Hydrocarbon resources at WIPP site New Mexico

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PREFACE

This report presents the results of a comprehensive estimate of the volume of oil and natural-gas resource underlying the Waste Isolation Pilot Plant (WIPP) land withdrawal area, which surrounds the WIPP site. The WIPP site is an underground repository for the storage of radioactive waste. The WIPP land withdrawal area occupies a 16 mil area centered on the WIPP site. It is located approximately 30 miles southeast of Carlsbad in east-central Eddy County, New Mexico. An additional one-mile-wide area surrounding the land withdrawal area was also evaluated.

The work for this report was undertaken by the New Mexico Bureau of Mines & Mineral Resources as part of a larger project in 1994 and 1995. That project evaluated all of the energy and mineral resources (especially potash, in addition to oil and gas) within the boundaries of the WIPP land withdrawal area and the additional one-mile-wide area. Work on that project was performed by the New Mexico Bureau of Mines & Mineral Resources for the Waste Isolation Division of the Westinghouse Electric Corporation under contract no. PO-75-WJJ644145Z. The Waste Isolation Division of the Westinghouse Electric Corporation has managed the construction and operation of the WIPP site.

The amount of natural resources underlying the WIPP land withdrawal area had not been evaluated for more than 10 years. The oil and gas situation of the area around WIPP changed dramatically between the time the previous estimates were made and the time when this study was undertaken. During the late 1980s and early 1990s, several oil and gas fields were discovered underneath lands adjacent to the land withdrawal area. The more prominent fields discovered during this time period are Livingston Ridge, Lost Tank, Los Medanos, and Cabin Lake. Their discovery turned previously unproductive lands into one of the most active oil and gas plays in the onshore United States. With the approach of the opening of WIPP as a nuclear waste repository, the need for a current estimate was made imperative by these recent discoveries of oil and gas.

Ronald F. Broadhead

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Rigorous quantitative estimates were made of oil, natural-gas, and natural-gas-condensate resources that exist beneath the 16 mil area of the WIPP land withdrawal area and an additional one-mile-wide study area around the WIPP site. Calculations were made for resources that are extensions of known, currently producible oil and gas resources thought to extend underneath the WIPP land withdrawal area with reasonable certainty *(probable resources).* Qualitative estimates were also made of oil and gas that may be present in undiscovered pools and fields beneath the WIPP land withdrawal area *(possible resources).* Possible resources were not quantified.

Probable resources consist mostly of oil and associated gas in Permian strata and nonassociated gas and gas condensate in Pennsylvanian strata. Most oil and associated gas production in the vicinity of the WIPP site is currently obtained from sandstone reservoirs in the Delaware Mountain Group (Permian) at depths of 7000-8000 ft. Sandstones and carbonates in the Bone Spring Formation (Permian) at depths of 8000-11,000 ft and carbonates in the Wolf camp Group (Permian) at a depth of approximately 12,000 ft are secondary oil reservoirs. Carbonates in the Strawn Group (Pennsylvanian) at a depth of approximately 13,000 ft are secondary, but important, reservoirs of gas and light oil or condensate. Most nonassociated gas and condensate production in the vicinity of the WIPP site has been obtained from sandstone reservoirs in the Atoka and Morrow Groups (Pennsylvanian) at depths of 13,000-14,000 ft.

Probable oil and condensate resources within the boundaries of the WIPP land withdrawal area are 12.3 million bbls of oil and gas condensate recoverable by primary production methods and an additional 6.4 million bbls of oil potentially recoverable by secondary recovery with waterfloods (Table 1). Probable resources within the one-mile-wide additional study area surrounding the WIPP land withdrawal area are 22.9 million bbls of oil and gas condensate recoverable by primary production methods and an additional 13.8 million bbls of oil potentially recoverable through waterflooding.

Probable gas resources within the boundaries of the WIPP land withdrawal area are 186 BCF gas (Table 1); 89% of this gas is nonassociated and will be produced from the deep Atoka and Morrow reservoirs. The remainder is associated gas, most of which will be produced from relatively shallow reservoirs in the Delaware Mountain Group. Probable gas resources underneath the one-mile-wide additional study area surrounding the WIPP land withdrawal area are 168 BCF gas; 79% of this gas is nonassociated and will be produced from the deep Strawn, Atoka, and Morrow reservoirs.

TABLE 1—Summary of probable natural-gas, oil, and gas-condensate resources under WIPP land withdrawal area and one-mile-wide additional study area around WIPP site.

	WIPP land withdrawal area	Additional study area
oil & condensate, million bbls primary recovery	12.3	22.9
oil, million bbls secondary recovery	6.4	13.8
natural gas, billion ft^3	186	168

In addition to *probable resources,* there are significant *possible resources* of oil, gas, and gas condensate beneath the WIPP land withdrawal area and the additional study area. These will be oil and associated gas in untapped sandstones of the Delaware Mountain Group in largely unexplored and unevaluated sandstones and carbonates of the Bone Spring Formation, and in carbonate reservoirs in the Wolfcamp and Strawn Groups. Possible resources of nonassociated gas and gas condensate will occur in sandstone reservoirs in the Atoka and Morrow Groups and in the pre-Pennsylvanian section (Siluro-Devonian and Ordovician strata). The elusive nature of possible resources makes their quantification difficult or impossible for an area of limited extent such as WIPP.

If production within the WIPP land withdrawal area is ever allowed, preferred development of oil and gas resources will be by drilling vertical wells to the main objectives (Delaware sandstones for oil and Morrow and Atoka sandstones for gas). In most cases, it will not be economically feasible to drill deviated or horizontal wells to develop and produce these resources. Also, the presence of multiple pay zones in vertical succession makes it highly desirable to use vertical wells for exploitation of oil and gas in the vicinity of the WIPP site. Use of vertical wells allows completion in several zones by a single well, some or perhaps most of which would not be economically feasible to develop without multiple completions in a single well. It is possible that oil reservoirs will be waterflooded when production by primary methods has declined to approximately 50% of its maximum rate.

INTRODUCTION

Oil and gas resources are typically divided into several categories (Potential Gas Committee, 1993; Energy Information Administration, 1994; Figs. la, lb). For purposes of this report, five categories of resources are referred to: 1) cumulative production; 2) proved reserves; 3) probable resources (extensions of known pools); 4) undiscovered recoverable resources; and 5) unrecoverable resources. *Cumulative production* is the total volume of crude oil, natural-gas condensate, and natural gas withdrawn (produced) from a pool or well. *Proved reserves* are an estimated quantity of crude oil, natural-gas condensate, or natural gas that analyses of geologic and engineering data demonstrate with reasonable certainty to be recoverable in the future from discovered oil and gas pools. Pools are considered proved on demonstrated ability to produce by either actual production or by conclusive formation tests (Potential Gas Committee, 1993), that is by drilling. This report restricts the definition of proved reserves to those producible resources identified as producible by existing wells (whether currently producing or abandoned). *Ultimate recovery* is the

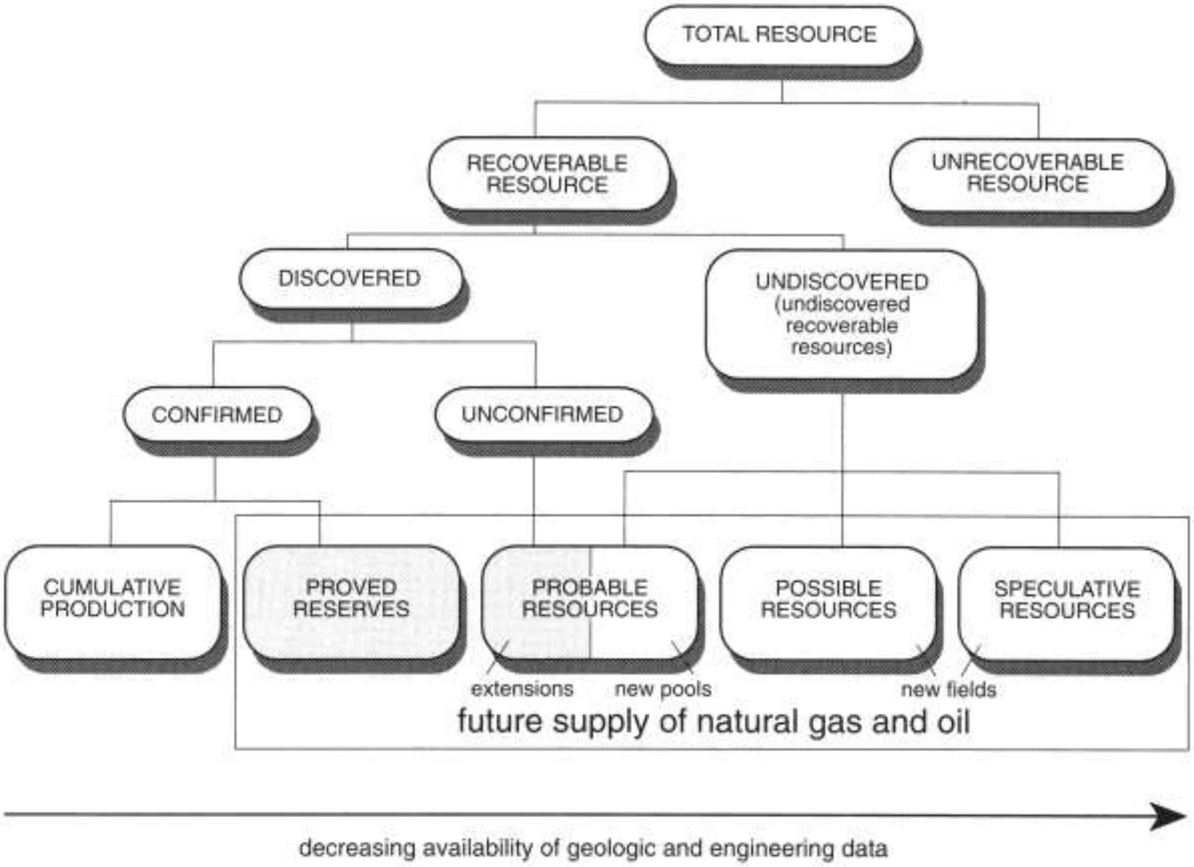


FIGURE 1a—Oil and natural-gas resource categories. From Potential Gas Committee (1993, fig. 2).

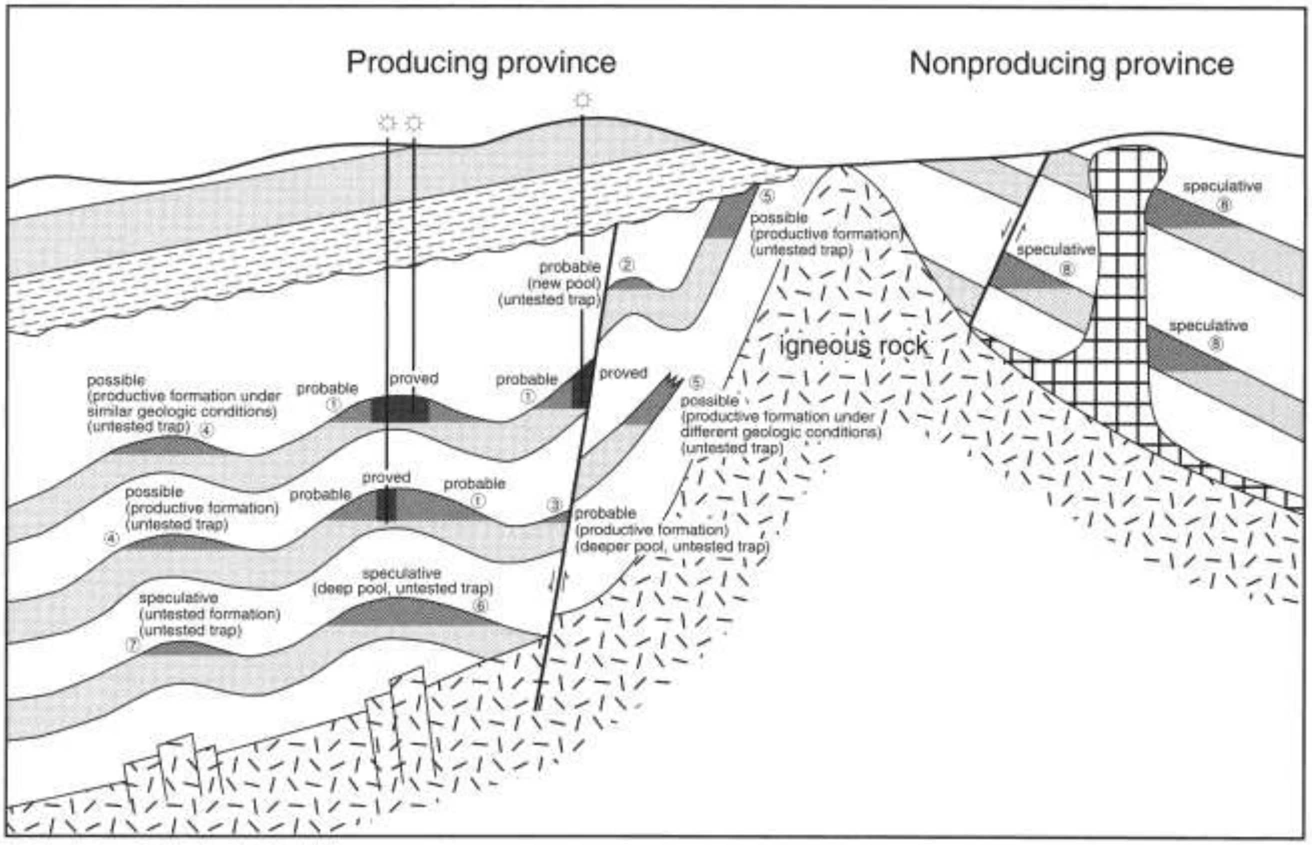


FIGURE 1b—Schematic representation of categories of potential gas resources. From Potential Gas Committee (1993, fig. 3).

TABLE 2—Estimated ultimate primary recovery and probable oil and gas resources under WIPP land withdrawal area for pools projected to extend underneath the WIPP land withdrawal area. KBO, thousand bbls oil; MMCF, million ft^3.

	Average primary recovery				Ultimate primary recovery		Cumulative production within WIPP land withdrawal area, 12/31/93		Probable resources primary recovery	
Pool	**oil, KBO**	**gas, MMCF**	**Spacing, acres**	**Proration units**	**oil, KBO**	**gas, MMCF**	**oil, KBO**	**gas, MMCF**	**oil, KBO**	**gas, MMCF**
Livingston Ridge Delaware (Livingston Ridge main pay)	89	116	40	18	1602	2088	0	0	1602	2088
Los Medanos Delaware complex (D zone pay)	76	166	40	107	8132	17,762	0	0	8132	17,762
Cabin Lake Delaware (B zone pay)	66	46	40	0	0	0	0	0	0	0
Quahada Ridge) SE Delaware (B zone pay	66	46	40	9	594	414	0	0	594	414
Los Medanos Bone Spring	111	239	40	4	444	956	0	0	444	956
Strawn	63	1,600	320	6	378	9600	0	0	378	9600
Atoka	70	8,000	320	16	1120	128,000	28	4664	1092	123,336
Morrow	6.7	2,000	320	16	107	32,000	0	0	107	32,000
TOTALS	—	—	—	—	**12,377**	**190,820**	**28**	**4664**	**12,349**	**186,156**

TABLE 3—Estimated ultimate primary recovery and probable oil and gas resources recoverable by primary production under one-mile-wide additional study area around WIPP land withdrawal area. KBO, thousand bbls oil; MMCF, million ft^3.

	Average primary recovery				Ultimate primary recovery		Cumulative production within WIPP land withdrawal area, 12/31/93		Probable resources primary recovery	
Pool	**oil, KBO**	**gas, MMCF**	**Spacing, acres**	**Proration units**	**oil, KBO**	**gas, MMCF**	**oil, KBO**	**gas, MMCF**	**oil, KBO**	**gas, MMCF**
Livingston Ridge Delaware (Livingston Ridge main pay)	89	116	40	97	8633	11,252	754	846	7879	10,406
Los Medanos Delaware complex (D zone pay)	76	166	40	121	9196	20,086	282	425	8914	19,661
Cabin Lake Delaware) (B zone pay	66	46	40	13	858	598	276	175	582	423
Quahada Ridge SE Delaware (B zone pay)	66	46	40	52	3432	2392	11	9	3421	2383
Los Medanos Bone Spring	111	239	40	8	888	1912	84	163	804	1749
Strawn	63	1600	320	7	441	11,200	18	1325	423	9875
Atoka	70	8000	320	16	1120	128,000	321	33,590	799	94,410
Morrow	6.7	2000	320	22	147	44,000	41	15,211	106	28,789
TOTAL					**24,715**	**219,440**	**1787**	**51,744**	**22,928**	**167,696**

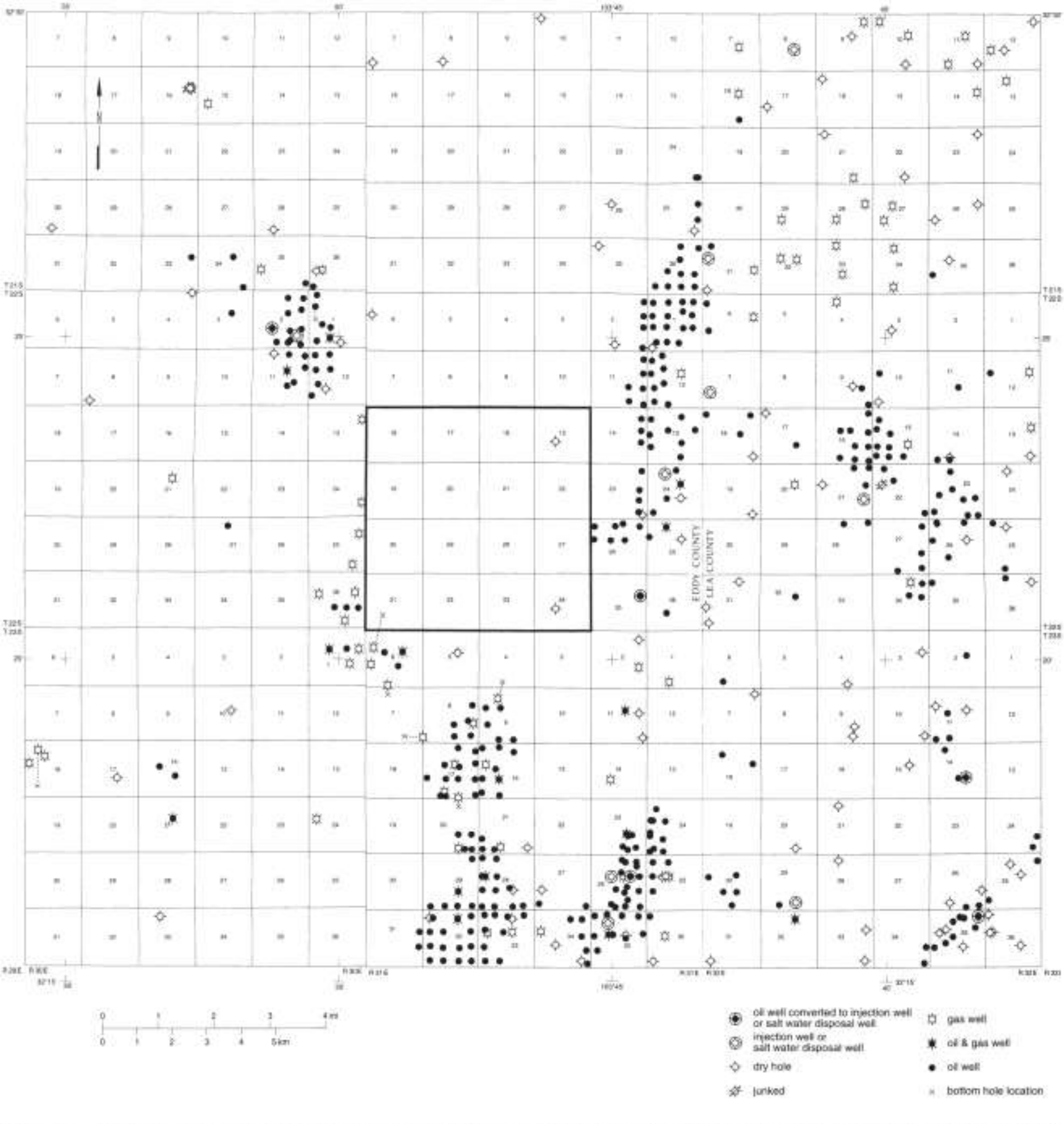


FIGURE 2—The WIPP site, surrounding one-mile-wide additional study area, nine-township project study area, and wells drilled for for oil and gas in the study area. Base from USGS topographic maps of Hat Mesa and Nash Draw 15-minute quadrangles.

sum of cumulative production and proved reserves or probable resources for a pool or individual well.

The remainder of the resource base consists of *potential resources.* These can be summarized as hydrocarbons that can be inferred to exist, but have not yet been proven by drilling. These can be grouped into: 1) *probable resources (extensions of known pools);* 2) *probable resources (new pools);* 3) *possible resources;* and 4) *speculative resources.* These subdivisions of potential resources are differentiated on the basis of available geologic, geophysical, and engineering data and studies. *Probable resources (extensions)* consist of oil and gas in pools that have been discovered but have not yet been developed by drilling; their presence and distribution can generally be surmised with a high degree of confidence. *Probable resources (new pools)* consist of oil and gas that are surmised to exist in undiscovered pools within existing fields. *Possible resources* are less assured; they are postulated to exist outside of known fields but within productive stratigraphic units in a productive basin or geologic province. *Speculative resources* are expected to be found in stratigraphic

TABLE 4—Summary of probable oil and gas resources recoverable by primary production under WIPP land withdrawal area, one-mile-wide additional study area, and the total area of WIPP land withdrawal area + additional study area. KBO, thousand bbls oil; MMCF, million ft^3.*

Pool	Probable resources, WIPP land withdrawal area oil, KBO	Probable resources, WIPP land withdrawal area gas, MMCF	Probable resources, additional study area oil, KBO	Probable resources, additional study area gas, MMCF	Probable resources, WIPP land withdrawal area + additional study area oil, KBO	Probable resources, WIPP land withdrawal area + additional study area gas, MMCF
Livingston Ridge Delaware (Livingston Ridge main pay)	1602	2088	7879	10,406	9481	12,494
Los Medanos Delaware Complex (D zone pay)	8132	17,762	8914	19,661	17,046	37,423
Cabin Lake Delaware (B zone pay)	0	0	582	423	582	423
Quahada Ridge SE Delaware (B zone pay)	594	414	3421	2383	4015	2797
Los Medanos Bone Spring	444	956	804	1749	1248	2705
Strawn	378	9600	423	9875	801	19,475
Atoka	1092	123,336	799	94,410	1891	217,746
Morrow	107	32,000	106	28,789	213	60,789
TOTALS	**12,349**	**186,156**	**22,928**	**167,696**	**35,277**	**353,852**

units, basins, or geologic provinces that have not yet been proven productive; estimates of speculative resources are the least assured of all resource estimates. *Unrecoverable resources* are dispersed in such minute accumulations or under such conditions that they cannot be extracted with existing or foreseeable technology.

In this report calculations are made for *cumulative production* and *probable resources (extensions of known pools)* for the 16 sections that constitute the WIPP site and for the 20 sections that constitute the one-milewide additional study area around the WIPP site (Fig. 2, Tables 1-4). Cumulative production consists of historical data; it is listed as a separate item. Proved reserves are included with probable resources (extensions of known pools) because the sum of these two factors is the main goal of this study; together, these include oil and natural gas that are likely to be produced from existing wells and from undrilled areas that are thought to overlie extensions of producing pools. No numerical estimates were made for undiscovered resources that may reside unknown beneath the WIPP land withdrawal area, because quantitative estimates of these resources are uncertain at best. However, geologic studies conducted as part of this project were used to make a qualitative evaluation as to the likelihood of new, undiscovered pools and fields being present. Unrecoverable resources are not estimated.

Cumulative production data were obtained from official state records collected by the New Mexico Oil Conservation Division of the New Mexico Energy, Minerals, and Natural Resources Department. The Oil Conservation Division is the state agency which is required by law to regulate oil and natural-gas drilling and production operations on state and private lands within the state. In addition, the Oil Conservation Division keeps records of all oil and natural-gas production within New Mexico. Monthly and annual reports subdivide production by pool, operator, and individual well; these reports are available in hard copy as monthly and annual reports published by the New Mexico Oil and Gas Engineering Committee. These data are also kept in digital-tape format by the Oil Conservation Division. Both digital and hard-copy forms of the data were used in preparation of this report.

Definitions

Several basic definitions having to do with terminology that describes the manner of occurrence and physical properties of crude oil and natural gas are integral to this report. Some of this terminology varies slightly in meaning from state to state (e.g. pool, field), from discipline to discipline (e.g. the term *petroleum* does not mean to geologists what it does to chemists; geologists generally use the term to describe all liquid, gaseous, and solid hydrocarbons in a reservoir, while chemists generally use the term as a synonym of crude oil), or even from worker to worker (the term reservoir can be confusing unless it is defined precisely). For purposes of clarity, terms fundamental to this report are defined below.

Oil (crude oil): Hydrocarbons that occur naturally in a liquid state within the reservoir and are produced in a liquid state at the wellhead. Volume of crude oil is measured in barrels (bbls or BO).

Gas (natural gas): Hydrocarbons that occur naturally in a gaseous state within a reservoir and are produced as a gas at the wellhead. Volume of natural gas is measured in thousand ft^3 (MCF), million ft^3 (MMCF), or billion ft^3 (BCF).

Condensate (gas condensate): Hydrocarbons that occur naturally in a gaseous state within the reservoir but condense to a liquid at the surface (wellhead) because of decreased temperature and pressure at the surface relative to temperature and pressure within the reservoir. It is often difficult to determine if a high-gravity (i.e. low density) liquid hydrocarbon is a light oil or a gas condensate.

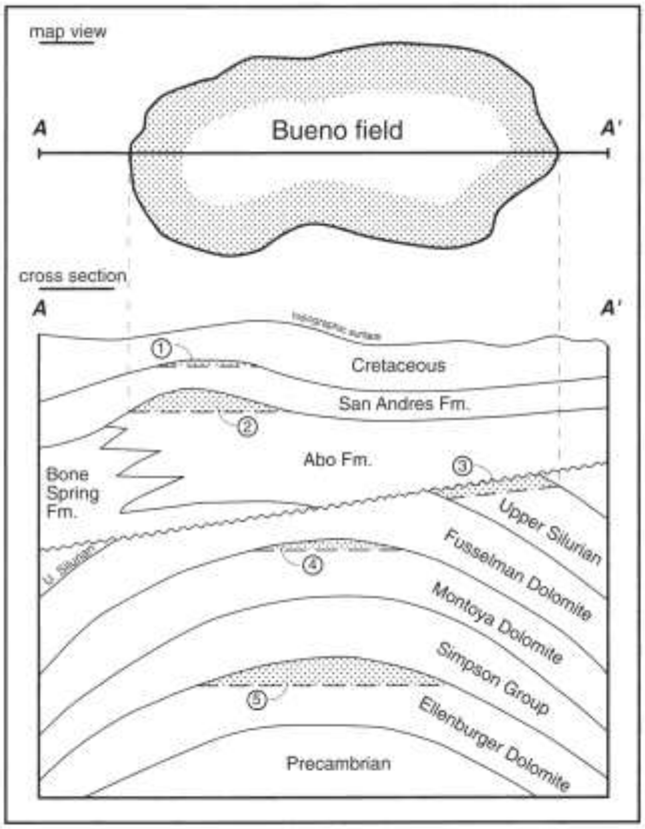


FIGURE 3—Relationship between a field and its constituent pools. The field name is *Bueno*. The five pools are: 1) *Bueno San Andres;* 2) *Bueno Abo;* 3) *Bueno Upper Silurian:* 4) *Bueno Montoya*; and 5) *Bueno Ellenburger*. From Broadhead (1993a).

Official production reports do not differentiate between gas condensates and crude oils. **It** is generally assumed as a first approximation that liquids produced from gas reservoirs are condensates and that liquids produced from oil reservoirs are true crude oils. This assumption is made throughout this report.

Associated gas: Natural gas that occurs with oil in the reservoir, either dissolved within the oil or as a free gas cap above a gas-oil contact.

Nonassociated gas: Natural gas that occurs in the absence of oil in the reservoir. Liquid hydrocarbons that are produced with nonassociated gas are condensates rather than oils.

Field (oil field, gas field; Fig. 3): An area characterized by geographically continuous production of oil and/or gas that may be produced from a single pay zone (stratum) or from several pay zones (multiple strata). This definition of field is consistent with regulatory and legal usage in New Mexico.

Pool (oil pool, gas pool; Fig. 3): A single discrete accumulation of oil or gas within a single trap. Several pools may lie in vertical succession in an area, or they may lie side by side or overlap laterally so as to constitute an areally continuous accumulation called a field. The pool name is made up of two parts:

1) the field name, usually derived from a geographic location (e.g. Bueno);
2) the stratigraphic name, derived from the stratigraphic unit that acts as the reservoir for **the** oil and/or gas (e.g. San Andres).

In this hypothetical example, the field name is Bueno and the pool name is Bueno San Andres. Other pools in this field are Bueno Abo, Bueno Upper Silurian, Bueno Montoya, and Bueno Ellenburger. This definition of pool is consistent with regulatory and legal usage in New Mexico.

Reservoir: A unit of porous and permeable rock in which crude oil, natural gas, or natural gas condensate are found and can be produced in economic quantities. This definition is consistent with regulatory and legal usage in New Mexico.

Methodology of resource estimation—primary recovery

Numerical estimates of crude-oil, natural-gas, and natural-gas-condensate resources recoverable through primary production techniques were made by geologically delineating areas of probable production. Historical production data from producing wells were used to calculate the volume of oil, gas, and gas condensate recoverable per unit area of reservoir. The area within the boundaries of potential production was calculated and multiplied by recoverable resource per unit area to give ultimate recovery. Probable resources of a pool are obtained by subtracting cumulative production from ultimate recovery.

Basic information for all wells drilled for oil and gas in a nine-township study area centered on the WIPP site (Fig. 2) was compiled from well records on file at the Subsurface Library of the New Mexico Bureau of Mines & Mineral Resources. Geophysical borehole logs were analyzed and correlated throughout the nine-township study area. Log correlations were used to produce structure contour maps of appropriate mapping datums and to isopach the primary pay zones in pools adjacent to the WIPP land withdrawal area. Structure contour maps were made of four stratigraphic surfaces, the structure of which may govern hydrocarbon entrapment in major producing reservoirs. These four surfaces are: 1) a prominent resistive log marker at the top of the lower Brushy Canyon Formation; 2) the top of the Wolfcamp; 3) the top of the Strawn Group; and 4) the top of the Morrow clastic section. Because of inaccuracies inherent in stratigraphic data obtained from scout cards and the omission of stratigraphic tops from many scout cards, log correlations made during the course of this study were used to calculate subsea levels necessary for contouring. Other maps unique to the analysis of each pool were also produced and are discussed at appropriate places below. These other maps, in conjunction with the appropriate structure contour maps, were then utilized to project the boundaries of known (i.e. discovered) hydrocarbon traps into undrilled /nonproductive areas beneath the WIPP land withdrawal area and the surrounding one-mile-wide study area. From these projections, estimates were made of the potentially productive area for each of the pools. Potentially productive area is given in terms of the number of potential drill sites based on proration units consistent

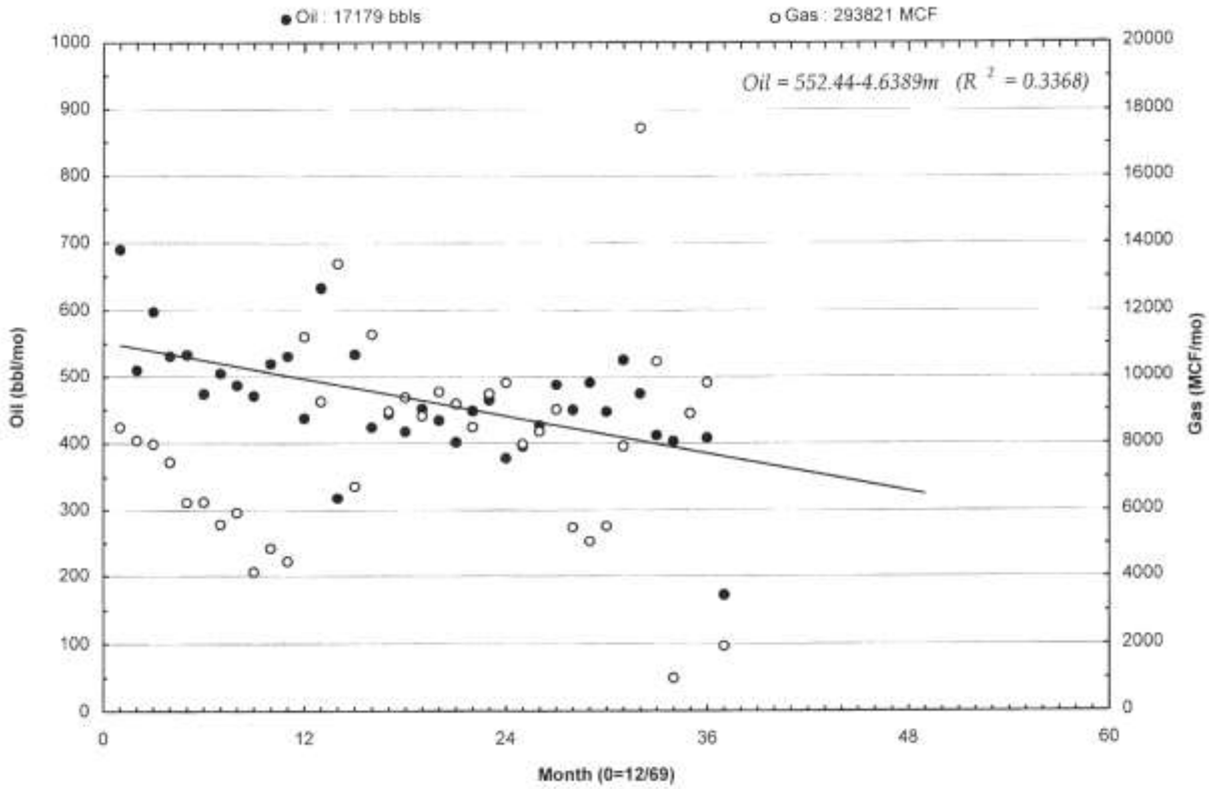


FIGURE 4—Typical time-dependent production plot for a well governed by linear production decline.

with established spacing in the vicinity of the WIPP site.

Quantitative resource assessment also utilized historical production data of producing wells to estimate ultimate recovery and reserves recoverable by primary production techniques. Monthly production data of oil, gas, and condensate in digital format were used to produce time-dependent production plots (see Figs. 4, 5 as examples). These digital production data were available for months up to and including December 1993. Then a computer program written with Mathematica was used to fit a custom production decline curve to each well (Figs. 4, 5). The area under the curve was then calculated by mathematical integration of the formula used to define the curve; this area is the *ultimate primary recovery* of oil, gas, or condensate *(ultimate primary recovery* is the total amount of oil and/or gas that a well could economically produce from the date of first production to the date of eventual abandonment if only primary production techniques are utilized). The well's reserves are equal to cumulative production subtracted from ultimate recovery (Fig. 6). Ultimate recovery of associated gas from oil wells was estimated by a more complex method described below.

Based on analysis of the data, the decline curve fitted to each well was either exponential or linear (Figs. 4, 5). The following general equations were used for each type of curve (Sustakoski and Morton-Thompson, 1992):

$q_t = q_i e^{-Dt}$ exponential decline
$q_t = q_i - n(t)$ linear decline
where: q_i = initial production rate (bbls/month or MCF/month),
q_t = production rate at time t,
t = time at which production rate is calculated (months),
D = initial decline rate expressed as a decimal,
n = linear decline slope (bbls/month).

An exponential decline curve was used to describe production data from most wells.

For each well, ultimate recovery was calculated for five lower limits of production rate (30, 60, 90,120, and 150 bbls /month for oil wells and 300, 600, 900, 1200, and 1500 MCF/month for nonassociated gas wells). At current oil and gas prices, the 150 bbl/month and 1500 MCF/month limits are economically appropriate as the minimum production rates.

Two calculations were performed in order to test the fit and appropriateness of the calculated production decline curves. First, a correlation coefficient (R^2) was calculated for comparison of the curve with known, historical production data. R^2 will vary between 0 and 1.0. A value of 0 indicates that there is no correlation between the actual production data and the calculated curve. A value of 1.0 indicates that the historical production data are defined exactly by the calculated production decline curve. Most values of R^2 were greater than 0.5, indicating a good curve fit. For many wells, R^2 was greater than 0.85, indicating an

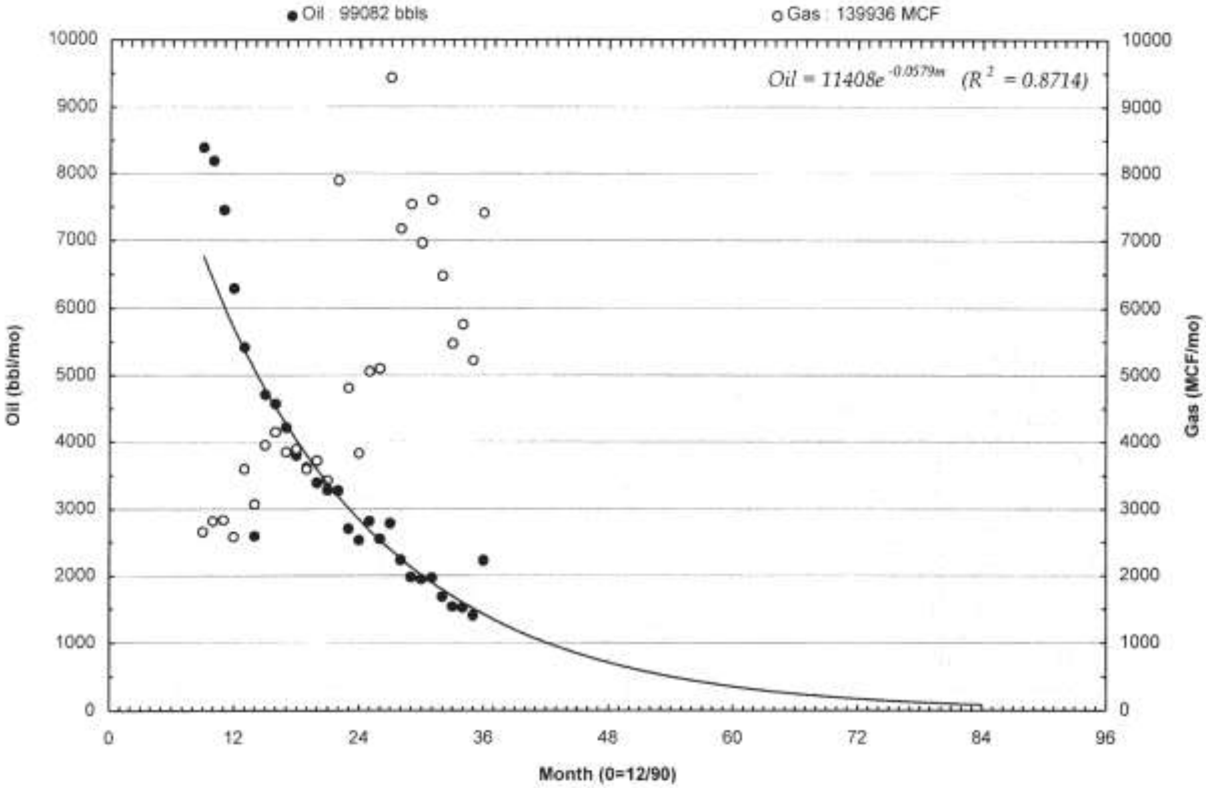


FIGURE 5—Typical time-dependent production plot for a well governed by exponential production decline.

excellent fit between the curve and the historical data points; this is especially true of wells completed in the Brushy Canyon Formation of the Delaware Mountain Group.

The second test of curve fit involved integrating the area under the decline curve from initial production of the well to the end of December 1993. This gives an estimate of cumulative production from initial well completion until the end of 1993. This value was then compared with actual cumulative production at the end of 1993. For most wells, the difference between the estimated (calculated) value and the actual value of cumulative production was less than 5%, indicating good representation of the production data by the calculated curve. In some cases, the difference between the two values was less than 2%, indicating that the calculated curve yields an excellent representation of actual production. Both tests of curve fit indicated that calculated curves could be used with confidence to predict future production and therefore to calculate reserves.

As mentioned previously, reserves of associated gas in oil wells were calculated by a different method (see Kloepper, 1993). In these wells, the economics are driven largely by oil production. This is especially true for productive oil wells in the vicinity of the WIPP site. These wells have low gas-oil ratios. A well is ultimately abandoned because daily oil production has fallen below an economic rate. For these wells, historical monthly values of gas-oil ratio were calculated from production data. A gas-oil ratio decline curve was plotted and projected to well abandonment based on projections of crude-oil production. Gas-oil ratios estimated by the curve were then multiplied by projected

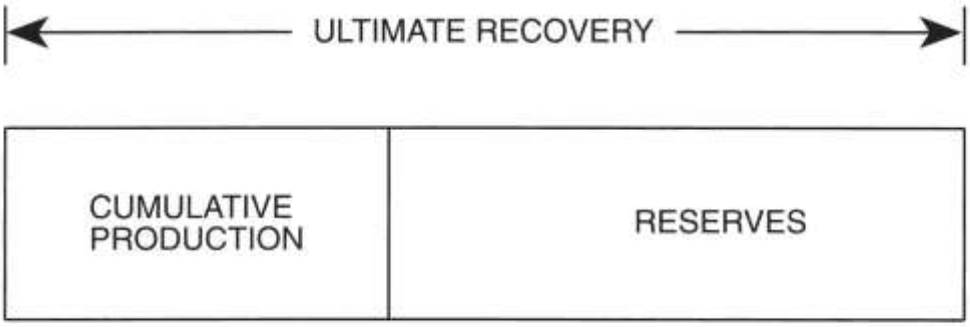


FIGURE 6—Relationship of ultimate recovery to cumulative production at time *t* and reserves at time *t*.

crude-oil production to obtain an estimate of past and future associated-gas production (i.e. ultimate recovery).

Only wells with at least 12 continuous months of production data were used in ultimate recovery calculations. Many wells had at least 36 months of production data prior to the end of 1993, and some wells had several years of production. Some wells have been re-entered since original completion. In most of these re-entered wells, the original producing zone has been abandoned and sealed off from the rest of the borehole by either a bridge plug or by cement. In these cases, the well has since been recompleted in a new zone, which is usually shallower than the original producing zone. Such a well may have been productive from two, three, or even four zones at different times in its history. Each zone is associated with its own production decline curve, and ultimate recovery was calculated separately for each zone.

Wells in which production has been significantly curtailed for economic or other reasons often do not yield a production history which is suitable for decline-curve analysis (see Kloepper, 1993). Ultimate recovery was not calculated for these wells. A few wells did not yield data that supported calculation of a decline curve. Unknown or unrecognized factors have left these wells with an erratic production history. Ultimate recovery was not calculated for these wells.

After ultimate recovery was calculated for individual wells, the average ultimate recovery per well was calculated for each major pay zone in pools adjacent to the WIPP land withdrawal area by the method outlined below. This concept of the average well is widely used in the petroleum industry (see Holmes et al., 1985). Although the concept of the average well is not suited to estimate resources for any one particular prospect, it can be used with confidence to estimate the resources under an area such as the WIPP site, which consists of multiple undrilled prospects in known hydrocarbon traps that are projected to extend underneath the site.

In order to calculate average ultimate recovery, a production decline curve for the average or typical well in each pool was established. The method used to generate this typical decline curve was dependent upon the quality and quantity of production data available in each pool. For Delaware pools, monthly production data were assembled for all wells for which ultimate recovery was calculated. Data were normalized to the first month of production for each well, and the average production for each month (normalized to the well's initial production) was then calculated. Based on these normalized average monthly production values, an average decline curve for wells in each oil and gas pool was calculated according to the method described above. For pools in formations other than the Delaware, construction of the typical decline curve is described under discussion of each pool.

Petroleum resources underneath the WIPP land withdrawal area and the surrounding one-mile additional study area were calculated for each oil and gas pool projected to extend underneath these areas (Tables 2-4). The potentially productive area for each pool was mapped by using the structure and stratigraphic maps to project boundaries of the traps from drilled producing areas into undrilled areas. Productive area was calculated in terms of proration units based on a spacing consistent with that in the pools adjacent to the WIPP land withdrawal area (Tables 2-4). The number of proration units was then multiplied by the average resources per well to estimate the total ultimate recovery for each pool in the WIPP land withdrawal area and in the additional study area. Resources of the pool are then equal to the ultimate recovery minus the cumulative production.

The petroleum geology and petroleum engineering characteristics of productive and potentially productive strata beneath the WIPP land withdrawal area are described below, as is the history of oil and gas drilling and production in the area. The geology of each stratigraphic unit and of the separate oil and gas pools within each stratigraphic unit is unique. The discussion is divided accordingly.

OIL AND GAS RESOURCES AND PETROLEUM GEOLOGY OF WIPP SITE

Overview

The WIPP site is situated in the Delaware Basin (Fig. 7). Strata range in age from Cambrian through Permian (Fig. 8). The Delaware Basin is the deep-marine part of the Permian Basin and is bordered on the north and west by the Northwest Shelf and on the east by the Central basin platform. The Permian Basin became differentiated into these paleobathymetric elements during the Pennsylvanian. By the Wolfcampian (Early Permian), the shelf margin was constructional rather than tectonic and was marked successively by the Wolfcamp, Abo, Getaway, Goat Seep, and Capitan bank and barrier reef complexes (Figs. 9, 10). Regional structural dip is toward the center of the Delaware Basin (Fig. 11). In the vicinity of the **WIPP** site, oil and natural gas have been extracted commercially from the Delaware, Bone Spring, Wolfcamp, Strawn, Atoka, and Morrow (Fig. 8). Presently nonproductive units which may bear undiscovered oil and natural gas in the area are (descending): Mississippian, Siluro-Devonian, and Ordovician sections; significant volumes of oil and gas are produced from these strati-graphic units elsewhere in the New Mexico part of the Permian Basin.

History of oil and gas drilling in WIPP area

According to comprehensive well records on file at the New Mexico Bureau of Mines & Mineral Resources, 532 wells had been drilled in search of oil and gas in the nine-township study area centered on the WIPP site as of the end of 1993 (Fig. 2). Additional drilling was done in 1994, but 1994 wells were not included in these statistics because complete data for the year were not available at the time this report was written. Few wells were drilled in the area prior to 1960 (Fig. 12). From 1960 until 1989 drilling activity increased but was sporadic and never exceeded 20

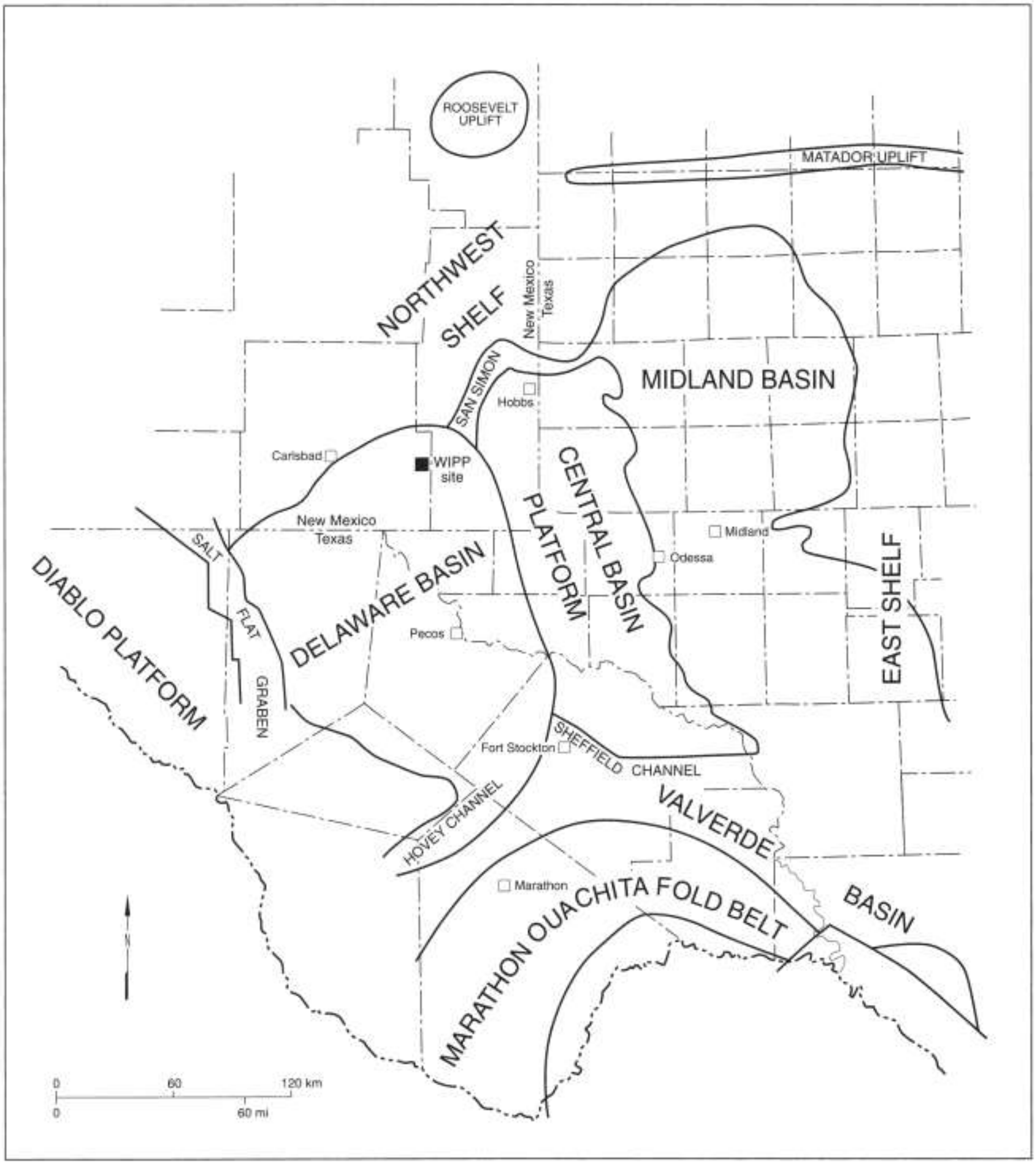


FIGURE 7—Location of WIPP site in relation to outline of Delaware Basin, southeast New Mexico.

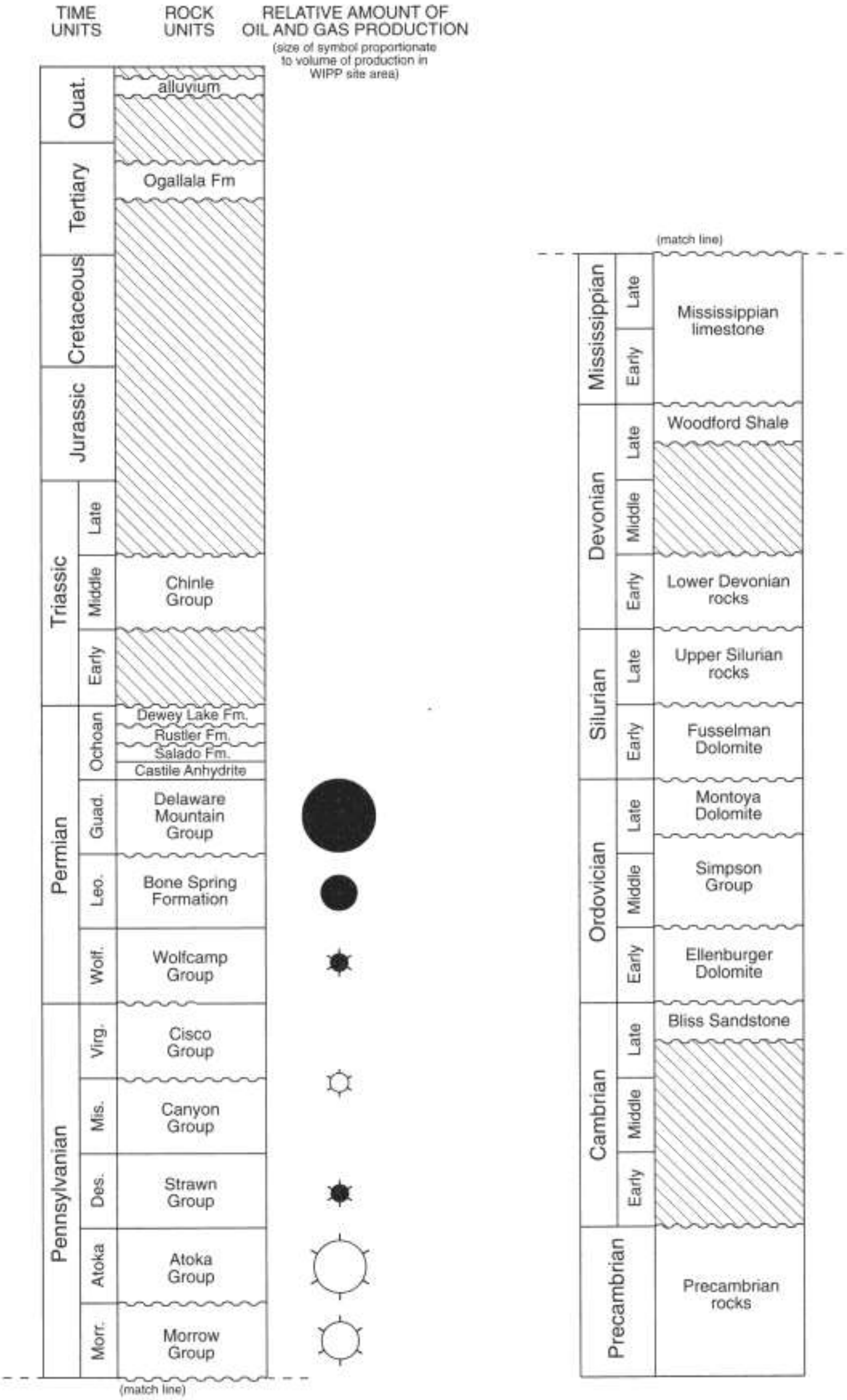
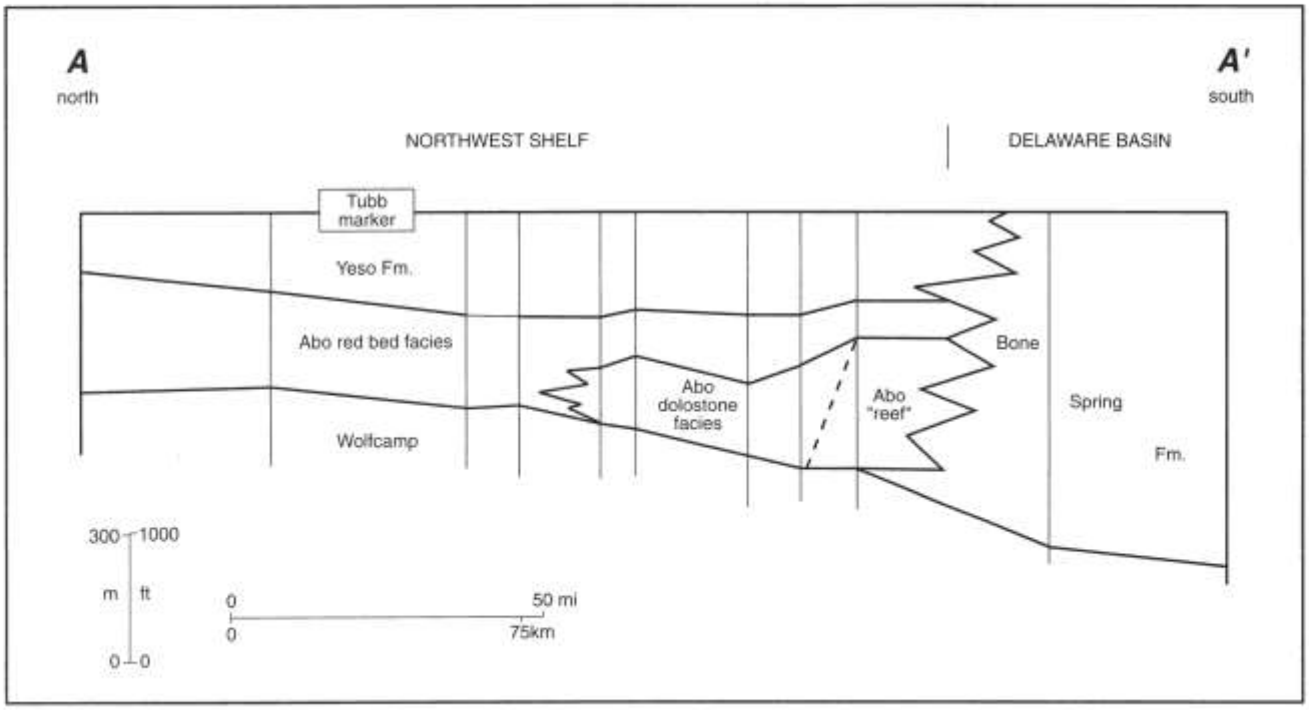


FIGURE 8—Stratigraphic column of Delaware Basin showing rock units productive of oil and gas in the vicinity of the WIPP site. No absolute or relative vertical time or depth scale implied. Data sources: Hills and Kottlowski (1983) and Speer and Broadhead (1993).


A
north
A'
south
NORTHWEST SHELF
DELAWARE BASIN
Tubb marker
Yeso Fm.
Abo red bed facies
Bone
Abo dolostone facies
Abo "reef"
Spring
Wolfcamp
Fm.
300 1000
m ft
0 0
0 50 mi
0 75km

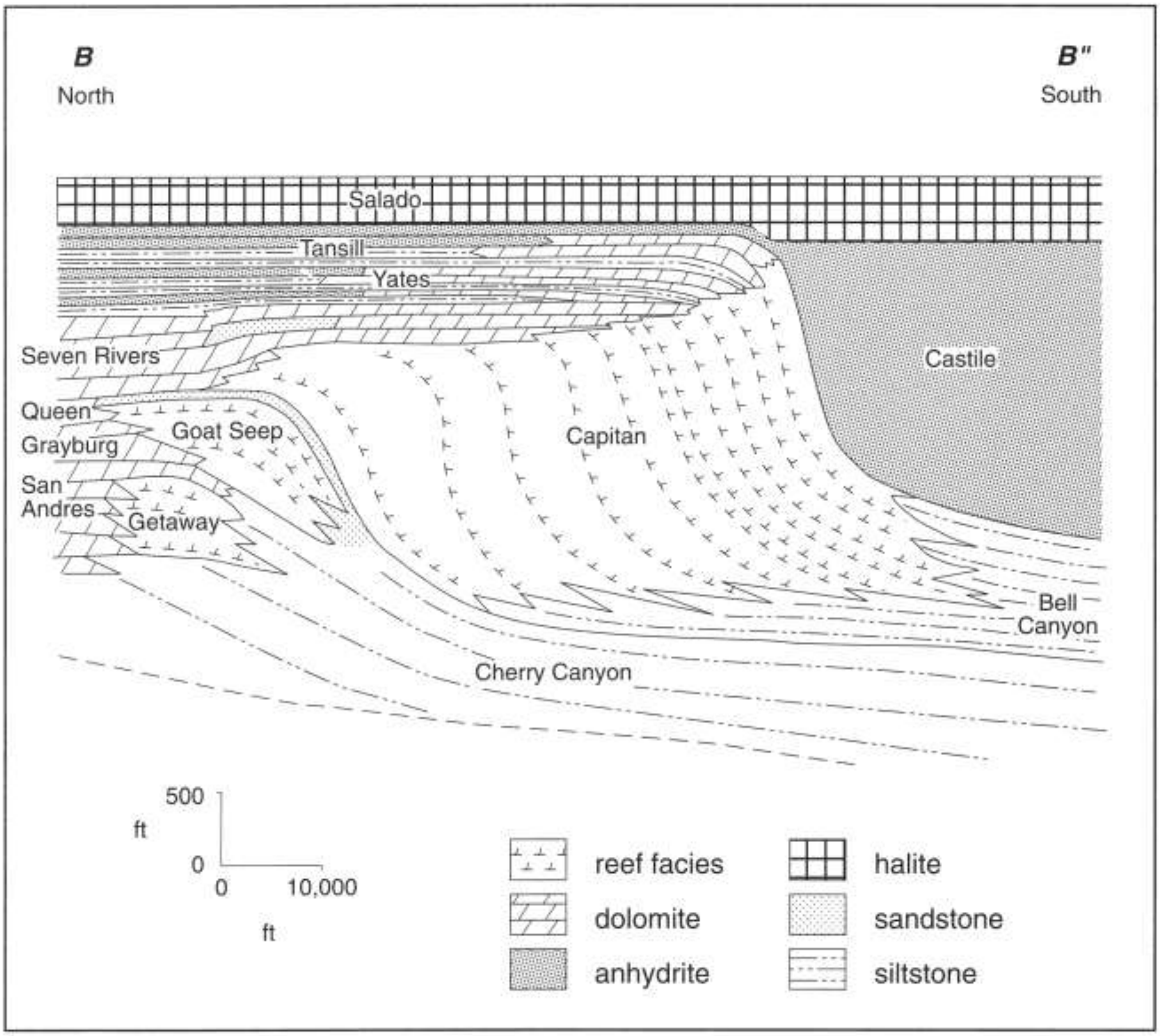

B
North
B"
South
Salado
Tansill
Yates
Seven Rivers
Queen
Goat Seep
Grayburg
San Andres
Getaway
Capitan
Castile
Bell Canyon
Cherry Canyon
500
ft
0
0 10,000
ft
reef facies
dolomite
anhydrite
halite
sandstone
siltstone

FIGURE 9—North–south stratigraphic cross section A–A' through Abo and lower Yeso strata showing location of Abo reef at boundary between Northwest shelf and Delaware Basin. Line of section in Fig. 7. After Broadhead (1984).

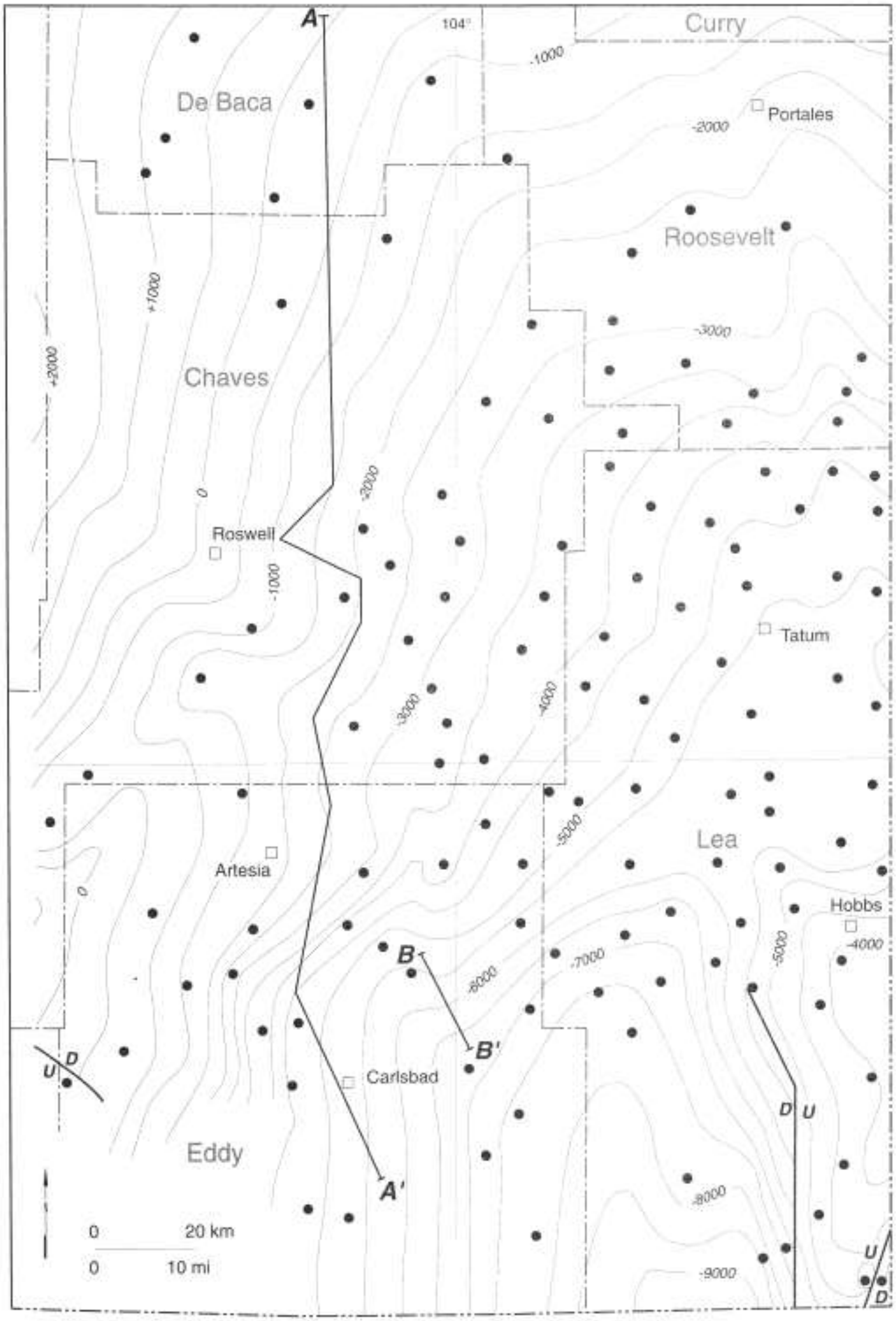


FIGURE 11—Structure on top of Wolfcampian strata, southeast New Mexico. After Meyer (1966). Cross sections are in Figs. 9, 10.

FIGURE 10—North–south cross section B–B' through Guadalupian and Ochoan strata, showing Getaway, Goat Seep, and Capitan shelf-margin barrier complexes. Line of section in Fig. 7. After Garber et al. (1989, fig. 10).

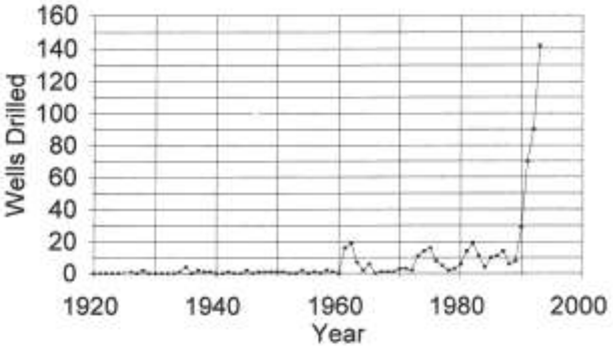


FIGURE 12—Annual number of oil and gas wells completed in nine-township study area centered on WIPP site. Data from well records on file at New Mexico Bureau of Mines & Mineral Resources Library of Subsurface Data.

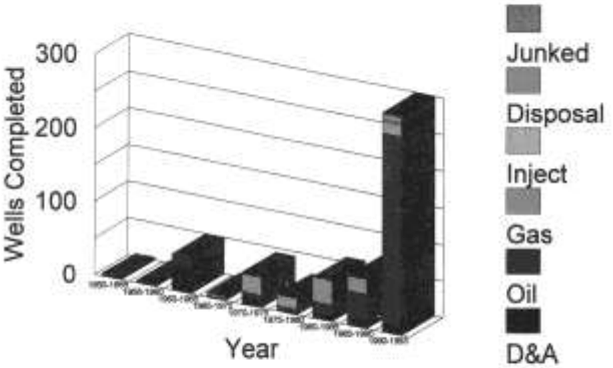


FIGURE 13—Time distribution of oil and gas wells by completion status for nine-township study area.

wells per year. In 1990, however, drilling increased markedly. Annual totals increased to a maximum of 140 wells per year during 1993; most of these wells were drilled for oil (Fig. 13) in the Brushy Canyon Formation of the Delaware Mountain Group. The increase in well completions during the 1990s can be partially attributed to opening up hitherto restricted areas of the Potash Area to drilling (see Ramey, 1995, for a summary of drilling restrictions in the Potash Area). However, the lower parts of the Delaware Mountain Group (Cherry Canyon and Brushy Canyon Formations) were not generally recognized as exploratory and development targets until the late 1980s and early 1990s. Prior to that time, they were usually bypassed during drilling with little or no thought that they might contain economic oil reservoirs. Although these two formations had been penetrated by thousands of wells throughout the Delaware Basin, few attempts were made to adequately test them.

The main reason for bypassing these formations during drilling was a lack of understanding of their reservoir production characteristics. Water saturations calculated from analysis of electric logs were often high and did not differentiate oil-productive sandstones from sandstones that would yield mostly water upon completion. However, recent developments in log analysis (Asquith and Thomerson, 1994) have made it possible to differentiate Delaware sandstones with a high percentage of movable hydrocarbons from those with a low percentage of movable hydrocarbons. This type of analysis, in conjunction with the discovery of several commercial oil pools in the Brushy Canyon Formation, set off an oil drilling boom throughout the Delaware Basin that continues to the present. The Delaware play is currently the primary exploration and development play in the Permian Basin and one of the most active oil plays in the United States. Of special note in the vicinity of WIPP was the discovery and development of commercial oil accumulations in the Brushy Canyon Formation at the Cabin Lake, Livingston Ridge, Lost Tank, and Los Medanos pools.

Prior to 1970, most drilling in the WIPP area was for shallow oil (4000-4500 ft) in the Bell Canyon Formation. With the exception of the Bell Canyon discovery at Triste Draw (Fig. 14), most of these exploratory wells were plugged and abandoned. Numerous oil shows were encountered by cores and drill-stem tests. These wells reached total depth in the Bell Canyon and were not drilled deep enough to reach the currently productive Cherry Canyon and Brushy Canyon reservoirs.

From 1970 until the mid-1980s most drilling in the vicinity of WIPP concentrated on gas (Fig. 13) in the Morrow and Atoka Formations. The stratigraphic component of the Morrow and Atoka plays was often neglected in lieu of drilling seismically defined structures. Most drilling for deep gas took place northeast of the WIPP site in T21S R32E (Fig. 2). With the opening of parts of the Potash Area to oil and gas exploration in the 1990s, deep gas in the Morrow and Atoka once again became a drilling target along the western boundary of the WIPP land withdrawal area (Fig. 2), where several wells have been drilled.

Oil and gas drilling within WIPP land withdrawal area

Three wells have been drilled for oil and gas within the boundaries of the WIPP land withdrawal area (Fig. 2, Table 5). Two wells, the Clayton Williams No. 1 Badger Federal and the Michael Grace No. 1 Grace Cotton Baby Federal, were drilled as vertical holes within the WIPP land withdrawal area during the 1970s. Both wells were abandoned without establishing production. In the Clayton Williams Badger Federal well, oil was recovered on a drill-stem test of sandstones in the Cherry Canyon Formation, but apparently no attempt was made to complete the well as a producer. The main pay zone in the upper Brushy Canyon at the Livingston Ridge pool and the lower Brushy Canyon D zone were not tested; neither of these zones was known to be commercially productive at the time the well was drilled. In the Michael Grace Cotton Baby Federal well, Bell Canyon sandstones were perforated through casing, but production was

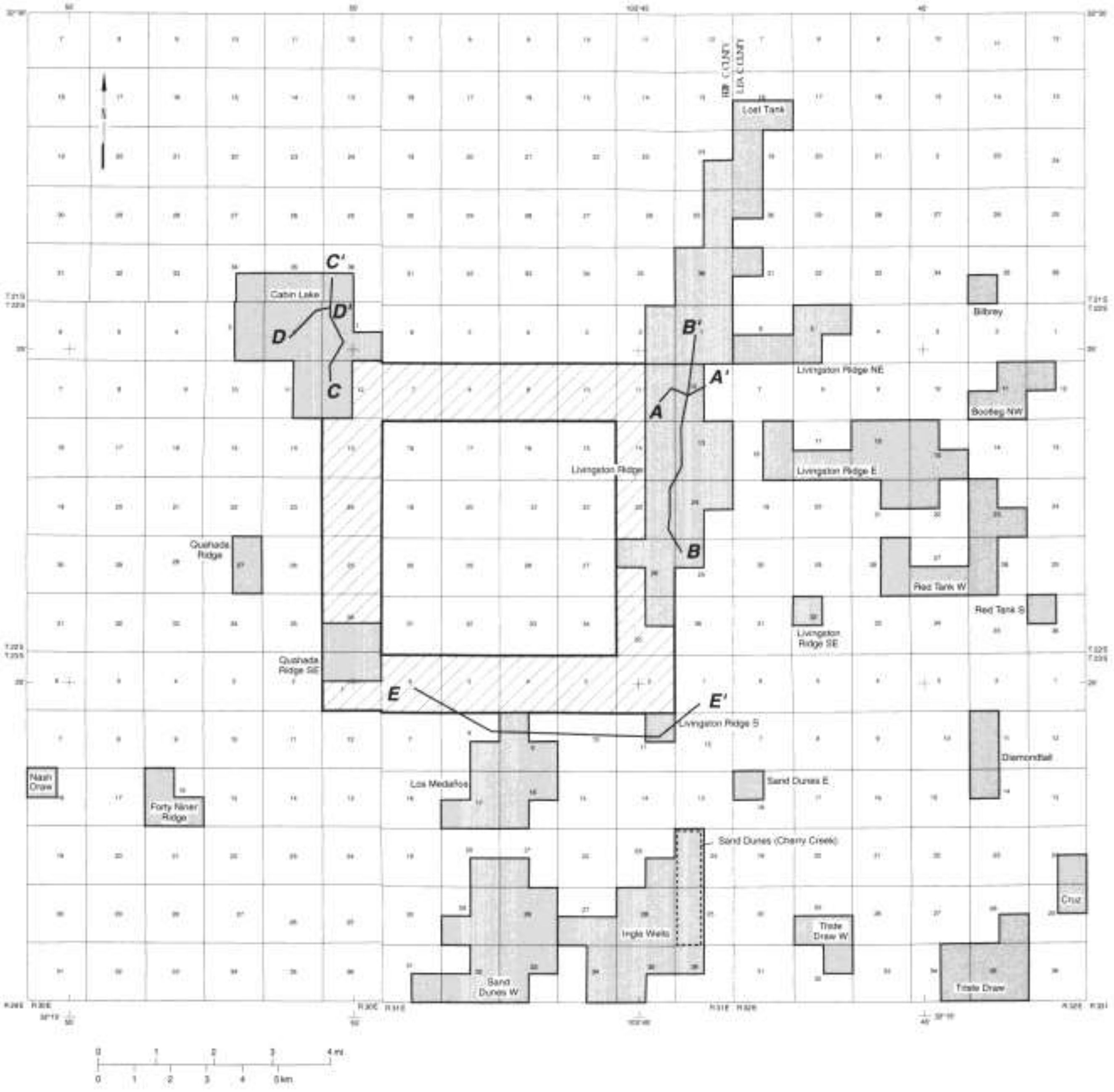


FIGURE 14—Designated oil pools in the Delaware Mountain Group within the nine-township study area, location of WIPP site and additional one-mile-wide study area, and locations of stratigraphic corss sections A–A′, B–B′, C–C′, D–D′, and E–E′ in Delaware Mountain Group.

not established. Although the well reached total depth in the upper part of the Brushy Canyon, there are no reports of tests in either the Brushy Canyon or Cherry Canyon.

The Perry R. Bass No. 13 James Ranch unit was drilled during 1982 from a surface location in sec. 6 T23S 31E. The hole was deviated to a bottom-hole location in the southwest quarter of sec. 31 T22S R31E, which underlies the WIPP land withdrawal area. Gas production was established in September 1982 from an Atoka sandstone reservoir at depths of 13,466 to 13,477 ft. The well remains productive and had pro duced a cumulative total of 4.664 billion ft^3 of nonassociated gas, 27.5 thousand bbls of condensate, and 2.8 thousand bbls of brine as of December 31, 1993. See Silva (1992, 1994) for some discussion of this well.

No additional wells have been drilled for oil and gas with either surface locations or bottom-hole locations within the boundaries of the WIPP land withdrawal area. Several shallow engineering and potash core holes were drilled within the boundaries of WIPP, but these holes were not drilled deep enough to penetrate strata productive of oil and gas. Griswold (in press) summarizes these shallow core holes.

TABLE 5—Oil and gas wells drilled within the boundaries of the WIPP land withdrawal area. D&A, dry and abandoned; DST, drill-stem test; rec, recovered.

Operator, well no., and lease	Location section-township-range	Total depth (ft)	Status	Formation at total depth	Comments
Clayton W. Williams No. 1 Badger Unit Federal	15-22S-31E	15,225	D&A	Mississippian	Completed 9/17/93. DST 6230 – 6297 ft (Cherry Canyon,)rec 190 ft oil & gas-cut drilling fluid + 780 ft drilling fluid. DST 14,035-14,200 ft (Morrow), rec 2700 ft watery brine + 300 ft water-cut drilling fluids. No production tests reported.
Michael P. Grace No. 1 Grace Cotton Baby Federal	34-22S-31E	6700	D&A	Brushy Canyon	Originally completed 1/22/74 at total depth of 4475 ft in Bell Canyon. Re-entered on 6/3/75 and drilled to new total depth of 6700 ft in Brushy Canyon. Recompleted 12/11/75. Perforated 4400– 4424 ft (Bell Canyon) and acidized—no production established.
Perry R. Bass No. 13 James Ranch Unit	6-23S-31E (surface location) 31-22S-31E (bottom-hole location)	15,708	gas well	Mississippian	Completed 9/13/82. Surface location south of WIPP site; hole deviated under WIPP site. Produces through perforations from 13,466 to 13,477 ft (Atoka). See section on oil & gas resources on the Atoka for further discussion of this well.

TABLE 6—Surface and bottom-hole locations of the eight wells proposed to be drilled deviated under the WIPP land withdrawal area by Bass Enterprises.

(1) James Ranch Unit #20
Surface Location: 200' FNL & 460' FWL, sec. 6 T23S R31E
Bottom Hole Location: 660' FSL & 660' FWL, sec. 31 T22S R31E
APD Received: April 14, 1993

(2) James Ranch Unit #21
Surface Location: 200' FNL & 1980' FWL, sec. 6 T23S R31E
Bottom Hole Location: 660' FSL & 1980' FWL, sec. 31 T22S R31E
APD Received: April 9, 1993

(3) James Ranch Unit #22
Surface Location: 200' FNL & 1980' FEL, sec. 6 T23S R31E
Bottom Hole Location: 660' FSL & 1980' FEL, sec. 31 T22S R31E
APD Received: April 9, 1993

(4) James Ranch Unit #23
Surface Location: 200' FNL & 660' FEL, sec. 6 T23S R31E
Bottom Hole Location: 660' FSL & 660' FEL, sec. 31 T22S R31E
APD Received: April 14, 1993

(5) James Ranch Unit #24
Surface Location: 500' FNL & 330' FEL, sec. 6 T23S R31E
Bottom Hole Location: 1650' FSL & 330' FEL, sec. 31 T22S R31E
APD Received: April 14, 1993

(6) James Ranch Unit #25
Surface Location: 200' FNL & 1650' FEL, sec. 6 T23S R31E
Bottom Hole Location: 1650' FSL & 1650' FEL, sec. 31 T22S R31E
APD Received: April 14, 1993

(7) James Ranch Unit #26
Surface Location: 200' FNL & 2310' FWL, sec. 6 T23S R31E
Bottom Hole Location: 1650' FSL & 2310' FWL, sec. 31 T22S R31E
APD Received: April 14, 1993

(8) James Ranch Unit #27
Surface Location: 1650' FSL & 200' FEL, sec. 36 T22S R30E
Bottom Hole Location: 1980' FSL & 660' FWL, sec. 31 T22S R31E
APD Received: April 14, 1993

Bass Enterprises submitted applications to drill eight wells within the boundaries of the WIPP land withdrawal area from surface locations outside of the site (Table 6) for purposes of establishing hydrocarbon production. The applications to drill were denied by the U.S. Bureau of Land Management in August 1994. See Ramey (1995) for a copy of the letter from the Bureau of Land Management to Bass Enterprises in which the applications to drill were denied.

DELAWARE MOUNTAIN GROUP

The Delaware Mountain Group (Guadalupian) is the major oil producing unit near the WIPP site (Fig. 14). It is subdivided into three formations (descending): Bell Canyon, Cherry Canyon, and Brushy Canyon. It was deposited basinward of the Getaway, Goat Seep, and Capitan shelf-margin and reef complexes (Fig. 15). The Delaware Mountain Group consists of sandstone, siltstone, shale, and minor (<5%) limestone, dolostone, and conglomerate (Harms and Williamson, 1988). In areas adjacent to the WIPP site, production is obtained from the Cherry Canyon and Brushy Canyon Formations, with most production coming from the Brushy Canyon.

The Bell Canyon Formation, at a depth of approximately 4500 ft, has been penetrated by most wells in the study area (Fig. 2). Most oil and gas exploratory wells drilled in the WIPP area prior to 1965 reached total depth in the upper or middle part of the Bell Canyon. Objectives were upper Bell Canyon sandstones. Sandstones in this part of the section have produced prolifically in southern Eddy and Lea Counties (Broadhead, 1993b; Broadhead and Speer, 1993). Notable pools in the Bell Canyon are Paduca, El Mar, and Mason North, all of which lie near the southern border of New Mexico with Texas (Fig. 15, see Berg,

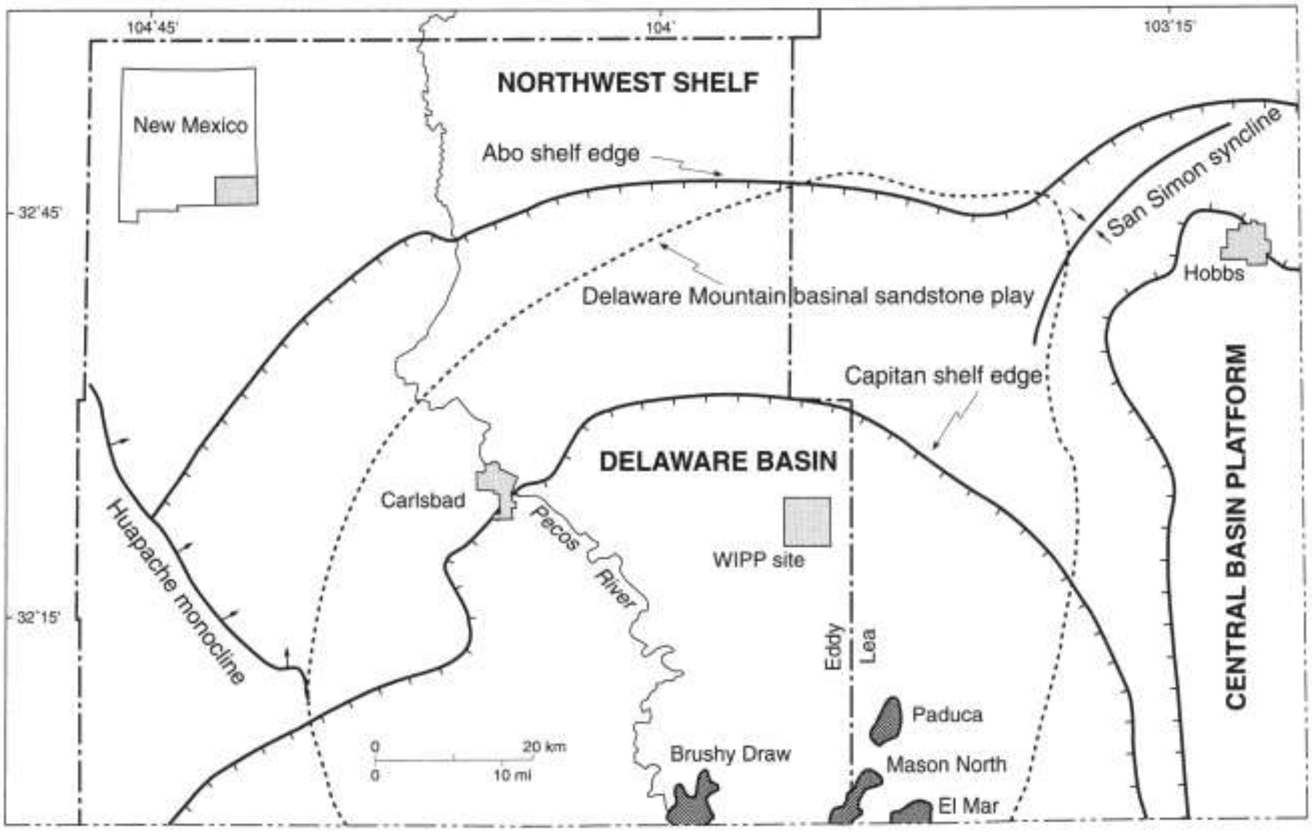


FIGURE 15—Outline of area in Delaware Basin in which productive Delaware reservoirs have been found ("Delaware Mountain basinal sandstone play"), and location of shelf edge during Abo deposition and during Capitan reef deposition. Shown are Delaware oil pools with production of more than 5 BCF associated gas as of December 31, 1990. From Broadhead (1993b).

1975, 1979; Harms and Williamson, 1988). Many of the Bell Canyon penetrations in the WIPP area encountered oil shows through drill-stem tests or in cores, but production has not been established. At present, reservoir-quality sandstones in the Bell Canyon are used for disposal of produced oil-field brines in the vicinity of WIPP (Table 7). Nearest Bell Canyon production is in the Triste Draw field in T23S R32E (Fig. 14).

The Cherry Canyon Formation has been penetrated and tested by numerous wells. Most of these wells have been drilled since 1970. Production of oil and associated gas from Cherry Canyon sandstones has been established at several fields in the WIPP area, including Livingston Ridge East, Livingston Ridge South, Red Tank West, Sand Dunes, Cabin Lake, and Fortyniner Ridge. The more prolific Cherry Canyon wells have estimated ultimate recoveries of more than 180,000 bbls of oil/ well. For reasons discussed below in sections on estimated resources at the individual fields, known hydrocarbon traps (probable resources) in the Cherry Canyon cannot be shown to extend through the WIPP land withdrawal area. It is possible,

TABLE 7—Active salt-water disposal (swd) and injection (inj) wells in study area as of December 31, 1993. Phillips No. WI-3 James A and WI-12 James A wells are used for pressure maintenance in Cabin Lake Delaware pool.

Location Sec-T-R	Operator	Well no. & lease	Injection depth	Stratigraphic unit	Type of well
2-22S-30E	Phillips Petroleum	W1-12 James A	5388–7408	Cherry Canyon/Brushy Canyon	inj
2-22S-30E	Phillips Petroleum	W1-3 James A	5647–7264	Cherry Canyon/Brushy Canyon	inj
24-22S-31E	Texaco	WD-5 Getty 24 Federal	4519–5110	Bell Canyon	swd
7-22S-32E	Yates Petroleum	WD-1 Flamenco Federal	4676–5814	Bell Canyon	swd
35-22S-31E	Yates Petroleum	1 David Ross AIT Federal	4500–5870	Bell Canyon/Cherry Canyon	swd
21-22S-32E	Strata Production	WD-1 Gilmore Federal	4807–6534	Bell Canyon	swd
14-23S-32E	Strata Production	1 Cuervo Federal	5499–5998	Bell Canyon	swd
26-23S-31E	Devon Energy	3-26 Todd Federal	4379–5700	Bell Canyon	swd
26-23S-31E	Devon Energy	2-26 Todd Federal	4460–5134	Bell Canyon	swd
29-23S-32E	Harvard Petroleum	1 James Federal	4885–4944	Bell Canyon	swd
35-23S-31E	Pogo Producing	1 Cal-Mon			swd
35-23S-32E	Tempo Energy	1 James Federal			swd

however, that undiscovered hydrocarbon traps (possible resources and probable resources-new pools) exist in the Cherry Canyon beneath the WIPP land withdrawal area.

The Brushy Canyon Formation is a prolific producer of oil and associated gas in oil pools adjacent to the WIPP land withdrawal area. Traps are largely stratigraphic, although some have a structural component. The top of the Brushy Canyon Formation has been picked at different log markers by different operators. The log marker used for the Brushy Canyon top in this study is the one used by most operators in the area. Sandstones in the Brushy Canyon are the sole or major producer at all the Delaware oil pools which are adjacent to the WIPP land withdrawal area, including the Livingston Ridge—Lost Tank pool, the Los Medanos-Sand Dunes West—Ingle Wells—Livingston Ridge South complex, the Cabin Lake pool, and the Quahada Ridge Southeast pool.

Depositional model and reservoir lithology of Delaware Mountain Group

The depositional setting and origin of the three formations that constitute the Delaware Mountain Group have been studied by numerous workers, including Harms and Williamson (1988), Berg (1975, 1979), Williamson (1979), Payne (1976), Jacka (1979), Bozanich (1979), Cromwell (1979), and Thomerson and Catalano (1994). The general depositional model for the Delaware is discussed here because an understanding of it was crucial to the construction and interpretation of stratigraphic contour maps of productive reservoir zones, and is essential to the projection of known (existing) traps under the WIPP land withdrawal area and the one-mile-wide additional study area.

Siltstones and shales in the Delaware were deposited mostly by suspension settling as thin, widespread beds that blanket the deep basin. Some of the siltstones and shales may represent distal deposition by turbidites and density currents. Straight to slightly sinuous channels were eroded into these fine-grained basinal sediments by deep-water density and turbidity currents. These currents moved down paleoslope, which dipped south to southeast in the vicinity of WIPP; channel axes are approximately parallel to paleoslope. These channels are filled by shelf-derived allochthonous sandstones. The exact mechanism of sand movement from the shelf into the basin has been ascribed to various similar mechanisms such as density currents and turbidity currents. Most recent workers have concluded that the sand was transported down the slope into the basin by density currents (Bozanich, 1979; Jacka, 1979; Harms and Williamson, 1988). Deposition occurred primarily in submarine fans at the toe-of-slope. Generally, these sand-rich channels within the fans are better defined and narrower in the Bell Canyon Formation than in the Cherry and Brushy Canyon Formations. Porosity of productive Bell Canyon sandstones typically ranges from 20 to 25%, and permeability typically ranges from 7 to 24 millidarcies (Broadhead, 1993b). Porosity and permeability of productive Cherry Canyon and Brushy Canyon sandstones are generally somewhat less than those of Bell Canyon sandstones (Steve Mitchell of Scott Exploration, pers. comm. 1994).

Detailed lithologic and petrographic descriptions of Delaware sandstone reservoirs that are productive adjacent to the WIPP land withdrawal area are not available in the literature. However, Thomerson and Asquith (1992) and Thomerson and Catalano (1994) have provided good descriptions of Brushy Canyon sandstone reservoirs in the Hat Mesa, Red Tank, and Livingston Ridge East pools. These pools are located within four miles of pools that produce adjacent to the WIPP land withdrawal area. Brushy Canyon reservoirs in these three pools are probably similar to Brushy Canyon reservoirs projected to extend underneath WIPP and can be used for gross reservoir description.

The Brushy Canyon reservoirs are coarse-grained siltstones and very fine-grained sandstones (Thomerson and Asquith, 1992; Thomerson and Catalano, 1994). Sorting is moderate to good and composition is subarkosic. Syntaxial quartz overgrowths, calcite, and dolomite are common cements. Dissolution of feldspars is widespread. Illite and mixed-layer illite/smectite are found as authigenic clays in pore spaces; detrital or depositional clay materials are uncommon. The authigenic illite is present as fibrous grain coatings that bridge pores. The mixed-layer clays occur as platy aggregates that radiate from grain surfaces. Authigenic chlorite has also been observed to fill depositional pores in some Delaware Mountain sandstones (Hays and Tieh, 1992; Walling et al., 1992). In general, productive reservoir-quality sandstones contain the least amounts of authigenic clays and cements.

Brushy Canyon sandstones are characterized by high irreducible water saturations and high residual-oil saturations (Thomerson and Asquith, 1992). This is due to the fine grain size and resulting small pore sizes in the sandstones, as well due to the authigenic clays that partially fill depositional pores. The fine-grained nature of the sediment has also resulted in the somewhat limited permeability described above.

Similar paleogeographic settings indicate that the Brushy Canyon under the WIPP land withdrawal area was deposited in the same depositional environment as the Brushy Canyon at the Red Tank and Livingston Ridge East Delaware pools 3 mi to the east. In those pools the Brushy Canyon was deposited in a sand-rich submarine fan and channel complex (Thomerson and Catalano, 1994). The lower part of the Brushy Canyon was deposited on an outer fan and basin plain at the distal fringes of the submarine-fan environment. The upper part of the Brushy Canyon was deposited on the middle and inner parts of the submarine fan as massive channel-fill, overbank, and levee deposits (Thomerson, 1994). Thomerson's interpretation fits the models of submarine-fan sedimentation advanced by Mutti and Ricci Lucchi (1978; Fig. 16) and Walker (1978; Figs. 17, 18). The Mutti-Ricci Lucchi model emphasizes the distribution of lithofacies on a fan and is perhaps best employed when sufficient core descriptions exist to map lithofacies in the subsurface.

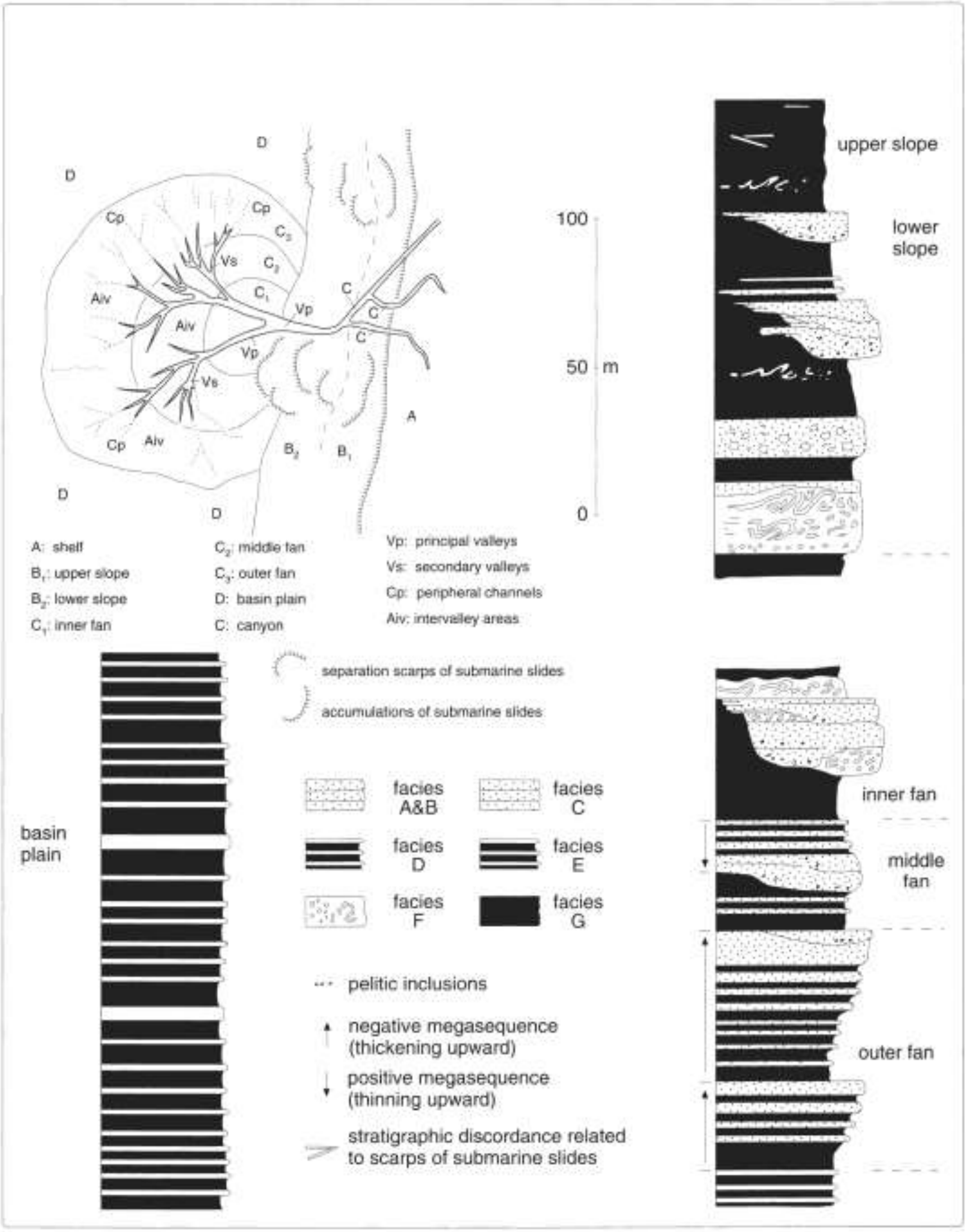


FIGURE16—Diagnostic characteristics of the principal associations of turbidite facies. From Mutti and Ricci Lucchi (1978, fig. 13).

The Walker model emphasizes vertical and lateral bedding variations within submarine-fan deposits and is perhaps best employed when analyzing and correlating geophysical logs. The Walker model is used in this study because resistivity and gamma-ray logs were used to map and define sediment distributions in the subsurface. The resulting maps are indispensable for the mapping of pool and trap boundaries in the Delaware Mountain Group.

Stratigraphic cross sections through the Brushy Canyon confirm Thomerson's interpretation of depositional environments [Figs. 14,19-23 (in pocket)]. The lowermost part of the Brushy Canyon consists of widely correlative sand-rich sediment packages. Although thickness of these packages changes from well to well, channeling and erosion of underlying sediments are not obvious. Individual sandstone beds are laterally continuous and the reservoirs are widespread. This is consistent with deposition on the lower fan and lower part of the mid-fan in the Walker model; thicker packages of sediments were deposited as unchannelized lobes downslope of fan channels.

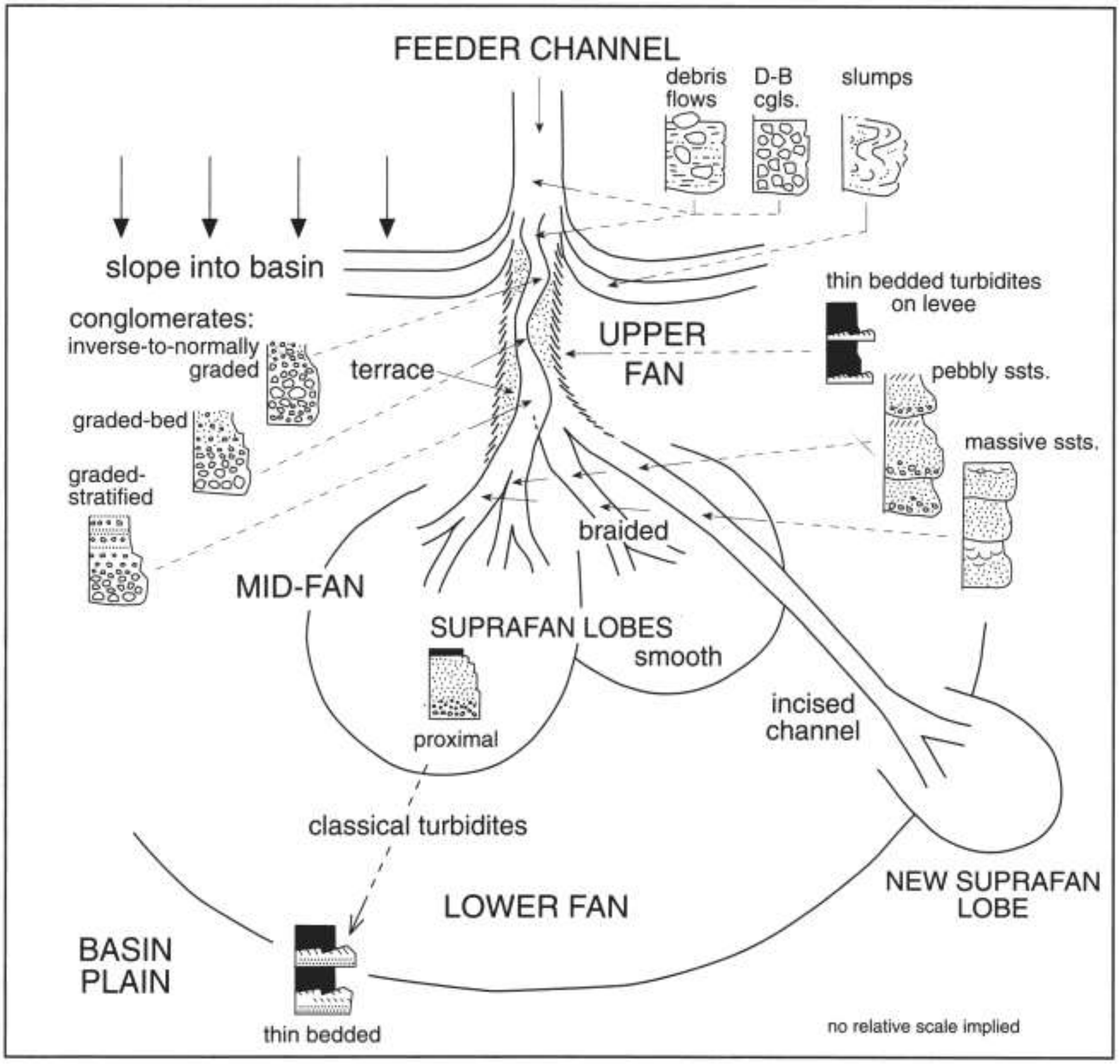


FIGURE 17—The Walker depositional and lithofacies model of submarine-fan sedimentation. From Walker (AAPG©1978, fig. 13, used with permission of the American Association of Petroleum Geologists).

Intervening areas of thinner sediment were interlobe areas. On the other hand, correlations in the upper part of the Brushy Canyon show the presence of sand-filled channels on the submarine fan (Figs. 19, 22). These channels thin and pinch out laterally. At Cabin Lake the channels erosionally truncate underlying sediments (Fig. 22). These stratigraphic relationships are consistent with the Walker model of the upper mid-fan and perhaps the lower parts of the upper fan.

The lowermost part (lower 300 ft or so) of the Cherry Canyon exhibits correlation and lithologic characteristics similar to the lower Brushy Canyon and was deposited in a lower-fan environment. This is consistent with a postulated highstand of sea level in the time interval between Brushy Canyon and Cherry Canyon deposition and cessation of submarine-fan deposition at the end of Brushy Canyon time (Guadalupian) (Jacka, 1979; Kerans et al., 1993). When sea level fell at the beginning of Cherry Canyon time (Guadalupian), submarine-fan deposition recurred within the Delaware Basin. In the vicinity of WIPP, deposition was again on the lower fan. Mid-fan and upper-fan deposition took place during late Cherry Canyon time as the submarine fan prograded in a basinward (southerly) direction.

Five depositional units in the Brushy Canyon were correlated and mapped throughout the study area (Figs. 19-23). These depositional units encompass the

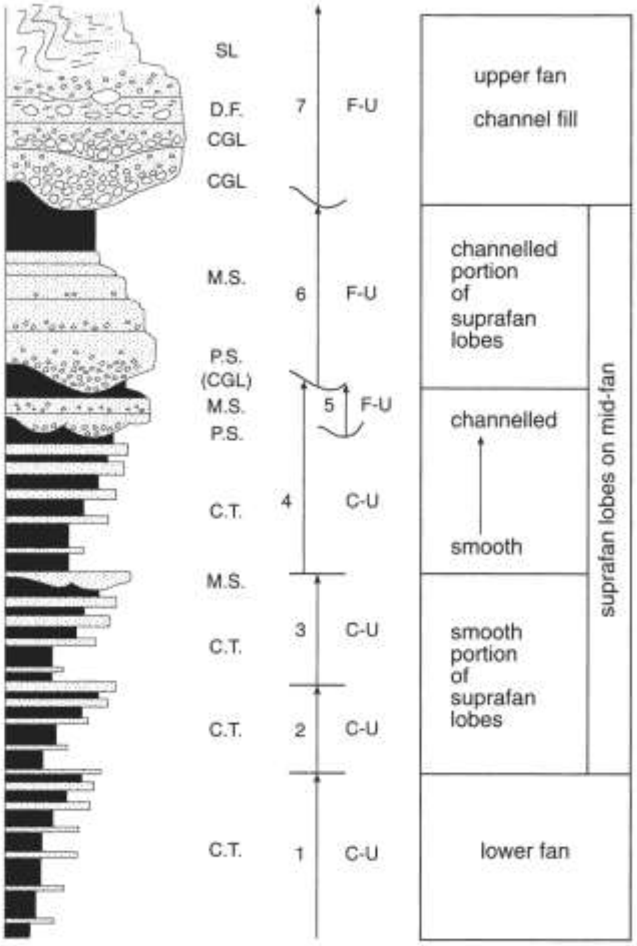


FIGURE 18—Idealized stratigraphic sequence developed as a result of propagation of a submarine fan. C–U represents thickening- and coarsening-upward sequence. F–U represents thinning- and fining-upward sequence. From Walker (AAPG©1978, fig. 14, used with permission of the American Association of Petroleum Geologists).

main oil-producing reservoirs in the Delaware pools adjacent to the WIPP land withdrawal area. The lower Brushy Canyon is subdivided into zones (descending) A through D. In the lower Brushy Canyon, the A zone consists of two resistive lime markers separated by sandstone. The B zone consists primarily of argillaceous ("shaley") sandstone and minor shale and limestone. It is the main pay at the Cabin Lake and Quahada Ridge Southeast pools. The C zone consists of two resistive lime markers separated by an interval of sandstone and shale. The D zone consists primarily of sandstone and minor shale and limestone. It is the main pay at the Los Medanos, Sand Dunes West, Ingle Wells, and Livingston Ridge South pools. The fifth depositional unit is in the uppermost Brushy Canyon; this unit, referred to as the *Livingston Ridge main pay,* is the main pay zone at the Livingston Ridge field. It consists mostly of argillaceous ("shaley") sandstone with minor shale and limestone.

Livingston Ridge—Lost Tank pool

The Livingston Ridge Delaware and Lost Tank Delaware pools lie along a north—south trend on the eastern boundary of the WIPP land withdrawal area. Production is from sandstones in the Delaware Mountain Group at a depth of approximately 7000 ft. The Livingston Ridge pool was discovered in 1988 and the Lost Tank pool was discovered in 1992. Subsequent drilling has brought defined boundaries of these two pools together. Development of these pools has been rapid, averaging 25 wells drilled per year from 1991 to 1993. At the end of 1993 there were 42 active producing wells in the Livingston Ridge pool and 37 active producing wells in the Lost Tank pool. Wells have been drilled on 40-acre proration (spacing) units in both pools. Production has been extended into the one-mile-wide additional study area, but no wells have been drilled within the WIPP land withdrawal area for purposes of developing these pools. Cumulative production from both pools totaled 3.6 million bbls of oil and 4.7 billion ft^3 of gas as of December 31, 1993 (Table 8).

Geologically, the Livingston Ridge and Lost Tank pools are interconnected and formed by the same hydrocarbon trap. The distinction between the two pools is regulatory. The main pay zone at the Livingston Ridge—Lost Tank Delaware pool is a channel in the upper part of the Brushy Canyon Formation (Figs. 19, 20). The isopach map of gross channel thickness (Fig. 24) shows a south-trending channel that attains maximum thickness in excess of 90 ft along the channel axis. The channel is filled with intercalated sandstone and shale. Examination of the gamma-ray and resistivity logs (Figs. 19, 20) indicates that percentage of sandstone and net thickness of sandstone decrease away from the channel axis; in other words, shale is more prevalent toward the channel margins than it is along the channel axis. The channel forms a reservoir common to both the Livingston Ridge and Lost Tank pools. Gross thickness of the perforated zone varies between 10 and 20 ft in most wells.

The trap in the main pay zone at Livingston Ridge—Lost Tank is stratigraphic. Economic production from the main pay zone is obtained where the gross channel thickness is more than 35-40 ft (Fig. 24). Structural dip is to the southeast (Fig. 25). Updip limits to economic production on the northwest coincide with lateral thinning of the channel, and for this report have been mapped conservatively at the 40-ft thickness contour (Fig. 24). Downdip limits to production on the southeast side of the pool are also mapped at the 40-ft thickness contour. Although production has been established where the channel is as thin as 33 ft, it appears that an insufficient volume of reservoir-quality sandstone is present in most of these thinner areas. In the area around the WIPP land withdrawal area structure does not control trap boundaries, although the presence of an unsuccessful test well in SE% NE% sec. 6 T22S R32E suggests that an oil-water contact or oil-water transition zone may be present where the top of the lower Brushy Canyon is at —4600 ft. The area within the 40-ft contour of channel thickness was used to project the oil accumulation in the Livingston Ridge main pay into undrilled areas (Fig. 26). Eighteen undrilled 40-acre units are indicated within the WIPP land withdrawal area, and 107

TABLE 8—Cumulative production as of 12/31/93 and 1993 annual production of oil, gas, and water from oil and gas pools projected to extend underneath the WIPP land withdrawal area. Totals include production from outside WIPP land withdrawal area and additional one-mile-wide study area. Livingston Ridge South Delaware pool did not produce until 1994. Livingston Ridge Northeast Delaware pool did not produce until 1994. Los Medanos East Morrow pool did not produce until 1994. MMCF, million ft^3; KBO, thousand bbls oil.

Pool	Producing formation	Spacing acres	Active wells (1993)	Cumulative oil (KBO)	Cumulative gas (MMCF)	Cumulative wtr (bbls)	1993 annual oil (bbls)	1993 annual gas (MMCF)	1993 annual wtr (bbls)
Livingston Ridge	Delaware	40	42	2345	2849	2755	636	1098	896
Lost Tank	Delaware	40	37	1258	1828	2272	384	841	889
LR-LT total			**79**	**3603**	**4677**	**5027**	**1020**	**1939**	**1785**
Los Medanos	Delaware	40	23	471	464	515	426	435	450
Sand Dunes W	Delaware	40	60	1938	4716	591	1758	4526	535
Ingle Wells	Delaware	40	38	637	1372	640	506	1144	499
Livingston Ridge S	Delaware	40	0	0	0	0	0	0	0
Los Medanos complex total			**121**	**3046**	**6552**	**1746**	**2690**	**6105**	**1484**
Quahada Ridge SE	Delaware	40	1	11	9	39	11	9	39
Cabin Lake	Delaware	40	33	1599	1279	3678	624	489	1159
Delaware total			**234**	**8259**	**12,517**	**10,490**	**4345**	**8542**	**4467**
Los Medanos	Bone Spring	40	2	84	163	4	6	11	0
Bone Spring total			**2**	**84**	**163**	**4**	**6**	**11**	**0**
Cabin Lake	Strawn	40	1	176	3508	1741	3	60	45
Los Medanos	Strawn	320	0	18	1325	24	0	0	0
Strawn total			**1**	**194**	**4833**	**1765**	**3**	**60**	**45**
Sand Dunes West	Atoka	320	5	1	4011	168	0	522	31
Livingston Ridge Northeast	Atoka	320	0	0	0	0	0	0	0
Los Medanos	Atoka	320	4	349	39,679	102	349	1527	8
Atoka total			**9**	**350**	**43,690**	**270**	**349**	**2049**	**39**
Cabin Lake	Morrow	320	0	2	5547	26	0	0	0
Los Medanos	Morrow	320	4	40	17,037	382	2	2379	19
Los Medanos East	Morrow	320	0	0	0	0	0	0	0
San Dunes North	Morrow	320	2	7	3864	5	0	142	1
Morrow total			**6**	**49**	**26,448**	**413**	**2**	**2521**	**20**

undrilled 40-acre units are indicated within the additional study area.

In most wells in the Livingston Ridge—Lost Tank pool, three casing strings are used during drilling and completion operations (Fig. 27). Typically, surface casing of 13 5/8-inch diameter is set and cemented at approximately 900 ft and an intermediate string of $8^3/8$-inch diameter casing is set and cemented at a depth of approximately 4000 ft. After the well has been drilled to total depth, 5 1/2-inch production casing is set and cemented to total depth of approximately 8400 ft. It has been the practice of most operators in the Livingston Ridge—Lost Tank pool to perforate casing and produce only from the main pay channel. Before economic production can be obtained, the pay zone must be acidized and artificially fractured. Volume of the acid load is typically 2000-7000 gallons. After acidization, the reservoir is hydraulically fractured. The size of fracture treatments varies widely, but a typical treatment uses 25,000-75,000 gallons of water and 50,000-100,000 lbs of sand; sand loads in excess of 250,000 lbs have been used.

Yates Petroleum Corp. has drilled several wells in the west half of the Livingston Ridge pool, but completed them differently from the other operators. All the wells perforated the Livingston Ridge main pay and in most cases also one to four other sandstones, and established commingled production from these sandstones. These other sandstones are present in the Brushy Canyon and lower part of the Cherry Canyon. Apparently, selection of perforation intervals was based on analyses of shows reported on the mudlogs and analyses of electric and porosity logs. From comparison of production data from these wells with data from wells in which only the main pay was perforated, it is thought that these additional pay zones will increase production incrementally; most production will still be obtained from the main pay zone. In most cases, Yates has reported only the gross interval of casing perforations. It is not possible to determine which sandstones have been completed in any one well except those present at the top and the base of the gross interval. Other operators may eventually re-enter their wells and perforate additional zones when

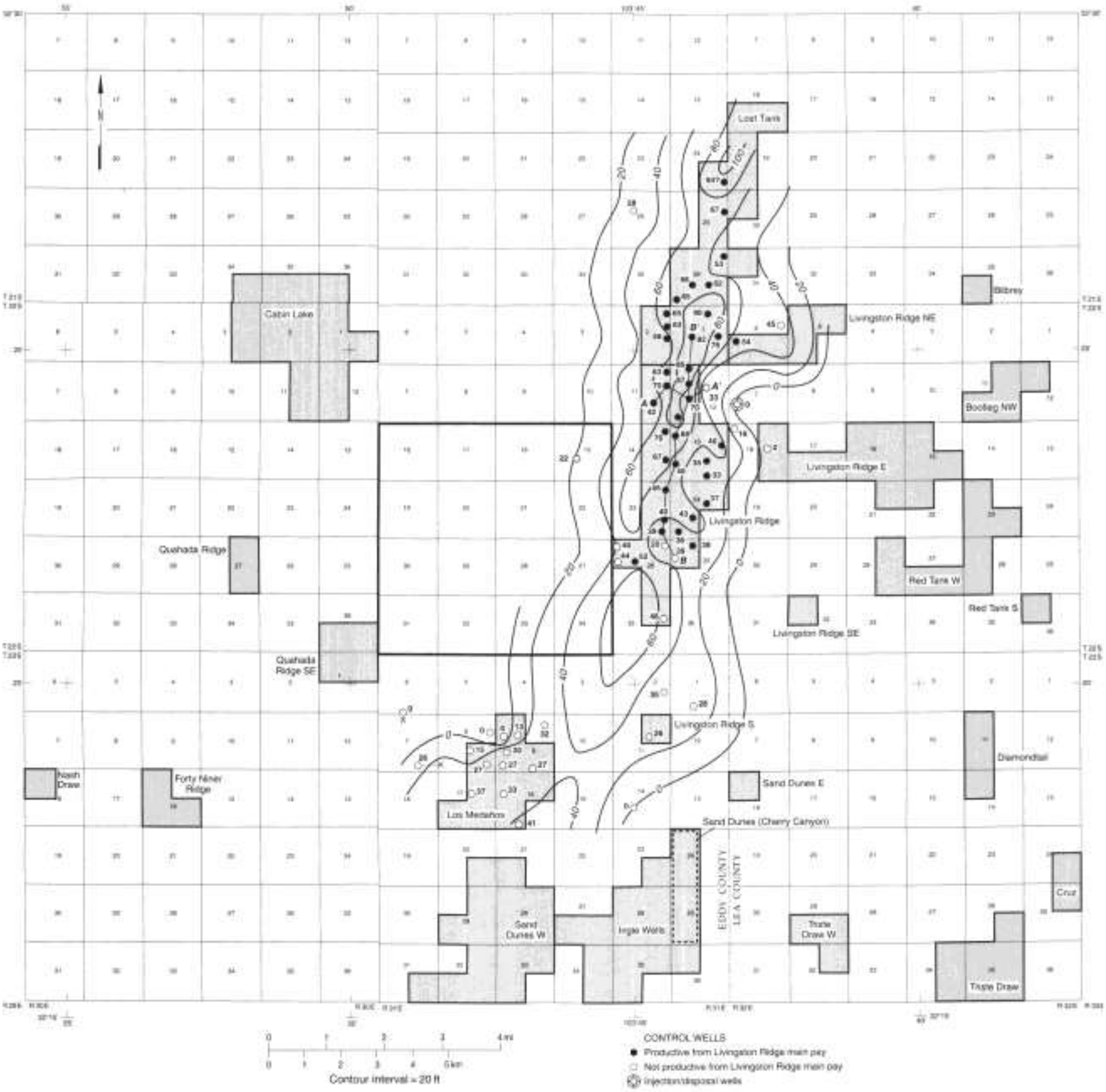


FIGURE 24—Isopach map of gross channel thickness of Livingston Ridge main pay zone. Only wells used as mapping control points are shown.

the main pay ceases to yield economic volumes of oil.

Ultimate primary recovery was calculated for 21 wells in the Livingston Ridge—Lost Tank pool. These wells produce solely or principally from the main pay zone. A few wells in the southwestern part of Livingston Ridge produce solely from sandstones in the D zone of the lower Brushy Canyon Formation (Fig. 28); ultimate primary recovery and reserves in those wells are discussed below in the section on the Los Medanos—Sand Dunes—Ingle Wells complex.

Ultimate primary recovery for the average well completed in the Livingston Ridge main pay is 89 thousand bbls oil (KBO) and 116 million ft^3 associated gas (MMCFG, Fig. 29). Ultimate primary recovery ranges from 25 to 166 KBO and 37 to 226 MMCFG for individual wells. It is estimated that there are 1602 thousand bbls oil (KBO) and 2088 million ft^3 gas from wells in which only the main pay was perforated, it is it is thought that these additional pay zones will increase production incrementally; most production will still be obtained from the main pay zone. In most cases, Yates has reported only the gross interval of casing perforations. It is not possible to determine which sandstones have been completed in any one well

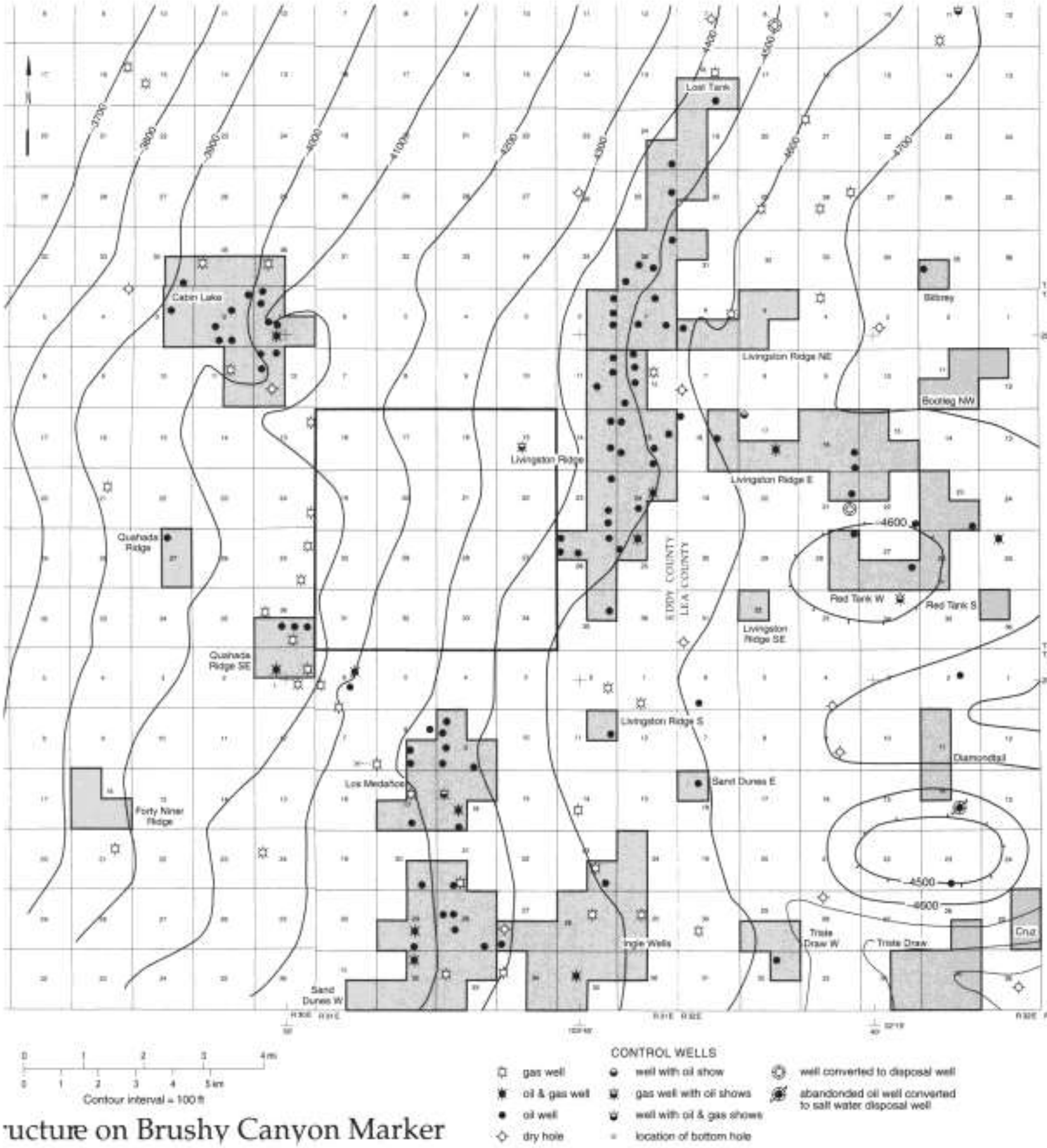


FIGURE 25—Structure contour map of marker bed at top of lower Brushy Canyon Formation. Only wells used as mapping control points are shown.

except those present at the top and the base of the gross interval. Other operators may eventually reenter their wells and perforate additional zones when the main pay ceases to yield economic volumes of oil.

Ultimate primary recovery was calculated for 21 wells in the Livingston Ridge—Lost Tank pool. These wells produce solely or principally from the main pay zone. A few wells in the southwestern part of Livingston Ridge produce solely from sandstones in the D zone of the lower Brushy Canyon Formation (Fig. 28); ultimate primary recovery and reserves in those wells are discussed below in the section on the Los Medanos-Sand Dunes-Ingle Wells complex.

Ultimate primary recovery for the average well completed in the Livingston Ridge main pay is 89 thousand bbls oil (KBO) and 116 million ft3 associated gas (MMCFG, Fig. 29). Ultimate primary recovery ranges from 25 to 166 KBO and 37 to 226 MMCFG for individual wells. It is estimated that there are 1602 thousand bbls oil (KBO) and 2088 million ft3 gas (MMCFG) that are producible via primary-recovery techniques from the Livingston Ridge main pay in the 18 undrilled proration units within the boundaries of the WIPP land withdrawal area (Table 2). This esti-

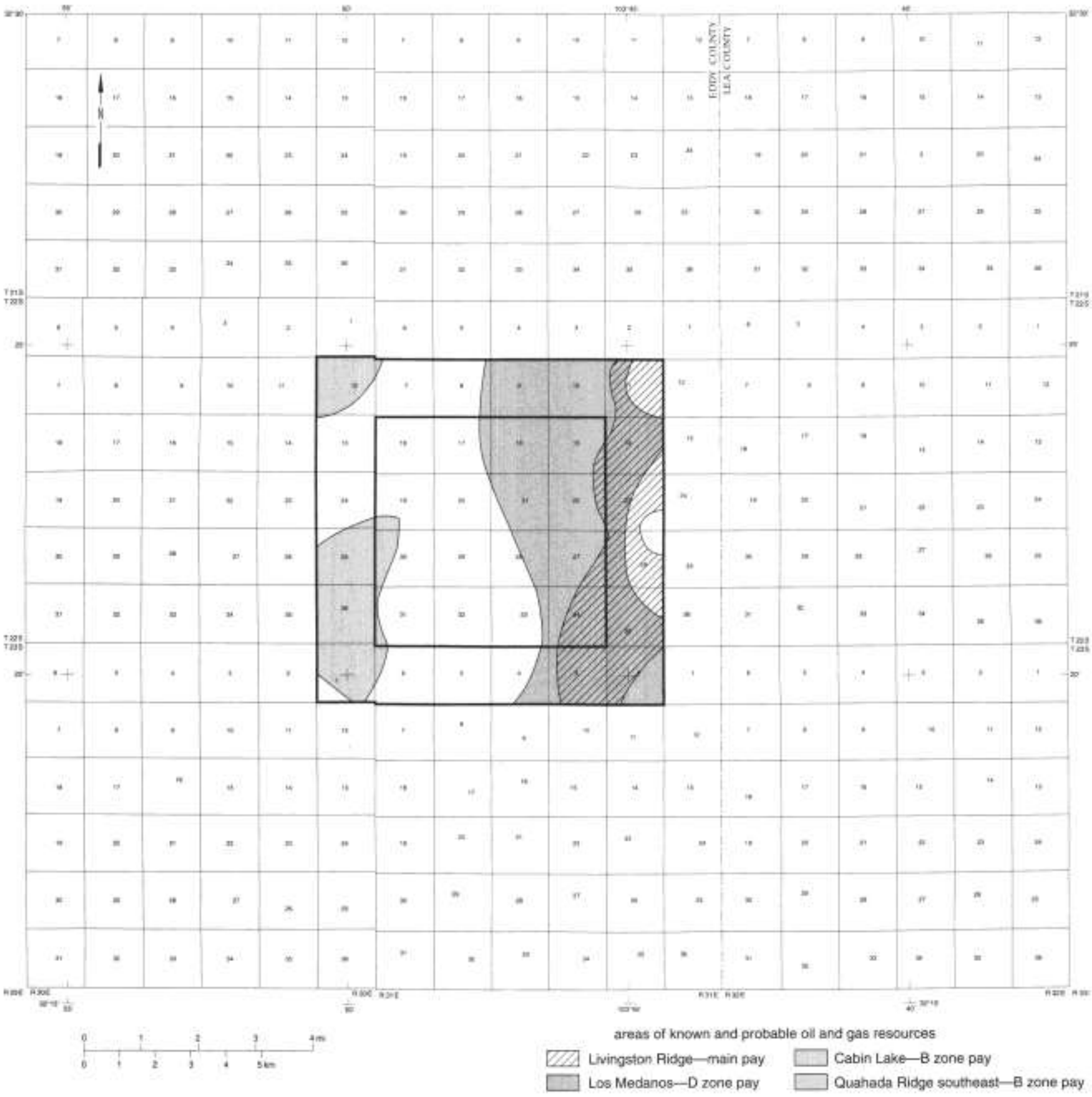


FIGURE 26—Areas of known and probable oil and gas resources within the WIPP site and one-mile-wide additional study area for Delaware pools projected to extend under the WIPP site.

mate of ultimate recovery is equal to probable resources, because the Livingston Ridge main pay has not been produced from under the WIPP land withdrawal area. There are additional 7879 KBO and 10,406 MMCFG probable resources within this pay zone in drilled and undrilled areas of the one-mile-wide additional study area (Table 3). Cumulative production from within the boundaries of the additional study area in the Livingston Ridge—Lost Tank pool was 754 KBO and 846 MMCFG as of December 31, 1993.

Los Medanos—Sand Dunes—Ingle Wells complex (Los Medanos complex)

The Los Medanos, Sand Dunes West, Ingle Wells, and Livingston Ridge South Delaware pools lie to the south of the WIPP site (Fig. 14). The main producing zone in these pools is the D zone of the lower Brushy Canyon Formation. Production is from sandstones at depths of approximately 7900 ft in the Los Medanos pool, 7800 ft in the Sand Dunes West pool, 8000 ft in the Ingle Wells pool, and 8100 ft in the Livingston Ridge South pool. The Los Medanos pool was discov-

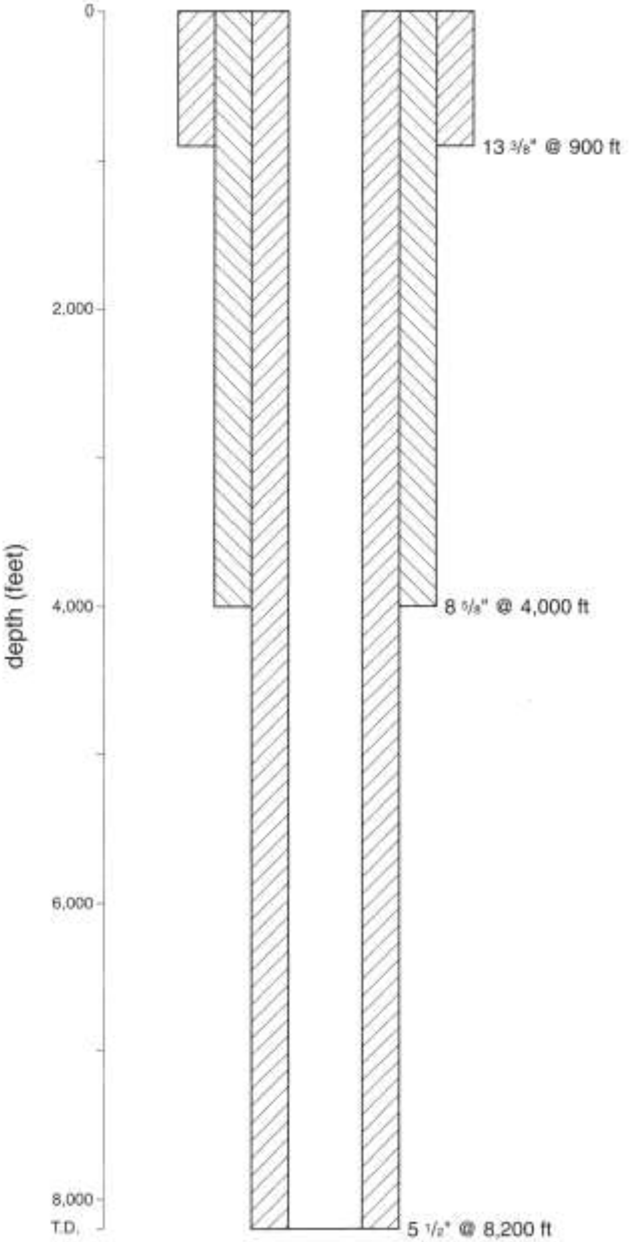


FIGURE 27—Casing program of typical well producing from Livingston Ridge main pay.

ered in 1991, Sand Dunes West in 1992, and Ingle Wells in 1989. The Livingston Ridge South Delaware pool was discovered in 1993. As of December 31, 1993, there were 23 active producing wells in the Los Medanos pool, 58 at Sand Dunes West, 38 at Ingle Wells, and only one at Livingston Ridge South. Wells have been drilled on 40-acre spacing in all four pools. Development has not yet been extended into the one-mile additional study area because of active potash leases in potentially productive areas (see Ramey, 1995, on limitations on oil and gas drilling in the potash area). Cumulative production from all four pools totaled 3 million bbls of oil and 6.5 BCF of gas as of December 31, 1993 (Table 8). Production from the lone well in the Livingston Ridge South pool had not been initiated as of the end of 1993.

Geologically, the Los Medanos, Sand Dunes West, Ingle Wells, and Livingston Ridge South pools are interconnected and are part of the same hydrocarbon trap, referred to in this report as the Los Medanos complex. The nomenclatural distinction among these pools is regulatory and stems from the widely separate locations of the discovery wells. Development drilling has expanded the areas of formal pool designation and has shown that the four pools are part of the same hydrocarbon trap.

The main pay zone in the Los Medanos complex is the D zone of the lower Brushy Canyon Formation (Fig. 23). The isopach of gross thickness of this zone (Fig. 28) indicates it is laterally continuous across the study area. Thickness of the D zone varies from less than 20 ft to more than 140 ft. Thicker areas define linear trends that are north-trending, northeast-trending, or northwest-trending. The D zone consists primarily of sandstone with lesser amounts of shale and only minor amounts of limestone. Thicker areas are not incised into underlying sediments and do not appear to represent channels. Instead, thickness variations are due to paleobathymetric relief on top of the D zone. The thick areas were deposited as lobes on the lower part of a submarine fan, and the intervening thin areas are interlobe deposits. Lithofacies grade from dominantly sandstone in the lobes to dominantly shale in the interlobe areas. A sandstone isolith map of the D zone in the Livingston Ridge and Los Medanos areas (Fig. 30) shows that trends of net sandstone thickness coincide with trends in gross thickness of the D zone (Fig. 28).

The trap that forms the Los Medanos complex is stratigraphic. Economic production from the D zone has been obtained where gross thickness of the D zone is more than 90 ft (Fig. 28). In most places this corresponds to a net sandstone thickness of more than 70 ft (Fig. 30). Thinner areas do not appear to contain sufficient reservoir-quality sandstone to yield economic levels of production. The trap at Los Medanos extends northward into the additional study area and under the WIPP land withdrawal area. Wells in the western part of the Livingston Ridge—Lost Tank pool also produce from the D zone. Several wells in sec. 26 T22S R32E in the Livingston Ridge pool obtain all of their production from the D zone. Further north in secs. 2 and 11 of the same township and in T21S R31E wells produce from the D zone, but most production appears to be obtained from the Livingston Ridge main pay of the upper Brushy Canyon; in these wells there is insufficient thickness of reservoir-quality sandstone within the D zone to sustain economic production levels, and the D zone is a secondary reservoir. The isopach and structure maps indicate that the D zone will be the probable primary producer in 107 40-acre proration units within the WIPP land withdrawal area and 121 40-acre proration units within the additional study area (Fig. 26).

Although Sand Dunes West and Ingle Wells sit astride an east-plunging structural nose, structure does not appear to exhibit major control on entrapment of oil and gas. Producing trends continue into off-structure areas; the northern part of Los Medanos, the southern part of Livingston Ridge, and Livingston

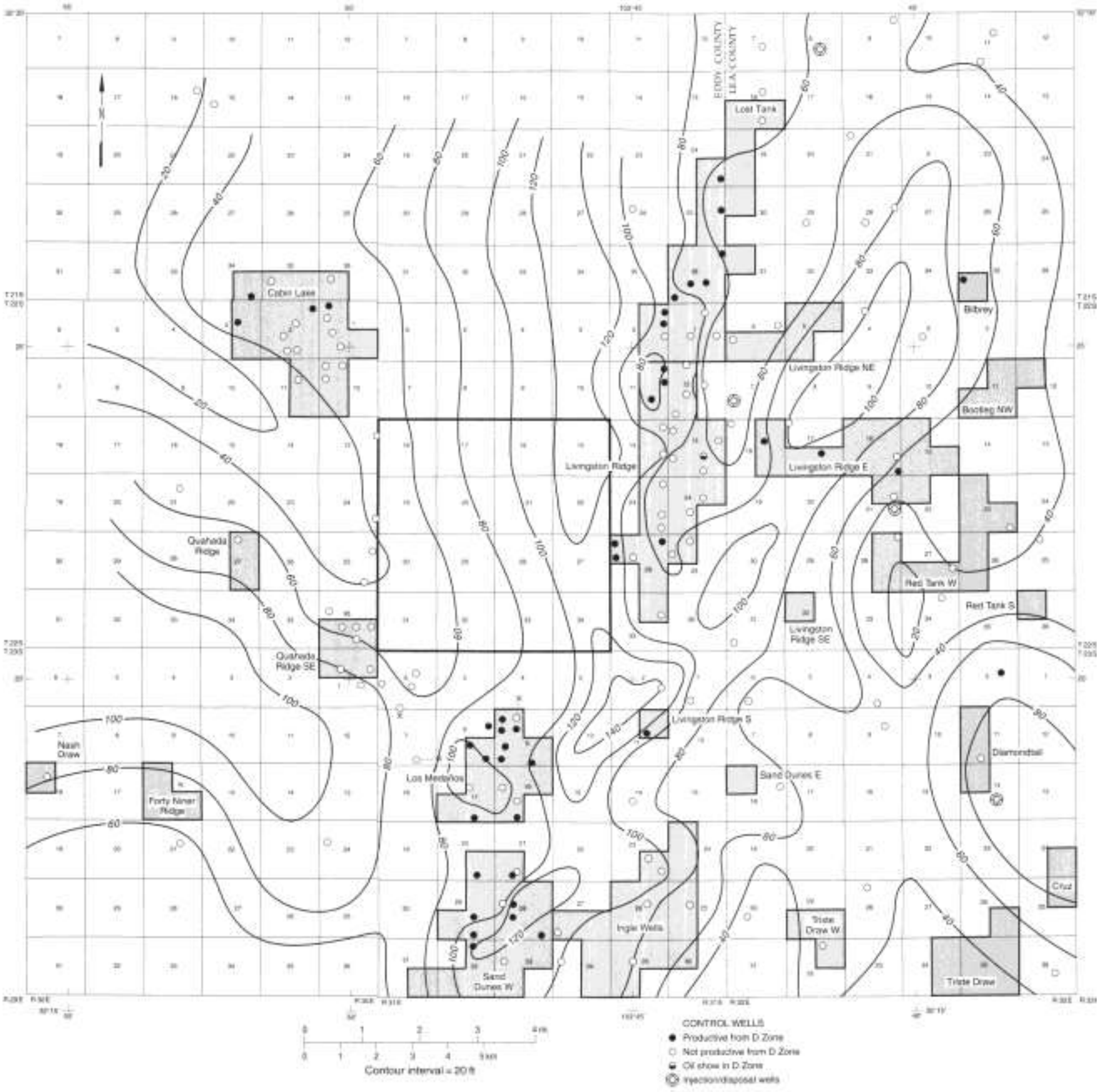
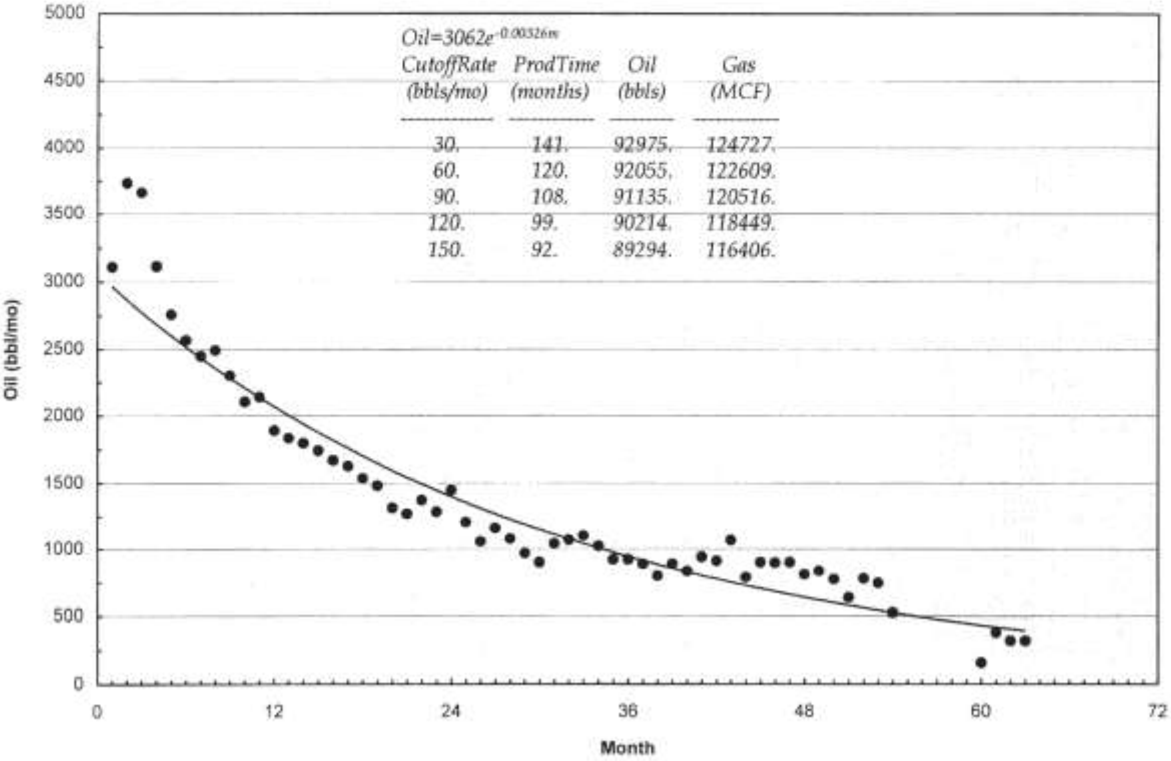


FIGURE 28—Isopach map of D zone of lower Brushy Canyon Formation. Only wells used as mapping control points are shown.

Ridge South are structurally low relative to Sand Dunes West.

Three casing strings are used during drilling and completion operations in most wells drilled to develop the lower Brushy D zone in the Los Medanos complex (Fig. 31). Typically, 13 3/8-inch surface casing is set and cemented at approximately 600 ft. An intermediate string of $8^{5}/8$-inch diameter casing is set and cemented at approximately 4100 ft in the uppermost part of the Bell Canyon Formation. Production casing of 5 1/2-inch diameter is then set and cemented to total depth of approximately 8100 ft. Casing is then perforated in the D zone. Before economic production can be obtained, the pay zone must be acidized and artificially fractured. Volume of the acid load is typically 1000-1500 gallons, but exceeds 2000 gallons in some wells. After acid treatment, the reservoir is hydraulically fractured. The size of fracture treatments varies widely; a typical treatment uses 25,000-70,000 gallons of water and 50,000-150,000 lbs of sand. Sand loads in excess of 200,000 lbs have been used.

Ultimate primary recovery was calculated for 12 wells in the Los Medanos complex. These wells produce from the main pay zone (the D zone). Ultimate



$Oil=3062e^{-0.00326m}$

CutoffRate (bbls/mo)	ProdTime (months)	Oil (bbls)	Gas (MCF)
30.	141.	92975.	124727.
60.	120.	92055.	122609.
90.	108.	91135.	120516.
120.	99.	90214.	118449.
150.	92.	89294.	116406.

FIGURE 29—Average production decline curve for wells productive from Livingston Ridge main pay, Livingston Ridge and Lost Tank Delaware pools. Also shown is the exponential equation used to generate curve.

recovery was determined for wells in the Los Medanos, Sand Dunes West, Ingle Wells, and Livingston Ridge pools. In the Livingston Ridge pool, the only wells for which ultimate recovery was calculated were those which produce solely from the D zone. The D zone in wells at the north end of Livingston Ridge and at Lost Tank is thin and forms a secondary reservoir; these wells were not used in estimation of ultimate recovery, because they produce from the fringe areas of the Los Medanos complex where the D zone is not economic by itself.

Ultimate primary recovery for the average well completed in the D zone of the Los Medanos complex is 76 KBO and 166 MMCF associated gas (Fig. 32, Table 2). These values will be somewhat less than estimates for only the Los Medanos and Sand Dunes West pools, because D zone wells at Livingston Ridge have estimated primary recoveries less than the value predicted by the average decline curve. Estimated primary recovery values for all D zone wells used in this study range from 13 to 277 KBO and 15 to 748 MMCF associated gas, but estimated primary recovery values from D zone wells at Livingston Ridge range from 26 to 69 KBO and 35 to 126 MMCF associated gas.

Estimated ultimate primary recovery for the D zone in the 107 undrilled 40-acre proration units within the WIPP land withdrawal area is 8132 KBO and 17,762 MMCF associated gas (Table 2). This is equal to resources, because the D zone has not been produced from underneath the WIPP land withdrawal area. A total of 282 KBO and 425 MMCF gas has been produced from the D zone within the one-mile-wide additional study area. Probable resources recoverable with primary production methods within this area are 8914 KBO and 19,661 MMCF gas (Table 3).

Cabin Lake pool

The Cabin Lake Delaware pool lies along the northwestern boundary of the WIPP land withdrawal area (Fig. 14). Although it is legally described as a single Delaware pool, production is mostly from two traps in two separate reservoirs. These reservoirs are the B zone of the lower Brushy Canyon Formation and sandstones in the middle part of the Cherry Canyon Formation. (Figs. 21, 22). Production in the lower Brushy B zone is from sandstones at a depth of approximately 7400 ft. Production in the Cherry Canyon is from sandstones at depths of 5500-5900 ft. In addition, there appears to be relatively minor production obtained from localized, scattered traps in the upper Bell Canyon at 3600 ft, and from the thin sandstones scattered throughout the Cherry Canyon and upper Brushy Canyon.

The Cabin Lake pool was discovered in 1986. Pool development has been rapid, averaging about seven new wells per year from 1987 through 1993. At the end of 1993 there were 33 active wells in the Cabin Lake pool, of which five were shut in. Wells have been drilled on 40-acre spacing, typical for the Delaware in southeast New Mexico. Production has been estab-

FIGURE 30—Sandstone isolith map of D zone, lower Brushy Canyon Formation. Only wells used as mapping control points are shown.

lished in the one-mile-wide additional study area, but no wells have been drilled within the WIPP land withdrawal area for developing this pool. Cumulative production for the entire Cabin Lake pool totaled 1.6 million bbls oil and 1.3 billion ft^3 associated gas as of December 31, 1994 (Table 8). Beginning in 1991, production was enhanced with a pressure-maintenance project. Pressure maintenance is accomplished by injection of water into sandstone reservoirs in the Cherry Canyon and Brushy Canyon from depths of 5600-7400 ft.

Two wells have been used for water injection (Table 7). In December 1993, 45,009 bbls of water were injected in the Phillips No. 3 James A well at an average injection pressure of 710 pounds per inch^2 (psi). During the same month, 70,166 bbls of water were injected in the Phillips No. 12 James A well at an average injection pressure of 390 psi. When the pressure maintenance project began, oil field waters produced from Phillips' wells in the area were used for injection (New Mexico Oil Conservation Division Order No. R-9500). These produced waters are presumably still the source of injection water.

Oil is trapped in combination multipay structural stratigraphic traps in the Cabin Lake pool. The primary trapping mechanism is structural, with oil accumu-

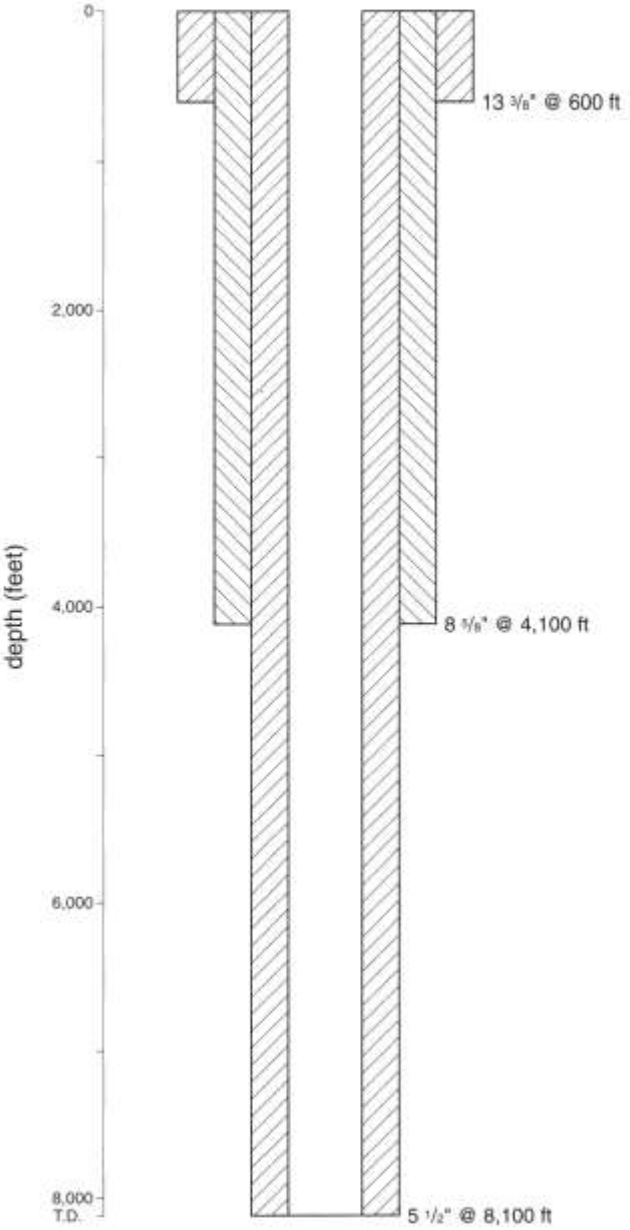


FIGURE 31—Casing program of typical well production from lower Brushy Canyon D zone in the Los Medanos complex.

lations in the various reservoirs localized on a southeast-plunging structural nose (Fig. 25). Depositional pinchout of reservoir sandstones to the northwest provides updip limits to oil accumulations in each reservoir. Oil-water contacts in the reservoir sandstones provide limits to production on the southeast (Fig. 33). The main pay in the one-mile-wide additional study area and the one with the most potential of extending into the WIPP land withdrawal area is the lower Brushy Canyon B zone. The isopach map of gross thickness of the B zone (Fig. 34) indicates maximum thickness in two distinct areas; one area is in the eastern (downdip) part of the Cabin Lake pool and the other area is in the northwestern, updip part of the pool. The B zone is not the major reservoir in the intervening thinner area. Productive Cherry Canyon reservoirs are limited to the updip (northwest) parts of the Cabin Lake pool and do not appear to extend into the WIPP land withdrawal area. Productive reservoirs in the B zone are present within sec. 12 T22S R30E in the additional study area. It is not known if the oil column in this reservoir extends downdip to the southeast because of an absence of drill holes. Therefore the extent of probable productive area within the B zone has been conservatively mapped to include only those portions of the reservoir known to be above an oil-water contact, and consists of 13 undrilled 40-acre proration units (Fig. 26) within the additional study area. Mapping does not indicate that oil accumulations extend underneath the WIPP land withdrawal area.

Three casing strings are used during drilling and completion operations in most wells drilled to develop Brushy Canyon and Cherry Canyon reservoirs at Cabin Lake (Fig. 35). Typically, $13^{3}/8$-inch surface casing is set and cemented at approximately 500 ft. An intermediate string of $8^{5}/8$-inch diameter casing is set and cemented at approximately 3700 ft. Production casing of 5 1/2-inch diameter is then set and cemented to total depth of approximately 7700 ft. The production casing is then perforated in the appropriate reservoir. Before economic production can be obtained, the pay zone must be acidized and artificially fractured. Volume of the acid load is typically 2000-4000 gallons. After acid treatment, the reservoir is hydraulically fractured. The size of fracture treatments varies, but they typically utilize 10,000-20,000 gallons of water and 20,000-30,000 lbs of sand in the Cherry Canyon and upper Brushy Canyon; in some wells, 13-26 tons of CO2 have been added to the treatment. In the lower Brushy Canyon B zone, typical fracture treatments are larger and utilize 30,000-120,000 gallons of water and 50,000-200,000 lbs of sand. Sand loads in excess of 400,000 lbs have been used in fracture treatments of the B zone.

Ultimate primary recovery was calculated for wells in the Cabin Lake pool with difficulty. The pressure-maintenance project affected production in most wells and rendered the production decline curves unusable. However, three wells in sec. 12 T22S R30E were used. For one of these, the Phillips No. 14 James E well, the production decline curve for B zone production was usable for calculation of ultimate recovery. Two other wells in sec. 12 that produce from the B zone have unsatisfactory decline curves, so their cumulative production was used as an estimate of *minimum* ultimate recovery. These wells were used because their cumulative production is several times the ultimate primary recovery calculated for the Phillips No. 14 James E well; apparently ultimate recovery in that well is not representative of the reservoir as a whole. Calculated average ultimate primary recovery per well is 66 KBO and 46 MMCF associated gas. A total of 276 KBO and 175 MMCF associated gas have been produced from the one-mile-wide additional study area. It is estimated that there are probable resources of 582 KBO and 423 MMCF associated gas producible via primary recovery techniques from the 13 undrilled 40-acre proration units within the additional study area (Table 3).

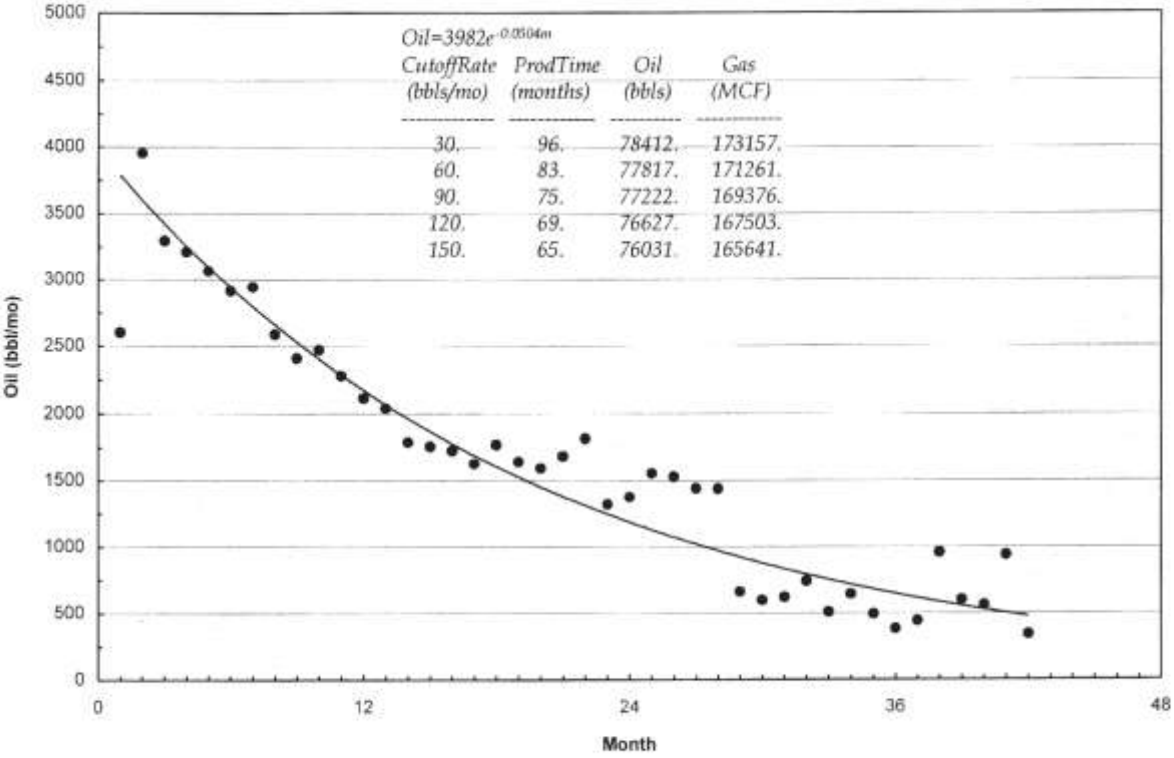


FIGURE 32—Average production decline curve for wells productive from D zone of lower Brushy Canyon Formation, Los Medanos complex. Also shown is the exponential equation used to generate curve.

Quahada Ridge Southeast pool

The Quahada Ridge Southeast Delaware pool lies along the southwest border of the WIPP land withdrawal area (Fig. 14). The pool produces oil and associated gas. Production is from the B zone of the lower Brushy Canyon Formation at a depth of approximately 7500 ft. The pool was discovered in 1993. Development of the pool has been slow, with only three wells drilled by the end of 1993 and two more in 1994. Wells were drilled on 40-acre spacing. At the end of 1993, there was only one active producing well in the pool; the other two wells drilled during 1993 have not yet been brought into production. Cumulative production from the pool totaled 11 KBO and 8.5 MMCF associated gas as of December 31, 1993 (Table 8). Although data are limited by a paucity of wells, the isopach map of the gross thickness of the B zone (Fig. 34) indicates a thick south-southeast trend in the southwest part of the WIPP land withdrawal area. These thick areas in the B zone coincide with thin areas in the underlying D zone (Fig. 28) and appear to be infillings of bathymetrically low interlobe areas in the lower submarine-fan environment. Although wells have penetrated the B zone outside of the established pool boundaries, they have been drilled for hydrocarbons in deeper strata and have not adequately tested B zone sandstones. The sparse data indicate that eco-

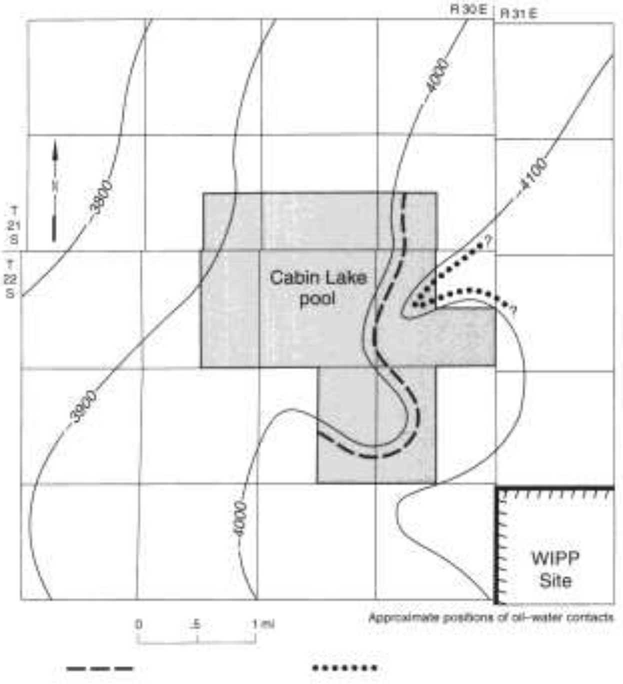


FIGURE 33—Structure map of top of lower Brushy Canyon Formation, Cabin Lake pool, showing postulated oil–water contacts in main reservoirs. Contours from Fig. 25.

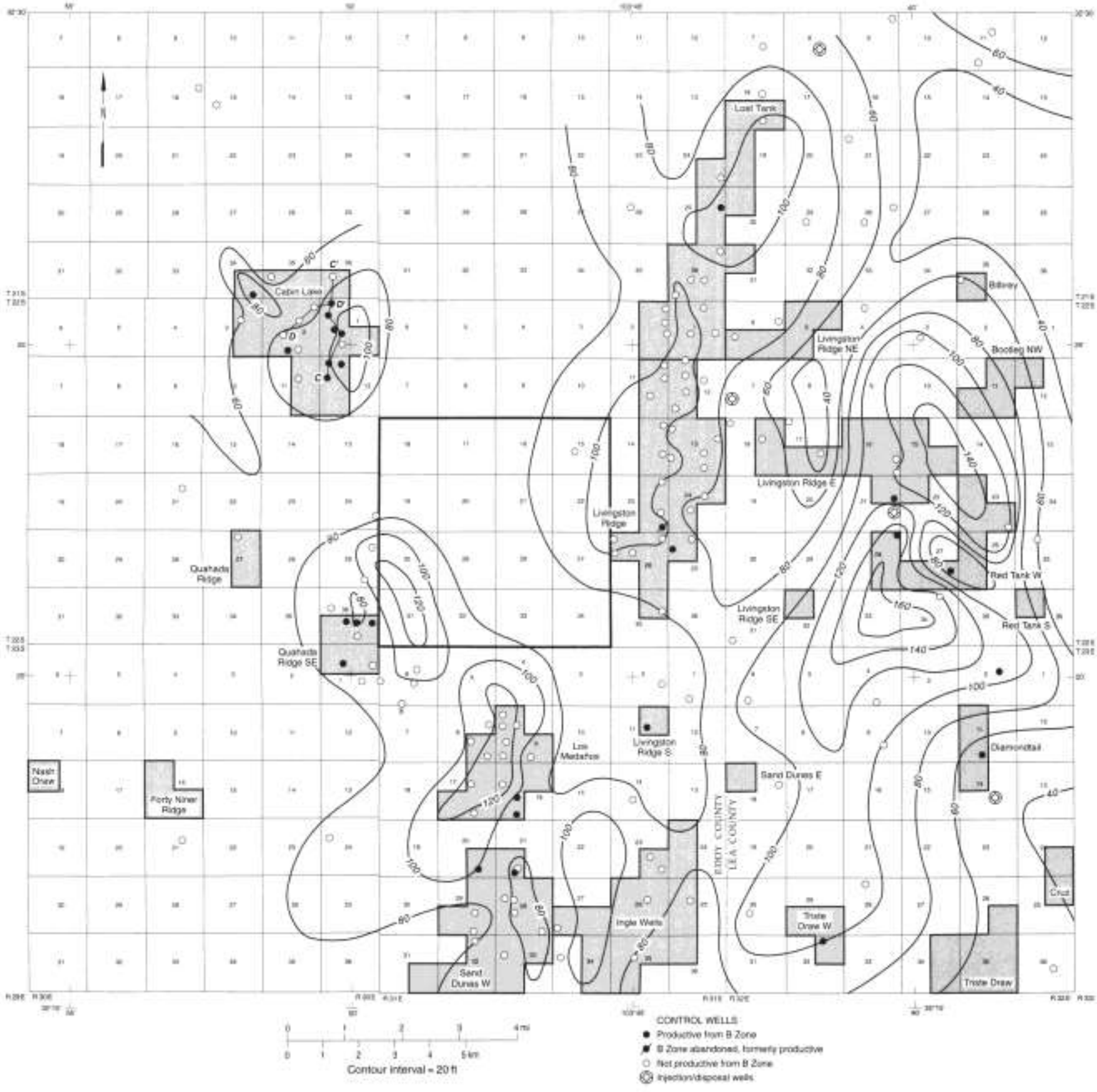


FIGURE 34—Isopach map of B zone of lower Brushy Canyon Formation. Only wells used as mapping control points are shown.

nomic production is limited to areas where the **B** zone is at least 80 ft thick; apparently, there is a sufficient net thickness of reservoir sandstones in these areas to yield economic volumes of oil.

The trap at Quahada Ridge Southeast is a combination structural/ stratigraphic trap. In addition to the stratigraphic control that reservoir thickness exerts, production may also be limited to the east by structure. Although data are sketchy, it appears that an oil-water contact may be approximately coincident with the —4100 ft contour of the top of the lower Brushy Canyon (Fig. 25). If this is true, then the isopach and structure maps indicate that there are nine undrilled 40-acre units within the WIPP land withdrawal area and 52 undrilled 40-acre units that have probable oil and gas within the additional study area (Fig. 26).

Three casing strings are used during drilling and completion operations in wells drilled to develop the lower Brushy Canyon B zone in the Quahada Ridge Southeast pool (Fig. 36). Typically, 13 3/8-inch surface casing is set and cemented at a depth of approximately 600 ft. An intermediate string of 8 5/8-inch casing is then set and cemented at a depth of approximately 3850 ft in the uppermost part of the Bell Canyon Formation. Production casing of 5 1/2-inch diameter is then set and cemented to total depth of approximate-

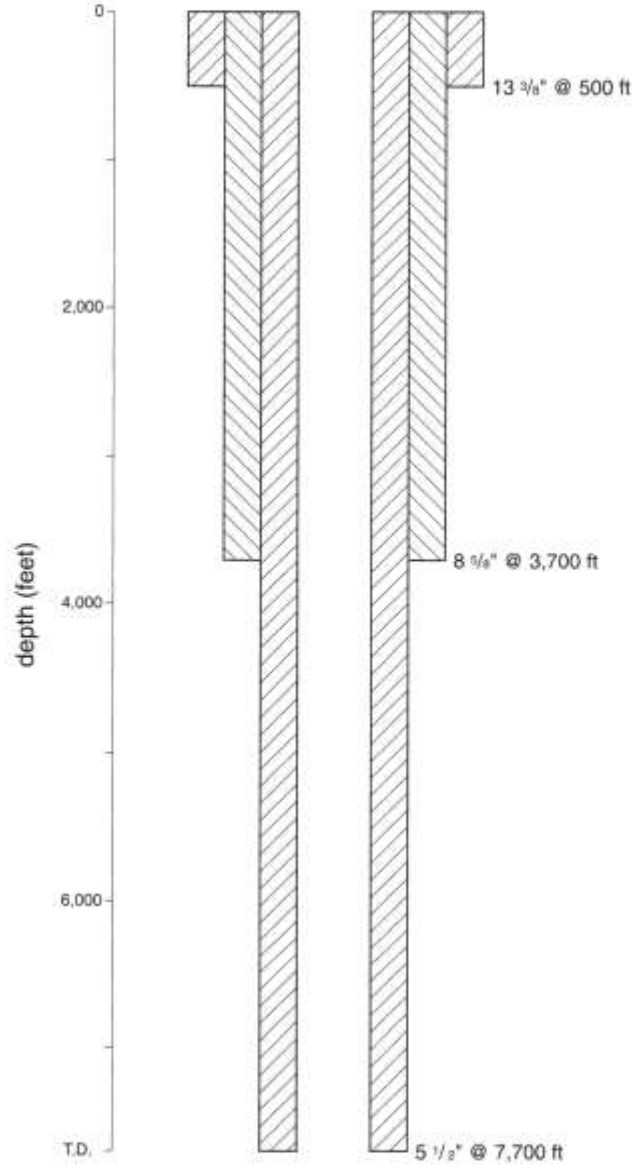


FIGURE 35—Casing program of a typical well producing from B zone of lower Brushy Canyon Formation, Cabin Lake Delaware Pool.

ly 7900 ft. Casing is then perforated in the B zone. Before economic production can be obtained, the pay zone must be acidized and artificially fractured. Volume of the acid load ranges from 1000 to 3000 gallons. After acid treatment, the well is hydraulically fractured. Fracture treatments use 20,000-40,000 gallons of water and 70,000-120,000 lbs of sand.

Wells in the Quahada Ridge Southeast pool have produced for an insufficient length of time to determine ultimate primary recovery with the production-decline technique used in this study. However, oil and gas are produced from the same reservoir that produces from the lower Brushy Canyon in the Cabin Lake pool. In the absence of other data, the same ultimate recovery data are used as for the Cabin Lake pool, 66 KBO and 46 MMCF gas for the average or typical well.

Estimated ultimate primary recovery for the B zone in the nine undrilled 40-acre proration units within the WIPP site is 594 KBO and 414 MMCF associated gas (Table 2). This is equal to probable resources, because the B zone has not been produced from underneath the WIPP site. Cumulative production from the additional study area was 11 KBO and 9 MMCF gas as of December 31, 1993. Probable resources are 3421 KBO and 2383 MMCF gas in the 52 undrilled 40-acre proration units in the additional study area (Table 3).

Economics and drilling for Delaware oil

The economics of drilling and completing a well in the Delaware Mountain Group will determine strategies and procedures employed in drilling wells and developing oil pools. Vertical wells, rather than deviated or horizontal wells, will be the choice of operators who wish to produce oil and gas from beneath the WIPP land withdrawal area, should the opportunity ever arise. If regulatory entities mandate that deviated wells must be drilled to tap into oil resources beneath WIPP, then drilling may become an economically unsound venture and few wells will be drilled until the price of oil rises sufficiently to warrant deviated or horizontal drilling (see Anselmo, this volume, for a discussion of oil and gas economics, and Hareland, 1995, for a discussion of horizontal drilling).

The costs of drilling and completing wells in the Delaware are listed in Table 9A. As can be seen, these costs more than double when the well must be deviated or drilled directionally. Wells drilled vertically, although expensive, are economically profitable. The intensive drilling activity in the area over the past few years attests to this; several operators have each drilled numerous vertical wells as economically sound business ventures. However, when wells are drilled with a deviation from the vertical, they become unprofitable or marginally profitable ventures and operators will use their funds to drill elsewhere.

The distribution of oil in multiple reservoir zones within the Delaware also makes it desirable to drill wells vertically. Ultimate recovery from Delaware pools will be increased if several pay zones in the Brushy Canyon and Cherry Canyon Formations can be produced from a single well. Yates Petroleum Corp. has instituted this practice in the Livingston Ridge—Lost Tank pool by commingling production from several zones upon initial completion; other operators may re-enter old wells in which the primary pay zone has been depleted in order to recomplete in secondary zones uphole. In either case, oil and associated gas will be produced from secondary zones that do not contain sufficient resources to justify drilling a well to produce from those zones alone.

Lower production costs also make it desirable to drill vertical rather than deviated wells in the Delaware. Delaware wells do not generally flow oil at the wellhead. Instead, oil must be produced by artificial lift. In most cases, this involves installing a pumpjack at the surface and a string of sucker rods within the wellbore. The sucker rods move vertically up and down while the well is being pumped (see Hareland, 1995). **In** a vertical well, this vertical movement poses

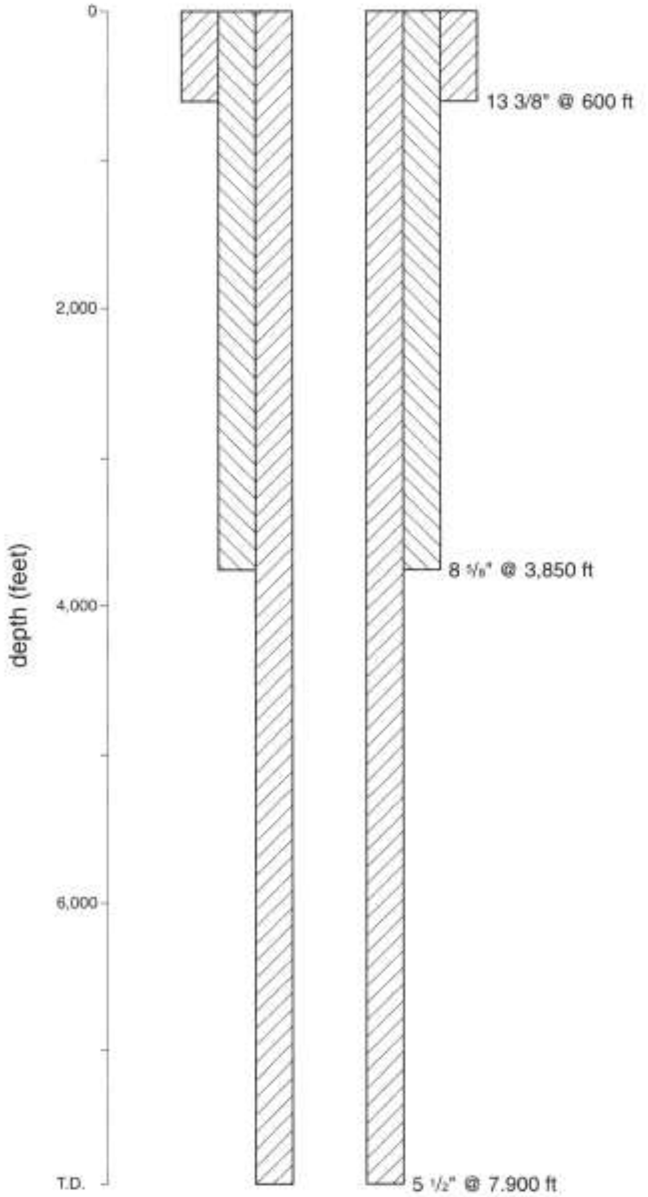


FIGURE 36—Casing program of a typical well production from B zone of lower Brushy Canyon Formation, Quahada Ridge Southeast Delaware pool.

little problem. However, in a deviated or horizontal well the rods rub against the casing during pumping and may wear through the casing, necessitating its premature replacement and thereby increasing production and maintenance costs.

Secondary recovery in Delaware pools

In the Delaware Basin, oil pools in the Delaware Mountain Group may produce for 10 years or more by primary recovery. When production declines to an uneconomic or marginally economic rate, a waterflood of the pool may be initiated in order to increase production rates and to increase ultimate recovery from the pool. No Delaware pools have yet been waterflooded within the nine-township study area. In the Cabin Lake pool, water is injected into two wells for purposes of pressure maintenance in the reservoir zones. The response of producing wells at Cabin Lake to water injection has been quite good (Fig 37), and indicates to some degree the suitability of Delaware reservoirs to waterflooding in the WIPP area, even though production histories are too short to calculate the incremental increase in production due to water injection.

Mature waterfloods in Delaware pools in other parts of the New Mexico portion of the Delaware Basin were analyzed in order to evaluate the potential of waterflooding for increased recovery in Delaware Mountain Group reservoirs. Records of the New Mexico Oil Conservation Division indicate that water has been injected into eight Delaware oil pools in southeast New Mexico for purposes of waterflooding and/or pressure maintenance (Table 10). As of the end of 1993, water was still being injected into all of these pools, an indication of the success of water injection programs.

Two of these pools were chosen for rigorous analysis, the Indian Draw Delaware pool of central Eddy County and the Paduca Delaware pool of southwest Lea County. The Indian Draw pool produces from sandstones in the Cherry Canyon Formation and the Paduca pool produces from sandstones in the Bell Canyon Formation. Depositional environments are similar to productive Delaware sandstones in pools adjacent to the WIPP land withdrawal area, but there are some differences. Sandstone reservoirs at Paduca were deposited in well-defined channels on submarine fans in the Bell Canyon (Harms and Williamson, 1988); depth to production is about 4700 ft. As noted previously, the Bell Canyon sandstones generally have higher permeability than Brushy Canyon sandstones, and channels in the Bell Canyon appear to be better defined than channels in the Brushy Canyon, perhaps reflecting deposition in the more proximal parts of the submarine-fan environment. Although the Indian Draw pool produces from the Cherry Canyon, it lies 18 mi west of the WIPP site and is in a similar paleogeographic location to Delaware reservoirs at WIPP, so reservoirs may be similar to those at WIPP except for shallower depths (3300 ft) at Indian Draw.

The production histories of the Indian Draw and Paduca pools were plotted with annual oil production as a function of time (Figs. 38, 39). The production-history curves show two distinct peaks. The first peak on each plot occurs a few years after pool discovery and reflects maximum production from primary-recovery techniques. The second peak occurs several years later. It reflects maximum production from the water-flood. Production begins to increase within two years of onset of waterflooding and peak production due to waterflooding occurs within three to four years.

Two distinct production trends can be seen on each of the plots. The first trend is for production by primary methods. The second trend is for production resulting from the waterflood. Each trend was extrapolated into the future with an exponential decline curve (Figs. 38, 39). The area under each curve was calculated to give estimated ultimate recovery for primary production and for waterflood production. Waterflooding is expected to increase ultimate recovery at the Paduca pool by 61% and at the Indian Draw

TABLE 9A—Approximate costs for drilling, completing, and operating Delaware oil wells in the WIPP area, 1994 dollars. Averaged, proprietary, and confidential data obtained from several operating companies.

well type	completion cost, producing well*	completion cost, dry hole*	operating costs, monthly	rate of return, percent
vertical hole	$600,000	$280,000	$2500	85%
deviated hole	$950,000–$1,320,000	$289,000+	$2500+	0–20%**

* includes tangible and intangible costs and, for producing wells, the cost of perforating, acidizing, fracturing, and installing production equipment.

** depending on drilling and completion costs.

TABLE 9B—Approximate costs for drilling and completing Strawn, Atoka, and Morrow wells in the WIPP area, 1994 dollars. Averaged, proprietary, and confidential data obtained from several operating companies.

well type	completion cost producing well*	completion cost, dry hole*
vertical hole, 13,700 ft	$1,225,000	$900,000
deviated hole, 13,700 ft	$1,837,500	$1,350,000
vertical hole, 15,000 ft	$2,000,000	$1,500,000
deviated hole, 15,000 ft	$3,000,000	$2,250,000

* includes tangible and intangible costs and, for producing wells, the cost of perforating, acidizing, fracturing, and installing production equipment.

pool by 81%. This is a significant increase in recoverable oil.

Worthington (1994) studied the Shugart East Delaware oil pool, located 21 miles north of WIPP. Production in this pool is from multiple stacked sandstones in the upper part of the Brushy Canyon Formation. Ultimate primary recovery was estimated to exceed 5 million BO and 10 BCF gas. Worthington estimated that an additional 5 million BO could be recovered through secondary recovery (waterflooding). This is approximately 100% increase in ultimate recovery.

These analyses can be applied with caution to estimate ultimate secondary recovery for pools projected to extend underneath the WIPP land withdrawal area. A 60% increase in ultimate recovery was selected for calculations because it represents the lesser (more conservative) value of the two analogous pools that were analyzed. Values of estimated ultimate secondary recovery and estimated total (primary plus secondary) recovery are given in Tables 11-13.

The low permeability and the presence of clays (variably illite, mixed layer illite/smectite, and chlorite) in Brushy Canyon sandstones may pose problems for secondary recovery that do not exist with many

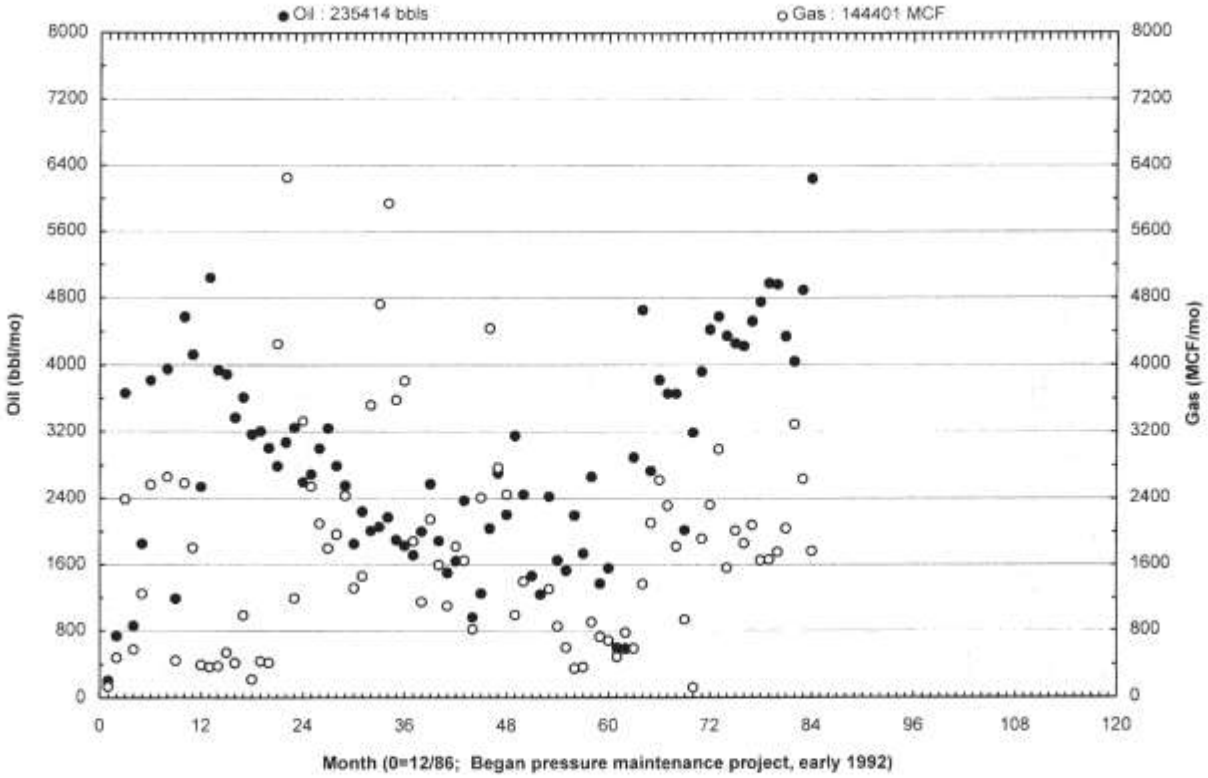


FIGURE 37—Historical monthly production of oil and gas, Phillips Petroleum Company No. 2 James A well, Cabin Lake Delaware pool. Water injection for pressure maintenance began in early 1992 (at approximately month 60). Note the rapid and sudden response of oil production to water injection.

TABLE 10—Oil pools in Delaware Mountain Group with water injection projects. Data from New Mexico Oil Conservation Division and New Mexico Oil & Gas Engineering Committee.

Pool	Reservoir unit	Year water injection commenced or permitted	No. of injection wells, 12/31/93
Brush Draw	Bell Canyon	1989	1
Cabin Lake	Cherry Canyon Brushy Canyon	1992	2
Cruz	Bell Canyon	1985	1
El Mar	Bell Canyon	1968	31
Indian Draw	Cherry Canyon	1980	10
Malaga	Bell Canyon	1967	3
Mason North	Bell Canyon	1968	1
Paduca	Bell Canyon	1972	19
Double X	Bell Canyon	1988	1
Parkway	Bell Canyon	1993	4

other oil reservoirs. These factors may act to increase costs associated with waterflood operations; such increased costs have been incorporated into the economic analyses of Anselmo (this volume). The relatively low permeability of the Brushy Canyon sandstones will require that injection and production wells be located on 20-acre spacing, in contrast to the existing 40-acre spacing that is allowed for primary production. One new injection well will need to be drilled for each existing production well. The production and injection wells will almost certainly be located on five-spot patterns. This need to double the number of wells will cause waterflood costs to significantly exceed primary-recovery costs.

The authigenic clays present within depositional pore space may affect secondary-recovery operations in two ways. First, they reduce permeability. Second, some chlorites are sensitive to changes in the chemistry of formation waters (Walling et al., 1992); injection of water with a significant difference in pH from native formation waters may cause retrogression of the chlorite and subsequent migration of clays or formation of permeability-reducing gels.

These deleterious effects of water injection can be mitigated or even eliminated by using Delaware formation waters for waterflood injection. These waters should be approximately in equilibrium with reservoir mineralogy. Finally, the analogous waterfloods that were used to derive a figure for ultimate secondary recovery are in Delaware reservoirs and they have been successfully waterflooded. This is a strong indication that Brushy Canyon reservoirs in the vicinity of WIPP can be successfully waterflooded. The recent initiation of a waterflood in the Avalon Brushy Canyon pool and Worthington's (1994) calculation of a 100% increase in oil recovery at Shugart East support

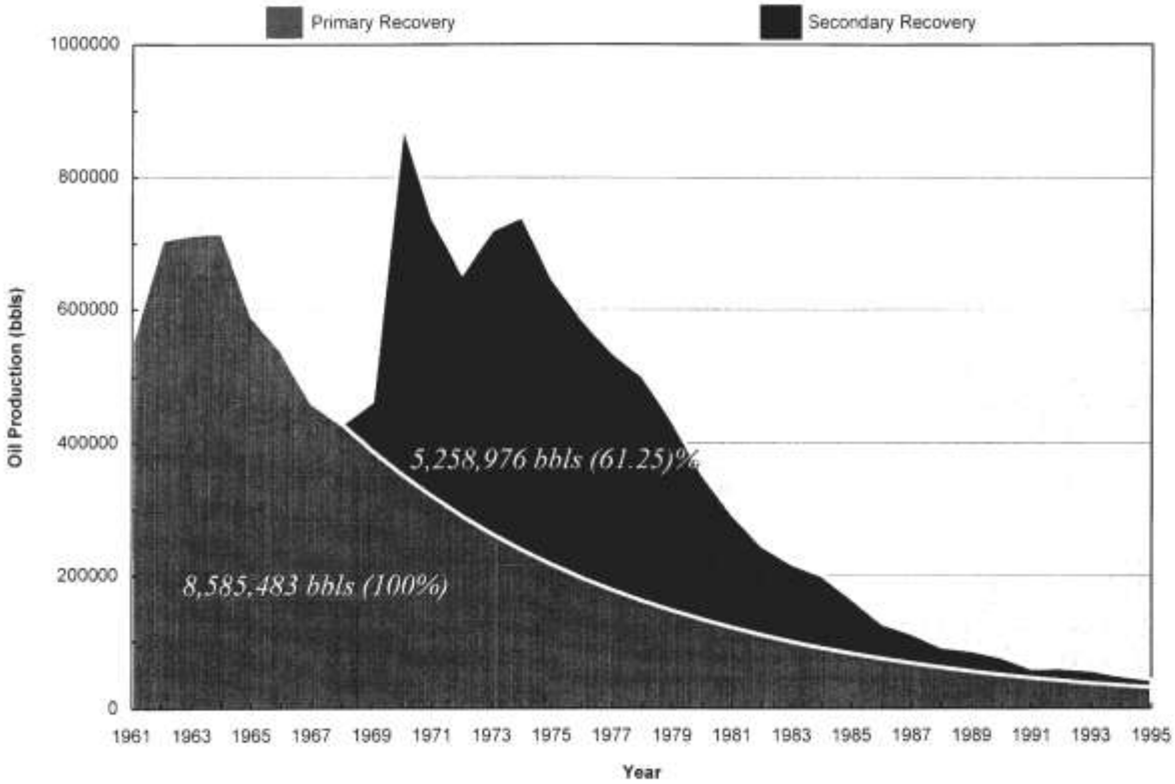


FIGURE 38—Annual production history of Paduca Delaware pool, with production curves for primary and secondary (waterflood) recovery projected into the figure, and estimated ultimate oil recovery by primary and secondary means.

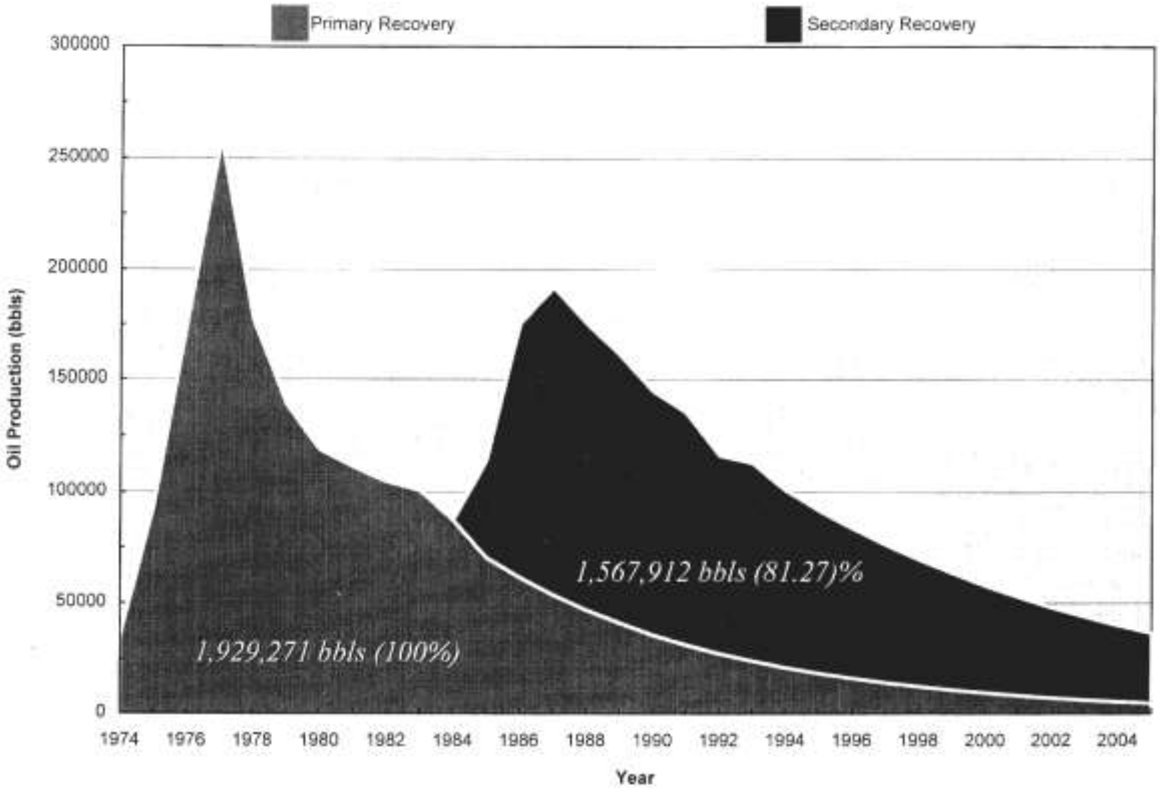


FIGURE 39—Annual production history of Indian Draw Delaware pool, with production curves for primary and secondary (waterflood) recovery projected into the future, and estimated oil recovery by primary and secondary means.

the conclusion that waterflooding the Brushy Canyon in the vicinity of WIPP will be technically possible and economically feasible.

The decision on whether or not to initiate waterfloods of Delaware oil pools in the vicinity of WIPP will rest primarily with the operators that produce from these pools. Many factors determine whether or not an operator will initiate a waterflood. These factors are mostly related to economics and include: 1) the ultimate secondary recovery expected from a waterflood; 2) costs associated with a waterflood, including the drilling of injection wells; 3) construction of surface facilities and injection facilities; 4) the cost of obtaining and processing injection water; 5) the cost of brine disposal, including the cost of drilling and equipping disposal wells; and 6) revenues obtained from oil and gas production (determined by production rates, oil prices, and to a lesser extent gas prices).

Even if a waterflood project is expected to be economically successful, it may not be initiated because of the limited financial resources that all operating companies face. Expected return on investment from a waterflood project must be compared to expected return on investment from other ventures; a waterflood will be initiated only if expected return on investment is favorable. The technical and economic viability of waterfloods in the vicinity of WIPP will be compared to the technical and economic viability of ventures conducted elsewhere.

It must be emphasized that the oil estimated to be available through secondary recovery (Tables 11-13) will be produced only if waterfloods are initiated while primary production is in progress. Once wells that produce by primary methods have been abandoned and plugged, then they will not be available for secondary-recovery operations. The high cost of reentering plugged wells, or of drilling replacement wells, may render secondary recovery uneconomic. The presence of operable wells used for primary recovery is essential for the economic viability of secondary recovery projects.

BONE SPRING FORMATION

The Bone Spring Formation (Permian: Leonardian) is a major oil-producing unit in the Delaware Basin (Broadhead and Speer, 1993). Bone Spring reservoirs are carbonate debris flows and siliciclastic turbidites deposited downslope of the Abo shelf edge (Fig. 9; Wiggins and Harris, 1985; Gawloski, 1987; Mazzullo and Reid, 1987; Sailer et al., 1989). These reservoirs are interbedded with and sealed by impermeable dark basinal shales and micritic carbonates. The Bone Spring is informally divided into six stratigraphic units in the Delaware Basin (Fig. 40). Carbonate debris

TABLE 11—Estimated ultimate primary and secondary (waterflood) oil recovery of probable resources in oil reservoirs under WIPP land withdrawal area.

Pool	Producing formation	Ultimate primary recovery KBO	Ultimate secondary recovery KBO	Total primary + secondary recovery KBO
Livingston Ridge	Delaware–Livingston Ridge main pay	1602	961	2563
Los Medanos complex	lower Brushy Canyon D zone	8132	4879	13,011
Cabin Lake	lower Brushy Canyon B zone	0	0	0
Quahada Ridge SE	lower Brushy Canyon B zone	594	356	950
Los Medanos	Bone Spring	444	222	666
Totals		**10,772**	**6418**	**17,190**

TABLE 12—Estimated ultimate primary and secondary (waterflood) oil recovery of probable resources in oil reservoirs under additional one-mile-wide study area.

Pool	Producing formation	Ultimate primary recovery KBO	Ultimate secondary recovery KBO	Total primary + secondary recovery KBO
Livingston Ridge	Delaware–Livingston Ridge main pay	8633	5180	13,813
Los Medanos complex	lower Brushy Canyon D zone	9196	5518	14,714
Cabin Lake	lower Brushy Canyon B zone	924	554	1478
Quahada Ridge SE	lower Brushy Canyon B zone	3432	2059	5491
Los Medanos	Bone Spring	888	444	1332
Totals		**23,073**	**13,755**	**36,828**

TABLE 13—Estimated primary and secondary (waterflood) oil recovery of probable resources in oil reservoirs under WIPP land withdrawal area and additional study area.

Pool	Producing formation	Ultimate primary recovery KBO	Ultimate secondary recovery KBO	Total primary + secondary recovery KBO
Livingston Ridge	Delaware–Livingston Ridge main pay	10,235	6141	16,376
Los Medanos complex	lower Brushy Canyon D zone	17,328	10,397	27,725
Cabin Lake	lower Brushy Canyon B zone	924	554	1478
Quahada Ridge SE	lower Brushy Canyon B zone	4026	2415	6441
Los Medanos	Bone Spring	1332	666	1998
Totals		**33,845**	**20,173**	**54,018**

flows in the second and third carbonates are the primary Bone Spring reservoirs in the Delaware Basin; they consist of dolomitized conglomerate breccias and dolomitized bioclast-peloid packstones with secondary porosity. Significant production is also obtained from carbonate debris flows in the first carbonate and siliciclastic turbidites in the first, second, and third Bone Spring sands. These turbidites are fine-grained sandstones cemented by dolomite and authigenic clays (Gawloski, 1987; Sailer et al., 1989).

Throughout the Delaware Basin, hydrocarbon traps in the Bone Spring are stratigraphic or combination stratigraphic /structural. Porous debris-flow and turbidite reservoirs were deposited in channels perpendicular to the shelf margin (Gawloski, 1987; Mazzullo and Reid, 1987; Sailer et al., 1989). Porous reservoirs pinch out depositionally updip or combination traps are formed by depositional pinchout of the reservoir across a structural nose.

Within the nine-township study area, the first, second, and third carbonates and the first, second, and third sands have been productive (Fig. 41). There has been little or no systematic attempt to evaluate, test, and explore for Bone Spring traps in this area. Generally, Bone Spring reservoirs have only been tested in wells drilled for deeper Atoka or Morrow targets. Usually, the Bone Spring will be tested in these wells only if a good show is noted on the mudlog or if open-hole density and neutron-porosity logs crossover each other and exhibit "gas effect." Numerous Bone Spring pools in the Delaware Basin have been discovered by re-entering old gas wells in which production from the Atoka or Morrow has declined to subeconomic levels; in these wells the Bone Spring may be perforated through casing if well logs or other data suggest the presence of hydrocarbons in commercial quantities.

Because many of the exploratory wells that have discovered oil in the Bone Spring originally targeted structural traps in deeper formations, discovered Bone Spring pools are generally located on structural noses (Fig. 42). With the exception of the Red Tank pool, development of known pools within the study area has been limited and incomplete because operators have concentrated on drilling for deeper gas in the Morrow and Atoka or shallower oil in the Delaware Mountain Group. Therefore, stratigraphic traps and stratigraphic trends have not been fully defined and the Bone Spring remains inadequately explored and developed in the area. It is highly likely that numerous significant commercial accumulations of oil and associated gas (possible resources) remain to be found, especially in stratigraphic traps in off-structure areas. The Potash Area, in particular, has been poorly explored because of restrictions on drilling (see Ramey, 1995, for a discussion of drilling restrictions in the potash area).

No hydrocarbons have been produced from the Bone Spring within the boundaries of the WIPP land withdrawal area. Only one pool, Los Medanos Bone Spring, is productive within the one-mile-wide additional study area. Data are insufficient to project production from other known (discovered) pools into the WIPP land withdrawal area or the additional study area, so only the Los Medanos pool is evaluated for probable resources.

Los Medanos Bone Spring pool

The Los Medanos Bone Spring pool lies on the southwestern boundary of the WIPP land withdrawal area (Fig. 41). Production is from sandstones in the third Bone Spring sand at a depth of 11,020 ft. The pool was discovered in 1982 by re-entering an abandoned Morrow gas well. As of the writing of this report, only three producing wells have been drilled in the pool. Spacing is 40 acres. The known extent of the pool is entirely within the one-mile-wide additional study area. Cumulative production from the pool was 84 KBO and 163 MMCF associated gas as of December 31, 1993. Most of this production came from one well. The other two wells were completed in December 1993 and January 1994 and contributed little or nothing to the pool cumulative total as of the end of 1993.

The Los Medanos Bone Spring pool appears to be a combination structural/ stratigraphic trap. The three wells in the pool have been drilled on an east-plunging structural nose (Fig. 42). Production appears to be limited on the west by an updip porosity pinchout or at least a reduction in porosity. An isopach map of the pay zone shows a north-trending thick area that may be a turbidite channel (Fig. 43). Figure 44 is a map of the average porosity of the pay zone. It was constructed by reading the porosities measured by the neutron and density-porosity logs at 2-ft intervals throughout the pay zone (which was mapped in Fig. 43). Then, the root mean square of the neutron and density porosities was calculated for each 2-ft interval in each well. Finally, this root mean square porosity was averaged throughout the pay zone in each well. The resulting data were contoured (Fig. 44). Although wells are too sparse to fully delineate the trap at Los Medanos, there appears to be a general decrease of porosity to the west (updip). Wells known to be productive from the pay zone have an average root mean square porosity higher than 12%. Wells with no established production from the pay zone have an average root mean square porosity lower than 12%.

Inasmuch as the porosity decrease appears to be in a westward rather than northward direction, it seems probable that production in sec. 6 may overlap northward into the southernmost part of sec. 31 T22S R31E (Fig. 43). Conservatively, four 40-acre proration units have probable resources within the WIPP land withdrawal area. Only one well in the pool has a production history sufficient to estimate ultimate primary recovery (Fig. 41). The value for this well, 111 KBO and 239 MMCF associated gas, is used as the average primary recovery for wells in the pool. The 136 month (11 year) production history of this well lends credibility to its use for a pool-wide average. Therefore, it is estimated that there are 444 KBO and 956 MMCFG producible via primary recovery from the four undrilled 40-acre proration units within the WIPP land withdrawal area (Table 11). There are additional 804 KBO and 1749 MMCFG as probable resources in the eight drilled and undrilled units in the additional study area (Table 12).

Three casing strings are used during drilling and completion operations for wells drilled in the Los Medanos Bone Spring pool (Fig. 45). Typically, surface casing of 11 3/4-inch diameter is set and cemented at approximately 600 ft, and an intermediate string of 8 5/8-inch diameter casing is set and cemented at a depth of approximately 3900 ft, just below the top of the Delaware Mountain Group. Production casing of 5 1/2-inch diameter is then set and cemented to total depth of approximately 11,300 ft. The pay zone needs to be hydraulically fractured to obtain economic rates of production in most wells. The size of fracture treatments at Los Medanos Bone Spring is not well established, but available data indicate a typical treatment

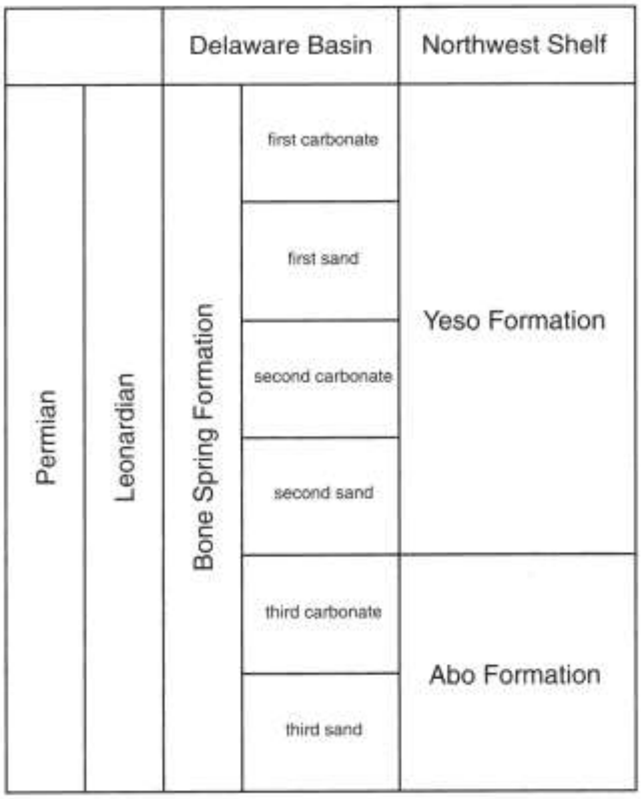


FIGURE 40—Stratigraphic column of the Bone Spring Formation in the Delaware Basin showing informal stratigraphic subdivisions and correlation with stratigraphic units on the Northwest shelf. From Broadhead (1993b), modified from Gawloski (1987) and Saller et al. (1989).

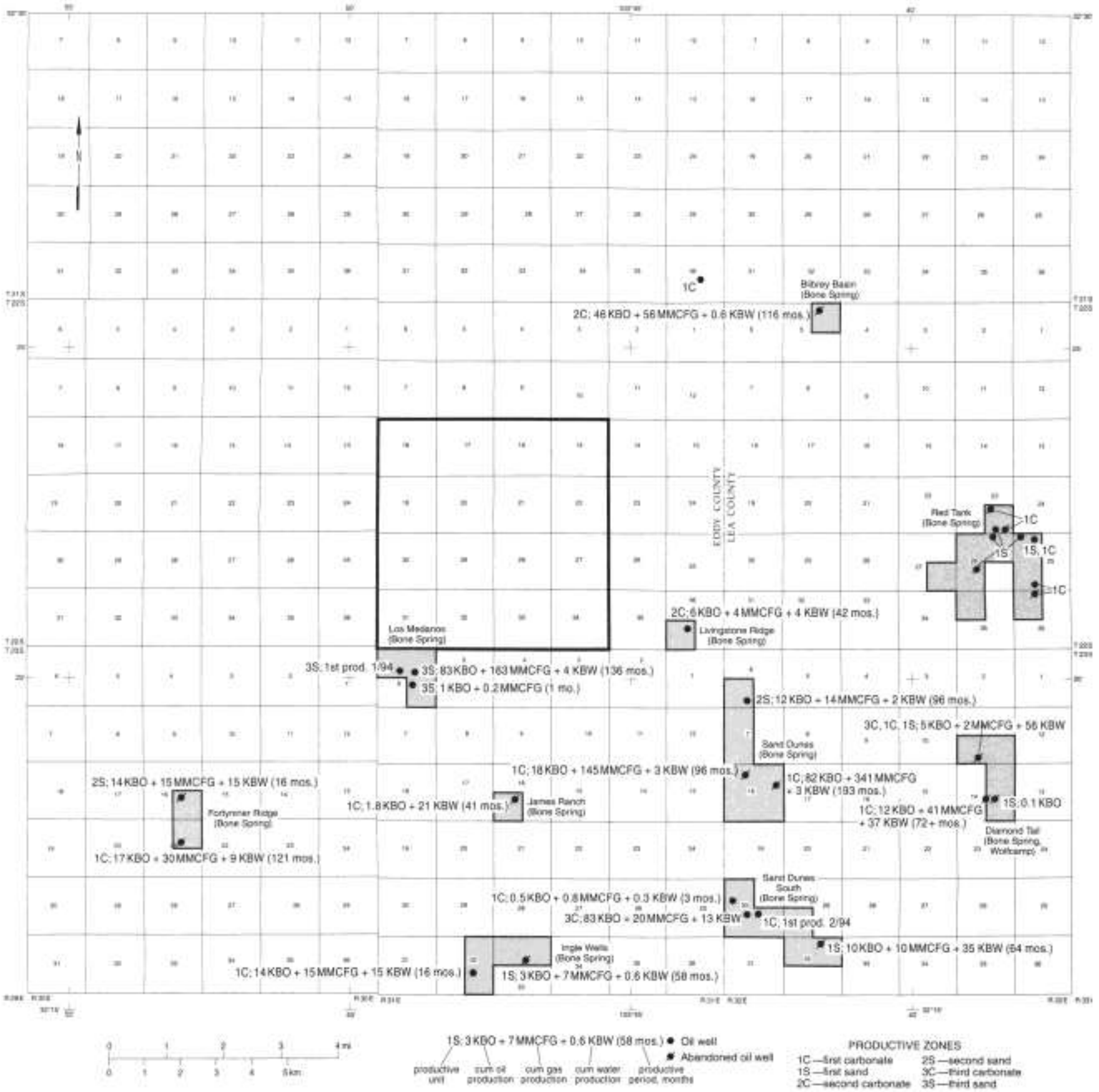


FIGURE 41—Cumulative production from wells producing from Bone Spring Formation and boundaries of designated Bone Spring oil pools. Shown are the stratigraphic units in the Bone Spring (Fig. 38) from which production is obtained.

may use 100,000 gallons of water and 120,000 lbs of sand.

Secondary recovery in Bone Spring pools

Secondary recovery in the Los Medanos Bone Spring pool will most likely consist of waterflooding the pay zone. Because of the relatively limited amount of production expected to be obtained from the Bone Spring under the WIPP land withdrawal area, detailed calculations have not been made for a projected increase in probable resources due to waterflooding. However, if a moderate increase in ultimate oil recovery of 50% is assumed, then it is estimated that an additional 222 KBO will be recovered from Bone Spring reservoirs under the WIPP land withdrawal area and an additional 444 KBO will be recovered from reservoirs under the one-mile additional study area (Tables 11-13).

WOLFCAMP GROUP

The Wolfcamp Group (Permian: Wolfcampian) is a major producer of oil and gas in the Permian Basin (Broadhead and Speer, 1993; Broadhead, 1993d). In general, Wolfcamp pools are productive of nonassociated gas in the Delaware Basin. On the Northwest

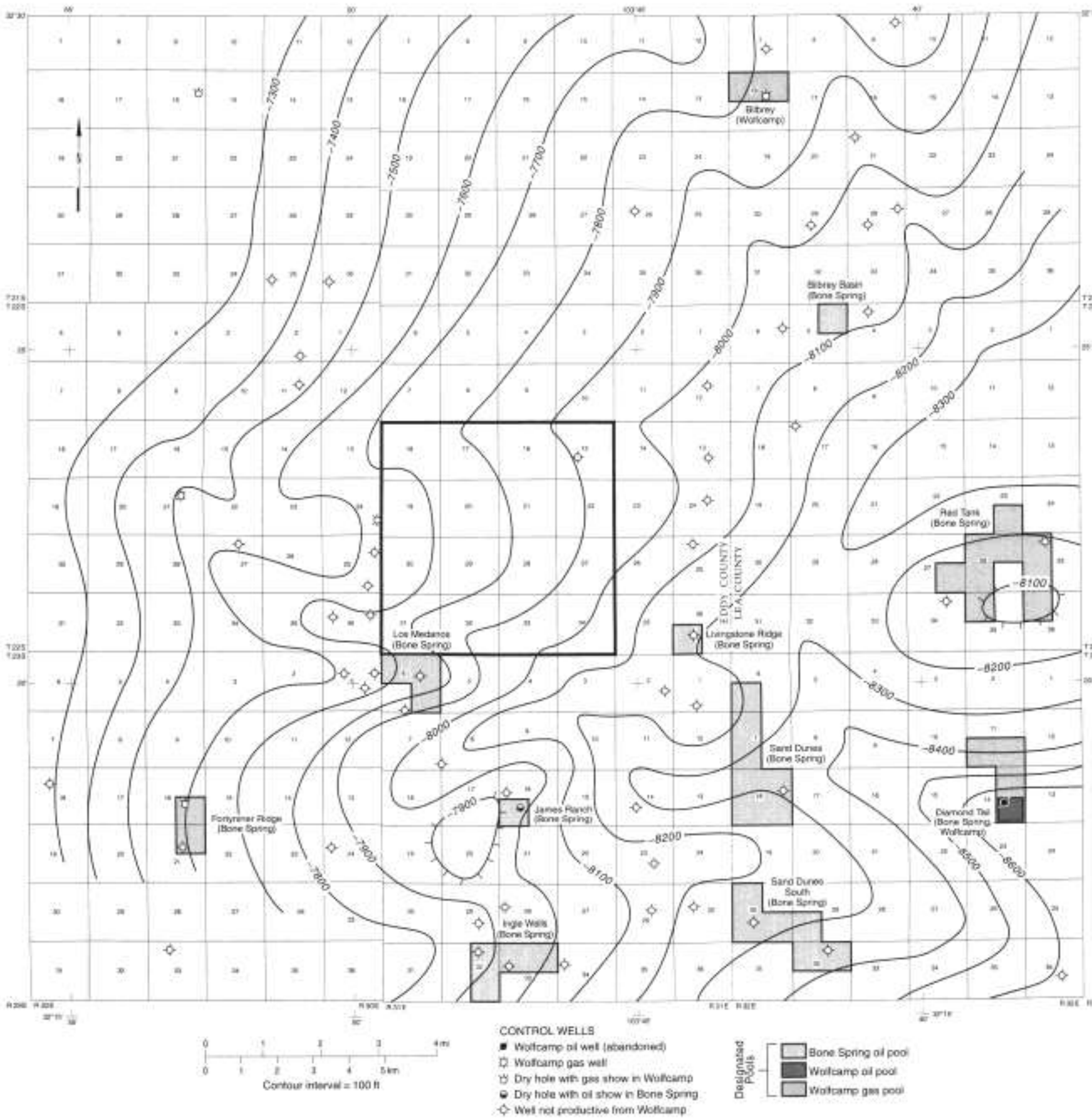


FIGURE 42—Structure on top of Wolfcamp Group and location of designated Bone Spring and Wolfcamp oil and gas pools.

Shelf and Central Basin Platform, most are productive of oil and associated gas. Wolfcamp reservoirs in the Delaware Basin were deposited in a deep basinal setting. Producing zones are thought to be either small algal carbonate mounds interbedded with dark basinal shales or scattered, thin basinal sandstones (Anderson, 1977).

Two oil and gas pools have been discovered within the nine-township study area (Fig. 42; Table 14). Uneconomic volumes (shows) of oil and gas have been recorded from three additional wells (Fig. 42). Both pools consist of a single productive well. Cumulative production from the Wolf camp in the nine-township study area is 15,692 BO, 9884 MCF gas, and 760 bbls brine water. No oil or gas has been produced from under the WIPP land withdrawal area or the one-mile-wide additional study area.

The Bilbrey Wolfcamp gas pool, located in sec. 18 T21S R32E, was discovered in 1985. Discovery was made by re-entry into an abandoned Morrow gas well. The interval from 12,100 to 12,138 ft was perforated and acidized. This interval is approximately 1000 ft below the top of the Wolfcamp. Initial potential was reported as 26 MCFG per day with an unreported volume of condensate. API gravity of the condensate was 47.9°. Cumulative production as of December 31, 1993

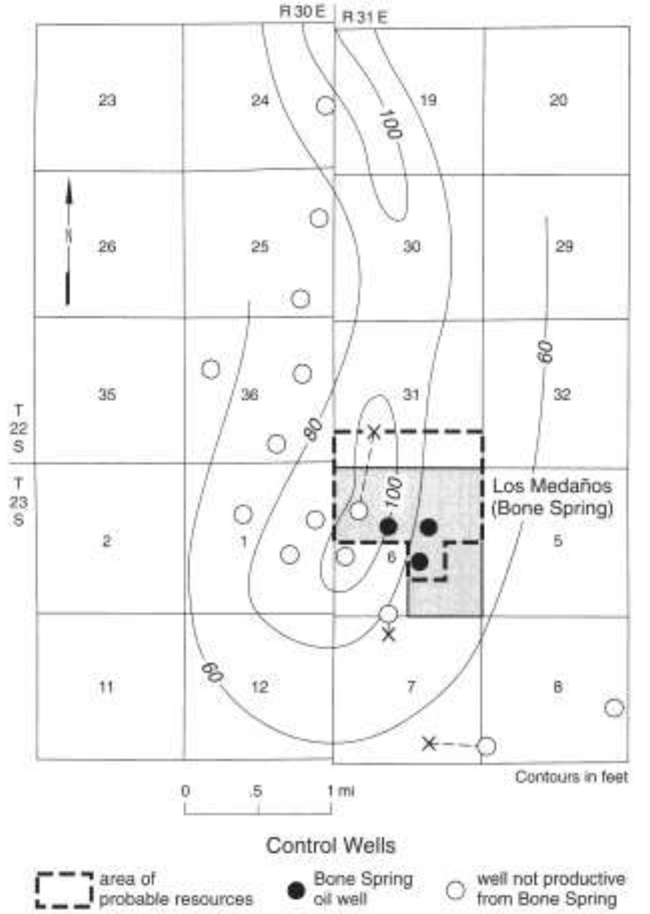


FIGURE 43—Isopach map of pay zone at Los Medanos Bone Spring pool and projected extent of possible oil and associated gas resources under WIPP site and one-mile-additional study area.

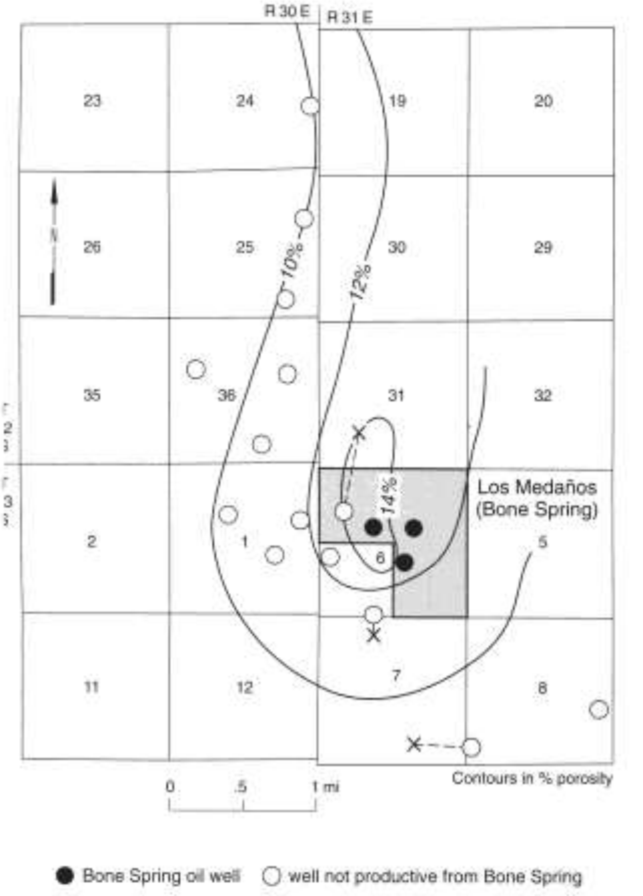


FIGURE 44—Isoporosity map of average root mean square of neutron and density porosities in pay zone, Los Medanos Bone Spring pool.

was 11,683 bbls condensate and 9884 MCF gas. Production in 1993 was 1101 bbls condensate and no gas. Subsequent to discovery, the pool has not been developed or defined by additional drilling.

The Diamondtail Wolfcamp oil pool, located in sec. 14 T23S R32E, was discovered in 1981 by a wildcat well that was unsuccessfully drilled for gas in the Morrow and Atoka. After unsuccessfully testing the Morrow and Atoka, the well was completed in the Wolfcamp through perforations from 12,181 through 12,193 ft. The perforated interval is approximately 200 ft below the top of the Wolfcamp. After perforation, the Wolfcamp was acidized and artificially fractured. Initial potential was reported as 38 bbls oil per day with a gas-oil ratio of 1974. API gravity of the oil was 48.8°. The well produced until 1987 when it was recompleted as a Bone Spring producer in the Diamondtail Bone Spring pool. Cumulative production from the Wolfcamp was 4009 bbls oil and 279 MCF gas (Table 14). The high gravity of the oil raises the question of whether this was a true oil well or a gas well with significant production of condensate. The extent of the Diamondtail Wolfcamp pool has not Been defined by additional drilling.

Probable resources of oil and gas are not estimated for the Wolfcamp Group. However, it is highly likely that possible resources exist under the WIPP land withdrawal area in undiscovered pools. The position of the WIPP site in the Delaware Basin and the recovery of hydrocarbons from wells in the study area indicate undiscovered hydrocarbons will most likely be gas with condensate. Traps will be stratigraphic or possibly combination structural/stratigraphic traps formed by updip porosity pinchouts on the east-plunging structural nose that occupies a large part of the WIPP land withdrawal area (Fig. 42). Oil, gas, and

TABLE 14—Production data for Wolfcamp oil and gas pools in study area. Production is cumulative to 12/31/93; abd, abandoned.

pool	Oil/gas	Producing formation	Spacing acres	Active wells (1993)	Cumulative oil (bbls)	Cumulative gas (MMCF)	Cumulative wtr (bbls)	1993 annual oil (bbls)	1993 annual gas (MMCF)	1993 annual wtr (bbls)
Diamondtail (abd)	oil	Wolfcamp	40	0	4009	279	639	0	0	0
Bilbrey	gas	Wolfcamp	320	1	11,683	9605	121	1101	0	0
Totals				**1**	**15,692**	**9884**	**760**	**1101**	**0**	**0**

condensate resources will probably be relatively minor compared with those in major producing units in the area (Delaware, Atoka, Morrow).

STRAWN GROUP

The Strawn Group is found in the vicinity of WIPP at depths ranging from approximately 12,400 to more than 13,600 ft. In this area the Strawn is generally composed of interbedded limestone and shale and ranges from less than 100 ft to more than 250 ft in thickness. Stratigraphically trapped hydrocarbons are found in isolated, southwest-northeast-trending limestone bioherms that are generally 10-20+ ft thick. Structurally, the Strawn dips regionally to the south and southeast, with minor local noses and closures which were probably formed by draping of Strawn strata over deeper paleogeographic highs (Fig. 46). Regionally, it appears that Strawn bioherm development is localized over these deeper paleogeographic features (Speer, 1993b). This also appears to be occurring in the area around the WIPP site.

Modest production has been established from the Strawn in four wells in the WIPP area at the Cabin Lake (secs. 1, 2, and 11 T22S R30E) and Los Medanos (sec. 1 T23S R30E) pools (Table 8; Fig. 47). These wells produce both condensate and gas, with cumulative production through 1993 totaling 193,758 barrels of condensate (BC) and 4.833 BCF (billion cubic feet) of gas. Three of these four wells appear to be economic producers, averaging approximately 63,000 BC and 1.6 BCF gas. Oil and gas production decline curves for a typical Strawn well are shown in Figs. 48 and 49. The number of producing Strawn wells in the area is insufficient to construct average decline curves, so curves from a typical well are shown instead.

Significantly, in a relatively new well drilled by Mitchell Energy during late 1993, the No. 1 Apache 24, a drill-stem test (DST) revealed what appears to be a significant new Strawn reservoir at a location directly adjacent to the western edge of the WIPP land withdrawal area in the NE 1/4 SE 1/4 sec. 24 T22S R30E (Fig. 47). This DST, which tested a 15-ft zone of porous limestone at 12,710 ft, flowed gas to surface in 20 minutes at a rate of 7.8 MMCFD. Flowing pressures reached 2649 lbs per in2 (psi) and shut in pressures were an initial 7,533 psi and a final 7,433 psi [Fig. 50 (in pocket)]. This zone has apparently not yet been produced, but, based on the DST, it should be capable of production similar to the aforementioned economic Strawn wells.

Accordingly, based on a standard Strawn gas proration unit size of 320 acres, it is probable that the two proration units within the WIPP land withdrawal area (the N 1/2 and S 1/2 sec. 19 T22S R31E) that are immediately adjacent to the No. 1 Apache 24 would be considered as having excellent potential for probable resources. Further development of this particular reservoir will almost certainly prove the existence of four additional proration units within WIPP (Fig. 51). It is possible that other such reservoirs are present within the boundary of the WIPP land withdrawal area. These, however, are conjectural and are classi-

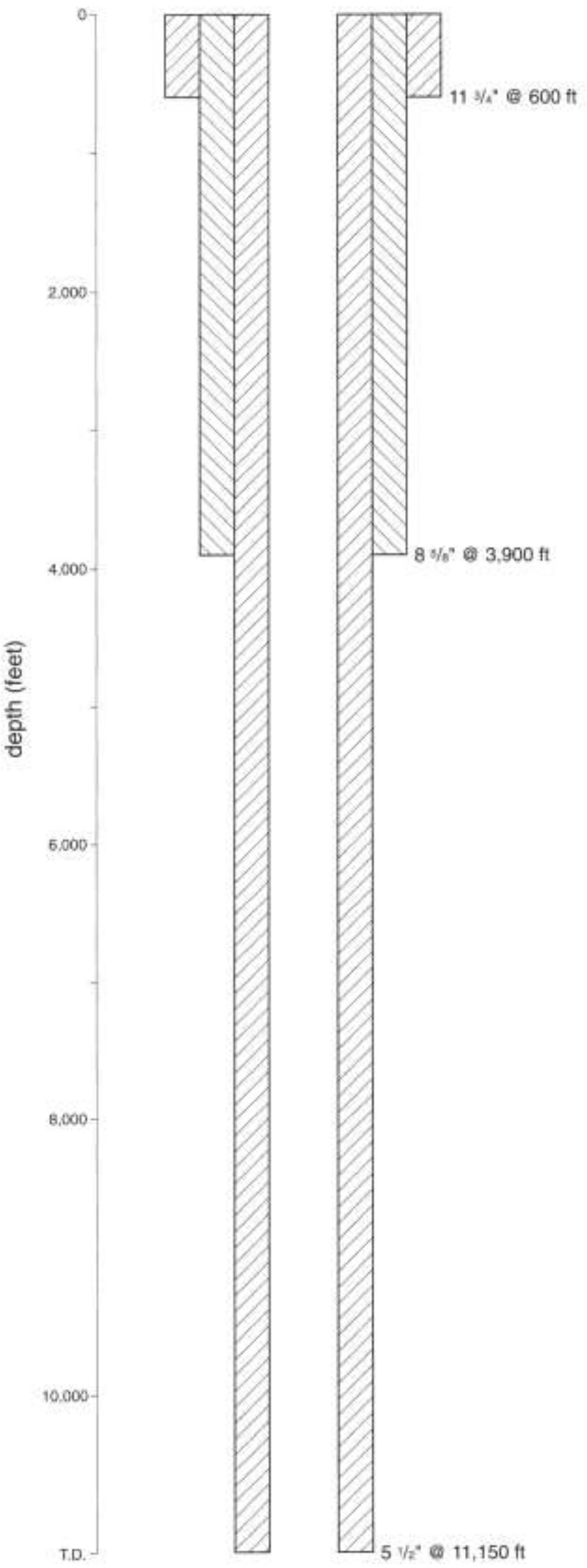


FIGURE 45—Casing program of a typical well in Los Medanos Bone Spring pool.

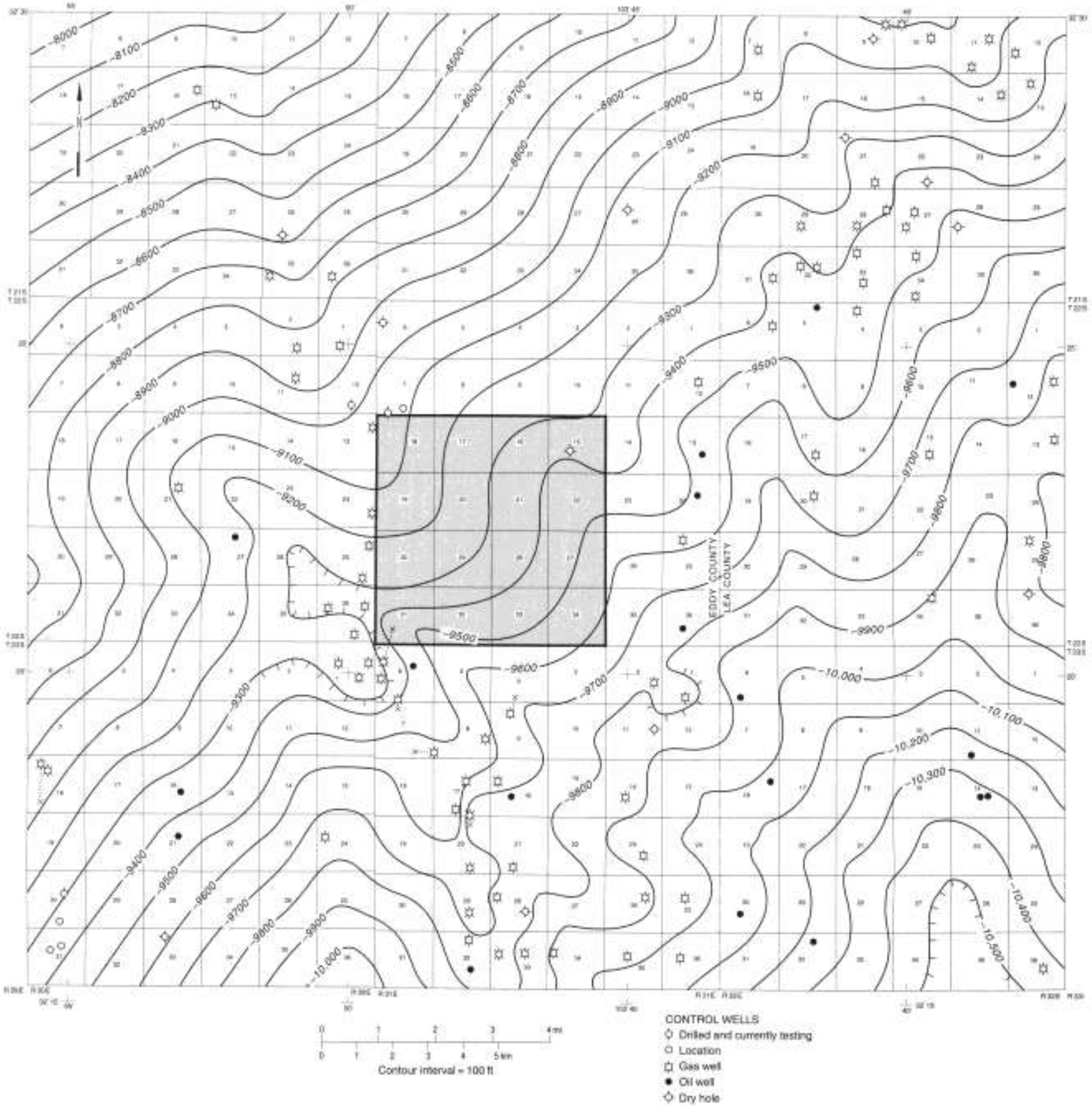


FIGURE 46–Structure contour map of top of Strawn Group.

fied as bearing possible resources. Consequently, only six proration units are estimated as having probable resources underneath the WIPP land withdrawal area (Fig. 51, Table 2) with probable resources of 9600 MMCF gas and 378 KBC. Probable resources in the seven drilled and undrilled proration units within the one-mile-wide additional study area are 9875 MMCF gas and 423 KBC.

ATOKA GROUP

The Atoka Group is found within the WIPP site area at depths of 12,700 to more than 13,700 ft. The Atoka is composed of interbedded limestone, sandstone, and shale and generally mimics the Strawn Group in structural configuration. It ranges from 210 ft to more than 270 ft in thickness.

Although prolific production has been established within the nine-township study area from this unit in both limestone and sandstone reservoirs, all of the productive wells found within or adjacent to the WIPP land withdrawal area produce primarily from one narrow and thin (5-15+ ft) lenticular sandstone channel deposit. This reservoir appears to be oriented roughly in a north-south trend (Fig. 52) and exhibits *extremely* good porosity and permeability characteris-

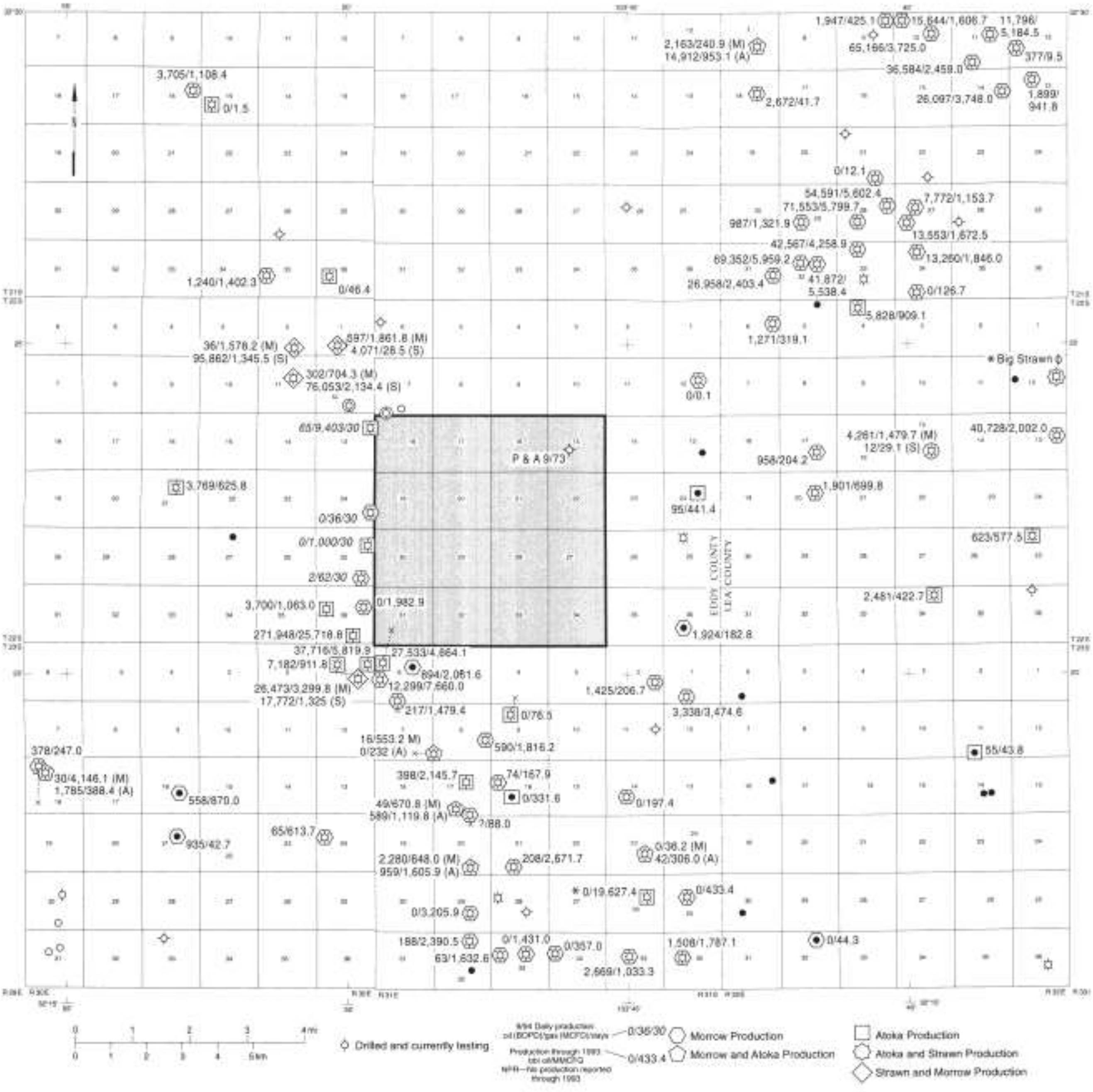


FIGURE 47—Cumulative oil, gas, and gas-condensate production as of December 31, 1993, for wells producing from pre-Permian reservoirs.

tics. Where trapped, in what appears to be a structurally enhanced stratigraphic trap, it produces prolific volumes of hydrocarbons. Evidence for this is the Shell Oil Co. (now Bass Enterprises) No. 1 James Ranch Unit well, which has produced over 25.7 BCF gas and roughly 272 KBC (Fig. 47). Seven wells have produced, or are currently producing, oil and gas from this particular reservoir. One well, the Bass Enterprises No. 13 James Ranch Unit, has a bottom-hole location within the WIPP land withdrawal area in the SE% SW% sec. 31 T22S R31E (Fig. 47). Total production through 1993 from the five wells producing at that time out of this trap, administratively designated the Los Medanos and Livingston Ridge Northeast Atoka pools (Table 8), was 348,079 BC and 38.178 BCF gas, giving an average of 69,615 BC and 7.636 BCF gas per well. Estimated ultimate recoveries push the per well average to over 8 BCF gas and 70 KBC. A gas production decline curve for as typical Atoka well is shown in Fig. 55. The wide variation in production among Atoka wells and an insufficient number of productive Atoka wells in the area prevented construction of an average decline curve; so a curve from a typical well is shown instead.

Four casing strings are used during drilling and completion operations for typical Atoka and Morrow

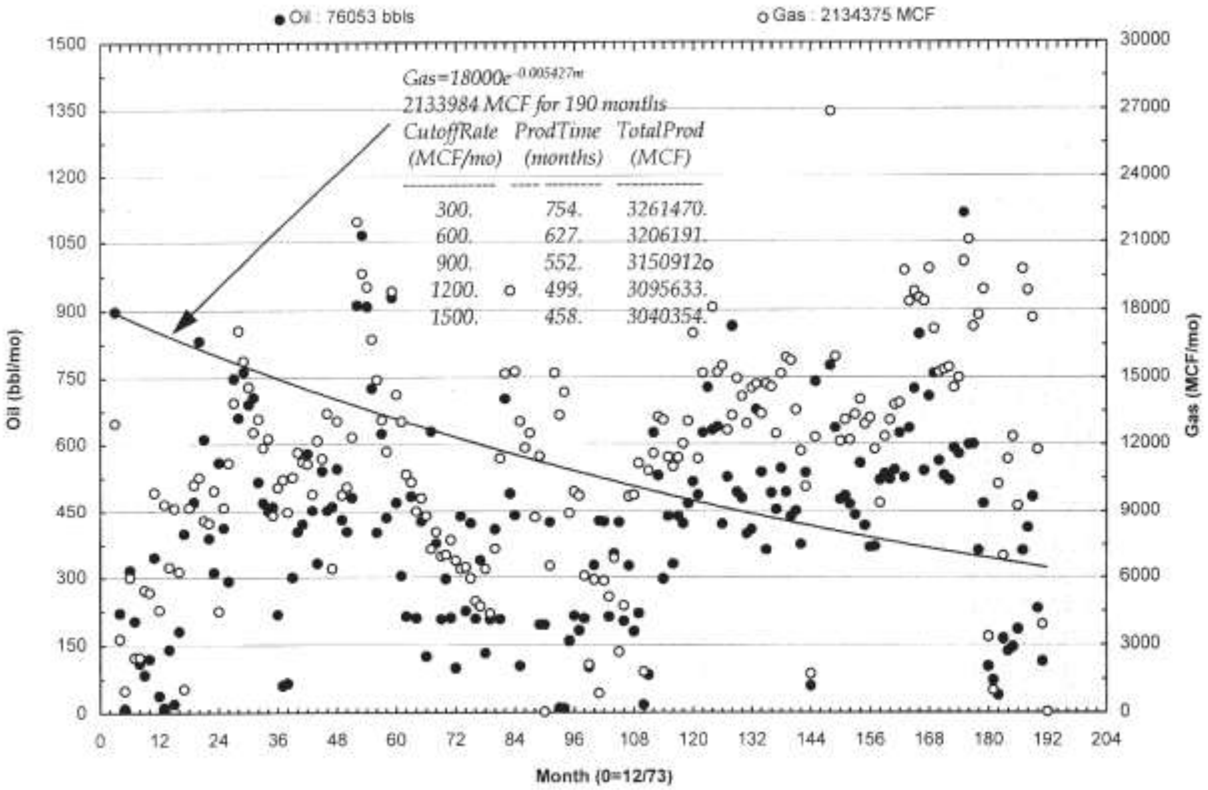


FIGURE 48—Typical gas production decline curve for wells producing from Strawn Group, WIPP site area. Well is Phillips Petroleum Company No. 1 James E well, located in sec. 11 T22S R30E.

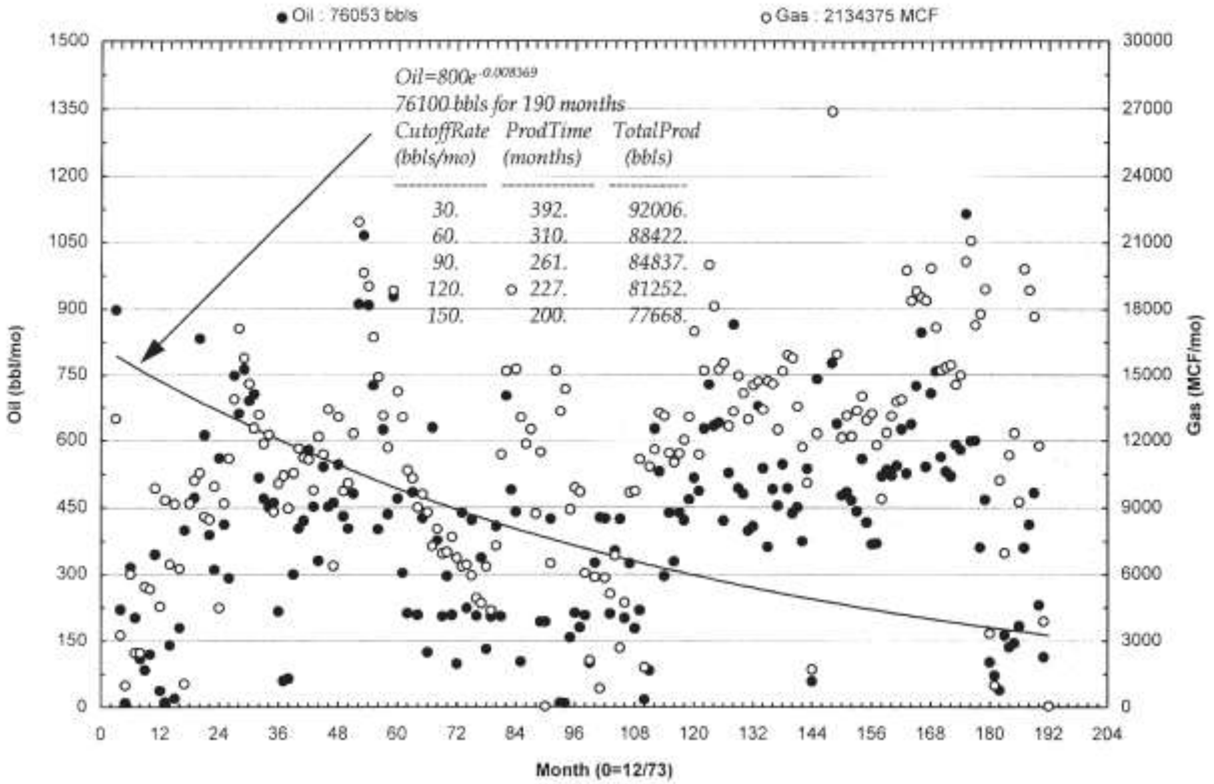


FIGURE 49— Typical oil production decline curve for wells producing from Strawn Group, WIPP site area. Well is Phillips Petroleum Company No. 1 James E well, located in sec. 11 T22S R30E.

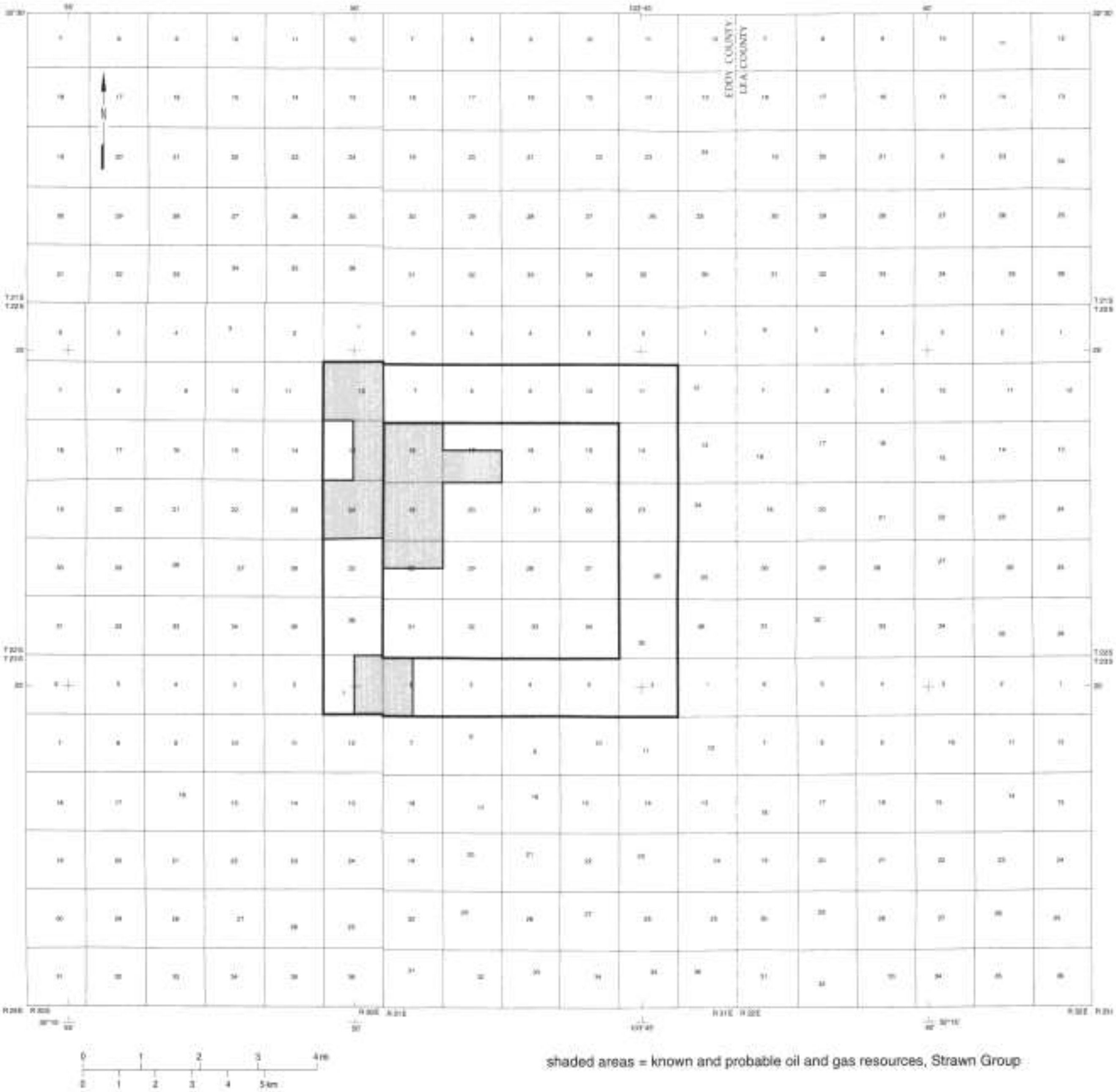


FIGURE 51— Areas of known and probable oil and gas resources within WIPP site and one-mile-wide additional study area for Strawn pools projected to extend under the WIPP site.

wells drilled in the vicinity of the WIPP site (Fig. 53). Typically, surface casing of 13^3/8-inch diameter is set and cemented at approximately 650 ft, and an intermediate string of 9^5/8-inch diameter casing is set and cemented at a depth of approximately 3700 ft. Casing of 7-inch diameter is then set and cemented to a depth of approximately 11,250 ft. Finally, 4 1/2-inch diameter production liner is set to total depth of up to 14,500 ft.

Mitchell Energy drilled two new productive wells to the reservoir less than 660 ft from the western boundary of the WIPP land withdrawal area in late 1993, the No. 1 Apache 13 (E 1/2 NE 1/4 sec. 13 T22S R30E) and the No. 1 Apache 25 (SE 1/4 NE 1/4 sec. 25 T22S R30E). Prolific reserves are apparently present in these wells, as evidenced by their September 1994 daily production of 9403 MCFD and 65 BCPD from the No. 1 Apache 13 and 1000 MCFD from the No. 1 Apache 25. At the time of this report, both Bass Enterprises and Yates Petroleum were drilling and/or completing wells in this reservoir. These wells are located in SW 1/4SE 1/4 sec. 12 T22S R30E and the SW 1/4SW 1/4 sec. 7 T22S R31E (Fig. 50).

Based on subsurface mapping of this particular reservoir, it appears that there is excellent potential for similar Atoka production within the confines of the WIPP land withdrawal area. The net-sand isolith map

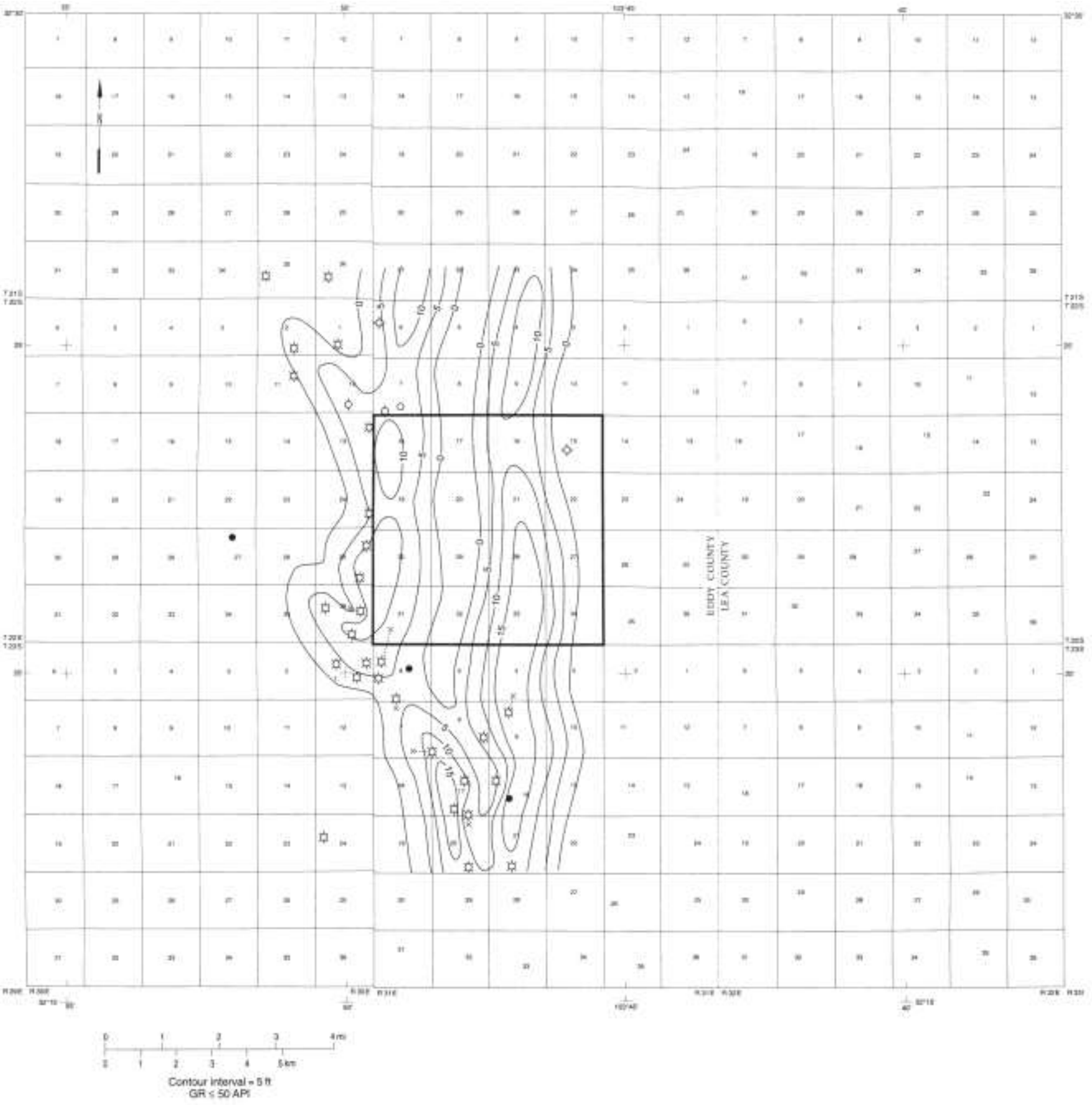


FIGURE 52—Sandstone isolith map, Atoka pay, WIPP site area.

(Fig. 52) shows that good sand development should be present in the western tier of sections within the WIPP land withdrawal area (secs. 18, 19, 30, and E 1/2 sec. 31 T22S R31E), giving up to seven 320-acre proration units containing probable gas resources in addition to the single location that presently produces (Fig. 54). An additional stratigraphically equivalent sand trend is mapped east of, and separated from, the existing production which may very well have production of similar quality (Fig. 52). As no production has yet been established on this trend, its ability to produce is rated at low to moderate probability. Eight additional proration units are estimated as bearing probable resources under the WIPP land withdrawal area (Fig. 54, Table 2). These 16 proration units have probable resources of 123,336 MMCF gas and 1,092 KBC. There are additional 94,400 MMCF gas and 799 KBC as probable resources in 16 drilled and undrilled proration units within the one-mile-wide additional study area (Fig. 54, Table 3).

MORROW GROUP

The Morrow Group is found within the WIPP site area at depths of 12,900 to more than 15,000 ft. The Morrow is divided into two distinct sections, an upper

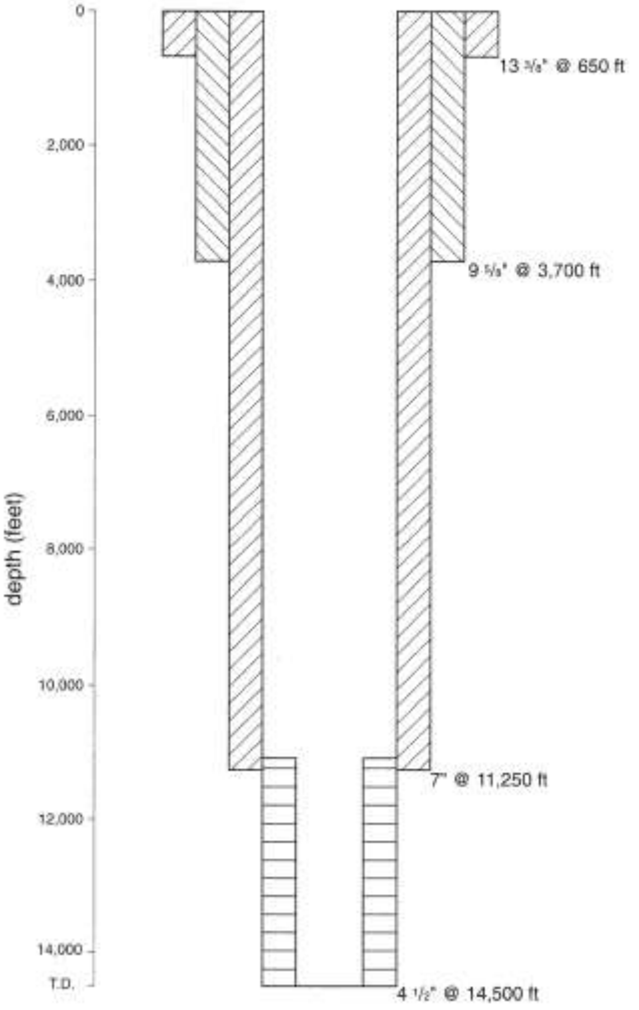


FIGURE 53—Casing program of a typical well producing from the Atoka or Morrow Groups, WIPP area.

part designated the Morrow lime, which is roughly 650 ft thick and composed principally of interbedded limestone and shale, and a lower part designated the Morrow clastic interval, which is 600-700+ ft of interbedded sandstone and shale (Figs. 50,56). Almost all Morrow production in this area comes from the Morrow clastic section, which produces principally nonassociated gas from multiple sandstones deposited in a variety of deltaic environments. These environments include channel, point-bar, channel-mouth bar, beach, off-shore bar, and delta-front facies (Speer, 1993c). Trapping is achieved in these sands by several mechanisms, which are generally some combination of stratigraphic, structural, and/or diagenetic factors (Speer, 1993c). Structurally, the Morrow mimics the Strawn in a regional sense, but seems to have more pronounced nosing and closure over inferred underlying paleostructures (Fig. 52). These structural anomalies appear in a general sense to enhance Morrow production.

Production has been established from several wells along the western, southern, and, to a lesser extent, the eastern margins of the WIPP land withdrawal area (Fig. 47). Cumulative production from these wells has been varied, ranging from less than 1 BCF to upward of 8 BCF per well. Most wells have produced only moderately, at somewhat less than 2 BCF per well through 1993.

Two wells have been drilled through the Morrow section within the confines of the WIPP site, the Clayton Williams Badger Federal Unit No. 1 (NE/SW sec. 15 T22S R31E) and the Bass Enterprises No. 13 James Ranch Unit, which was directionally drilled to a bottom-hole location in the SE 1/4 SW 1/4 sec. 31 T22S R31E (Fig. 57). A drill-stem test in the Badger Federal Unit No. 1 tested the upper part of the Morrow clastic interval with no success, and indicates poor sandstone development at its location (Fig. 56, in pocket). The No. 13 James Ranch Unit well did not test any of the Morrow section even though some potentially productive sandstone seems to be present (Fig. 50). This well is completed and producing from the aforementioned Atoka reservoir and may or may not be productive in the Morrow.

Wells completed in the Morrow at the end of 1993 by Mitchell Energy immediately to the west of the WIPP land withdrawal area give somewhat mixed information regarding the potential of the Morrow surrounding them. As cross section F—F' (Fig. 50) indicates, these wells, the No. 1 Apache 24 (NE 1/4 SE 1/4 sec. 24 T22S R30E) and the No. 2 Apache 25 (SE 1/4 SE1/4 sec. 25 T22S R30E), penetrated what appears to be prolifically productive Morrow based on the quality and quantity of sandstones present and the excellent initial potential (IP) tests. However, examination of the limited amount of production information available for these wells indicates that they are not yet producing anywhere near the volumes indicated by their IP tests. September 1994 daily production averaged less than 100 MCFD for both wells combined. As such, these two wells do not conclusively evaluate productive capability of adjacent acreage within the WIPP land withdrawal area.

Due to the complex nature of both Morrow sandstone deposition (multiple stacking of distinct sandstones) and trapping mechanisms (a combination of stratigraphic, structural, and/or diagenetic factors), it is very difficult to ascertain the probability and quality of any Morrow production within the WIPP land withdrawal area. Certainly it can reasonably be assumed, based both on adjacent production and sandstone development, that a minimum of six 320-acre proration units along the western edge of the boundary should be capable of an average cumulative production approximately equal to the "average" production established for the area (approximately 2 BCF per well). A gas production decline curve for a typical Morrow well is shown in Fig. 58. The wide variation in production among Morrow wells and an insufficient number of productive Morrow wells in the area prevented construction of an average decline curve, so a curve from a typical well is shown instead. With the apparent presence of a distinct structural nose trending across the WIPP site, which should enhance the productive potential for the Morrow (Fig. 57), and

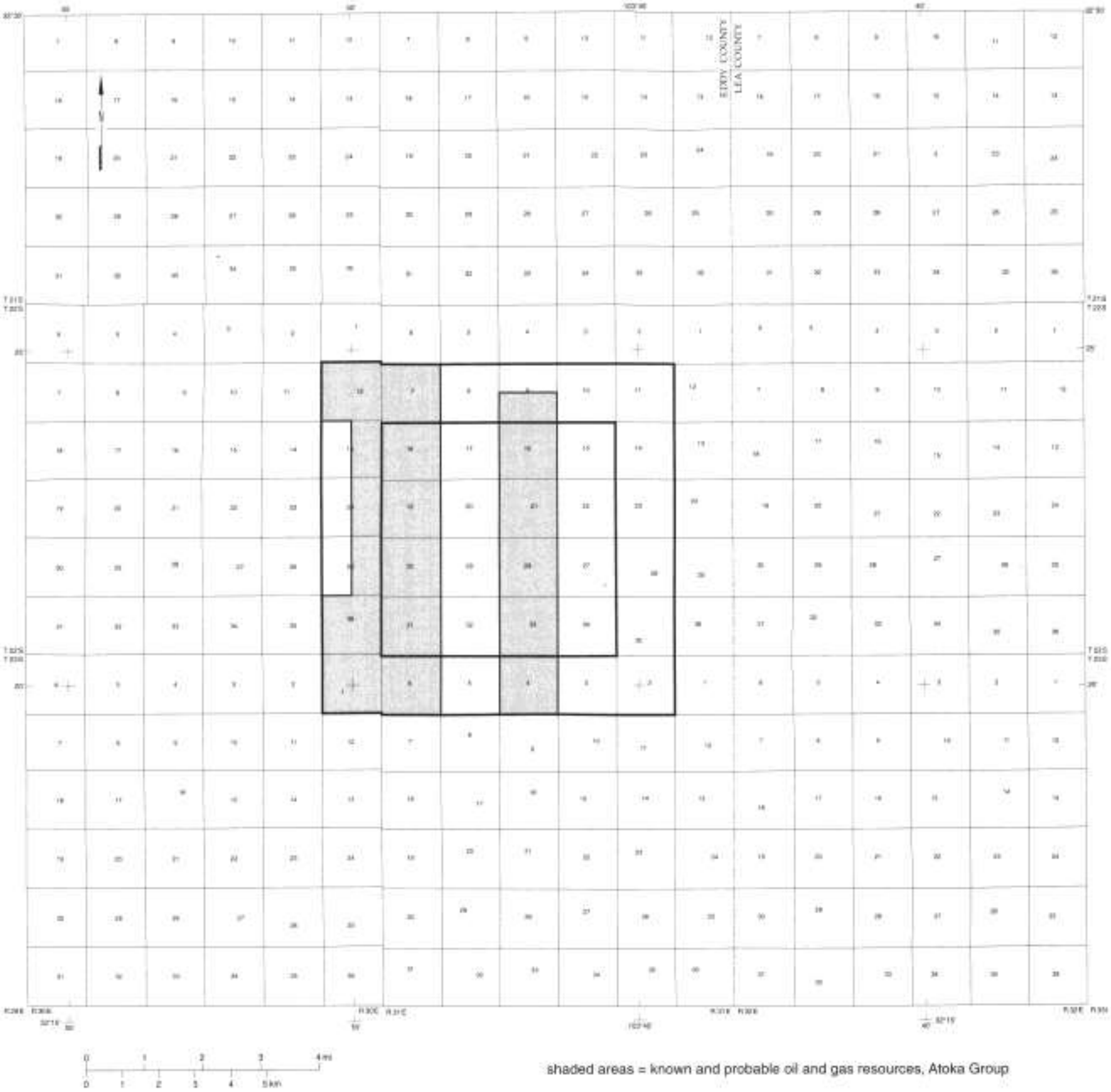


FIGURE 54—Areas of known and probable oil and gas resources within WIPP site and one-mile-wide additional study area for Atoka pools projected to extend under the WIPP site.

using nearby developed areas for analogies (T21S R32E and T23S R31E; Fig. 50), additional estimated 10 locations may be present under the WIPP site (Fig. 59; Table 2). Probable resources within these 16 proration units are 32,000 MMCF gas and 107 KBC. Additional 28,789 MMCF gas and 106 KBC are present in the 22 drilled and undrilled proration units within the one-mile-wide additional study area that surrounds the WIPP land withdrawal area (Fig. 59; Table 3).

ECONOMICS AND DRILLING FOR PENNSYLVANIAN GAS

Although significant Pennsylvanian probable resources are almost certainly present under the WIPP land withdrawal area, their recovery is critically dependent on several economic factors. The most important and variable of these include, but are not limited to, drilling and completion costs, wellbore deviation costs, and product price. Since controls on prices of oil and gas are independent of geological and engineering parameters, they are not included in this discussion (Anselmo, this volume, for a discussion of oil and gas prices).

Most wells which have been drilled in the vicinity of WIPP below the Permian section, which were not specifically set up as Devonian or deeper tests, have penetrated well into the Morrow clastic interval, most

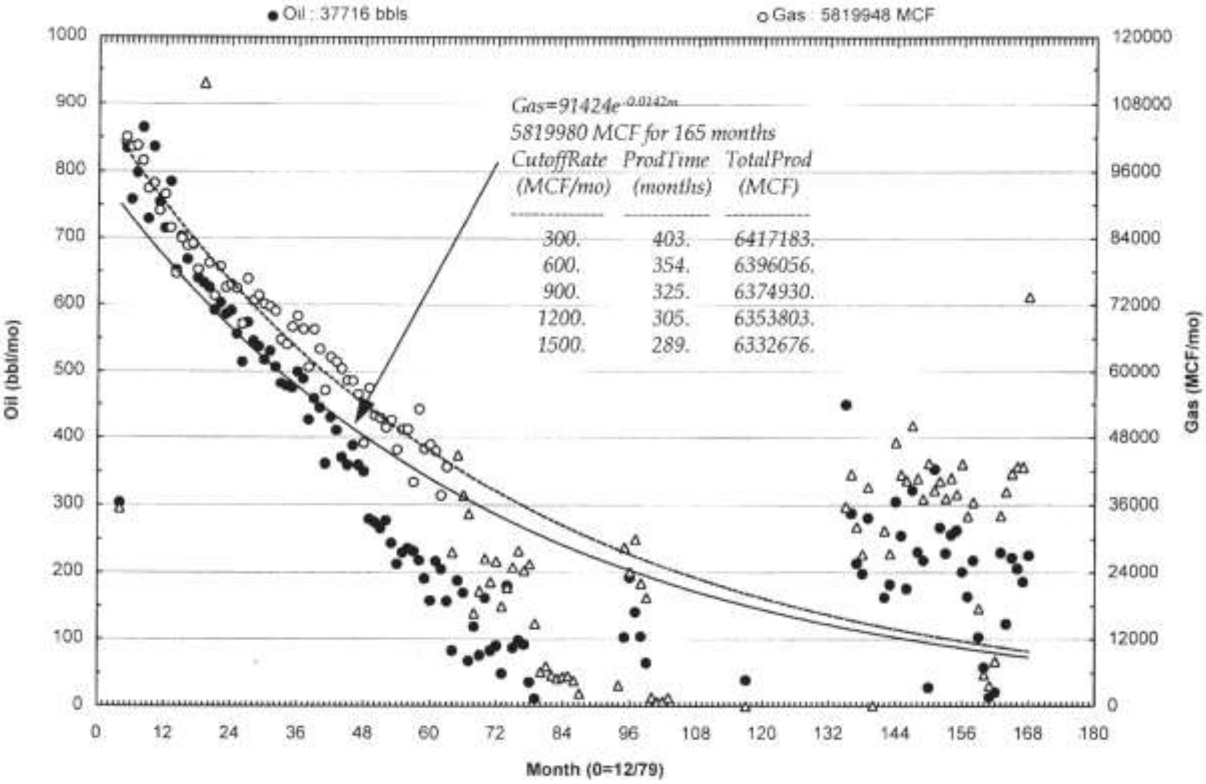


FIGURE 55—Typical gas production decline curve for wells producing from Atoka Group, WIPP site. Well is Bass Enterprises No. 10 James Ranch Unit, located in sec. 1 T23S R30E.

often reaching a total depth approximately 100-150 ft into the Barnett Shale (Figs. 50, 56). The Morrow is most often the target of deeper Pennsylvanian tests in this area, even when the primary objective may be uphole in the Strawn or Atoka Groups. This is due to the relatively minor incremental cost of the additional drilling as opposed to the significantly increased odds of finding economical reserves from the numerous Morrow pay zones which might be penetrated. Currently, the cost of a typical vertical Morrow well in this area ranges from roughly $900,000 dry-hole cost and $1,225,000 for a completed well of 13,700 ft, to well in excess of $1,500,000 dry hole cost and $2,000,000 completed cost for a well exceeding 15,000 ft in depth (Table 9b). If there is specific need to deviate a wellbore of this depth, well costs increase dramatically. It is estimated that for an 1100 ft deviation at this depth range, completed well costs would increase by approximately 45-50+%, which speaks nothing of the added risk involved in drilling, maintaining, and producing a deviated wellbore. It is obvious that vertical Pennsylvanian wells are quite expensive in this area due to their extreme depth and strict drilling parameters. With the additional cost which any deviation would add, the economic justification for drilling based on expected reserves would be significantly decreased.

PRE-PENNSYLVANIAN SECTION

A significant amount of sedimentary rock, approximately 5700 ft, is present below the Permian section in the vicinity of the WIPP site. These strata range from Pennsylvanian to Cambrian in age (Fig. 8), and are at depths ranging from approximately 12,000 ft to over 18,000 ft within the WIPP land withdrawal area.

To date, numerous oil and gas reservoirs have been discovered and developed within the Pennsylvanian section in this area. The most significant of these are found in the Strawn, Atoka, and Morrow Groups. Deeper zones of interest, found primarily in the Siluro-Devonian and Ordovician intervals, have been tested in several wells around the WIPP site, with no success to date (Fig. 60). These deeper reservoirs are composed primarily of porous carbonate shelf facies; the most common hydrocarbon traps are closed structures exhibiting significant amounts of relief (Speer, 1993a). It is probable that no such structure, and hence no economic hydrocarbon accumulation, exists in these deeper zones within the confines of the WIPP land withdrawal area. Consequently, based on available data, it appears that the Pennsylvanian Strawn, Atoka, and Morrow formations are the only pre-Permian stratigraphic units with significant economic oil and gas potential underneath the WIPP site.

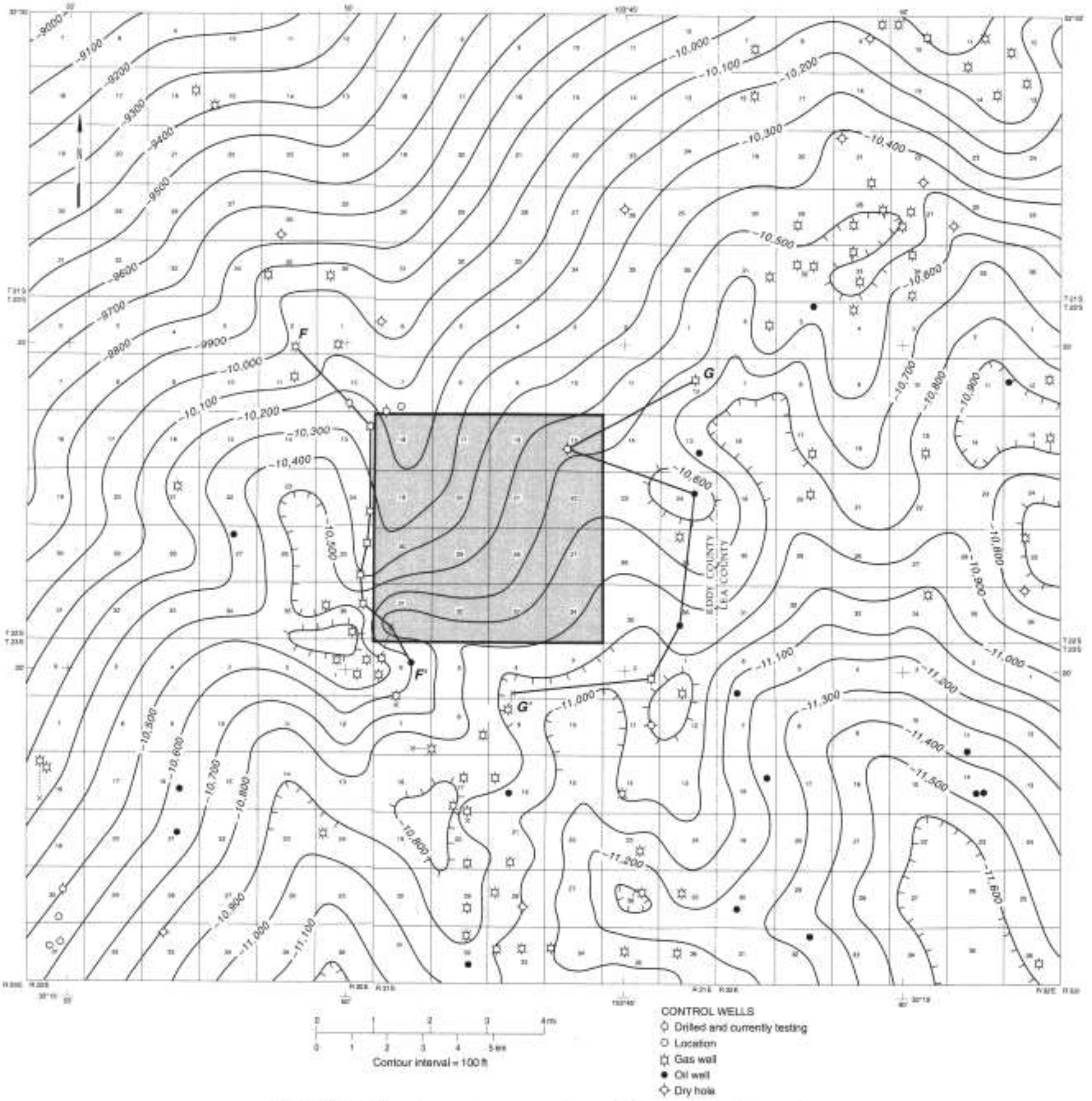


FIGURE 57—Structure contour map of top of Morrow clastic interval.

PROJECTED FUTURE OIL AND GAS PRODUCTION

Future oil, gas, and gas-condensate production was projected (estimated) on an annual basis for oil and gas pools with probable resources underneath the WIPP land withdrawal area and surrounding one-mile-wide additional study area. Projections were made separately for each oil and gas pool or reservoir stratum projected to extend under the WIPP land withdrawal area.

Projections for primary recovery were made using the following factors:

1) The average or typical production decline curves generated for each of the pools (primary recovery).
2) Wells presently producing within the WIPP land withdrawal area and additional study area and the expected remaining production life for each of these wells.
3) Projected future rates of drilling for undrilled proration spacing locations identified as containing probable resources, assuming that WIPP is not closed to drilling—future rates of

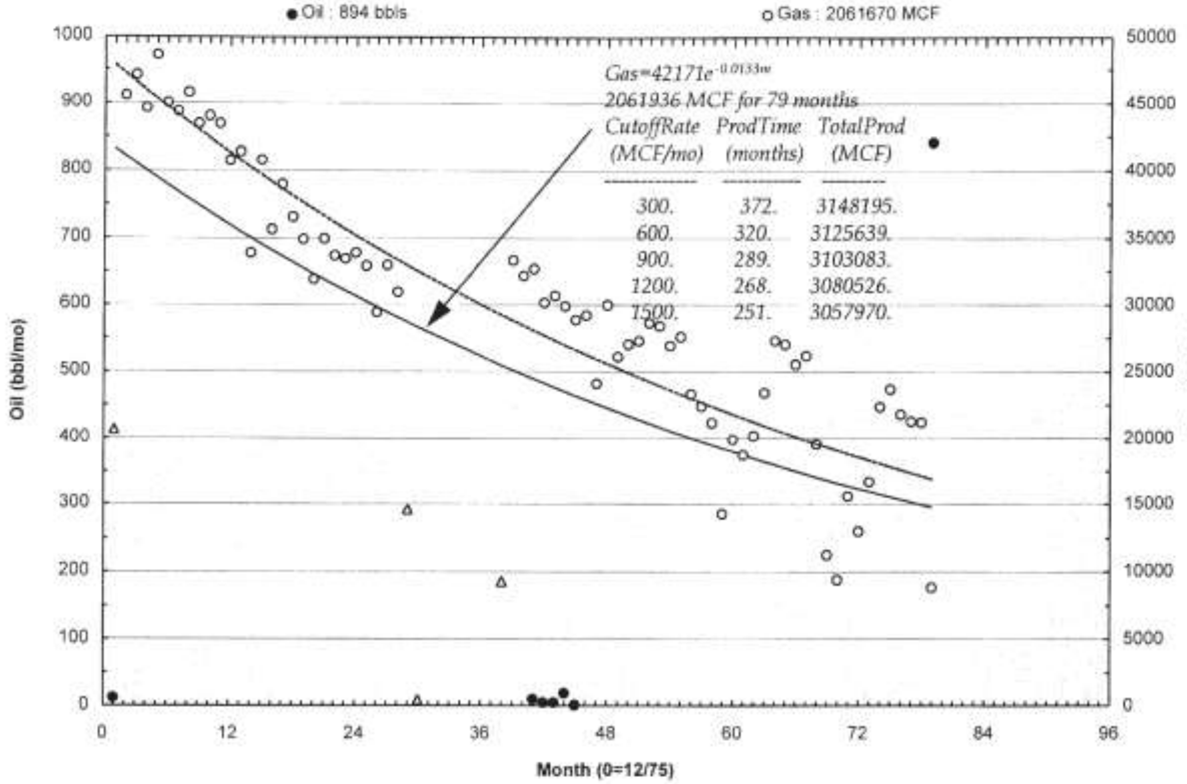


FIGURE 58—Typical gas production decline curve for wells producing from Atoka Group, WIPP site area. Well is Conoco Inc. No. 7 James Ranch Unit, located in sec. 6 T23S R31E.

drilling were based on historical rates of drilling in each oil and gas pool projected to extend underneath WIPP.

4) Estimated probable oil and gas resources recoverable by primary production methods.

Projections for secondary (waterflood) recovery were made using the following factors:

1) Estimated probable oil and gas resources recoverable by waterflood production methods.
2) Estimated future annual primary production of oil and gas.
3) Historical secondary recovery rates of analogous waterflooded oil pools as a function of primary production and decline in primary production.

The resulting estimates of future primary oil and gas recovery and future secondary oil recovery are presented in Figs. 61-68 and in Tables 15 and 16. These results were used to calculate the estimated value of oil, gas, and gas condensate underneath the WIPP land withdrawal area and additional study area (see Anselmo, this volume).

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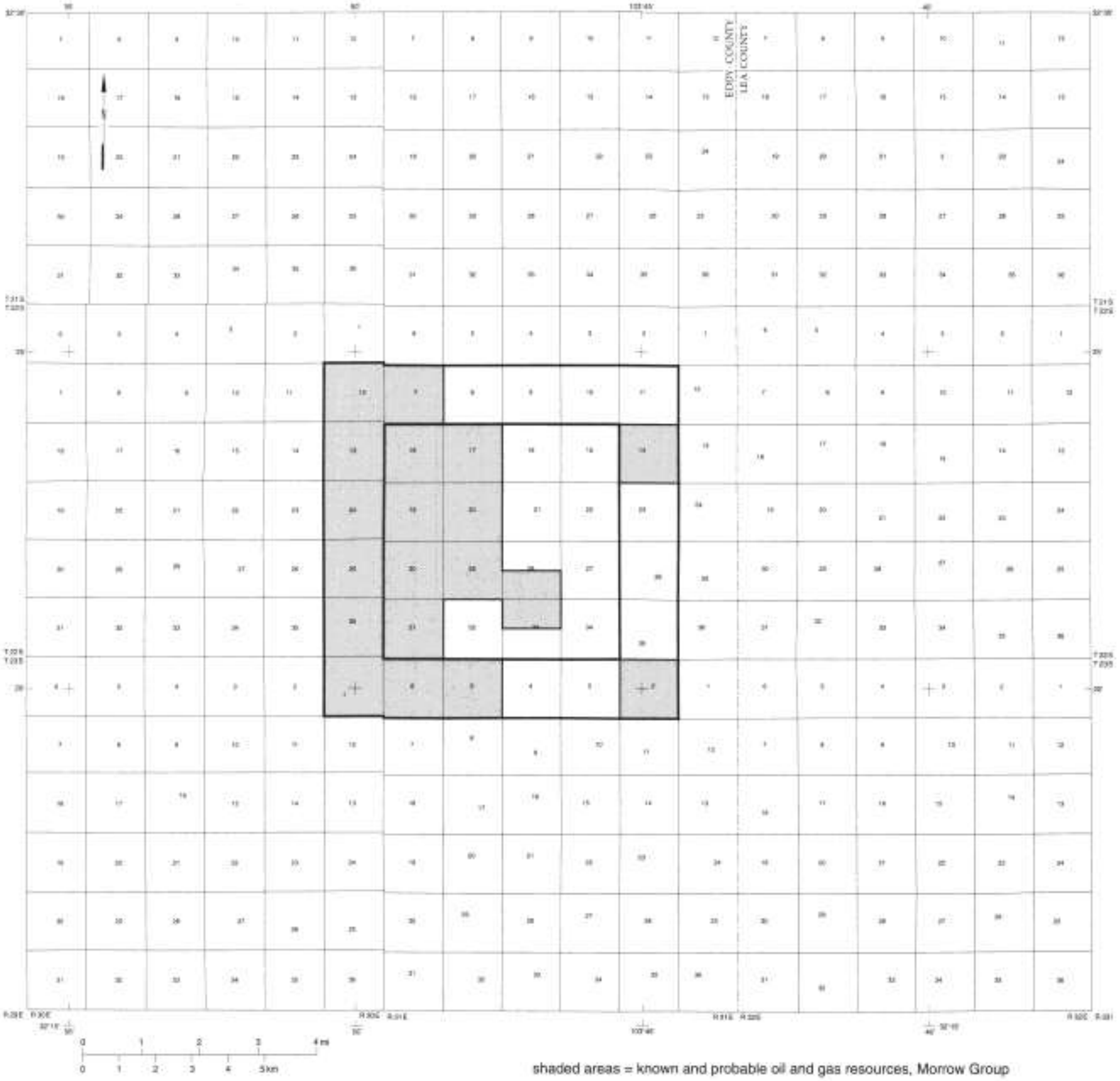
(References begin on page 71)



shaded areas = known and probable oil and gas resources, Morrow Group

FIGURE 59—Areas of known and probable oil and gas resources within WIPP site and one-mile-wide additional study area for Morrow pools projected to extend under the WIPP site.

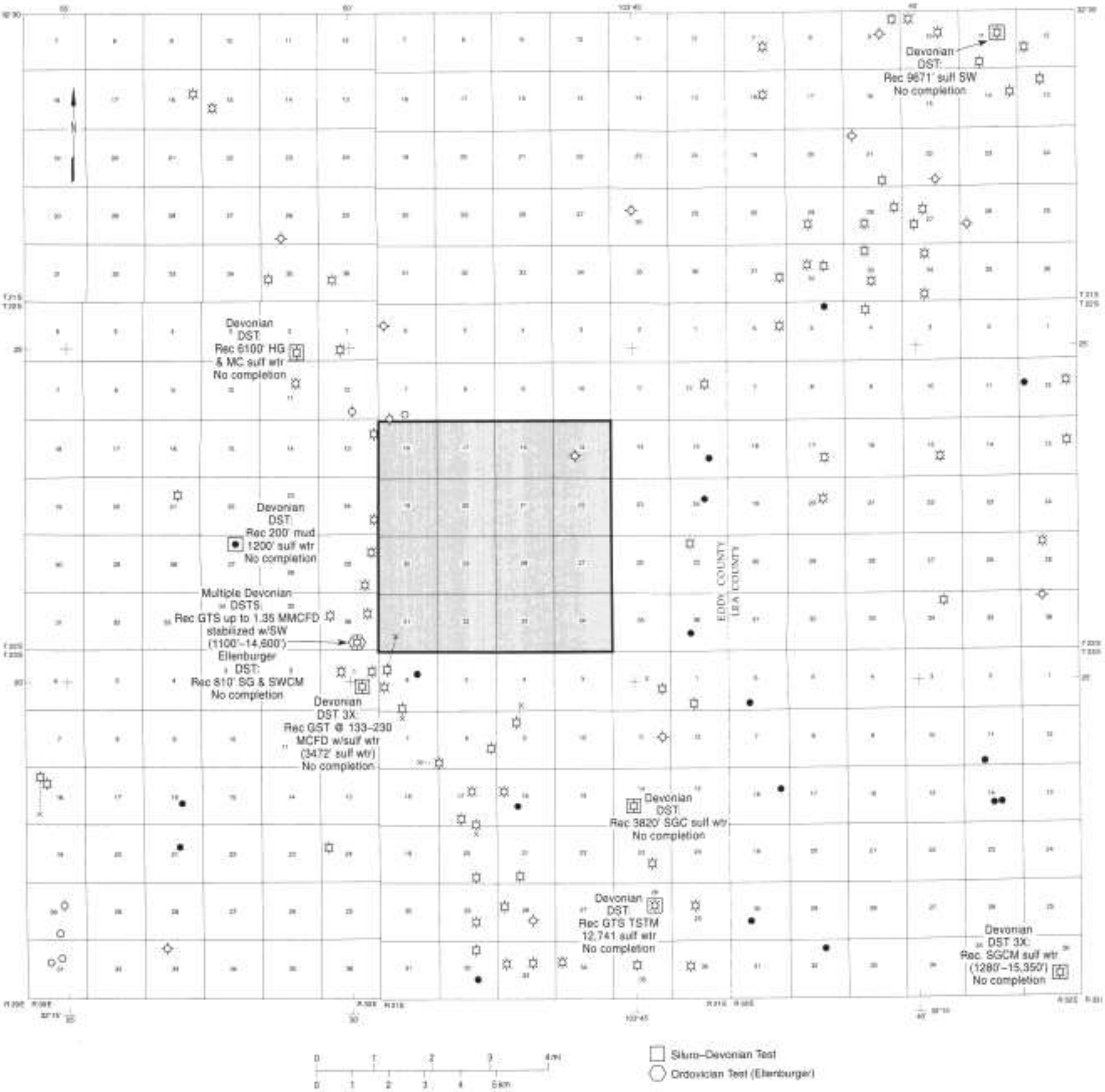


FIGURE 60—Wells that have penetrated pre-Mississippian strata within the study area. DST, drill stem test; Rec, recovered; HG&MC, heavy gas- and mud-cut salt water; sulf wtr, sulphur water; GTS, gas to surface; MMCFD, million ft^3 per day; SW, salt water; SG&SWCM, slight gas- and salt water-cut mud; SGC, slight gas-cut; SGCM, slight gas-cut mud.

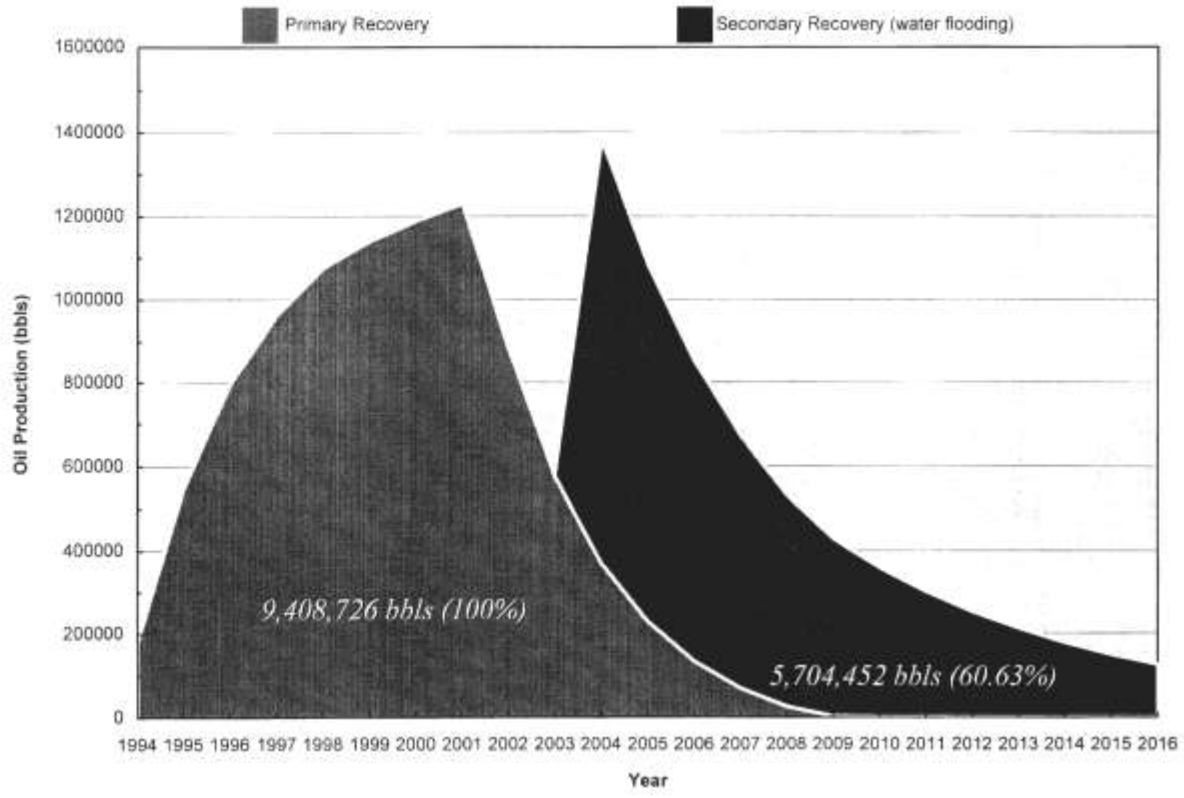


FIGURE 61—Projected future annual oil production from upper Brushy Canyon main pay, Livingston Ridge–Lost Tank pools for WIPP site and surrounding one-mile-wide additional study area. Separate projections are given for primary recovery and secondary (waterflood) recovery.

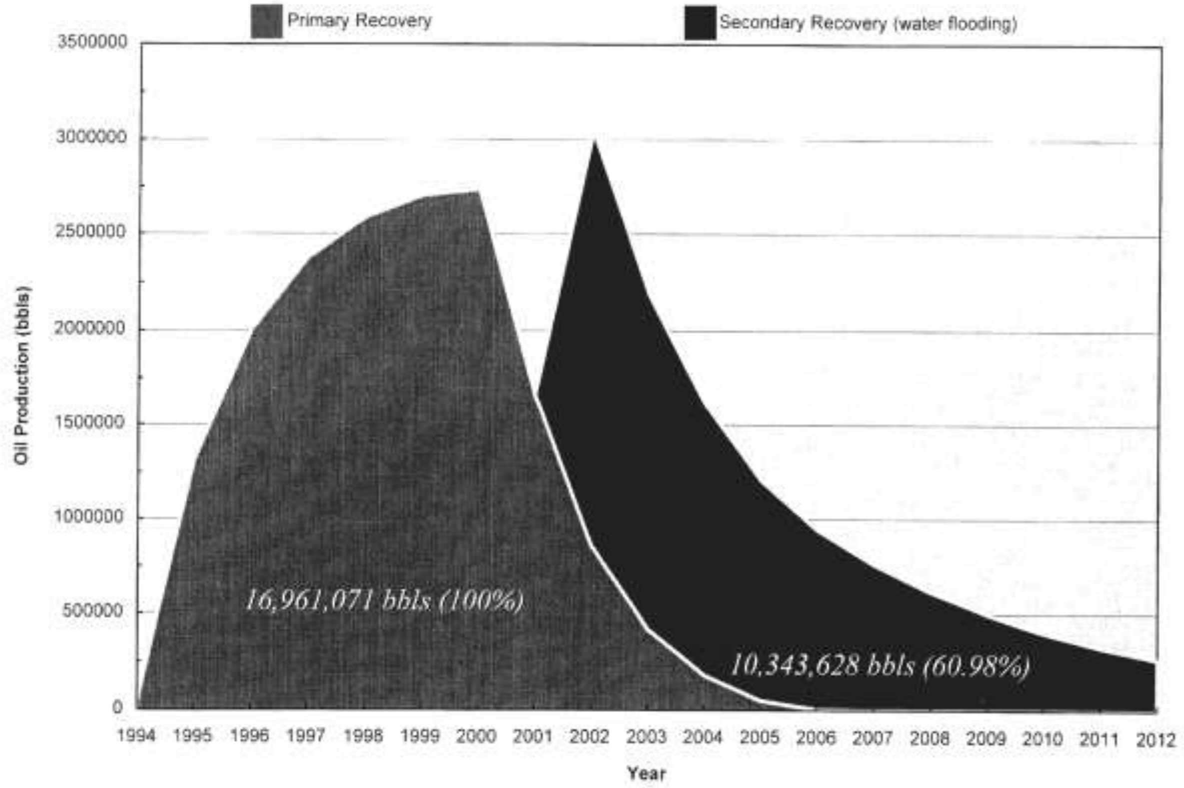


FIGURE 62—Projected future annual oil production from lower Brushy spring Canyon D zone, Los Medanos Delaware complex for WIPP site and one-mile-wide additional study area. Separate projections are given for primary recovery and secondary (waterflood) recovery.

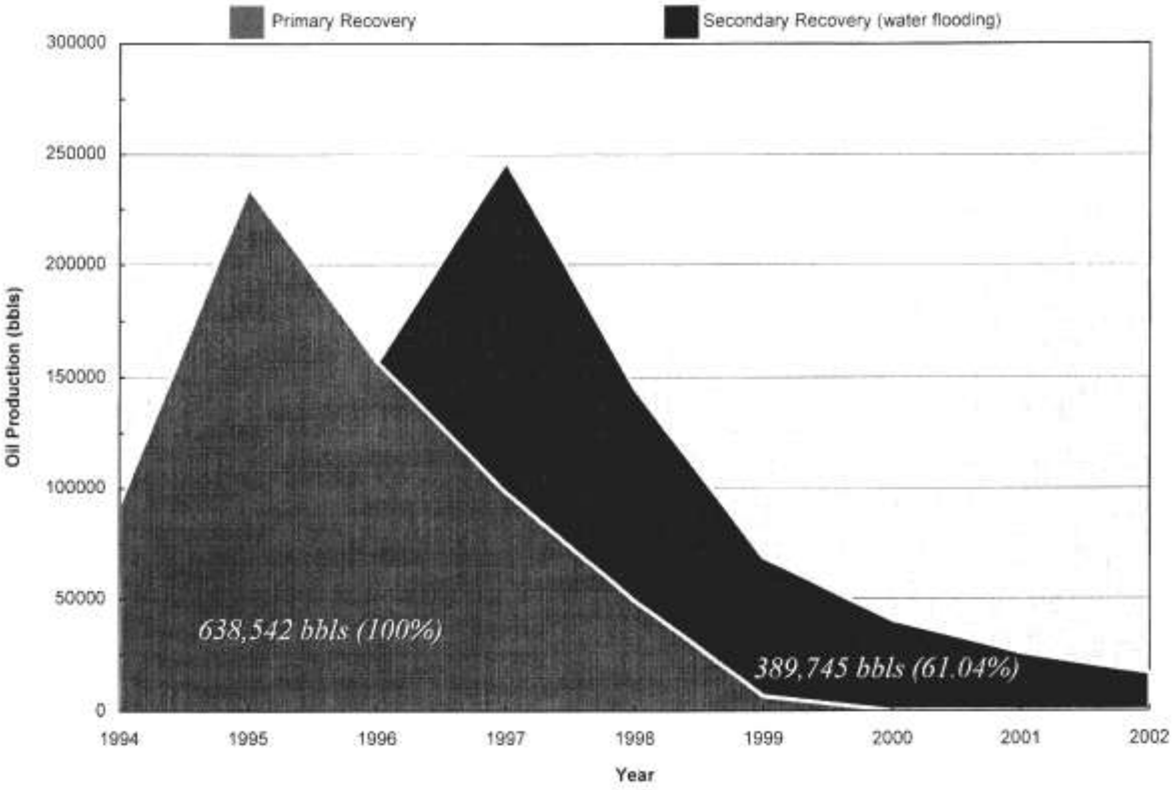


FIGURE 63—Projected future annual oil production from lower Brushy Canyon B zone, Cabin Lake Delaware pool for WIPP site and one-mile-wide additional study area. Separate projections are given for primary recovery and secondary (waterflood) recovery.

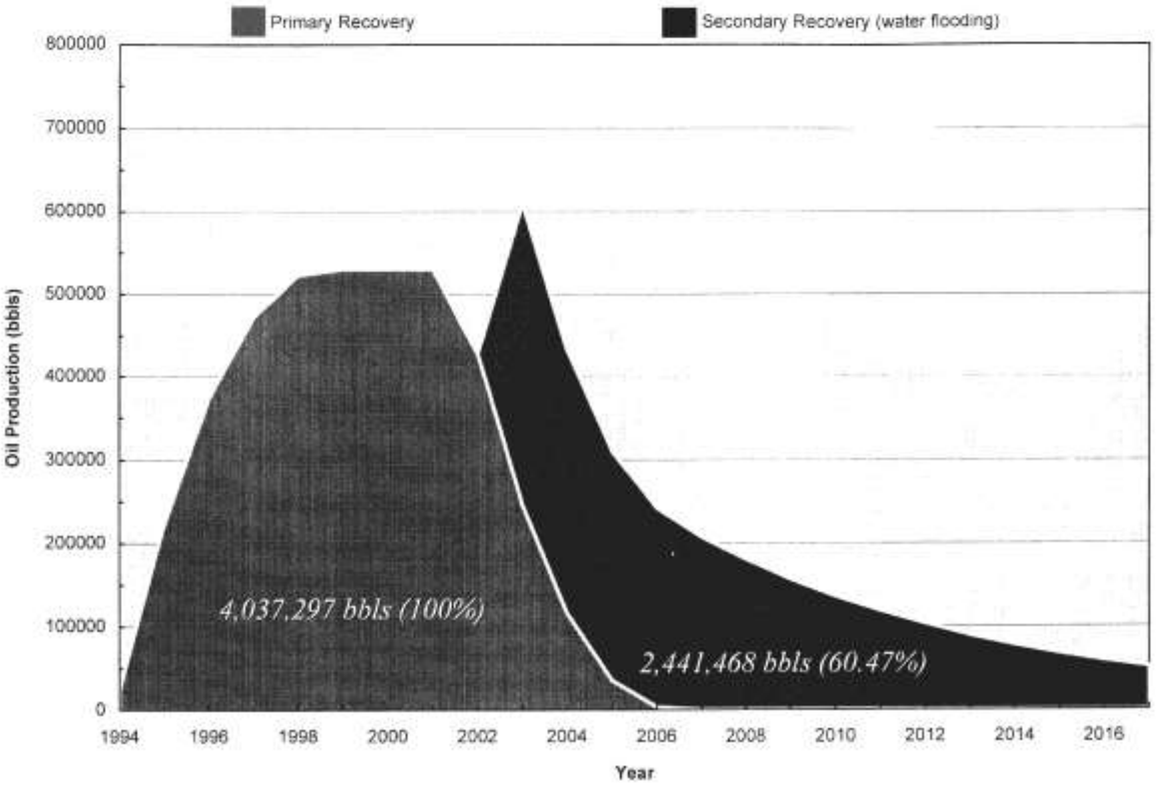


FIGURE 64—Projected future annual oil production from lower Brushy Canyon B zone, Quahada Ridge Southeast pool for WIPP site and one-mile-wide additional study area. Separate projections are given for primary recovery and secondary (waterflood) recovery.

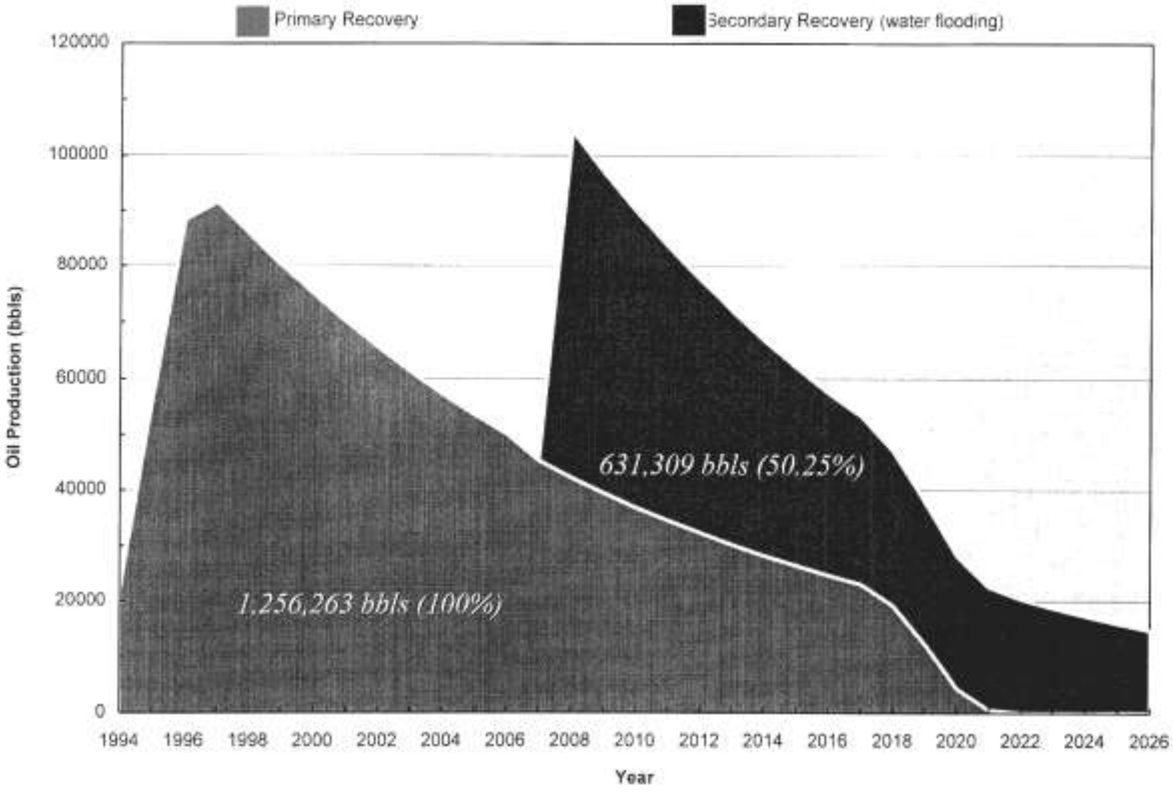


FIGURE 65—Projected future annual oil production from Third Bone Spring sandstone, Los Medanos Bone Spring pool for WIPP site and one-mile-wide additional study area. Separate projections are given for primary recovery and secondary (waterflood) recovery.

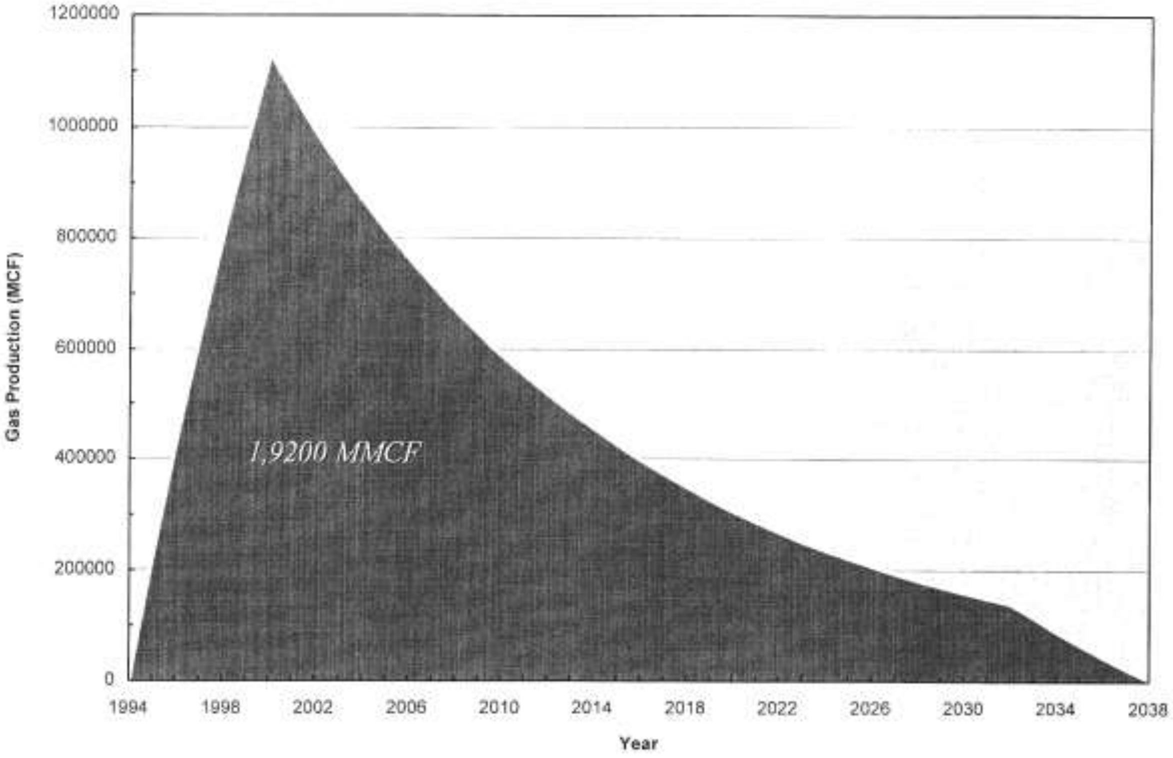


FIGURE 66—Projected future annual gas production from Strawn Group for WIPP site and one-mile-wide additional study area.

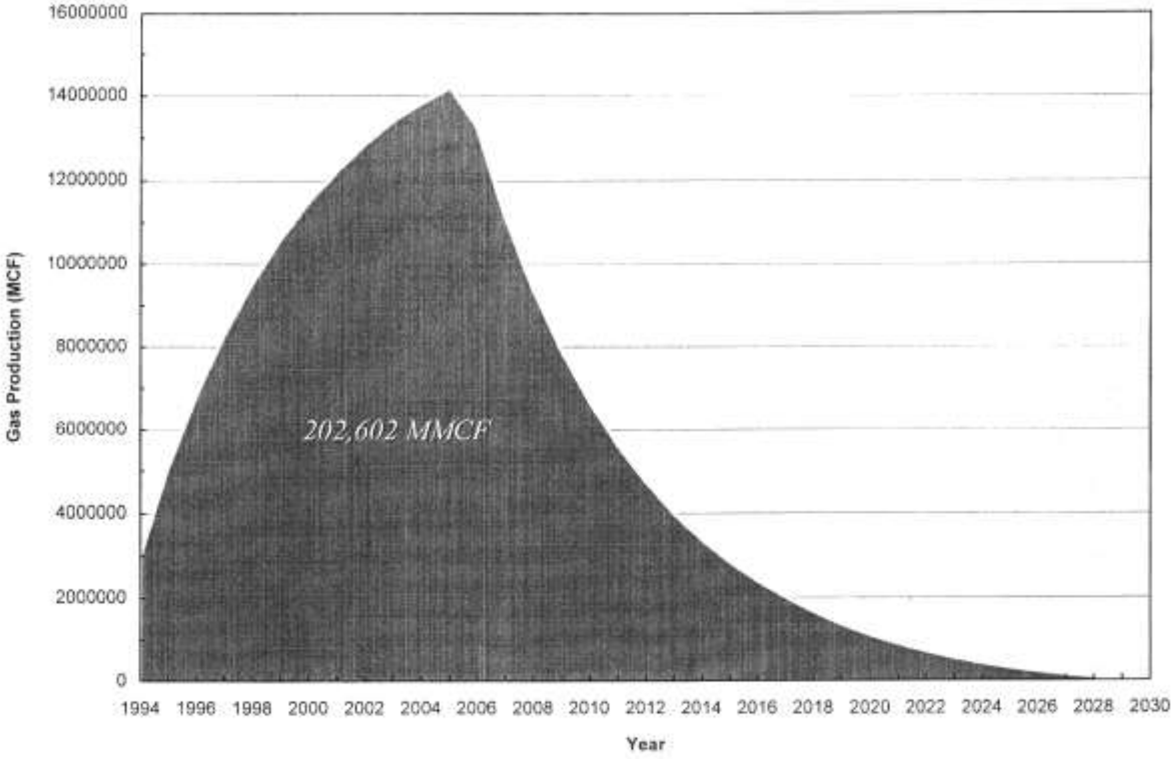


FIGURE 67—Projected future annual gas production from Atoka Group for WIPP site and one-mile-wide additional study area.

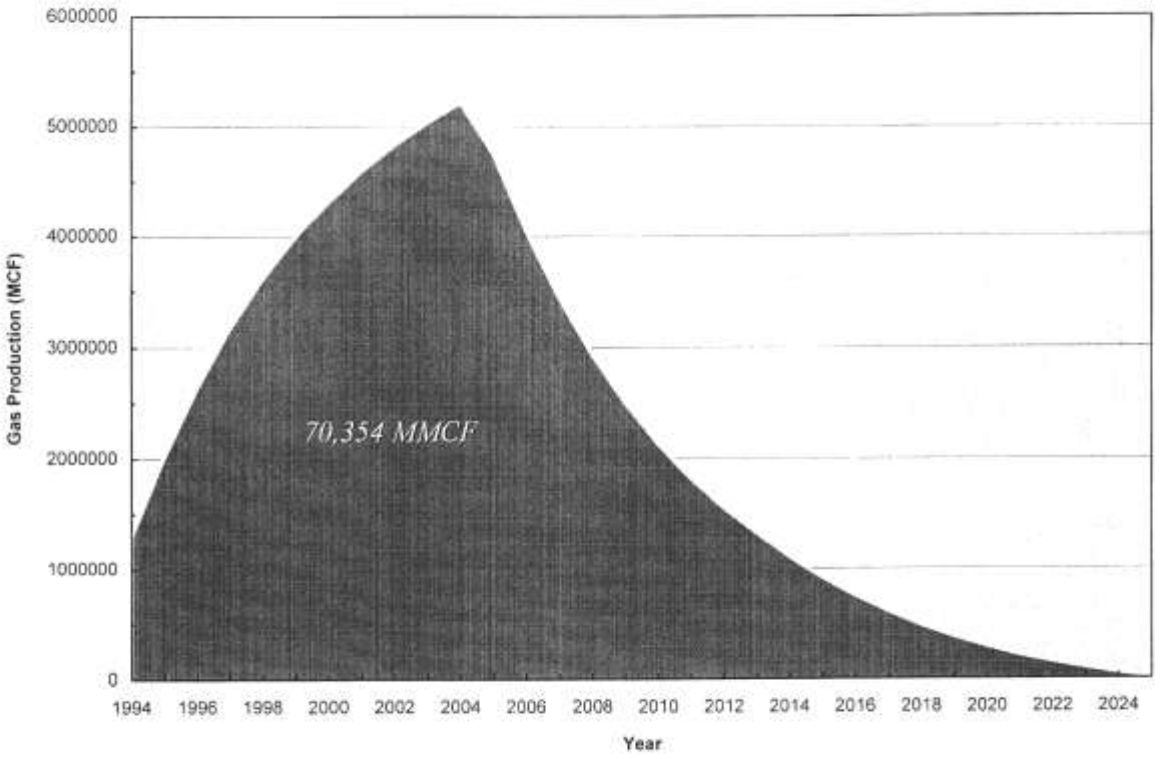


FIGURE 68—Projected future annual gas production from Morrow Group for WIPP site and one-mile-wide additional study area.

TABLE 15A—Livingston Ridge Delaware pool: projected future annual oil and gas production (primary recovery) for probable resources identified under WIPP land withdrawal area (LWA) and one-mile-wide additional study area.

Year	Wells		Oil (KBO)		Gas (MMCF)	
	WIPP LWA	Addt area	WIPP LWA	Addt area	WIPP LWA	Addt area
1994	0	15	0	180	0	279
1995	2	27	61	487	51	524
1996	4	39	102	694	100	758
1997	6	51	130	834	140	958
1998	8	63	149	927	173	1112
1999	10	69	161	978	197	1203
2000	12	72	170	1019	214	1284
2001	16	82	236	993	278	1307
2002	18	82	220	665	281	1038
2003	16	70	145	431	222	756
2004	14	58	95	274	165	520
2005	12	46	61	167	116	335
2006	10	34	39	95	77	198
2007	8	22	23	46	48	98
2008	6	10	11	14	25	30
2009	2	0	3	0	6	0

TABLE 15B—Los Medanos Delaware complex: projected future annual oil and gas production (primary recovery) for probable resources identified under WIPP land withdrawal area (LWA) and one-mile-wide additional study area.

Year	Wells		Oil (KBO)		Gas (MMCF)	
	WIPP LWA	Addt area	WIPP LWA	Addt area	WIPP LWA	Addt area
1994	0	5	0	45	0	122
1995	17	24	610	706	1064	1261
1996	34	42	942	1065	1830	2082
1997	51	61	1124	1259	2316	2597
1998	68	76	1224	1368	2605	2912
1999	85	95	1278	1428	2770	3096
2000	102	114	1292	1444	2815	3147
2001	90	96	862	799	2064	2020
2002	73	77	448	411	1211	1147
2003	56	58	222	199	642	586
2004	39	39	98	83	295	252
2005	22	20	30	19	94	60
2006	5	1	4	1	13	3

TABLE 15C—Cabin Lake Delaware pool: projected future annual oil and gas production (primary recovery) for probable resources identified under WIPP land withdrawal area (LWA) and one-mile-wide additional study area.

Year	Wells		Oil (KBO)		Gas (MMCF)	
	WIPP LWA	Addt area	WIPP LWA	Addt area	WIPP LWA	Addt area
1994	0	6	0	93	0	65
1995	0	13	0	235	0	164
1996	0	12	0	157	0	110
1997	0	9	0	98	0	68
1998	0	7	0	49	0	34
1999	0	7	0a	7	0	5

TABLE 15D—Quahada Ridge Southeast Delaware pool: projected future annual oil and gas production (primary recovery) for probable resources identified under WIPP land withdrawal area (LWA) and one-mile-wide additional study area.

	Wells		Oil (KBO)		Gas (MMCF)	
Year	WIPP LWA	Addt area	WIPP LWA	Addt area	WIPP LWA	Addt area
1994	0	1	0	24	0	17
1995	1	8	26	198	18	138
1996	2	15	45	329	31	228
1997	3	22	58	414	41	289
1998	4	29	65	458	46	319
1999	5	35	66	464	46	323
2000	5	35	66	464	46	323
2001	5	35	66	464	46	323
2002	6	30	92	336	64	234
2003	5	23	60	187	42	130
2004	4	16	34	82	24	57
2005	3	9	15	21	10	14
2006	2	2	2	2	1	1

TABLE 15E—Los Medanos Bone Spring pool: projected future annual oil and gas production (primary recovery) for probable resources identified under WIPP land withdrawal area (LWA) and one-mile-wide additional study area.

	Wells		Oil (KBO)		Gas (MMCF)	
Year	WIPP LWA	Addt area	WIPP LWA	Addt area	WIPP LWA	Addt area
1994	0	3	0	22	0	38
1995	2	5	18	38	28	65
1996	4	7	35	54	56	91
1997	4	8	32	59	54	102
1998	4	8	30	55	53	99
1999	4	8	28	58	51	96
2000	4	8	26	48	50	93
2001	4	8	25	45	48	90
2002	4	8	23	42	46	86
2003	4	8	22	40	44	83
2004	4	8	20	37	43	79
2005	4	8	19	35	41	76
2006	4	8	18	32	39	73
2007	4	8	17	29	37	65
2008	4	7	15	27	36	62
2009	4	7	14	25	34	59
2010	4	7	14	23	32	56
2011	4	7	13	22	31	53
2012	4	7	12	20	29	50
2013	4	7	11	19	28	48
2014	4	7	10	18	26	45
2015	4	7	10	17	25	43
2016	4	7	9	16	24	41
2017	4	7	8	15	22	38
2018	4	7	8	11	21	30
2019	4	5	5	7	13	19
2020	2	3	1	3	3	8
2021	0	1	0	1	0	2

TABLE 15F—Strawn reservoirs: projected future annual oil and gas production (primary recovery) for probable resources identified under WIPP land withdrawal area (LWA) and one-mile-wide additional study area.

	Wells		Oil (KBO)		Gas (MMCF)	
Year	WIPP LWA	Addt area	WIPP LWA	Addt area	WIPP LWA	Addt area
1994	0	0	0	0	0	0
1995	1	1	6	6	110	110
1996	2	2	12	12	213	213
1997	3	3	17	17	310	310
1998	4	4	21	21	400	400
1999	5	5	25	25	485	485
2000	6	6	29	29	565	565
2001	6	6	26	26	529	529
2002	6	6	24	84	496	496
2003	6	6	22	22	464	464
2004	6	6	20	20	435	435
2005	6	6	18	18	408	408
2006	6	6	16	16	382	382
2007	6	6	14	14	358	358
2008	6	6	13	13	335	335
2009	6	6	12	12	314	314
2010	6	6	11	11	294	294
2011	6	6	10	10	276	276
2012	6	6	9	9	258	258
2013	6	6	8	8	242	242
2014	6	6	7	7	227	227
2015	6	6	6	6	213	213
2016	6	6	6	6	199	199
2017	6	6	5	5	187	187
2018	6	6	5	5	175	175
2019	6	6	4	4	164	164
2020	6	6	4	4	153	153
2021	6	6	4	4	144	144
2022	6	6	3	3	135	135
2023	6	6	3	3	126	126
2024	6	6	3	3	118	118
2025	6	6	2	2	111	111
2026	6	6	2	2	104	104
2027	6	6	2	2	97	97
2028	6	6	2	2	91	91
2029	6	6	2	2	85	85
2030	6	6	1	1	80	80
2031	6	6	1	1	75	75
2032	6	6	1	1	70	70
2033	6	6	1	1	58	58
2034	5	5	1	1	45	45
2035	4	4	1	1	33	33
2036	3	3	0	0	22	22
2037	2	2	0	0	11	11
2038	1	1	0	0	2	2

TABLE 15G—Atoka reservoirs: projected future annual condensate and gas production (primary recovery) for probable resources identified under WIPP land withdrawal area (LWA) and one-mile-wide additional study area.

	Wells		Oil (KBO)		Gas (MMCF)	
Year	WIPP LWA	Addt area	WIPP LWA	Addt area	WIPP LWA	Addt area
1994	0	5	0	29	0	3020
1995	1	6	13	36	1274	3821
1996	3	6	36	30	3624	3222
1997	4	7	42	37	4330	3992
1998	5	8	47	43	4926	4641
1999	6	9	52	48	5429	5188
2000	8	9	68	39	7127	4375
2001	9	10	68	45	7285	4964
2002	10	11	69	50	7418	5461
2003	11	12	69	53	7530	5780
2004	13	12	82	44	8899	4944
2005	14	12	80	48	8779	5425
2006	15	11	78	40	8678	4566
2007	15	11	64	32	7319	3835
2008	15	10	53	27	6172	3229
2009	15	10	43	22	5205	2723
2010	15	10	35	18	4390	2297
2011	15	10	29	15	3702	1938
2012	15	10	24	12	3122	1633
2013	15	10	19	10	2633	1377
2014	15	10	16	8	2220	1162
2015	15	10	13	7	1872	980
2016	15	10	11	5	1579	826
2017	15	10	9	4	1332	697
2018	15	10	7	3	1123	549
2019	15	8	6	3	928	440
2020	14	7	5	2	742	370
2021	12	7	4	2	603	292
2022	11	6	3	1	487	225
2023	10	5	2	1	390	169
2024	9	4	2	1	288	141
2025	7	4	1	1	221	99
2026	6	3	1	0	165	63
2027	5	2	1	0	118	32
2028	4	1	0	0	59	25
2029	2	1	0	0	27	2
2030	1	0	0	0	2	0

TABLE 15H—Morrow reservoirs: projected future annual condensate and gas production (primary recovery) for probable resources identified under WIPP land withdrawal area (LWA) and one-mile-wide additional study area.

	Wells		Oil (KBO)		Gas (MMCF)	
Year	WIPP LWA	Addt area	WIPP LWA	Addt area	WIPP LWA	Addt area
1994	0	6	0	2	0	1298
1995	1	8	0	3	306	1718
1996	3	9	1	3	873	1770
1997	4	11	1	4	1050	2121
1998	6	12	2	4	1507	2114
1999	7	14	2	4	1590	2414
2000	9	14	3	4	1967	2353
2001	10	16	3	5	1983	2618
2002	12	17	4	5	2302	2537
2003	13	19	4	6	2269	2775
2004	15	20	5	6	2546	2671
2005	16	20	5	6	2476	2277
2006	16	20	5	6	2111	1941
2007	16	20	5	6	1799	1648
2008	16	19	5	6	1534	1401
2009	16	19	5	6	1308	1194
2010	16	19	5	6	1115	1018
2011	16	19	5	6	950	868
2012	16	19	5	6	810	740
2013	16	19	5	6	691	631
2014	16	19	5	6	589	523
2015	16	15	5	5	501	415
2016	15	13	5	4	415	333
2017	13	12	4	4	333	272
2018	12	10	4	3	272	211
2019	10	9	3	3	211	168
2020	9	7	3	2	168	123
2021	7	6	2	2	123	93
2022	6	4	2	1	93	58
2023	4	3	1	1	58	38
2024	3	1	1	0	38	12
2025	1	0	0	0	12	0

TABLE 16—Projected future annual oil production (due to waterflooding) for probable resources under WIPP land withdrawal area (LWA) and one-mile-wide additional study area.

Year	Oil Production (KBO) WIPP LWA	Oil Production (KBO) Additional study area
1997	0	149
1998	0	96
1999	0	62
2000	0	40
2001	0	26
2002	1030	1172
2003	893	1240
2004	885	1879
2005	724	1563
2006	593	1301
2007	486	1084
2008	419	945
2009	345	792
2010	285	664
2011	236	558
2012	195	469
2013	62	282
2014	53	242
2015	46	207
2016	40	178
2017	18	63
2018	9	19
2019	9	17
2020	8	16
2021	7	15
2022	7	14
2023	6	12
2024	6	12
2025	5	11
2026	5	9

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Valuation of oil and gas resources at the Waste Isolation Pilot Plant (WIPP) site additional area and combined area

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SUMMARY

The concern of this section is presentation of valuation results and discussion of the method by which estimated oil and gas reserves at the projected Waste Isolation Pilot Plant (WIPP), the designated additional area around the plant, and the combined area comprising both WIPP and the additional area were evaluated. A Monte Carlo sampling method was used to generate random-walk price data for the period 1995-2030. Although a 35-year time frame was used, most oil and gas activity will occur over a decade or so once activity begins. Expected-revenue present values (PV) for both oil and gas are presented. Expected net present values (NPV) for the decision(s) to invest in oil and gas from the perspective of a single firm are also presented. Discount rates of 15% and 10% were used in the study. Overall results are presented first, then the method used is briefly described.

RESULTS

Oil and gas deposits at the WIPP site, additional area, and combined (WIPP site plus the additional area) area were valued via simulation using reserve data from the New Mexico Bureau of Mines & Mineral Resources (NMBMMR) and random-walk modeling of market commodity prices. Data are provided in the cases of both a 15% and a 10% discount rate for future cash flows. Expected Net Present Values, written as E(NPV), were calculated for cash flows anticipated from oil and gas development activities from the perspective of a single firm. These values represent the average of the present values of all the cash flows associated with each simulation run.

TABLE 1—Expected Revenue Present Values [E(PV)] at a discount rate of 15% (millions of dollars).

	Combined Area	WIPP Area	Additional Area
Oil	390	130	260
Gas	200	100	100

Total-revenue present values were also calculated and are provided as an indication of the overall worth of oil and gas deposits at the actual WIPP site and in the additional and combined areas. Total revenue present values are presented in the attachments as PV Rev. Like E(NPV) values, revenue values are expected present values, as they are the average of the expected present values generated by each simulation run.

The expected present value of combined oil reserves is $390 million at a discount rate of 15%. A histogram of distribution of the expected present value [E(PV)] results for 1008 simulations is presented in Figure 1. All histograms presented in this section represent 1008 simulation runs. The distribution is symmetric at around $400 million, and the likelihood an E(PV) value lower than $300 million or higher than $500 million is small—on the order of about 4%. As may be seen in Table 1, the E(PV) of WIPP site oil reserves is estimated to be $130 million, and the E(PV) of additional-area reserves is estimated to be $260 million. The E(PV) for combined area gas reserves is $200 million at 15%. This E(PV) distribution, with all its observations between $150 million and $275 million, is shown in Figure 2. The E(PV)s for the WIPP and and additional-area gas reserves are both estimated as $100 million at 15%. These data are also in Table 1.

The E(PV) for combined oil reserves is about $520 million if a discount rate of 10% is used. Figure 3 depicts these data, and Figure 4 contains E(PV) data for combined gas reserves at 10%. The distributions in both Figure 3 and Figure 4 are somewhat skewed. The 10% E(PV) for WIPP site oil reserves is estimated to be $180 million. Combined gas reserves have an estimated E(PV) of $280 million at 10%. WIPP site gas reserves have an estimated E(PV) of $130 million. The data are summarized in Table 2.

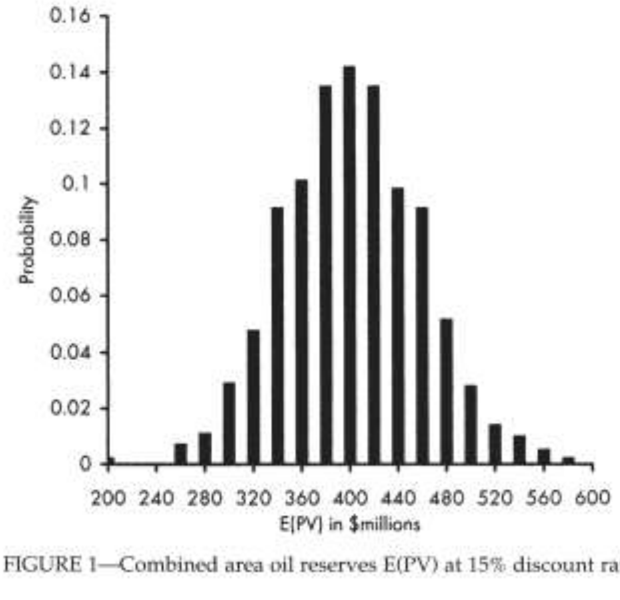

FIGURE 1—Combined area oil reserves E(PV) at 15% discount rate.

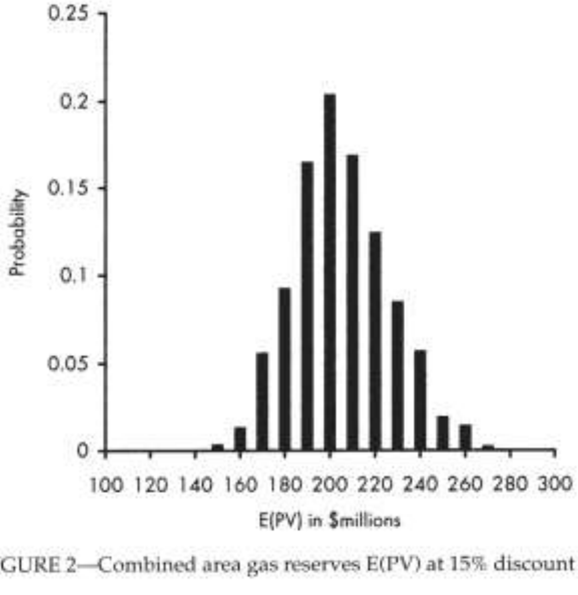

FIGURE 2—Combined area gas reserves E(PV) at 15% discount rate.

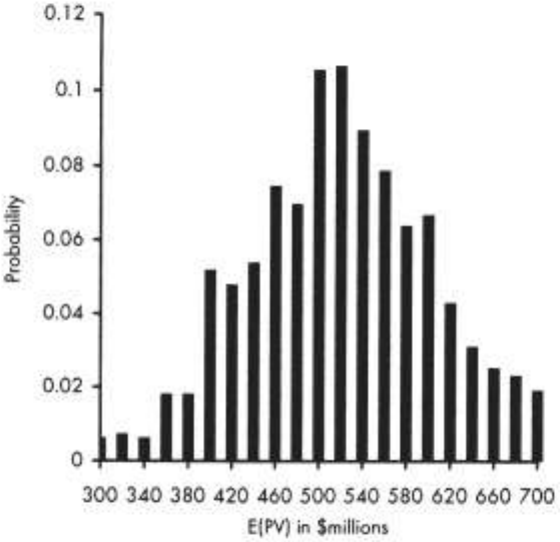

FIGURE 3—Combined area oil reserves E(PV) at 10% discount rate.

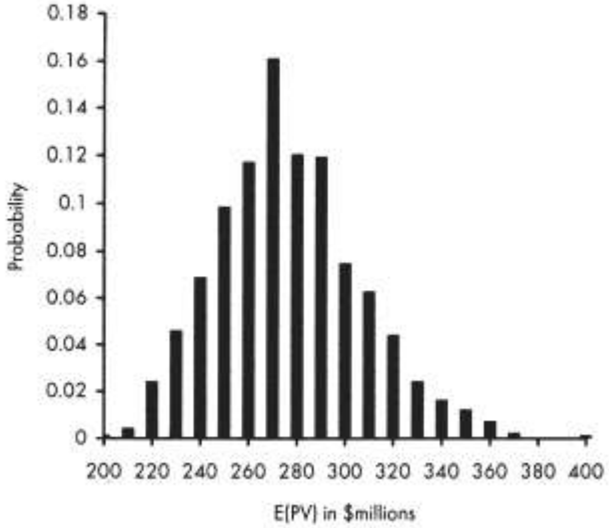

FIGURE 4—Combined area gas reserves E(PV) at 10% discount rate.

With respect to actual exploration and development of oil and gas resources, the concern is the net present value of anticipated cash flows. For this study, oil and gas extraction operations within the combined area were valued from the perspective of a single firm. Although there are (at least) several oil and gas firms operating in the Eddy County area, use of the single firm perspective presents an estimated aggregate valuation of revenues and cash flows from oil and gas development.

Simulation data provide the cash-flow estimates, which were aggregated and averaged to yield expected net present values. From the perspective of a firm engaged in extraction of oil and gas deposits from this area of the state, a 15% discount rate leads to the following conclusions from the simulations runs [E(NPV) data for oil and gas using a 15% discount rate are summarized in Table 3]:

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TABLE 3—Exp
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The Expected Net Present Value E(NPV) of oil production in the combined area is about $37 million. As may be seen in Figure 5, this E(NPV) distribution is skewed. Also, note that negative E(NPV) values occurred in the simulation. Based on the simulation result, the probability of a negative present value of actual cash flows using a 15% discount rate is about 0.09.

The E(NPV) for oil production within the boundaries of the WIPP site is $13 million at 15%.

The E(NPV) for oil production within the additional area is $24 million at 15%.

The E(NPV) at 15% for gas production in the combined area is $96 million. See Figure 6. As was the case with Figure 5, the distribution for combined area gas E(NPV) is not symmetric. However, no negative E(NPV) values were obtained in the simulations.

The E(NPV) for gas production within the additional area is $50 million.

The E(NPV) for gas production within the boundaries of the WIPP site is $46 million with a 15% discount rate.

From the perspective of a firm engaged in extraction of oil and gas deposits from this area, a 10% discount rate leads to the following conclusions from the simulation runs [E(NPV) data are summarized in Table 4]:

The Expected Net Present Value E(NPV) of oil production in the combined area is $74 million. See Figure 7. This distribution is skewed to the left and some negative E(NPV)s were calculated. Based on the simulation runs, the probability of oil operations having an aggregate cash flow with a negative present value is about 0.08. Although the distribution in Figure 7 peaks in the $97.5 million interval, the average (expected) value is about $74 million—reflecting the skewed nature of the distribution. $74 million is twice as large at the comparable 15% figure because of the decreased discount rate.

The E(NPV) for oil production within the boundaries of the WIPP site is $27 million.

The E(NPV) for oil production within the additional area is $47 million at 10%.

The E(NPV) at 10% for gas exploration in the com-

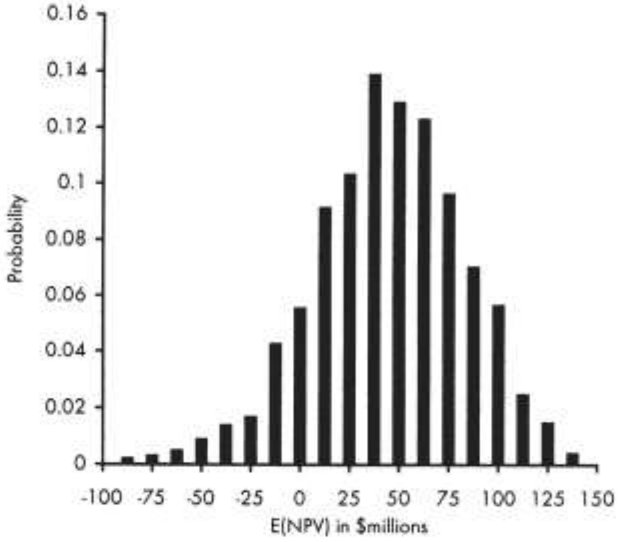

FIGURE 5—Combined area oil cash flow at 15% discount rate.

biped area is $133 million. See Figure 8. The shape of the distribution is similar to the one in Figure 6. As in the 15% case, no simulation outputs were negative.

The E(NPV) for gas production within the boundaries of the WIPP site is $64 million.

The E(NPV) for gas production within the additional area is about $69 million.

Taxes and potentially foregone tax revenues were also studied via the simulation. Values for severance, state and corporate taxes, as well as royalty payments were simulated. Expected present values [E(PV)s] are presented in Tables 5 and 6 for oil and gas at a 15% discount rate. Tables 7 and 8 contain data associated with a 10% discount rate. Because these are rounded figures from separate simulations, values from the additional and WIPP areas may not exactly sum to reported combined area values.

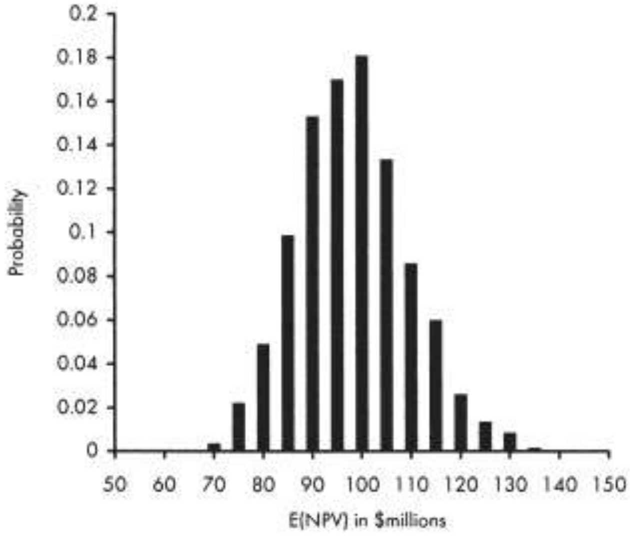

FIGURE 6—Combined area gas cash flow at 15% discount rate.

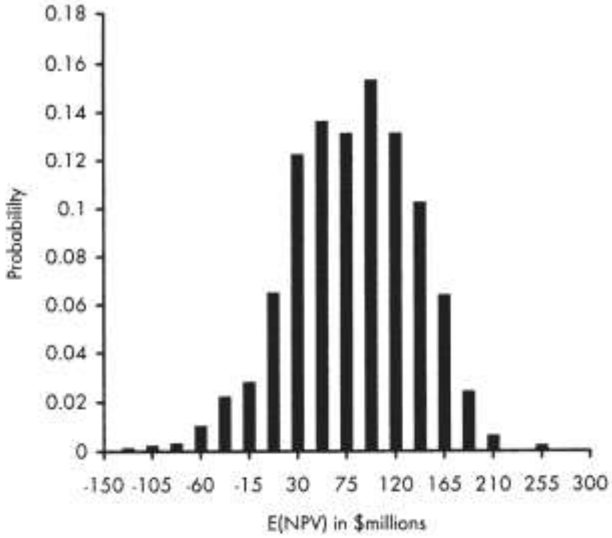

FIGURE 7—Combined area oil cash flow at 10% discount rate.

TABLE 4—Expected Net Present Values [E(NPV)] for oil and gas at a discount rate of 10% (in millions of dollars).

	Combined Area	WIPP Area	Additional Area
Oil	74	27	47
Gas	133	64	69

SIMULATION METHOD

Oil and gas reserve estimates for the WIPP site, additional area, and combined area were provided by specialists at the New Mexico Bureau of Mines & Mineral Resources. A simulation model was constructed for both oil and gas in each of the three zones of interest. Key model inputs, in addition to reserve data, included the initial price of the commodity, the unit cost of extraction, severance-tax rates, state and federal corporate taxes, the depreciation schedule assumed for capital investments, and the discount rate.

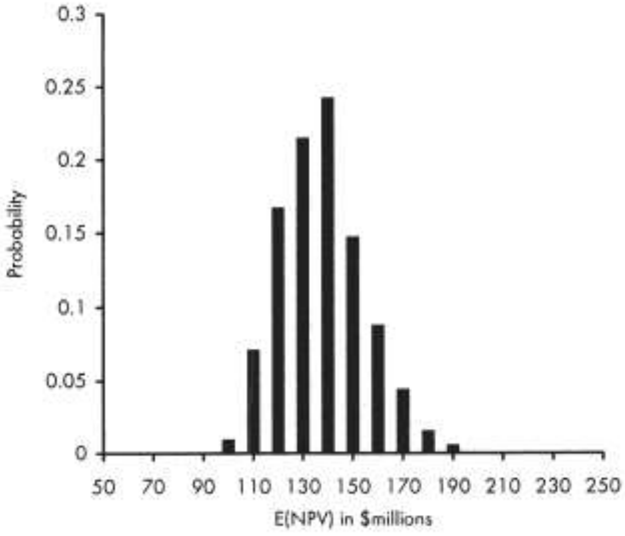

FIGURE 8—Combined area gas cash flow at 10% discount rate.

TABLE 5—Present Values of taxes and royalties on oil production at a 15% discount rate (in millions of dollars).

	Severance Tax	State Tax	Corporate Tax	Royalties
Combined Area	9.827	11.47	49.90	49.05
Additional Area	6.493	7.66	32.87	32.29
WIPP Area	3.378	3.91	17.04	16.70

TABLE 6—Present Values of taxes and royalties on gas production at a 15% discount rate (in millions of dollars).

	Severance Tax	State Tax	Corporate Tax	Royalties
Combined Area	5.044	10.22	43.62	25.20
Additional Area	2.611	5.39	22.05	12.92
WIPP Area	2.42	4.98	20.62	12.11

TABLE 7—Present Values of taxes and royalties on oil production at a 10% discount rate (in millions of dollars).

	Severance Tax	State Tax	Corporate Tax	Royalties
Combined Area	6.77	14.02	60.78	63.87
Additional Area	8.36	9.35	40.02	41.81
WIPP Area	4.372	5.10	21.03	21.86

TABLE 8—Present Values of taxes and royalties on gas production at a 10% discount rate (in millions of dollars).

	Severance Tax	State Tax	Corporate Tax	Royalties
Combined Area	6.70	13.33	57.27	33.48
Additional Area	3.46	7.21	29.99	17.31
WIPP Area	3.38	6.92	28.63	16.88

Development of a method to anticipate future market prices for oil and gas was a key issue. Time units were years, and the time frame simulated was 1995-2030.

Forecasting is as much an inexact art as a science, particularly when the forecasting horizon is 35 years. Thus, although historical prices for Eddy County oil and gas were modeled using time-series methods, a simulation approach was used to value these resources. Annual market prices were simulated using a random-walk methodology (an excellent reference is Karlin and Taylor, 1975), which is discussed below. Depletion was calculated using the standard methodology, which may be found in Stermole and Stermole (1993).

The time frame considered was 1995-2030. Market prices and extraction and well-maintenance costs were considered on an annual basis, and anticipated productivity data—for both new and injection wells—were provided on an annual basis. A sample (this sample does not include actual data used in the study for both investment and operating costs) simulation run for the years 1995-2000 is provided in Table 9.

The six measures of interest are in the bottom six rows of Table 9. PV Rev refers to annual revenue present value observations, which are calculated from annual total operating revenues (Total Op Revs). PVCFlow signifies cash-flow present values which are calculated based on annual cash flows. PV SevTax, PV StateTax, PCV CorpTax, and PV Royal refer to severance taxes, state taxes, corporate taxes, and royalties, respectively.

Key assumptions and features associated with the oil and gas cash flows used in the simulation include: All calculations are performed from 1 January 1995. That is, oil and gas extraction activities in the three zones of interest are treated as a capital project that was evaluated (and undertaken) on 1 January 1995. Reasons for this starting date are found elsewhere in this report.

Drilling capital expenditures are recovered using a seven-year Accelerated Cost Recovery System depreciation method (Stermole and Stermole, 1993).

Revenues are treated as if realized monthly, and taxes and royalties are treated as if they are paid on a quarterly basis.

Simulations were run for each year from 1995 to 2030. Each simulation run consisted of 48 simulated oil price "paths" from 1995 to 2030. The Monte Carlo simulations generated numbers for each year for the present value of the market value of the reserves (PV Rev) and the present value of the total cash flow for each simulation run (PV CFlow). As is standard practice in financial analysis (for example see Levy and Sarnat, 1994), cash flows attributable to the decision to drill for oil or gas are the sum of income after taxes, depreciation, and depletion less investment. Summary data were also generated for the present value of severance-tax flows (PV SevTax), state corporate tax flows (PV StateTax), federal corporate tax flows (PV Corp Tax), and royalty-payment flows (PV Royal).

Specifics regarding simulation input variables are provided below.

Market prices

Prices for oil (per barrel) and gas (per thousand cubic feet) were generated using a random-walk method known as a Wiener process. Historical Eddy County oil and gas prices were analyzed using time-series techniques to show that these historical prices may be modeled as a random process. Use of a Wiener process is attractive in situations such as this one because the uncertainty associated with the commodity-market price estimate in a given year is an increasing function of the forecast time horizon. So, as price forecasts move away from 1995, the uncertainty associated with those forecasts increases (Dixit and Pindyck, 1994).

Weiner processes are less sophisticated than other stochastic-process techniques, and are grounded in three major assumptions. The first, known as the Markov property, states that only current information is useful for forecasting future price paths. Thus, prediction of future prices based on historical price data will not enable speculators to "beat the market." The fact that oil is a major global commodity—and is

TABLE 9—Sample oil simulation. This sample does not include actual data used in the study for both investment and operating costs.

Year	1995	1996	1997	1998	1999	2000
New Wells	22	22	20	20	20	20
Inj Wells						107
Total Wells	22	44	64	84	104	123
Investment	13200000	13200000	12000000	12000000	12000000	60150000
Total Prod	733099	1172687	1404920	1538256	1612839	1654706
Sec Recovery						
Price/bbl	18	17.33203313	17.94481361	17.92289792	22.46395026	23.29897748
Total Op Revs	13195782	20325050	25211028	27570005	36230735	38552958
Total Op Cost	660000	1320000	1920000	2520000	3120000	3690000
Severance Tax	287008	442070	548340	599648	788018	838527
Depreciation	0	1886280	5118960	7229760	8584560	9555840
Royalties	1649473	2540631	3151379	3446251	4528842	4819120
NI Bef Depl	10599301	14136069	14472349	13774346	19209315	19649471
Depletion	1979367	3048758	3781654	4135501	5434610	5782944
Taxable Inc	8619934	11087311	10690695	9638845	13774705	13866527
State Tax	1215115	1402636	1372493	1292552	1606878	1613856
Corp Tax	2930778	3769686	3634836	3277207	4683400	4714619
Net Income	4474041	5914989	5683366	5069086	7484427	7538052
Cash Flow	-6746592	-2349973	2583980	4434347	9503597	-37273164
MonthlyPV	11.07931197	9.544922546	8.223032863	7.084213533	6.103110886	5.257882518
QuarterlyPV	3.651384127	3.1514114	2.719898392	2.347471124	2.026039169	1.748619896
PV Rev	12183349	16166752	17275926	16275984	18426683	16892244
PV CFlow	-6228966	-1869193	1770679	2617822	4833459	-16331493
PV SevTax	261994	348286	372857	351914	399139	366566
PV StateTax	1109213	1105071	933260	758557	813899	705505
PV CorpTax	2675349	2969958	2471596	1923287	2372188	2061019
PV Royal	1505715	2001643	2142858	2022494	2293903	2106702

therefore subject to many of the same political and/or macro-economic based price shocks as other commodities (and financial instruments)—makes the first assumption reasonable.

Second, each (in this case, annual) price change is independent of all other annual price changes. This assumption may not be as easily defended, though assuming that annual average prices are independent of previous (and future) prices is reasonable.

The third assumption is that annual price changes are normally distributed. Based on the analysis of historical annual price data conducted for this study, we cannot refute this assumption. The trouble with this assumption is that very large price swings are possible. In fact, negative prices are theoretically possible. However, since all data reported are the result of (at least) 1008 sumulation runs, potential negative-price impacts are negated.

The starting price per barrel (in 1995) used in the simulations was $18. Note that, in Table 9, the simulated price ranges from $18 /bbl in 1995 to $24.26/bbl in 1999. The starting price (per mcf) used for gas was $1.75; gas prices were constrained to have an annual floor price of $0.75 / mcf. This approach is quite conservative given the current and anticipated trends in global energy markets.

Figure 9 is an example of simulated threes oil price paths from 1995 to 2030. Individual price paths have a tendency to wander and vary considerably. However, the number of runs conducted resulted in an average oil price of $17.99, which is quite conservative given historical oil price volatility and anticipated future market conditions. The average gas price over all sumulation runs was $1.76.

There is little doubt that global demand for petroleum products, fueled in large part by the continued industrialization that much of the world's population is currently experiencing, will soon increase dramatically and remain at high levels. Continued industrialization and rising standards of living, particularly in Asia, will combine with the unstable political situation in the Middle East to put increased long term pressure on domestic oil (and, to a lesser extent, gas) reserves. The only real question concerning the increase in demand is the timing of the first shock(s).

The Wiener-process method used in this study does not allow for any drastic upward (or downward) nonrandom travels in these commodity prices. This is a

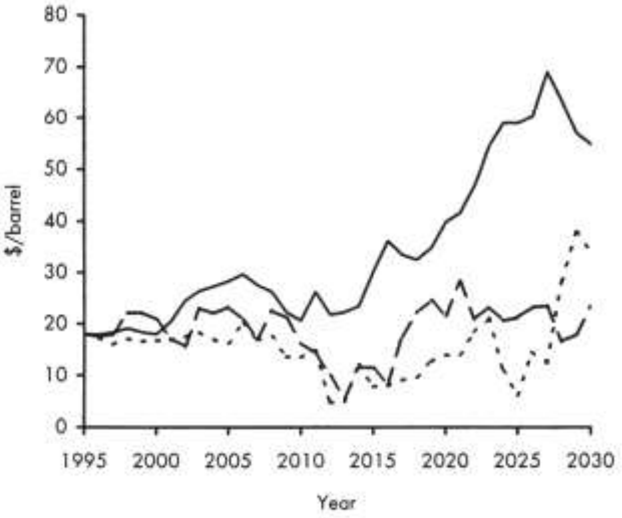

FIGURE 9—Simulated annual oil prices 1995–2030.

conservative approach, as factors contributing to upward price movements are much more likely in the time-frame considered in this study than are factors contributing to downward pressure on oil and gas market prices. It is important to note that the Wiener process approach was selected after analysis of Eddy County historical oil and gas price data provided by the New Mexico Bureau of Mines & Mineral Resources. Historical data were not available for new (oil and gas) and recovery-well capital investment and ongoing well operating costs.

Capital and operating costs

Confidential capital costs for new and injection wells were provided to the NMBMMR by area operators, as were data concerning monthly well operating costs. These data were used as simulation inputs; after much discussion these costs were treated as constant across the time period considered in the study.

Constant costs were used for several reasons. Most importantly, in the absence of historical data no connection could be made between historical trends (and time series) and any cost forecasting method. Second, the use of constant costs is partly justified by the conservative approach taken to forecasting market prices. Third, technological changes have had a profound effect on drilling and extraction capabilities. There is no reason to expect that technological advances will not continue apace. Barring huge inflation shocks in the next 35 years (another difficult and risky prediction problem), it is anticipated that technology will serve to offset inflationary effects on capital and operating costs in the oil and gas industry. The main justification for constant costs in this study, though, remains the lack of historical data.

Taxes and royalties

The state of New Mexico assesses severance taxes on revenues attributable to minerals extracted within the state. Rather than attempting to predict factors which might contribute to alterations in the severance-tax rate, a rate of 2.5% of oil and gas revenues was used for the study period. A royalty rate of 12.5% of revenues was used in the study.

Capital investment and other tax incentives that oil and gas companies periodically receive from political entities were likewise ignored in this work. In addition to presenting a major limited-data prediction problem, consideration of tax incentives would involve acquisition of additional proprietary data from area producer firms. An average corporate-tax rate of 34% was therefore used.

All taxable income (listed as Taxable Inc in Table 9) is assumed to be New Mexico income for state-tax purposes. New Mexico corporate tax rates are 4.8% of taxable income under $500,000, $24,000 plus 6.4% of the excess over $500,000 for amounts between $500,000 and $1,000,000, and $56,000 plus 7.6% of the excess over $1,000,000 for taxable income over $1,000,000.

Discount rate

Results are presented above for 10% and 15% discount rates. Estimation of discount rates for risky investment projects (the perspective taken in this study was one of viewing oil and gas exploration activity in the zones of interest as risky investment projects) is generally a difficult and inexact process. The standard finance theory-based method (for an excellent discussion of the process of determining discount rates see Copeland et al.,1990) revolves around estimating a market-based firm specific cost of capital (discount rate) using a publicly traded firm's beta value.

Beta values for oil companies (Value Line Investment Survey, 17 March 1995) with some type of operational presence in the Eddy County region range from 0.6 (Exxon) to 0.95 (Unocal). These values are below the market average beta of 1 and point to the use of a lower rate (such as 10%) to discount cash flows from oil and gas operations. 15% may be seen as a conservative upper bound.

Given the extent of current successful drilling and extraction activity in the general area of the WIPP site and the future of the market for oil and gas products, the profitability risk associated with oil and gas operations in the Eddy County area is relatively grounded in market price risk. A precise discount rate for different firms operating in the WIPP area is difficult to estimate (particularly in the absence of debt/equity ratio and other financial data for said firms). Pinpointing a discount rate for a 35-year project is quite risky in and of itself. In this case, if one must choose between 10% and 15% rates, current levels of activity in the region and market factors point to a 10% discount rate for oil and gas.

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Selected conversion factors*

TO CONVERT	MULTIPLY BY	TO OBTAIN
Length		
inches, in	2.540	centimeters, cm
feet, ft	3.048×10^{-1}	meters, m
yards, yds	9.144×10^{-1}	m
statute miles, mi	1.609	kilometers, km
fathoms	1.829	m
angstroms, Å	1.0×10^{-8}	cm
Å	1.0×10^{-4}	micrometers, µm
Area		
in^2	6.452	cm^2
ft^2	9.29×10^{-2}	m^2
yds^2	8.361×10^{-1}	m^2
mi^2	2.590	km^2
acres	4.047×10^{3}	m^2
acres	4.047×10^{-1}	hectares, ha
Volume (wet and dry)		
in^3	1.639×10^{1}	cm^3
ft^3	2.832×10^{-2}	m^3
yds^3	7.646×10^{-1}	m^3
fluid ounces	2.957×10^{-2}	liters, l *or* L
quarts	9.463×10^{-1}	l
U.S. gallons, gal	3.785	l
U.S. gal	3.785×10^{-3}	m^3
acre-ft	1.234×10^{3}	m^3
barrels (oil), bbl	1.589×10^{-1}	m^3
Weight, mass		
ounces avoirdupois, avdp	2.8349×10^{1}	grams, gr
troy ounces, oz	3.1103×10^{1}	gr
pounds, lb	4.536×10^{-1}	kilograms, kg
long tons	1.016	metric tons, mt
short tons	9.078×10^{-1}	mt
oz mt^{-1}	3.43×10^{1}	parts per million, ppm
Velocity		
ft sec^{-1} (= ft/sec)	3.048×10^{-1}	m sec^{-1} (= m/sec)
mi hr^{-1}	1.6093	km hr^{-1}
mi hr^{-1}	4.470×10^{-1}	m sec^{-1}
Pressure, stress		
lb in^{-2} (=lb/in^2), psi	7.03×10^{-2}	kg cm^{-2} (kg/cm^2)
lb in^{-2}	6.804×10^{-2}	atmospheres, atm
lb in^{-2}	6.895×10^{3}	newtons (N)/m^2, N m^{-2}
atm	1.0333	kg cm^{-2}
atm	7.6×10^{2}	mm of Hg (at 0°C)
inches of Hg (at 0°C)	3.453×10^{-2}	kg cm^{-2}
bars, b	1.020	kg cm^{-2}
b	1.0×10^{6}	dynes cm^{-2}
b	9.869×10^{-1}	atm
b	1.0×10^{-1}	megapascals, MPa
Density		
lb in^{-3} (= lb/in^3)	2.768×10^{1}	gr cm^{-3} (= gr/cm^3)
Viscosity		
poises	1.0	gr cm^{-1} sec^{-1} *or* dynes cm^{-2}
Discharge		
U.S. gal min^{-1}, gpm	6.308×10^{-2}	l sec^{-1}
gpm	6.308×10^{-5}	m^3 sec^{-1}
ft^3 sec^{-1}	2.832×10^{-2}	m^3 sec^{-1}
Hydraulic conductivity		
U.S. gal day^{-1} ft^{-2}	4.720×10^{-7}	m sec^{-1}
Permeability		
darcies	9.870×10^{-13}	m^2
Transmissivity		
U.S. gal day^{-1} ft^{-1}	1.438×10^{-7}	m^2sec^{-1}
U.S. gal min^{-1} ft^{-1}	2.072×10^{-1}	l sec^{-1} m^{-1}
Magnetic field intensity		
gausses	1.0×10^{5}	gammas
Energy, heat		
British thermal units BTU	2.52×10^{2}	calories, cal
BTU	1.0758×10^{2}	kilogram-meters, kgm
BTU lb^{-1}	5.56×10^{-1}	cal kg^{-1}
Temperature		
°C + 273	1.0	°K (Kelvin)
°C + 17.78	1.8	°F (Fahrenheit)
°F - 32	5/9	°C (Celsius)

**Divide by* the factor number to reverse conversions.
Exponents: for example 4.047×10^{3} (see acres) = 4,047; 9.29×10^{-2} (see ft^2) = 0.0929

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CONTENTS OF POCKET

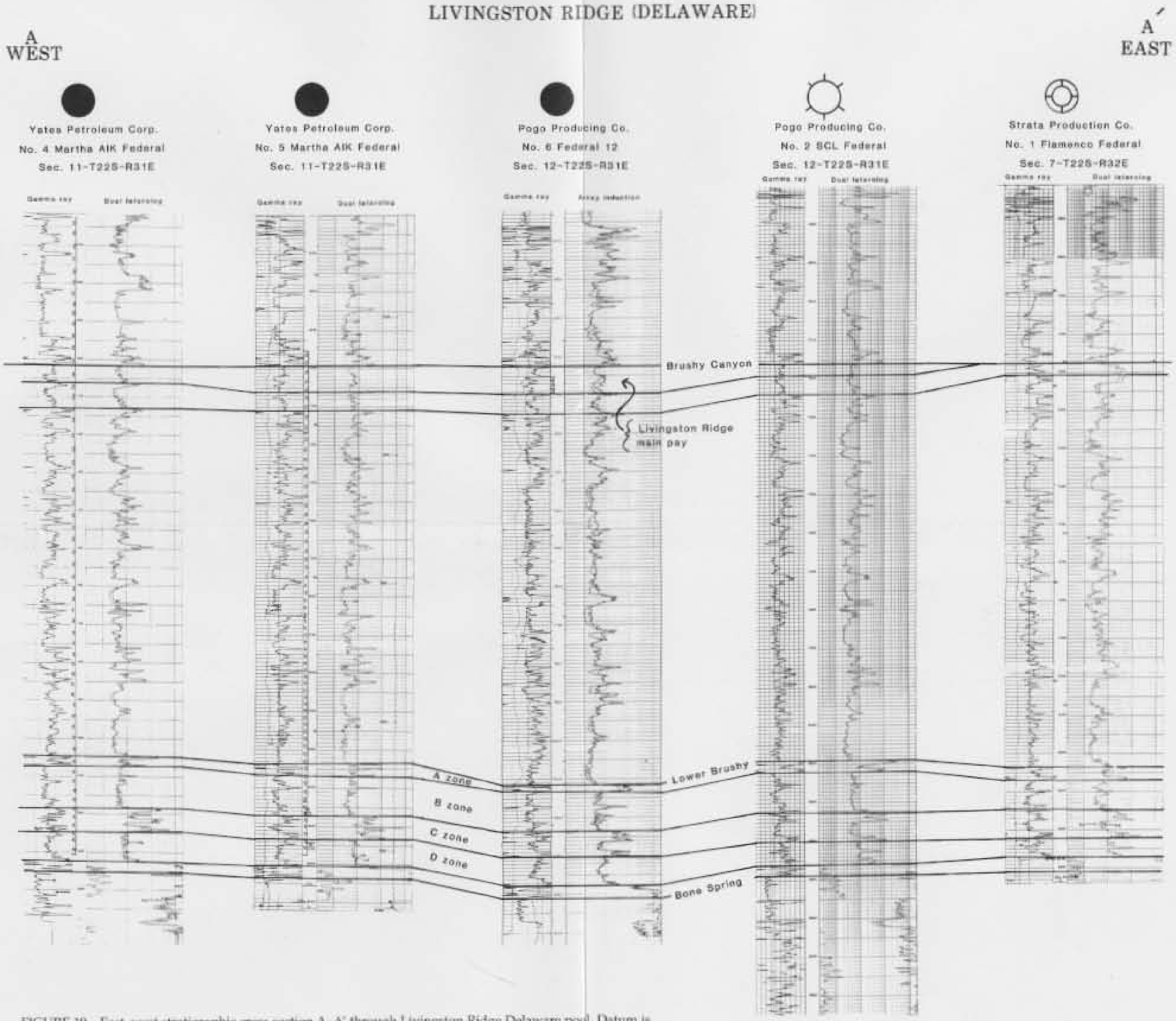

FIGURE 19—East-west stratigraphic cross section A–A' through Livingston Ridge Delaware pool. Datum is top of Brushy Canyon Formation. See Figs. 14, 24 for location.

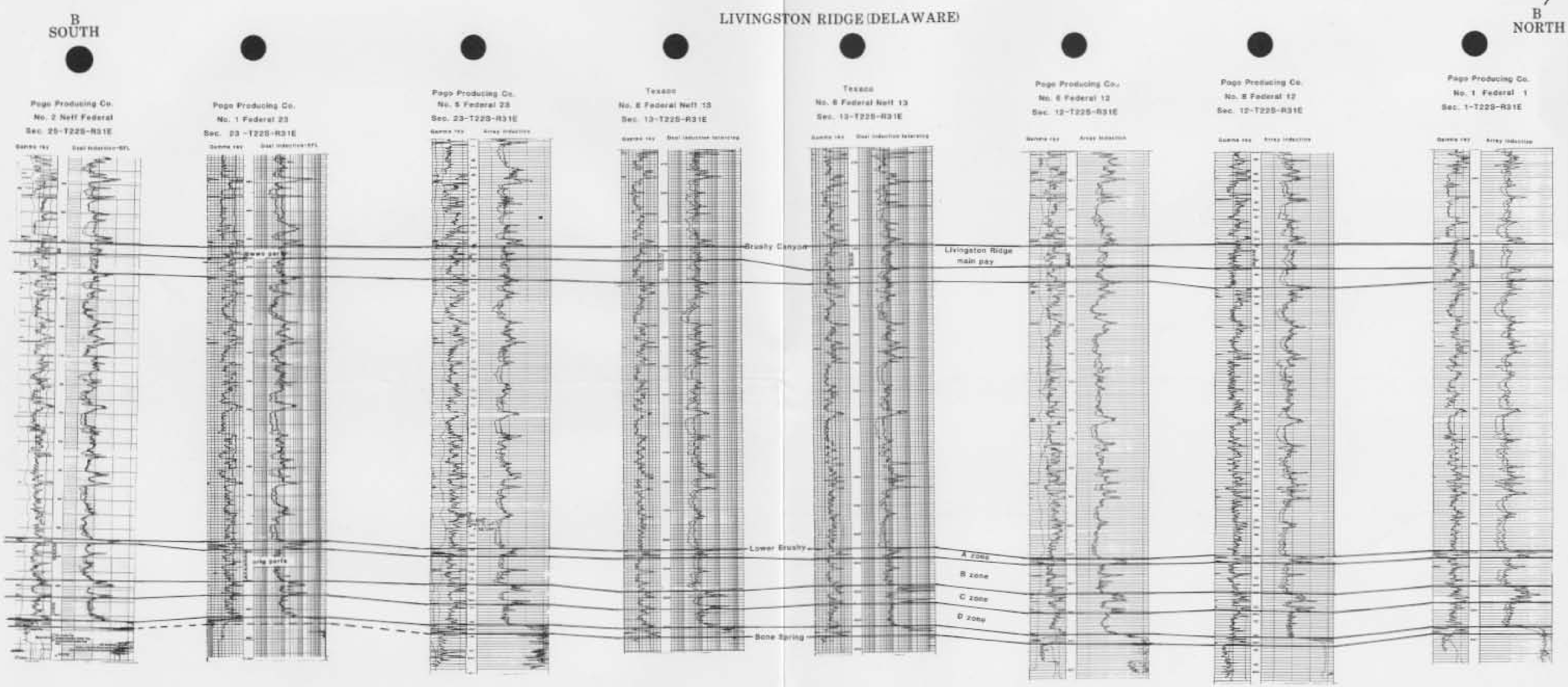

FIGURE 20—North–south stratigraphic cross section B–B′ through Livingston Ridge Delaware pool. Datum is top of Brushy Canyon Formation. See Figs. 14, 24 for location.

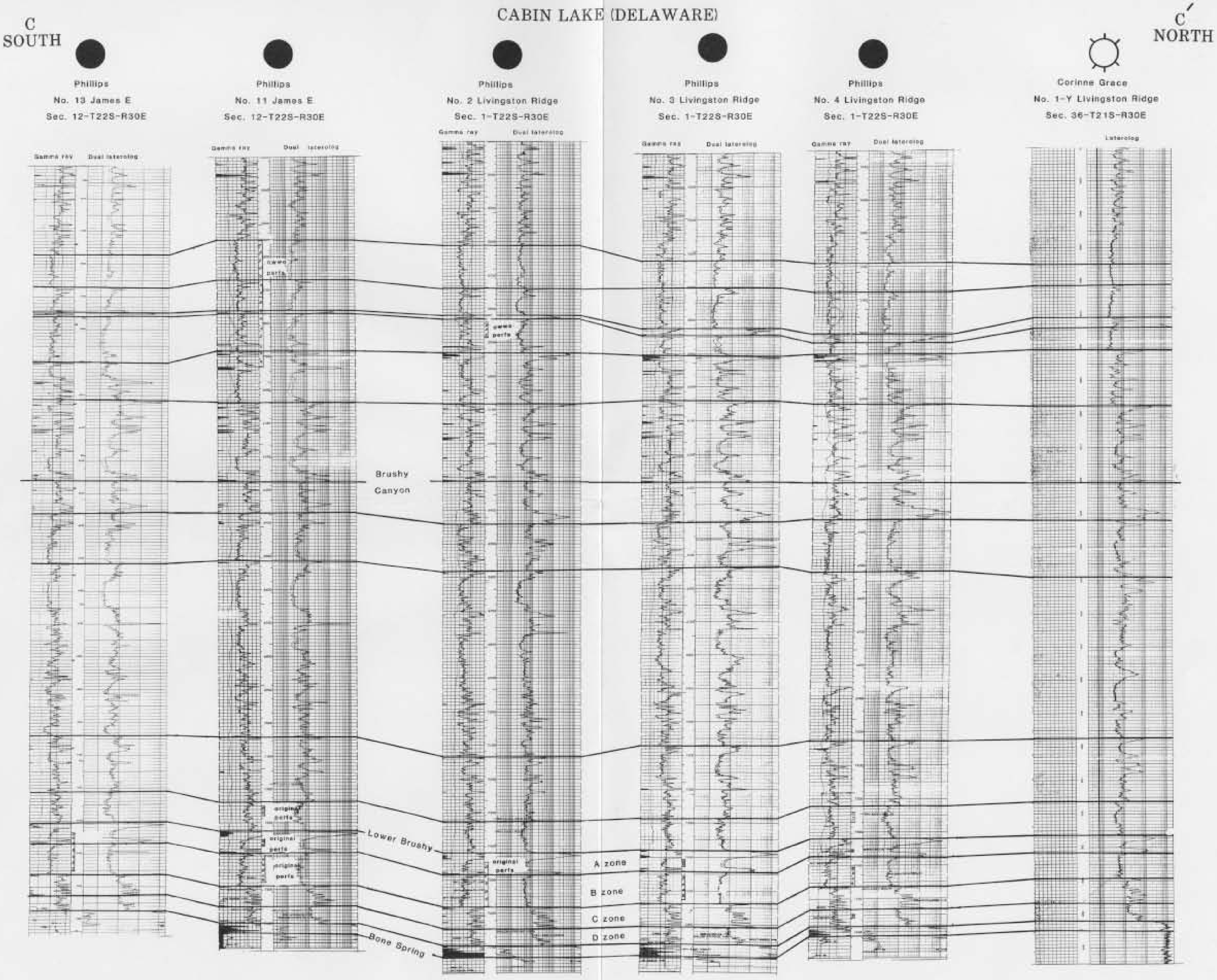

FIGURE 21—North–south cross section C–C′ through Cabin Lake Delaware pool. Datum is top of Brushy Canyon Formation. See Figs. 14, 34 for location.

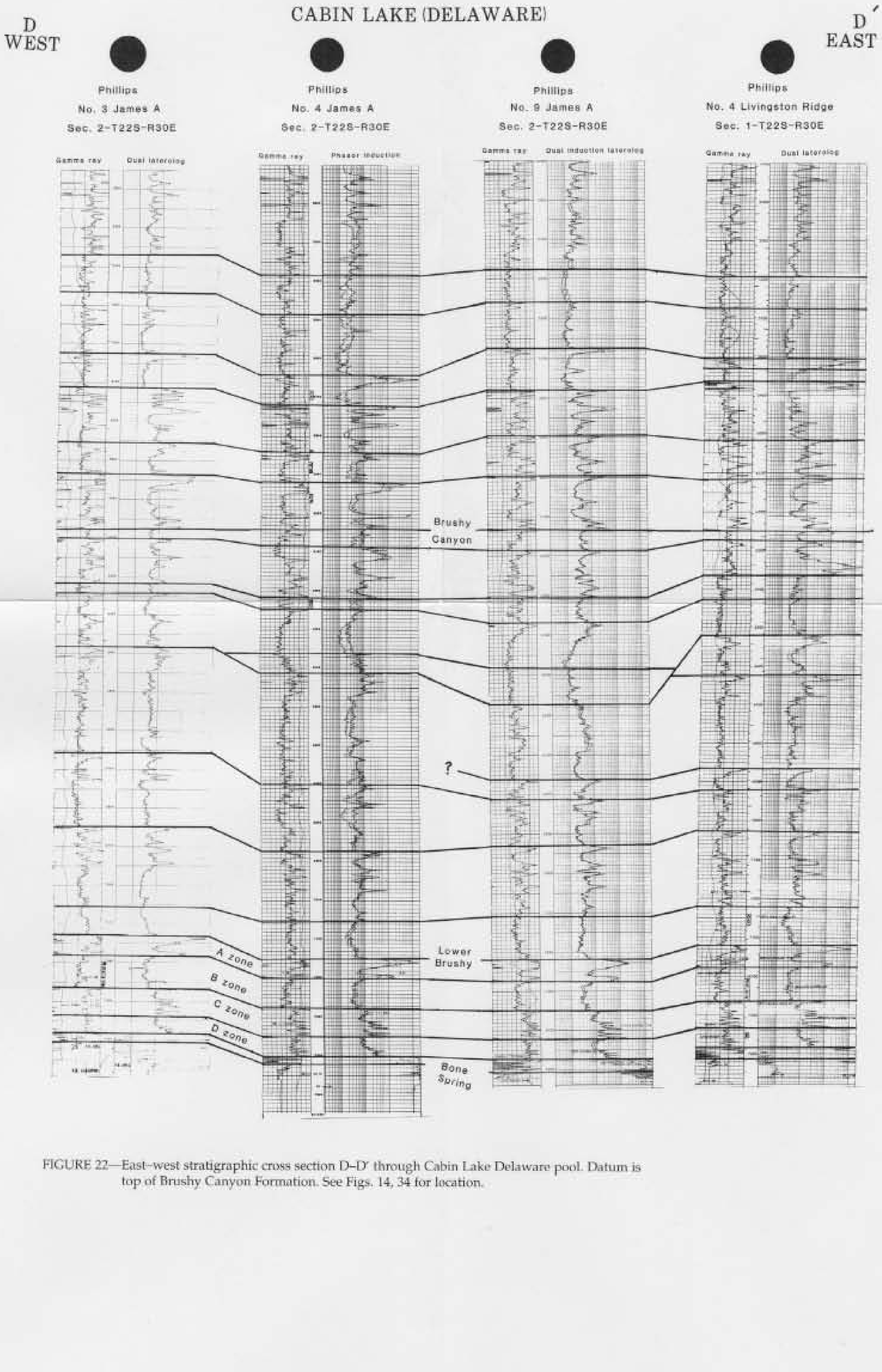

FIGURE 22—East–west stratigraphic cross section D–D′ through Cabin Lake Delaware pool. Datum is top of Brushy Canyon Formation. See Figs. 14, 34 for location.

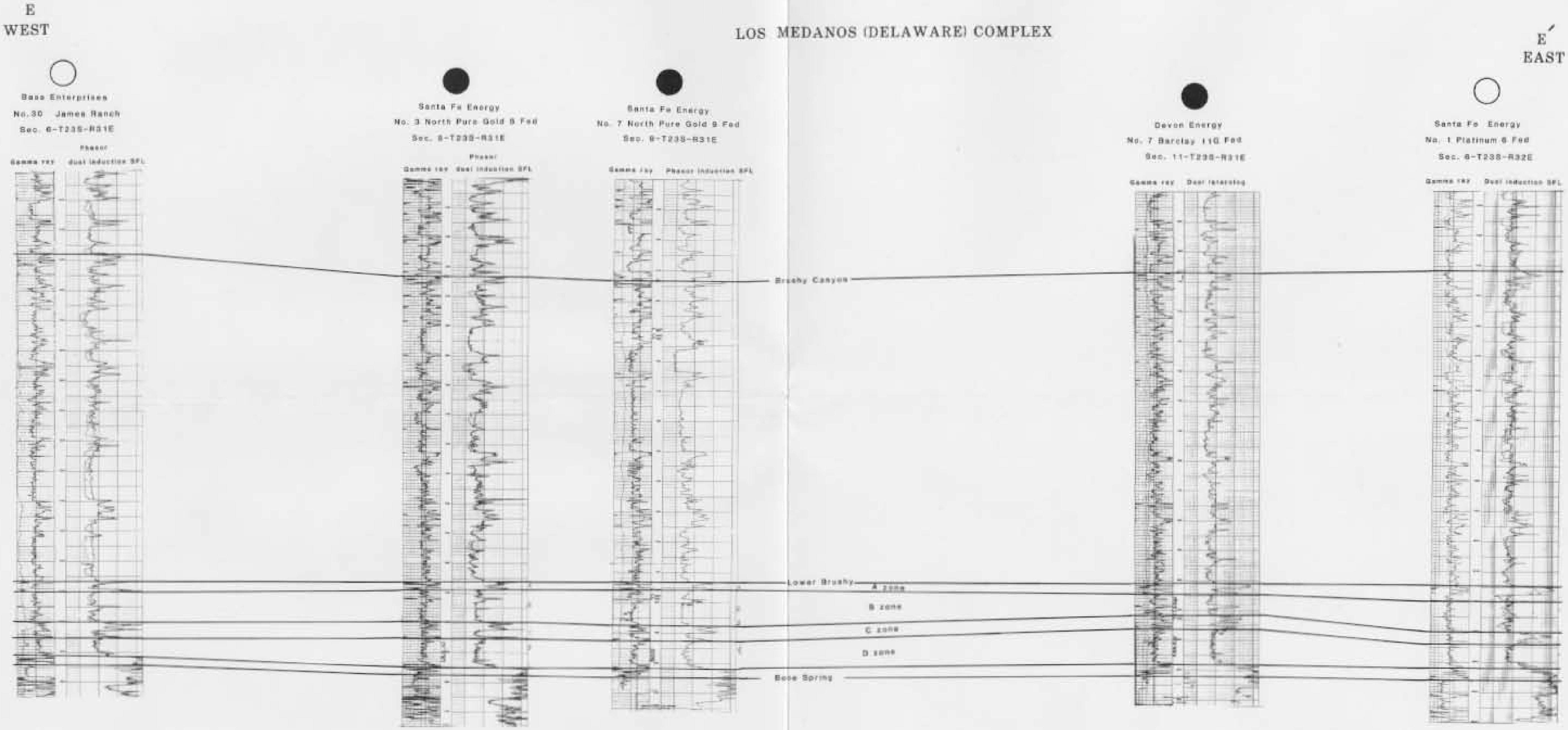

FIGURE 23—East-west stratigraphic cross section E–E′ through Los Medanos–Sand Dunes–Ingle Wells complex. Datum is top of lower Brushy Canyon Formation. See Figs. 14, 28 for location.

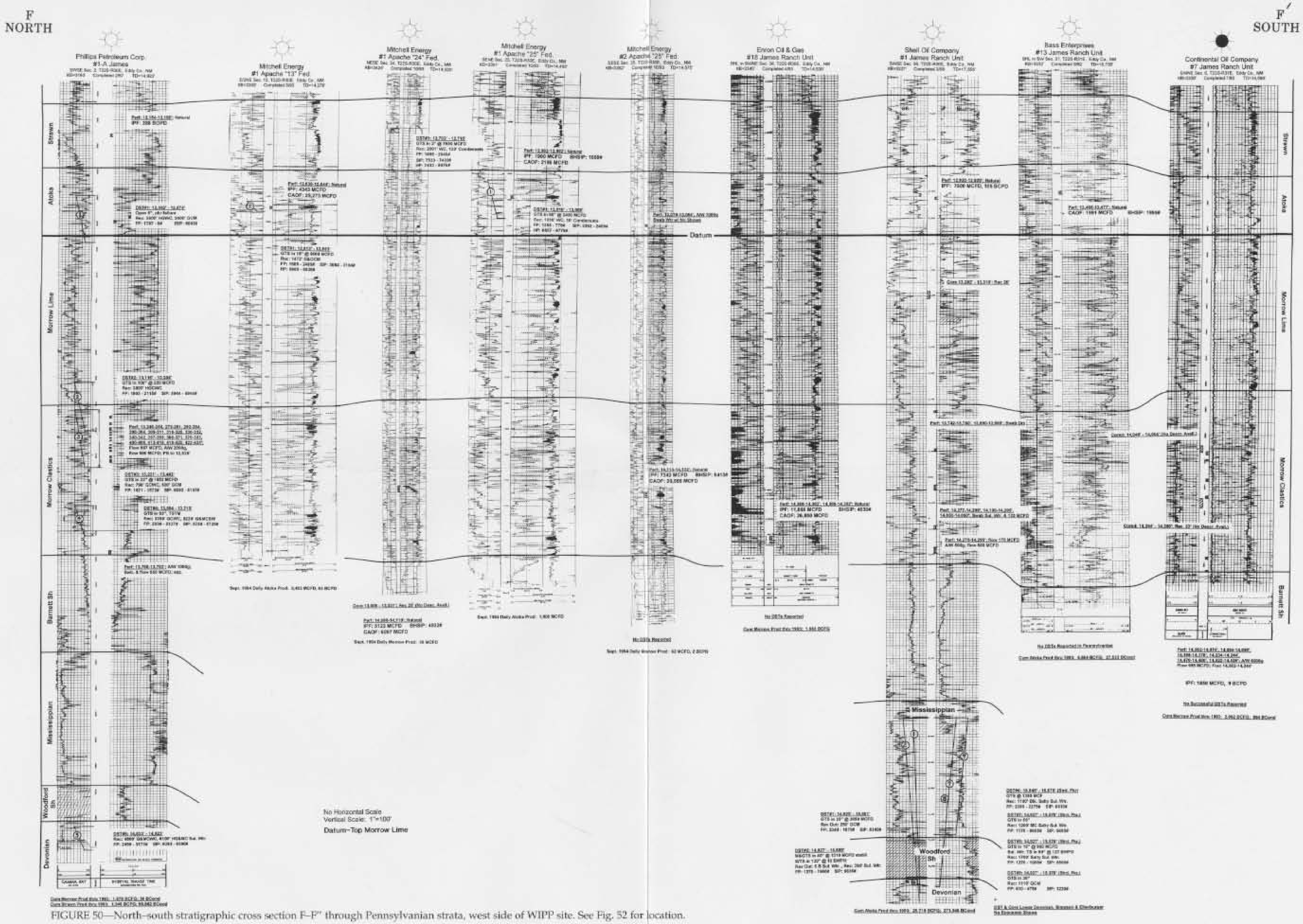

FIGURE 50—North–south stratigraphic cross section F–F′ through Pennsylvanian strata, west side of WIPP site. See Fig. 52 for location.

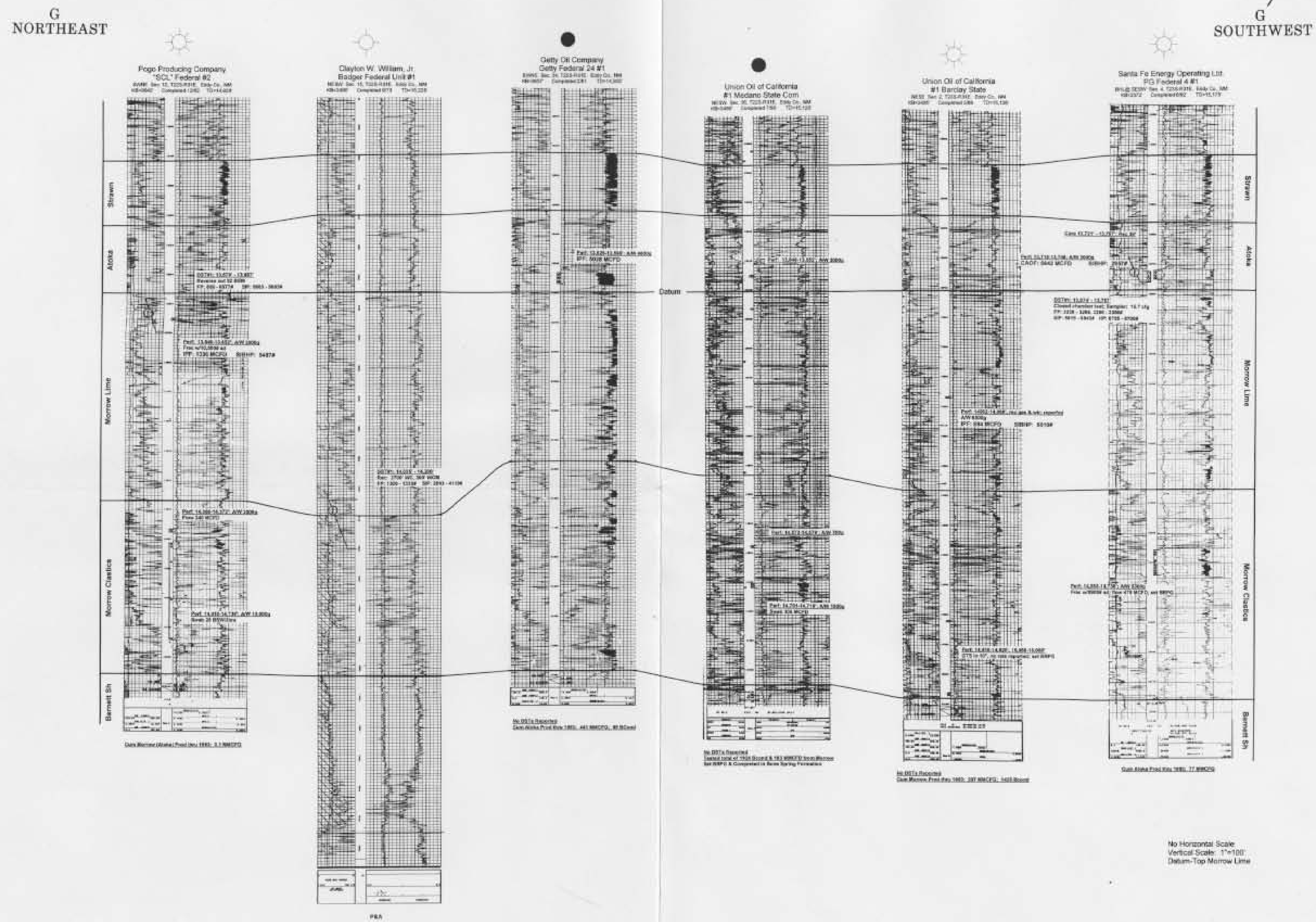

FIGURE 56—North–south stratigraphic cross section G–G' through Pennsylvanian strata, west side of WIPP site. See Fig. 52 for location.

HYDROCARBON RESOURCES AT WIPP SITE, NEW MEXICO

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