000 ft (reservoirs of the Norphlet and Tuscaloosa Formations included here). An explanation for this change in rate of porosity decrease is not known, but the data suggest that porosities high enough for commercial production of gas may be present at depths greater than expected (see Hester, this volume, and Schmoker, this volume). The ranges of clastic and carbonate porosities are not significantly different.

More than 6.2 TCFG have been produced from significant deep reservoirs in the Gulf Coast Basin (table 28). Of this, 2.6 TCFG have been produced from Tertiary reservoirs and 0.6 MMCFG from offshore Texas and

Table 28. Known recovery, proven reserves, and cumulative production for deep significant reservoirs and fields in the Gulf Coast Basin by major lithology.
[Data from NRG Associates (1990) for all reservoirs below 14,000 ft (4,267 m) producing either natural gas or oil, or both. Gas is in millions of cubic feet; oil is in millions of barrels]

	Major reservoir lithology			
	Total	Clastic	Carbonate	Mixed
Gas				
Known recoverable	13,262,291	11,110,291	1,679,000	473,000
Proven reserves	6,628,587	5,676,587	719,000	233,000
Cumulative production	6,192,094	4,993,094	960,000	239,000
Oil				
Known recoverable	881,805	330,805	551,000	--
Proven reserves	128,226	56,226	72,000	--
Cumulative production	590,579	111,579	479,000	--

Table 29. Deep significant reservoirs in the West Coast–Alaska region by geologic age and producing formation and trap type.
[Data from NRG Associates (1990) for all reservoirs below 14,000 ft (4,267 m) producing either natural gas or oil, or both]

Field	Geologic age and producing rock unit	Basin	Trap type
Rio Viejo	Miocene Stevens Sandstone	San Joaquin, California	Stratigraphic
Fillmore	Pliocene-Pleistocene Pico Sandstone	Ventura, California	Stratigraphic
Beaver Creek	Oligocene-Miocene Tyonek Sandstone	Cook Inlet, Alaska	Structural

Louisiana Tertiary reservoirs. Clastic reservoirs have produced approximately five times as much gas as carbonate reservoirs.

OTHER REGIONS

The preceding four regions account for 369 of the 377 deep significant reservoirs in the NRG data file. Only two deep significant reservoirs are in California, in the Ventura and San Joaquin basins in southern California (Rio Viejo field, Kern County, and Fillmore field, Ventura County, table 29). Both fields have multiple reservoirs and are classified as oil fields. The Beaver Creek field in the Cook Inlet area, Alaska, is classified as a gas field. The deep Rio Viejo reservoir is at 14,100 ft (4,297 m), the Fillmore reservoir is at 14,250 ft (4,343 m), and the Beaver Creek reservoir is at 14,800 ft (4,511 m). All three reservoirs produce from Tertiary sandstone (table 29). The California reservoirs have an average reservoir porosity of 31 percent, and the Alaska reservoir has an average porosity of 28 percent (fig. 4). The West Coast–Alaska region has a known recoverable resource of 0.26 TCFG (table 30).

Table 30. Known recovery, proven reserves, and cumulative production for deep significant reservoirs in the West Coast–Alaska region by major lithology.
[Data from NRG Associates (1990) for all reservoirs below 14,000 ft (4,270 m) producing either natural gas or oil, or both. Gas is in millions of cubic feet; oil is in millions of barrels]

	Major reservoir lithology		
	Total	Clastic	Carbonate
Gas			
Known recoverable	264,900	264,900	--
Proven reserves	179,912	179,912	--
Cumulative production	84,988	84,988	--
Oil			
Known recoverable	27,650	27,650	--
Proven reserves	5,067	5,067	--
Cumulative production	22,583	22,583	--

Only five deep significant fields, each containing a single deep reservoir, are in the Williston Basin, in McKenzie County of westernmost North Dakota, but none exceeds 14,200 ft (4,328 m) in depth (table 31). Croff and Bear Den fields are oil fields and North Fork, Cherry Creek, and Poe fields are oil and gas fields. All reservoirs are between 14,003 and 14,188 ft (4,268–4,325 m) depth and produce from dolomite of the Ordovician Red River Formation. The reservoirs are classified as having structural or combination structural and stratigraphic traps. Only one porosity value (11 percent, Cherry Creek field, Red River reservoir; fig. 4) is recorded in the NRG file for Williston Basin significant reservoirs. The Williston Basin province has a known recoverable resource of 38 BCFG (table 32).

Large volumes of deeply buried sedimentary rocks are in other basins in the United States where no significant gas production now exists. Recent work by Palacas (this volume) indicates that parts of the Midcontinent rift system may contain source rocks capable of generating natural gas below 15,000 ft (4,572 m). A minor amount of drilling has occurred in other deep Rocky Mountain basins (fig. 2) including the Raton, Albuquerque, and Crazy Mountains basins, and the recoverable natural gas resource is unknown. Analysis of drilling data by Wandrey and Vaughan (this volume) show that many deeper parts of productive basins

Table 31. Field and reservoir, average depth, reservoir lithology, trap type, and field classification of deep significant reservoirs in the Williston Basin.
[Data from NRG Associates (1988) for all reservoirs below 14,000 ft (4,267 m) producing either natural gas or oil, or both. Leaders (--) indicate data are not available]

Field	Reservoir	Average depth to production (feet)	Reservoir lithology	Trap type	Field type
Croff	Red River	14,116	Dolomite	Structural	Oil.
Bear Den	Red River	14,188	Dolomite	Structural	Oil.
North Fork	Red River	14,048	Dolomite	Combination	Oil-gas.
Cherry Creek	Red River	14,003	Dolomite	--	Oil-gas.
Poe	Red River	14,077	Dolomite	Combination	Oil-gas.

Table 32. Known recovery, proven reserves, and cumulative production for significant deep reservoirs in the Williston Basin by major lithology.
[Data from NRG Associates (1988) for all reservoirs below 14,000 ft 4,267 m). Gas is in millions of cubic feet; oil is in millions of barrels. Leaders (--) indicate production data are missing]

	Major reservoir lithology		
	Total	Clastic	Carbonate
Gas			
Known recoverable	38,142	--	38,142
Proven reserves	25,334	--	25,334
Cumulative production	12,808	--	12,808
Oil			
Known recoverable	1,945	--	1,945
Proven reserves	1,014	--	1,014
Cumulative production	931	--	931

have not been adequately drilled even where source- and reservoir-rock conditions are good. In the 1995 U.S. Geological Survey National Petroleum Assessment, 152 of approximately 600 petroleum plays assessed contained reservoir rocks at least in part buried below 15,000 ft (Dyman and others, 1996; Dyman, unpublished data). Studies of large computerized data files suggest that additional significant quantities of deep natural gas remain to be found in sedimentary basins of the United States.

REFERENCES CITED

Al-Shaieb, Z., Puckette, J., Ely, P., and Tigert, V., 1992, Pressure compartments and seals in the Anadarko Basin, *in* Johnson, K.S., and Cardott, B.J., eds., Source rocks in the southern Midcontinent: Oklahoma Geological Survey Circular 93, p. 210–228.

Curtis, D.M., 1991, The northern Gulf of Mexico Basin, *in* Gluskoter, H.J., Rice, D.D., and Taylor, R.B., eds., Economic geology, United States: Geological Society of America, The Geology of North America, v. P–2, p. 301–324.

Dwights Energy Data, 1985, Petroleum Data System (through 1985): Available from Dwights Energy Data Corp., Oklahoma City, Oklahoma 73108.

Dyman, T.S., Spencer, C.W., Baird, J., Obuch, R., and Nielsen, D., 1992, Geologic characteristics of deep natural gas resources based on data from significant fields and reservoirs, *in* Dyman, T.S., ed., Geologic controls and resource potential of natural gas in deep sedimentary basins in the United States: U.S. Geological Survey Open-File Report 92–524, 287 p.

Dyman, T.S., Wilson, M., and Beeman, W.R., 1996, Deep natural gas resources of the United States, *in* USGS assessment of potential additions to oil and gas reserves of the United States: U.S. Geological Survey Digital Data Series 30.

Law, B.E., and Clayton, J.L., 1987, The role of thermal history in the preservation of oil at the south end of the Moxa arch, Utah and Wyoming—Implications for the oil potential of the southern Green River Basin [abs.], *in* Carter, L.M.H., ed., U.S. Geological Survey research on energy resources—1988, Program and abstracts: U.S. Geological Survey Circular 1025, p. 27.

Mancini, E.A., and Mink, R.M., 1985, Petroleum production and hydrocarbon potential of Alabama's coastal plain and territorial waters, *in* Perkins, B.F., and Martin, G.B., eds., Habitat of oil and gas in the Gulf Coast: Society of Economic Paleontologists and Mineralogists Annual Research Conference, 4th, Proceedings, p. 25–42.

Mast, R.F., Dolton, G.L., Crovelli, R.A., Root, D.H., Attanasi, E.D., Martin, P.E., Cooke, L.W., Carpenter, G.B., Pecora, W.C., and Rose, M.B., 1989, Estimates of undiscovered conventional oil and gas resources in the United States—A part of the Nation's energy endowment: U.S. Geological Survey and Minerals Management Service, 44 p.

NRG Associates Inc., 1990, The significant oil and gas fields of the United States (through December 31, 1988): Available from NRG Associates, Inc., P.O. Box 1655, Colorado Springs, Colorado 80901.

Palacas, J.G., 1992, Can carbonate rocks be sources of commercial petroleum deposits? *in* Johnson, K.S., and Cardott, B.J., eds., Source rocks in the southern Midcontinent, 1990 symposium: Oklahoma Geological Survey Circular 93, p. 256–266.

Perry, W.J., Jr., 1989, Tectonic evolution of the Anadarko Basin region, Oklahoma: U.S. Geological Survey Bulletin 1866–A, 19 p.

Schmoker, J.W., 1986, Oil generation in the Anadarko Basin, Oklahoma and Texas—Modelling using Lopatin's method: Oklahoma Geological Survey Special Publication 86–3, 40 p.

Takahashi, K.I., and Cunningham, K.I., 1987, Map showing wells drilled for oil and gas deeper than 15,000 feet (about 4,600 m) in the conterminous United States and offshore: U.S. Geological Survey Oil and Gas Investigations Map OM–220, scale 1:5,000,000.

Trask, P.D., and Patnode, H.W., 1942, Source beds of petroleum: Tulsa, Oklahoma, American Association of Petroleum Geologists, 566 p.