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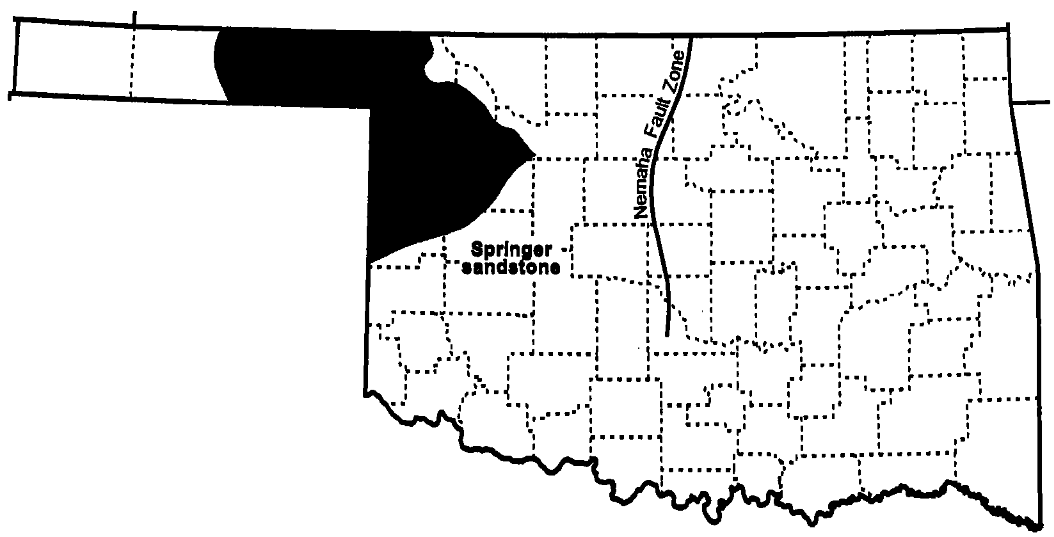
Springer Gas Play in Western Oklahoma



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Springer Gas Play in Western Oklahoma

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Richard D. Andrews

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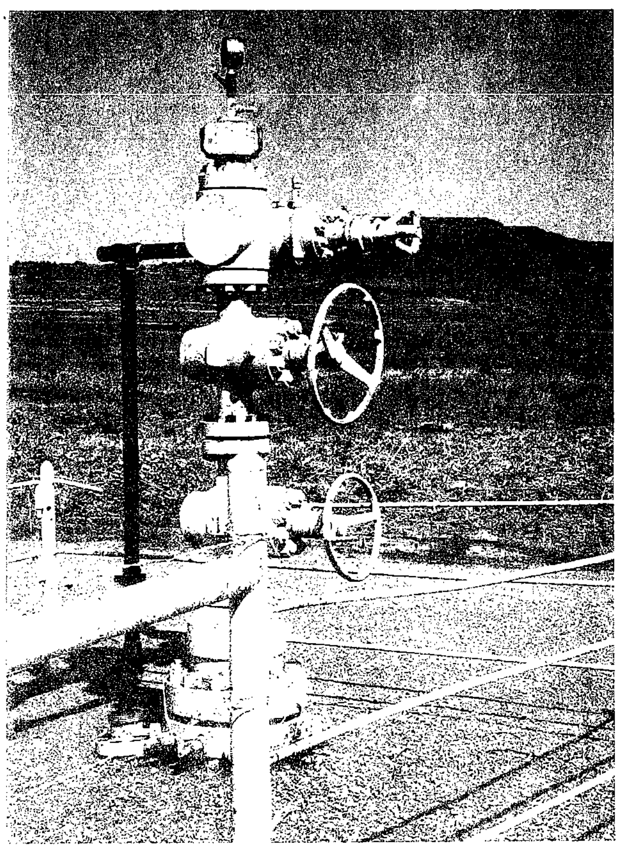
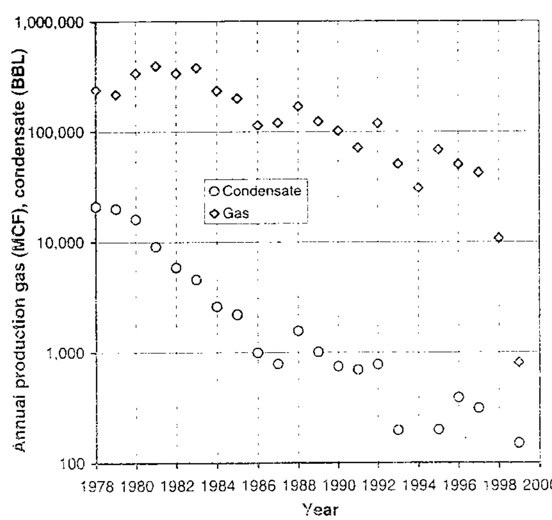
Front Cover

The Springer formation in western Oklahoma is one of the most prolific gas and gas-condensate reservoirs in the State. Since the first wells were completed in the Anadarko basin in the early 1950s, the Springer has produced ~7.8 TCF gas and ~50 MM barrels oil from more than 4,000 wells.

The Springer is generally thought to be composed of three sandstone reservoirs—the Cunningham, Britt, and Boatwright, in descending order. These occur in the west-central and south-central parts of the State, as shown in the cover map. However, the Springer has correlative carbonate facies in northwestern Oklahoma and in the eastern part of the Oklahoma Panhandle, as shown in the cover map. These carbonate rocks are stratigraphically equivalent to the Britt and Boatwright sandstone facies. This relationship and the implications of hydrocarbon production from both reservoirs is discussed in this publication.



Photograph by Richard D. Andrews



Mustang Production Co. drilled the No. 1-29 Dobbins well in 1977, and production was first established in March 1978. The well is in the E½SW¼ sec. 29, T. 15 N., R. 11 W., and is one of several wells producing from a north–south trend called the "Old Woman" channel. This incised-channel trend is identified on Plate 2 of this publication.

Completion reports indicate that this and other nearby wells produce from a lower Morrow sandstone. The production interval in this well is 10,400 to 10,402 ft. Studies of production reallocation by IHS Energy Group, Oklahoma City, indicate that the producing interval is, in fact, the Britt sandstone of the Springer Group. Misidentification of sandstone units in the lower Morrow–upper Springer interval, as in this well, is common in industry. The current reallocation effort by IHS was intended to make production reporting more accurate and uniform.

Cumulative production from the Mustang Dobbins well through January 1999 (date of last production) was 3.412 billion cubic feet of gas and 89,454 barrels of condensate. The production-decline curves are shown next to the photograph. The well is several miles south of Watonga on the west side of State Highway 270.

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Regional Overview of the Springer Gas Play

Richard D. Andrews
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INTRODUCTION

Springer and Morrow reservoirs are commonly stacked upon one another, making their identity confusing. This study is intended to aid in the correlation of Springer Group zones and assist in the application of accepted subsurface nomenclature. Therefore, this investigation is intended to complement the recently published report on the Morrow gas play by Andrews (1999). The current study focuses on strata directly below the Morrow Group and above the lower Chesterian Chester limestone/Caney Shale. It was aided by field investigations conducted in conjunction with the Oklahoma Geological Survey's Springer field trip and guidebook by Hemish and Andrews (2001).

One of the main objectives of this study was to map the general distribution of the three principal informal sandstone members of the Springer formation in the Anadarko basin (Cunningham, Britt, and Boatwright, in descending order), identify their depositional environments, and correlate Springer sandstone facies of the Anadarko basin with the time–stratigraphic equivalent Springer carbonate facies on the Anadarko shelf of northwestern Oklahoma and Panhandle areas.

An equally important objective was to correlate informal subsurface units of the Springer Group between the Anadarko and Ardmore basins, and to correlate the subsurface Springer in the Ardmore basin to outcrop. This required a grid of cross sections stretching from distal carbonate facies in northwestern Oklahoma to surface exposures along the flanks of the Caddo anticline in south-central Oklahoma in Carter County. A major obstacle in relating the different terminologies from one area to another involved subsurface facies changes in addition to stratigraphic changes between surface exposures and the subsurface. Another major impediment involved complex folding and faulting in the Ardmore basin and southern Anadarko basin, which made correlations difficult. And finally, the most difficult problem of correlating subsurface units between basins is the major fault separating the two basins. An eastern extension of the Mountain View fault that divides the Ardmore from the Anadarko basin (in this volume referred to as the Doyle–Reagan fault) has several thousand feet of vertical displacement and possibly significant lateral displacement. This makes the correlation of principal sandstone members between the two basins extremely difficult and problematic. In order to address these problems throughout the entire Springer play, it was necessary to incorporate, in a general way, the geology and stratigraphy in the Ardmore basin, although the emphasis of this investigation is the Anadarko basin and shelf areas of western Oklahoma.

Even today, the term *Springer* means different things to different people, and over the last 78 years, this name has evolved to define a variety of rock units. The nomenclature problem was compounded by the use of local subsurface reservoir names during development of large oil and gas reserves in rock units correlative with the same general stratigraphic interval as that originally described at the surface many miles away. The most comprehensive discussion of the historical evolution of the term *Springer* comes from Straka's Ph.D. dissertation (1969), and it is recommended to every Springer geologist. The present study in no way addresses this tremendous nomenclature problem but briefly summarizes it as follows.

The use of the term *Springer* began in 1922 by Goldstone in reference to the lowermost member of the former Glenn Formation, which included most of the Pennsylvanian strata in the Ardmore area. These "Springer" sediments are well exposed less than 1 mi northeast of the town of Springer and also along the flanks of the Caddo anticline 3 mi southwest of Springer—hence the name.

In 1929, Tomlinson proposed dropping the name *Glenn Formation* because of the potential problems of referring such a large stratigraphic section to a single formation. He further proposed the elevation of the name *Springer* to formation status, embracing three sandstone members—the Rod Club, Overbrook, and Lake Ardmore, in ascending order.

In 1956, Harlton combined the Springer strata of Tomlinson (1929) and the underlying shale unit (Goddard Formation) into the Springer Group. He also is responsible for elevating the overlying Morrowan Dornick Hills strata to group rank. He named three formations, of which the Golf Course Formation is pertinent in this study because it contains the lowermost Morrow sandstone, the Primrose Member, which is referred to frequently in this volume.

The prominence of the Springer play, like the Morrow play, is due to the relatively large reserve base of individual wells and moderate drilling depths. The bulk of production in the Anadarko basin occurs at relatively shallow to moderate depths of 7,000 ft in the northern part of the play to 14,000 ft along the eastern part of the play. Additionally, some prolific production comes from depths greater than 14,000 ft in the deep Anadarko basin.

The Springer formation in the Anadarko basin, regardless of facies, is primarily a gas reservoir but also yields varying amounts of condensate, depending on depth. Figure 1 shows gas and oil production over the past 21 years from well completions in only the Springer reservoir. This plot shows annual production trends of gas and oil from ~191 billion cubic feet of gas (BCFG) and 15 million barrels of oil (MMBO) in 1979 to present-day rates of ~148 BCFG and 4.4 MMBO annually. During this period, the maximum annual gas production from the Springer only was ~232 BCFG (1986). Annual gas production from the Springer has been relatively constant over the past 10 years. Figure 2 shows gas and oil production from wells having Springer production commingled with production from other reservoirs, most notably the overlying Morrow. A significant amount of this production is probably attributed to the Springer—perhaps 25–35 BCFG—which is relatively small compared to the entirely Springer production of Figure 1. Annual production data are given in Table 1. Many Springer fields have been fully developed with increased-density drilling and location exceptions, and many other fields have significant development potential remaining. A listing of Springer fields is given in Appendix 5, which shows important reservoir and production information that can be used to characterize Springer reservoirs throughout the Anadarko basin.

The Springer formation was a common drilling objective in the Anadarko basin during the late 1950s and 1960s. During this time, high-volume exploration and development gas wells were completed in both shallow and deep Springer reservoirs in Binger, Eakly–Weatherford, and Elm Grove fields in addition to the areally extensive and relatively shallow Watonga–Chickasha trend. During the 1970s, Fay East, Nobscot, Putnam, Oakwood, and Seiling fields were developed. And in the 1980s, Springer carbonates in Chester, Cedardale, Mocane–Laverne, and Lovedale fields began producing. Some of the most significant development drilling during the 1990s took place in Verden, Eakly–Weatherford, the Cement area, and the Watonga–Chickasha trend. Overall Springer drilling activity is plotted in Figure 3A, which clearly shows the rapid rise and fall of Springer completions during the past five decades.

The Springer formation is still highly prospective for gas exploration and development in certain parts of the Anadarko basin, and Springer sandstone bodies with excellent hydrocarbon potential are continually being found. Some of the most recent high-volume gas wells are being developed in the Cement field area and along the Mountain View fault, where the Springer is overturned. Historically, the average per-well cumulative gas production is illustrated in Figure 3B. This graph was constructed by calculating the cumulative production of all wells completed during a particular year and dividing that value by the total number of wells completed in that year. The average cumulative production figures for wells completed prior to about 1975 incorporate reserves that are close to total ultimate recovery, whereas wells completed more recently are not yet completely depleted and production is continuing. Yet despite this situation, the graph clearly has an upward trend, beginning from a low value of less than 0.9 BCFG/well in 1976 to ~1.5 BCFG/well in 1997. Production data used to construct both graphs in Figure 3 are shown in Table 2 and include Springer production from both sandstone and carbonate reservoirs.

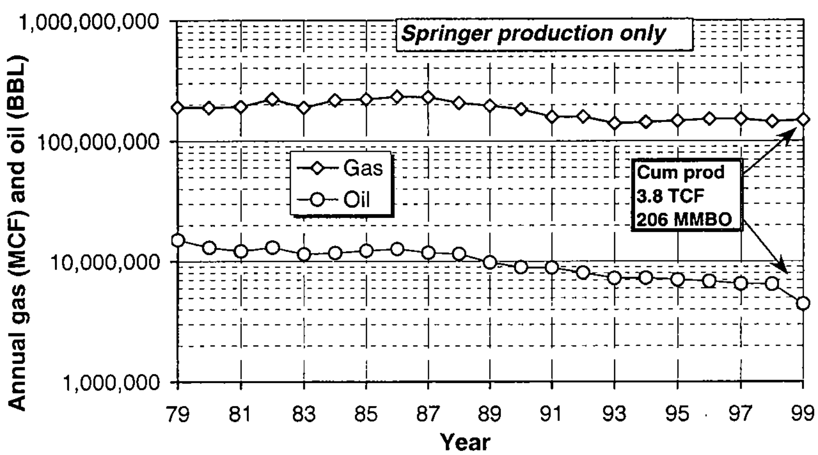

Figure 1. Annual gas and oil production from the Springer Group. Data from Natural Resources and Information System (NRIS), developed at the University of Oklahoma; data are current through 1999.

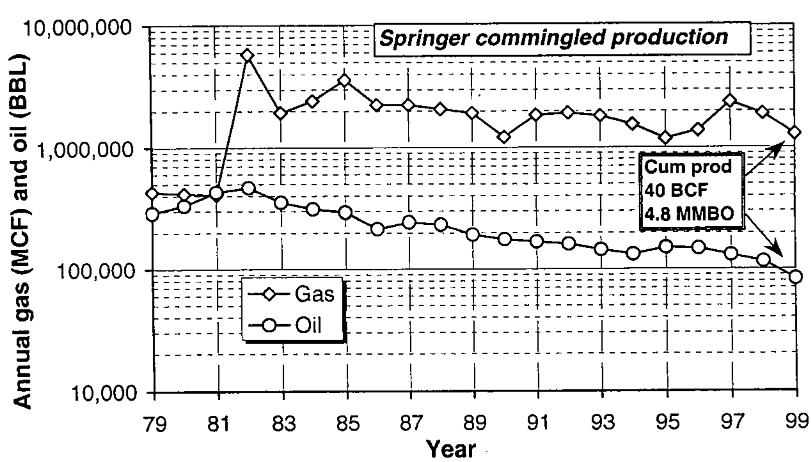

Figure 2. Annual gas and oil production from the Springer Group commingled with production from other reservoirs. Data from NRIS, current through 1999.

TABLE 1. — Springer and Commingled Springer Production 1979–1999

Year	Annual liquids (bbl)	Cum. liquids (bbl)	Annual gas (MCF)	Cum. gas (MCF)
		Springer production only		
1979	15,089,882	15,089,882	190,903,686	190,903,686
1980	13,016,974	28,106,856	187,985,478	378,889,164
1981	12,147,376	40,254,232	191,402,080	570,291,244
1982	13,030,397	53,284,629	221,636,469	791,927,713
1983	11,455,478	64,740,107	188,043,954	979,971,667
1984	11,715,201	76,455,308	216,918,064	1,196,889,731
1985	12,263,737	88,719,045	220,952,014	1,417,841,745
1986	12,669,148	101,388,193	232,294,780	1,650,136,525
1987	11,780,539	113,168,732	230,928,356	1,881,064,881
1988	11,546,087	124,714,819	206,308,198	2,087,373,079
1989	9,778,089	134,492,908	195,586,141	2,282,959,220
1990	8,921,152	143,414,060	182,993,148	2,465,952,368
1991	8,849,338	152,263,398	157,704,212	2,623,656,580
1992	8,016,963	160,280,361	158,383,186	2,782,039,766
1993	7,238,264	167,518,625	138,963,301	2,921,003,067
1994	7,254,138	174,772,763	142,592,297	3,063,595,364
1995	7,002,560	181,775,323	146,174,181	3,209,769,545
1996	6,809,579	188,584,902	151,411,409	3,361,180,954
1997	6,497,274	195,082,176	151,346,609	3,512,527,563
1998	6,441,492	201,523,668	143,540,648	3,656,068,211
1999	4,428,380	205,952,048	147,755,276	3,803,823,487
		Commingled Springer production		
1979	289,784	289,784	431,480	431,480
1980	332,640	622,424	414,585	846,065
1981	429,541	1,051,965	407,649	1,253,714
1982	468,515	1,520,480	5,783,584	7,037,298
1983	354,134	1,874,614	1,941,505	8,978,803
1984	313,203	2,187,817	2,419,462	11,398,265
1985	293,860	2,481,677	3,593,383	14,991,648
1986	215,031	2,696,708	2,245,599	17,237,247
1987	243,455	2,940,163	2,249,966	19,487,213
1988	233,525	3,173,688	2,078,315	21,565,528
1989	193,258	3,366,946	1,929,073	23,494,601
1990	177,372	3,544,318	1,216,423	24,711,024
1991	168,935	3,713,253	1,846,922	26,557,946
1992	161,314	3,874,567	1,922,778	28,480,724
1993	144,708	4,019,275	1,820,155	30,300,879
1994	132,631	4,151,906	1,545,960	31,846,839
1995	151,240	4,303,146	1,177,914	33,024,753
1996	148,619	4,451,765	1,382,805	34,407,558
1997	131,271	4,583,036	2,375,977	36,783,535
1998	115,914	4,698,950	1,904,132	38,687,667
1999	82,987	4,781,937	1,287,810	39,975,477

Data from NRIS.

Figure 4 is a graph showing the relationship between pressure decline and ultimate recovery. The vertical axis represents ultimate recovery calculated to a pressure decline of 50 pounds per square inch (psi). The horizontal axis of this figure represents the amount of gas recovered to date divided by the pressure drawdown during the producing period (initial pressure minus current pressure). All trend lines are mathematical derivations of a power equation used in MS Excel© software. The range of values used to create each trend can be seen from the five different codes identified in the figure explanation. The Springer carbonates clearly have the highest amount of recovered gas per psi drawdown, although these wells generally have ultimate recovery of less than ~6 BCFG. The Springer sands, on the other hand, generally have a smaller amount of gas recovered per psi drawdown, but those wells usually have a higher ultimate recovery than Springer carbonate wells. Another way to interpret these data is to select a well with a particular ultimate recovery, say 3 BCFG. The carbonate reservoirs produce ~2,000 MCFG per psi drawdown, whereas the sandstone reservoirs produce <500 MCFG per pressure drawdown, about one-fourth the efficiency of the Springer carbonates. This may be due to better vertical and horizontal drainage in the carbonates, less compartmentalization, larger reservoir volume, greater horizontal drainage area, or some other factor(s). Because the Springer sandstone reservoirs lie at greater depths than the correlative carbonate reservoirs (initial reservoir pressure is greater deeper in the basin; see discussion of pressure gradients later in this chapter), the pressure drawdown (initial pressure minus final pressure) is larger in the sandstones in comparison to the carbonates.

More than 4,000 wells have produced from the Springer either as single-zone completions or as commingled with production from other reservoirs. This breakdown is summarized in Table 2. On an individual reservoir basis, the Springer carbonate facies have more completions than the individual sandstone members. However, on a per-well basis, the sandstone reservoirs produce more gas than their carbonate counterparts. Based on production data from IHS Energy Group (2000), the total cumulative gas production from inception of the Springer play in the Anadarko basin is ~7.8 trillion cubic feet of gas (TCFG) and ~50 MMBO (Table 3). A summary of single-zone completions in the Springer is given in Table 4, which shows that the average amount of gas produced is highest from the sandstone reservoirs and lowest in the carbonate reservoirs, although the recovery per psi drawdown is greatest in the carbonate reservoirs.

Regional changes in sea level, and possibly large-scale fault displacements along the borders of regional structural provinces, affected the pattern of deposition in the Springer formation in the Anadarko basin. Most sandstone accumulations occur in northwest–southeast trends that are parallel to the ancient Springer oceanic coastline. The use of "trendology" as an exploration method was also adopted (often incorrectly) for overlying Morrow deposits. The prevalent Springer trends are applicable to most sandstone members, because they commonly were deposited as northwest–southeast-trending offshore bars on the shallow oceanic shelf of the Anadarko basin. Some exceptions to these sandstone trends do occur, primarily with the Cunningham and Britt, which locally occurs in north–south-trending incised channels, and also with the Boatwright, which in the deep basin may occur as turbidite deposits. The prevailing trend of the Springer carbonate facies (Britt and Boatwright) is not as clear. Some carbonate reservoirs, particularly in the Oklahoma Panhandle, also have pronounced northwest–southeast trends. Many fields within these trends have reservoirs consisting of oolitic shoals that also paralleled the ancient Springer coastline. Detailed geological studies of Lookeba and Sickles North fields and of the Cedardale area (Parts II, III, and V of this volume) illustrate some of these patterns of deposition in both the sandstone and carbonate reservoirs. The identification of various sandstone facies is usually possible from well logs, but this is generally not the case for carbonate reservoirs.

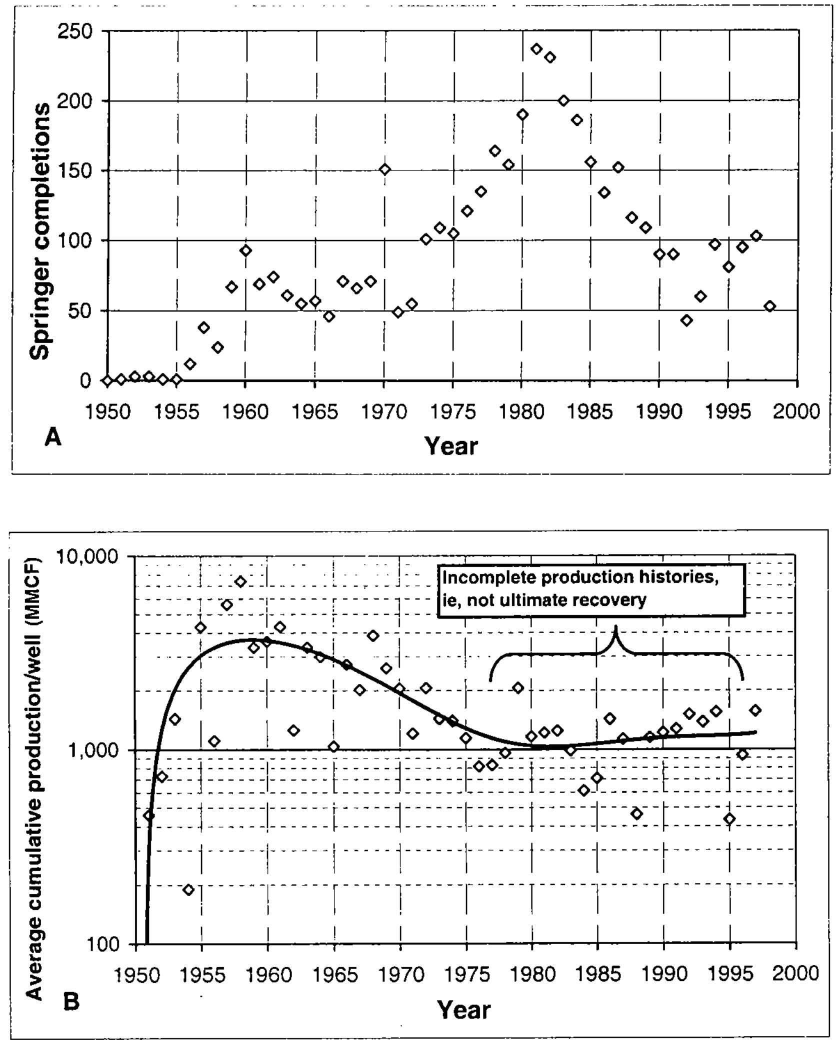

Figure 3. Springer well completions, 1950–1998 (*A*), and average cumulative production per well (MCFG), 1950–1997 (*B*). From IHS Energy Group (2000). Production and well count include both sandstone and carbonate reservoirs.

MORROW–SPRINGER BOUNDARY AND CLAY MINERALOGY OF SHALES

As a matter of practical convenience, it has generally been thought that the Morrow–Springer contact in the Anadarko basin represents the Pennsylvanian–Mississippian boundary. On well logs, this contact is usually picked from conductivity logs where a sharp *increase* in conductivity (a sharp *decrease* in resistivity) is evident in the Springer shale.

Peace (1989) reported the results of a core research study by the late Dr. Leonard R. Wilson, professor emeritus at the University of Oklahoma. The research was intended to determine the position of the Mississippian–Pennsylvanian boundary on the basis of palynological evidence. A continuous core from 13,736 to 14,103 ft was recovered from the Apexco No. 1-A Buell well in the SE¼ NW¼ sec. 10, T. 11 N., R. 12. W., in Caddo County, Oklahoma (see Appendix 4), which straddles the Morrow–Springer formation boundary, as picked from wireline logs (Fig. 5). The conductivity-log inflection point defining the boundary was picked at ~13,833 ft by Peace (1989), but an alternative pick by this author places the boundary at ~13,874 ft, 41 ft lower. Ten samples were taken, as shown on the well log (Fig. 5), to determine whether or not the

TABLE 2. — Springer Well Completions and Average Cumulative Production per Well (MMCF)

Year	Number of completions	Avg. production per well (MMCF)
1950	0	0
1951	1	459
1952	3	729
1953	3	1,437
1954	1	190
1955	1	4,285
1956	12	1,112
1957	38	5,618
1958	24	7,415
1959	67	3,358
1960	93	3,600
1961	69	4,300
1962	74	1,257
1963	61	3,354
1964	55	2,994
1965	57	1,038
1966	46	2,733
1967	71	2,019
1968	66	3,871
1969	71	2,616
1970	151	2,047
1971	49	1,210
1972	55	2,062
1973	101	1,435
1974	109	1,401
1975	105	1,147
1976	121	817
1977	135	830
1978	164	959
1979	154	2,062
1980	190	1,166
1981	237	1,221
1982	231	1,250
1983	200	985
1984	186	612
1985	156	709
1986	134	1,430
1987	152	1,133
1988	116	461
1989	109	1,153
1990	90	1,224
1991	90	1,278
1992	43	1,509
1993	60	1,382
1994	97	1,548
1995	81	433
1996	95	932
1997	103	1,563
1998	53	
Total	4,380	

Data from IHS Energy Group (2000). Data include both sandstone and carbonate reservoirs.

biostratigraphic Mississippian–Pennsylvanian systemic boundary closely coincides with the lithostratigraphic Springer–Morrow formation boundary. Peace (1989) indicated that Dr. Wilson determined that the overall palynomorph assemblage in the Buell core was more diagnostic of a Morrowan flora than a Chesterian one. The upper five samples from the lower Morrow Primrose section had distinctly Morrowan or younger palynomorphs. The lower samples in the upper Springer Cunningham interval indicated questionable ages, owing to the high degree of thermal maturity of the samples, which may have influenced the presence or absence of a diagnostic Mississippian microflora. Nevertheless, Peace concludes that the palynological systemic boundary where the Buell well was drilled is possibly not coincident with the lithostratigraphic top of the Springer. As shown in the stratigraphic column of Figure 8, a thin interval at or just above the upper Cunningham level is questionably placed within the lower Morrowan Series of the lowermost Pennsylvanian System.

In the Ardmore basin, the Morrow–Springer contact in the subsurface is also chosen at a point at which the conductivity *increases* abruptly in well logs. However, this contact *is* within the Lower Pennsylvanian, as the systemic boundary has been established on the basis of conodonts that occur in shale at a point well below the Lake Ardmore Sandstone but above the Overbrook Sandstone (Kleehammer, 1991). Previous interpretations placed this boundary at the base of the Target Limestone, which occurs near the base of the Lake Ardmore Sandstone interval. The Lake Ardmore Sandstone of the Ardmore basin is Morrowan in age and is roughly correlative with Cunningham sandstone of the Anadarko basin.

In 1958, Weaver studied the clay mineralogy of the Morrow and Springer intervals and discovered major differences between the two. Morrow shale is characterized by a high percentage of illite and "varying amounts of chlorite, kaolinite, and mixed-layer illite–montmorillonite and/or montmorillonite" (Weaver, 1958, p. 289). Springer shales, on the other hand, are "characterized by the abundance of montmorillonite and mixed-layer illite–chlorite–montmorillonite, and the *lack* of illite" (p. 283). A comparison of clay mineralogies for these two groups is shown in the correlation chart of Figure 6. The typical X-ray patterns of Morrow and Springer (Chester) clays are shown in Figure 7. These clay differences also are probably responsible for the different responses observed on well logs through this interval.

Weaver (1958) noticed that Springer samples taken from outcrop (Ardmore basin) have a weathered form of 14–15 Å montmorillonite. The corresponding X-ray-diffraction peak indicates the presence of two layers of water with either Ca^{2+} or Mg^{2+} as the exchange cations. Subsurface samples that were not weathered "generally have peaks ranging from 11 to 12.5 Å, indicating that most of the montmorillonite layers have only one layer of water and that the exchange cation is predominantly Na^{+}" (p. 283). The significance of this is that in the Anadarko basin, Weaver identified "a mixed or transition shale interval between the Springer shales and the overlying Morrow shales." Weaver suggested that "this mixed zone,

TABLE 3. — Springer Production Data by Reservoir

Population reservoir name	Total	Single zone	Commingled with Springer	Commingled with non-Springer
Well count				
Cunningham	817	344	108	365
Britt	779	392	127	260
Britt carbonate	1,649	559	398	692
Boatwright	269	110	88	71
Boatwright carbonate	1,845	586	391	868
Cum. all reservoirs	5,359			
Gas cum. (MCF)				
Cunningham	1,783,561,807	790,720,433	227,429,769	765,411,605
Britt	1,861,901,297	1,118,359,588	309,239,566	434,302,143
Britt carbonate	1,802,067,439	720,131,822	375,856,930	706,078,687
Boatwright	659,177,890	267,190,829	261,842,954	130,144,107
Boatwright carbonate	1,718,980,396	622,493,641	373,905,998	722,580,757
Cum. all reservoirs	7,825,688,829			
Oil cum. (bbl)				
Cunningham	9,920,697	3,250,675	1,119,271	5,550,751
Britt	12,376,241	6,566,131	1,122,019	4,688,091
Britt carbonate	14,443,292	5,613,766	1,455,585	7,373,941
Boatwright	2,868,546	1,212,017	1,049,118	607,411
Boatwright carbonate	10,280,866	2,262,136	1,175,445	6,843,285
Cum. all reservoirs	49,889,642			
Average oil per completion (bbl)				
Cunningham	12,158	9,450	10,460	15,208
Britt	15,928	16,793	8,905	18,031
Britt carbonate	8,921	10,225	3,761	10,796
Boatwright	10,744	11,119	12,059	8,555
Boatwright carbonate	5,636	3,874	3,093	7,957
Springer (undiff.)	9,768	9,562	5,881	11,243
Average gas per completion (MCF)				
Cunningham	2,185,738	2,298,606	2,125,512	2,097,018
Britt	2,396,269	2,860,255	2,454,282	1,670,393
Britt carbonate	1,113,074	1,311,716	971,207	1,033,790
Boatwright	2,468,831	2,451,292	3,009,689	1,833,016
Boatwright carbonate	942,423	1,065,914	983,963	840,210
Springer (undiff.)	1,523,256	1,779,917	1,547,150	1,240,219

Data from IHS Energy Group (2000).

which is 100–200 ft thick, is apparently a mechanical mixture of the underlying montmorillonitic or mixed-layer Springer shales and the overlying highly illitic Morrow shale" (p. 285). The mixed-zone shale was also characterized by the weathered form of montmorillonite (14–15 Å) in comparison to the unweathered 11–12.5 Å variety.

Weaver further investigated shales beneath the "Springer" Markham sandstone in the northern part of the Ardmore basin in Doyle field (just south of the Doyle fault, which separates the Anadarko basin from the Ardmore basin). He found that the shales directly under the Markham sandstone contain a two-water-layer variety of montmorillonite like that found in the mixed interval, indicating that in this area the Springer–Morrow boundary may actually lie beneath the Markham in the northernmost part of the Ardmore basin. Apparently the Mark-

TABLE 4. — Comparison of Springer Reservoir Single-Zone Completions[a]

		Average recovery		Recovery factor	
Reservoir name	Count	Gas (MCF)	Oil (bbl)	Decline[b] (units are MCF/psi)	MCF/psi[c]
Cunningham sandstone	342	2,151,893	9,090	564	545
Britt sandstone	386	2,857,148	12,834	565	536
Britt carbonate	566	1,312,824	9,568	1,193	948
Boatwright sandstone	110	2,451,292	11,119	467	563
Boatwright carbonate	639	1,009,654	3,437	1,011	814

[a]All single-zone completions with initial bottom-hole-pressure data. Data from IHS Energy Group (2000).
[b]Calculated by dividing average well production (MCF) by average pressure decline (psi), i.e., initial minus final pressure.
[c]Ultimate recovery divided by initial bottom-hole pressure.

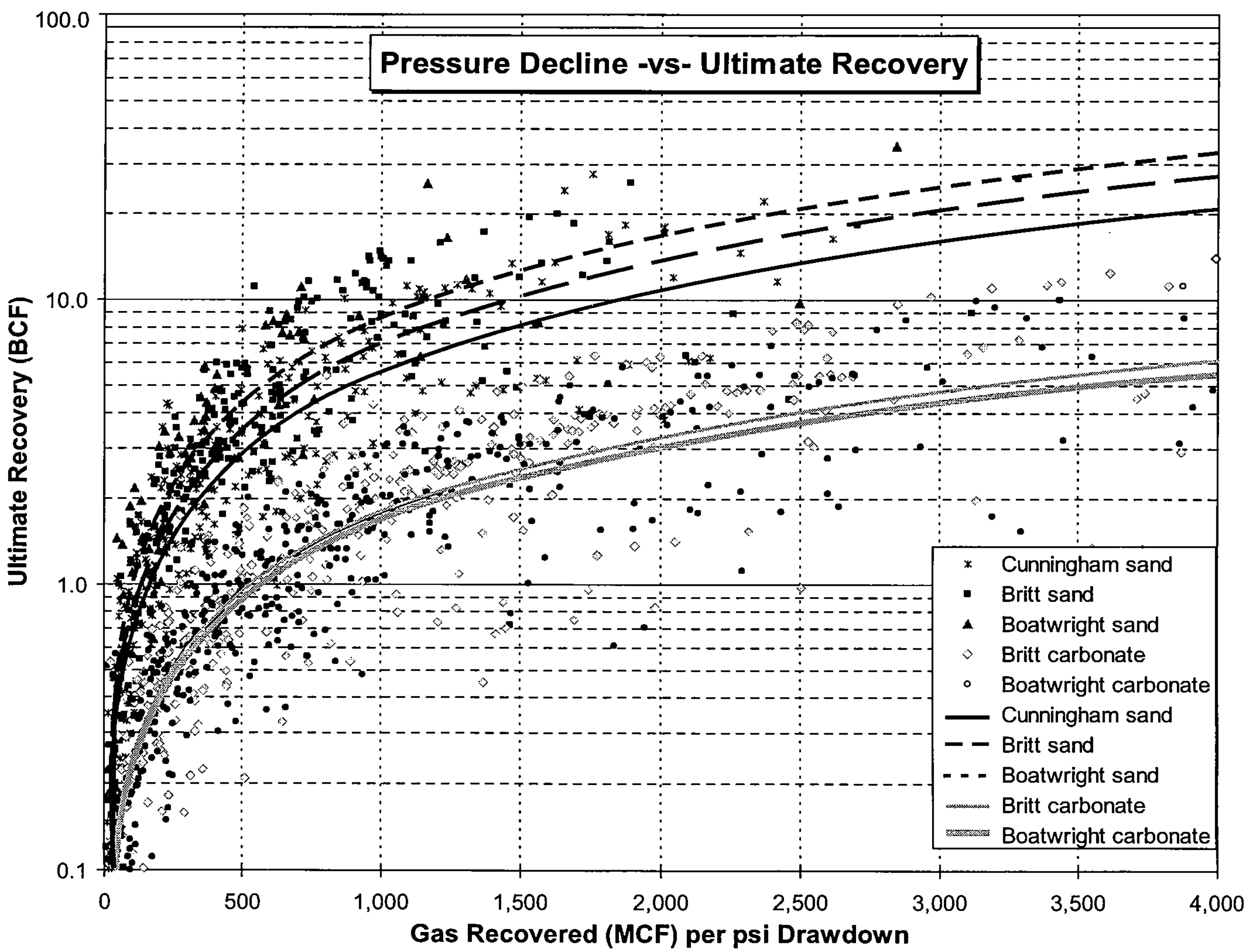

Figure 4. Plot showing ultimate recovery of gas (BCF) from Springer reservoirs versus gas recovered/pressure drawdown. From IHS Energy Group (2000).

ham sandstone occurs at or above the top of the Cunningham–Lake Ardmore strata.

These findings really complicate the interpretation of the Mississippian–Pennsylvanian systemic boundary in the subsurface of the Ardmore and Anadarko basins. It seems likely that this boundary occurs below the conductivity inflection point used in well logs to separate the lithostratigraphic Morrow and Springer units, and below the Cunningham–Lake Ardmore zones. In the southern Anadarko basin and the northern Ardmore basin, the Mississippian–Pennsylvanian boundary may be transitional instead of unconformable.

STRATIGRAPHY

Springer sediments in the Anadarko and Ardmore basins are mostly Late Mississippian to very Early Pennsylvanian in age. They are not exposed along the margins of the Anadarko basin, but they are exposed along the flanks of principal structures in the Ardmore basin and along the basin's margin, where formal surface terminology was adopted. The surface names have not been applied for the subsurface mainly because of correlation difficulties to the northwest across the Ardmore basin and into the Anadarko basin. The nomenclature problem was further compounded when numerous informal subsurface names were adopted by the geological community on the basis of well-log attributes or the names of significant producing leases. An attempt to correlate this hodgepodge of nomenclature is shown in Figure 8. In the subsurface, the Springer is reported to be up to 5,000 ft thick in the deep Anadarko basin. In this study, the thickest Springer section represented on regional cross sections is ~4,700 ft (well 7, section C–C′, Pl. 8, in envelope). At the surface, the Springer appears much thicker, with a maximum measured thickness of about 7,000 ft, as computed from Figure 9 (Hemish and Andrews, 2001).

Although not an objective of this study, some differences were noted between Springer sandstones in the subsurface and those exposed on outcrop in the Ardmore basin. The major differences recognized by McBride (1986) include the following: (1) siderite and dolomite are common in the subsurface but not at the surface, (2) subsurface sandstone has an overall larger grain size, and (3) chlorite and kaolinite are abundant in the subsurface but not in outcrop samples. Surface investigations by the author revealed that siderite was commonly found as concretions and sand-grain staining in all of the Rod Club Sandstone exposures examined in addition to being found in thin layers within the Springer shale. Chlorite, though not visually detected in the Springer sandstone, was also found by the author to be abundant in the exposed Primrose Sandstone.

The Springer Group is almost always bounded unconformably by the overlying Morrow Group. The Morrow–Springer contact is regarded as a regional erosional unconformity; therefore, the Morrow may be underlain by any one of the many informally and formally named sandstone units of the Springer, as shown in the stratigraphic-nomenclature chart (Fig. 8). In the deepest part of the Anadarko basin, just north of the Doyle–Reagan fault system, the Springer–Morrow interval may have undergone uninterrupted, continuous deposition. The basal contact of the Springer is thought to be mostly conformable with either the Chester limestone (northern Anadarko basin and shelf) or Caney shale (southern Anadarko basin and Ardmore basin). Both of these subjacent units are early Chesterian in age. Local exceptions to the conformable lower bounding surface do occur at some places in the Anadarko basin; Springer sands were often deposited in deeply incised channels, the basal contacts of which cut

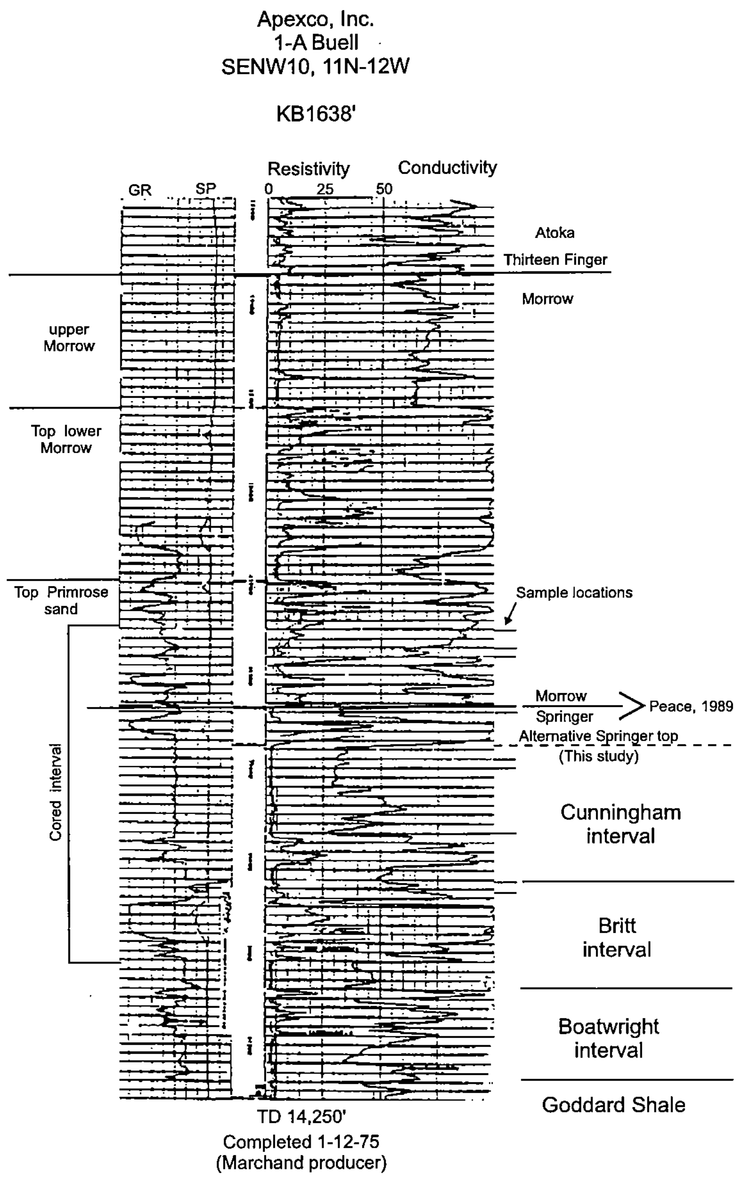

Figure 5. Cored interval and sample locations used to interpret Morrow–Springer contact in the Apexco No. 1-A Buell well. Modified from Peace (1989). *GR* = gamma ray; *SP* = spontaneous potential.

into older Springer strata and sometimes into the underlying Chester limestone.

In this report, for reference within both the Anadarko and Ardmore basins, the term *Springer* is used both as a formation and a group name. The Springer Group, therefore, is composed of two formations, the lower being the Goddard and the upper being the Springer. Both of these formations consist of marine shale and scattered sandstone zones. These sandstone zones are likewise identified in the stratigraphic columns of Figures 8 and 9.

In the Anadarko basin, the Springer formation of the Springer Group contains three main sandstone components that are, from youngest to oldest, the Cunningham, Britt, and Boatwright. The Britt and Boatwright sands have carbonate equivalents in the Panhandle and northwestern parts of Oklahoma that appear to be both stratigraphically and approximately time-correlative with the sandstones. The Cunningham sandstone has no corresponding carbonate facies in Oklahoma. In the deep Anadarko basin, the Britt sandstone interval includes several sandstone zones with local, informal names such as *Anderson* and *Spiers.*

The three sandstone intervals of the Springer formation in the Anadarko basin seem to correlate with the three sandstone members of the Springer Formation mapped on outcrop in the Ardmore basin: the Lake Ardmore, Overbrook, and Rod Club Sandstones, in descending order. But four principal Springer sandstone units occur in the subsurface of the Ardmore basin and south of the Doyle–Reagan fault: Markham, Aldridge, Humphreys, and Sims, in descending order. These sandstone units are not easily correlated northward into the Anadarko basin or to the southeast, where the Springer crops out in the Ardmore basin. The approximate correlative position of each of these sandstone units is shown in Figure 8.

DISCUSSION OF SPRINGER SANDSTONES IN THE ANADARKO BASIN, INCLUDING PETROLOGY

Cunningham Sandstone

The Cunningham interval probably contains the most sandstone of any of the three Springer members in the Anadarko basin. Sandstone extends north to Ts. 19–20 N. in parts of Dewey and Ellis Counties in northwestern Oklahoma and thickens southward to the limit of the basin along the Mountain View fault (Pl. 1, in envelope). In the northern and northeastern parts of the play, the Cunningham consists principally of one sandstone zone, but farther basinward the sandstone content increases to multiple zones, commonly with a combined thickness of more than 200–300 ft (see regional cross sections A–A′, B–B′, and C–C′, Pls. 6–8, in envelope). Most sandstone occurs as marine deposits in the form of offshore bars, although in places incised channels more than 100 ft thick have cut into older Springer sediments. Much of the Cunningham sandstone is tight and nonproductive, but some trends have secondary porosity sufficient for excellent hydrocarbon production. In these cases, the sandstone has porosity of 6–12% and even much more. In most instances, the Cunningham is not a good reservoir unless it has at least 6% porosity, regardless of depth (see Lookeba and Sickles North field studies, Parts II and III of this volume).

Deep in the Anadarko basin the Cunningham becomes increasingly tight, which is an impediment to deep drilling in some places. As an example, the Cunningham sandstone was cored below 15,000 ft in the Arkansas Western well, T. 13 N., R. 17 W. Porosity measurements

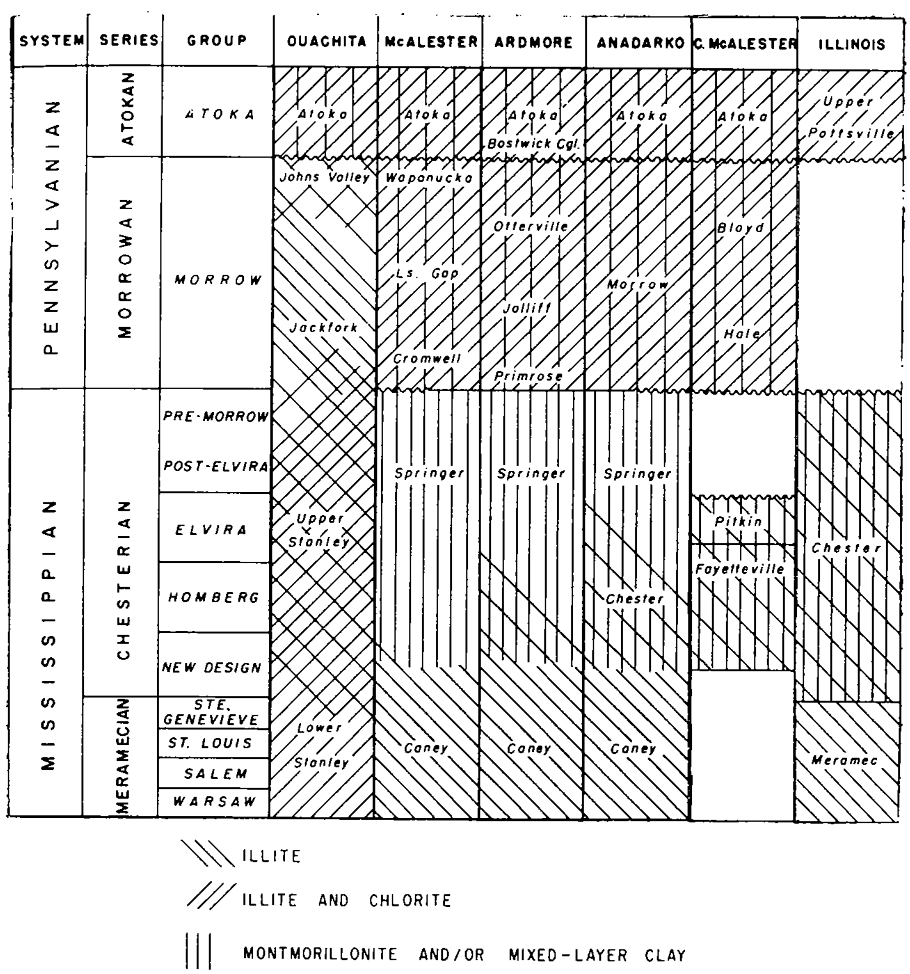

Figure 6. Correlation chart of Upper Mississippian and Lower Pennsylvanian rocks based on clay mineralogy. From Weaver (1958, fig. 2).

TABLE 5. — X-Ray Diffraction Mineral Percentages for Springer and Morrow Sandstones in Ardmore and Anadarko Basins, Oklahoma
(from McBride, 1986)

Sample identification number		Quartz	Feldspar	Calcite	Ferro-dolomite	Siderite	Pyrite	Kaolinite	Chlorite	Illite	Mixed layer illite/ smectite	Smectite
MS1-1	Rod Club	97					1	2		trc		trc
MS4-3	Overbrook	94	3					3		trc		trc
MS3-6	Lake Ardmore	91	2			trc	1	1		1		4
MS6-1B	Primrose	93	2				1	trc		trc		4
GR-1	Cunningham	75		15	2	4			4			
S-1	Primrose	92	2	trc			1	2	3	trc		
S-3	Primrose	91	2				1	2	2	1	1	
P-9	Primrose	94			4				2			
P-12	Primrose	90			trc		1	3	3	1	2	
B-6	Cunningham	91		2	2			trc	5			
B-8	Cunningham	96		1	trc				3			
O-7	Primrose	89	1	trc			3	2	2	1	2	

closely matched those of the cross-plot porosity in the logs and usually was <6% (Fig. 10A). The corresponding permeability was also small, about half a millidarcy (md).

The Cunningham sandstone was described by McBride (1986), using Folk's (1974) classification scheme, from 10 thin sections obtained from four well cores. From these samples, McBride determined that the Cunningham is fine to medium grained, well sorted, and subrounded. Mineralogically, the Cunningham plots toward the mature end of the subarkose and sublitharenite groupings or in the quartzarenite grouping on the QFR diagram (Fig. 11). This diagram shows that the Cunningham is composed largely of quartz (Q) grains with lesser amounts of feldspar (F) and rock fragments (R). According to McBride, the primary feldspar is K-feldspar, with lesser amounts of plagioclase. Rock fragments include sedimentary, volcanic, and fossil fragments. Sedimentary fragments consist of siltstone, collophane grains, chert, and glauconite pellets. Heavy minerals include zircon, tourmaline, and epidote. Chlorite and kaolinite are the principal clay constituents. X-ray-diffraction analyses of the Cunningham, the other Springer sandstones, and the Morrowan Primrose Sandstone are summarized in Table 5.

According to McBride (1986), the Cunningham contains siderite clasts that are more abundant than in any other Springer unit. The sandstone is very firm and is generally well cemented with both carbonate (calcite and

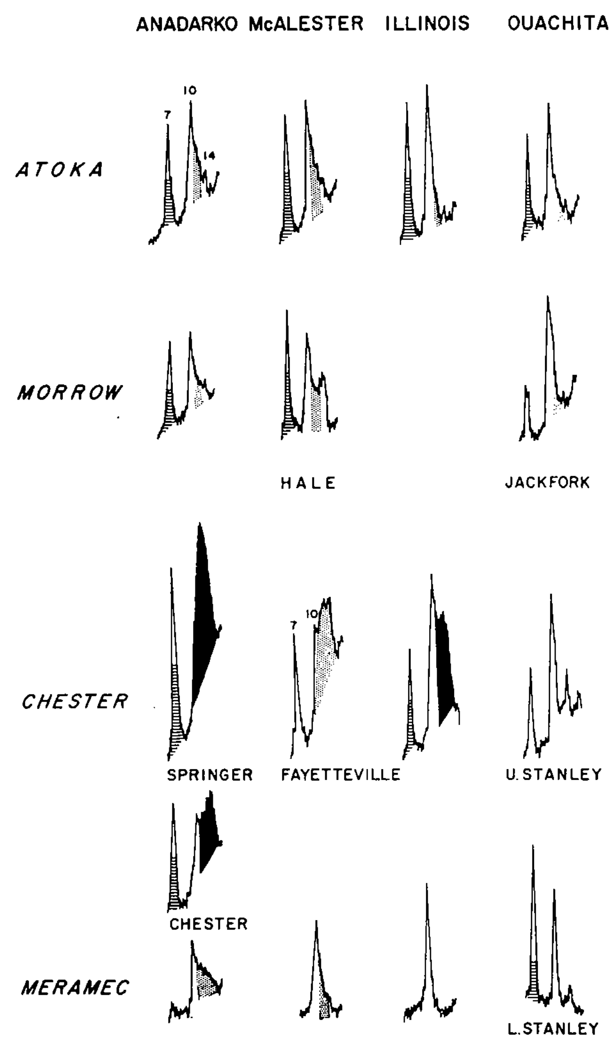

Figure 7 *(right)*. Typical X-ray-diffraction patterns of Upper Mississippian and Lower Pennsylvanian shales. Stippled—mixed-layer illite–montmorillonite; solid—montmorillonite; horizontal-lined—kaolinite; open 10 Å—illite; open 7 Å and 14 Å—chlorite. From Weaver (1958, fig. 3).

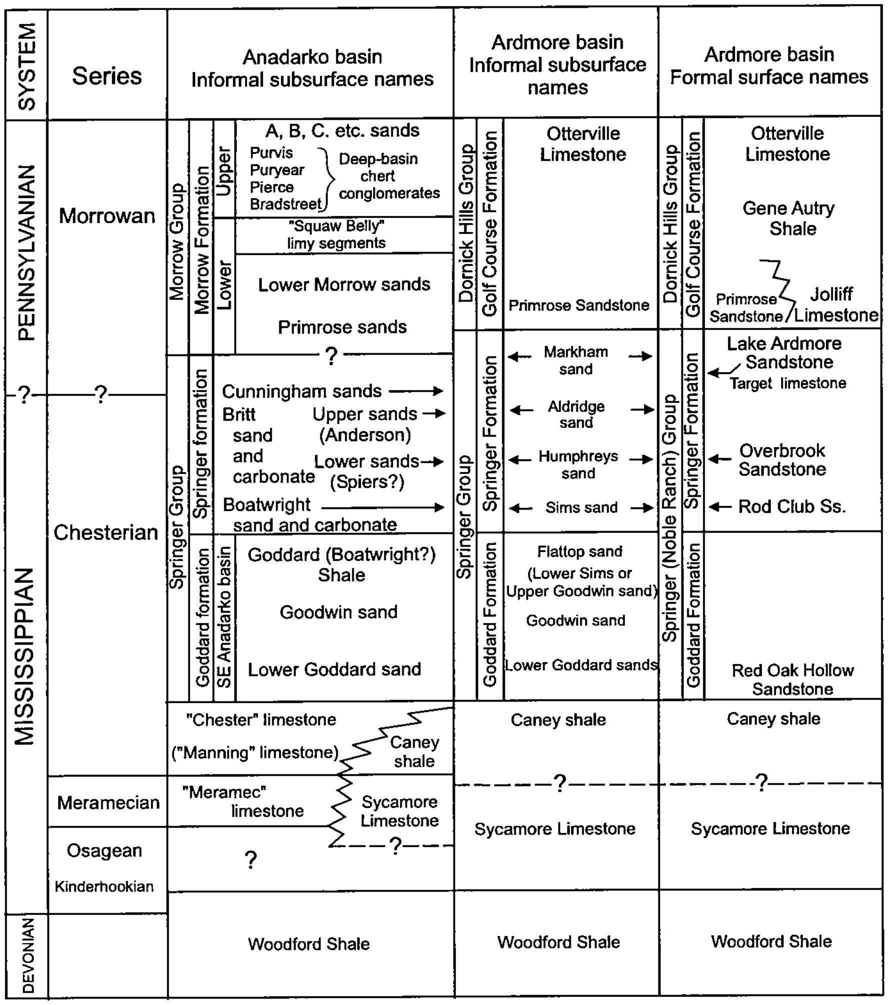

Figure 8. Stratigraphic-nomenclature chart of the Springer Group and bounding strata in the Anadarko and Ardmore basins in western Oklahoma. Modified from Kleehammer (1991), McBride (1986), Peace (1964), and Peace (1989).

dolomite) and silica overgrowths. The most common authigenic clays within the sandstone are chlorite, kaolinite, and minor amounts of illite (Table 5).

Britt Sandstone

Throughout most of the Anadarko basin, the Britt interval consists of two sandstone zones and interbedded shale. The combined sandstone thickness is generally less than 100 ft (see regional cross sections A–A′, B–B′, Pls. 6, 7, in envelope). Yet despite this, the Britt is probably the most productive unit in the Springer Group (see summary, Table 4). The Britt interval thickens abruptly into the deep Anadarko basin to more than 1,000 ft, where additional informal names, such as *Spiers* and *Anderson*, are used to refer to certain sandstone zones. Scout cards commonly use these names interchangeably, so their exact stratigraphic hierarchy is not particularly relevant. These names are included in regional cross sections B–B′ and C–C′ of Plates 7 and 8 (in envelope).

The Britt sandstone is widespread through much of the Anadarko basin (Pl. 2, in envelope). It extends south of a diagonal line stretching from northeastern Dewey County (T. 19 N., R. 14 W.) to southwestern Roger Mills County (T. 12 N., R. 26 W.). North of this line, the Britt changes facies from sandstone to limestone. The Britt carbonates are usually called *Chester* by most industry people, but the real Chester limestone lies distinctly lower in the section, as shown on the regional cross sections. The transition from sandstone to carbonate occurs throughout a relatively narrow corridor only a few miles wide. Although this study does not treat the carbonate facies in great detail, they do appear to represent a shallow-marine carbonate bank adjacent to the Britt sandstone trend. These relationships are shown on the regional sandstone-trend map of Plate 2 (in envelope) and on regional cross section B–B′ (Pl. 7, in envelope). Attention is drawn to the photoelectric (PE) log traces of wells 8 and 9. Well 8 has a carbonate value of 5, whereas the same interval in well 9 has a value of only 2–3, which indicates sandstone. The corresponding porosity and resistivity in both logs are also representative of limestone and sandstone, respectively.

The Britt sandstone occurs in two distinct facies, much like those in the Cunningham. As mapped on Plate 2 (in envelope), a prominent north–south-trending incised-channel complex along the eastern margin of the subsurface play is part of the "Old Woman" channel complex of Davis (1974). At an oblique angle to this trend are the more traditional marine-bar facies that trend northwest–southeast. The marine deposits occur as offshore bars. Much of the Britt sandstone is tight or wet and nonproductive, but some trends contain secondary porosity sufficient for excellent hydrocarbon production. In these cases, the sandstone has a porosity of 6–12% and at places much more. Deep in the Anadarko basin, however, the Britt becomes increasingly tight, which is an impediment to deep drilling at some places in the basin. As an example, the Britt sandstone was cored below 15,800 ft in the Arkansas Western well, T. 13 N., R. 17 W. Measurements in high-porosity zones closely matched those of the cross-plot porosity in the logs and were almost invariably <8% (Fig. 10B). The corresponding permeability was exceedingly low, mostly <0.20 md. As with the overlying Cunningham sandstone, the Britt is generally not a good reservoir with less than 6% porosity regardless of depth (see Lookeba and Sickles North field studies, Parts II and III of this volume).

The Britt sandstone was described by McBride (1986), using Folk's (1974) classification scheme, from four thin sections obtained from two well cores. From these samples, McBride determined that the Britt is generally very fine to fine grained, well sorted, and subrounded. Mineralogically, the Britt is composed mostly of quartz grains with lesser amounts of feldspar. This makes the Britt sandstone predominantly a quartzarenite to a subarkose, depending on the amount of feldspar. Some intervals contain abundant fossil fragments that tend to skew the QFR diagram toward the sublitharenite classification. K-feldspar is more abundant than plagioclase.

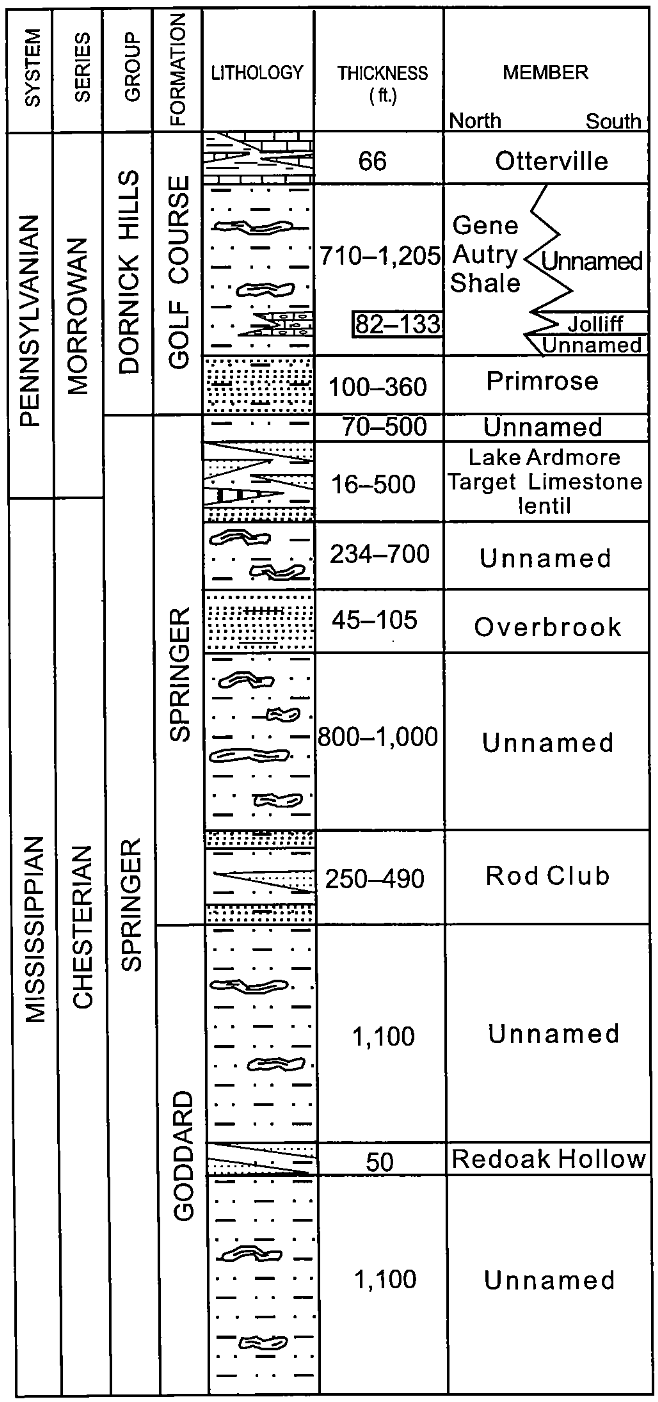

Figure 9. Stratigraphic chart of the Springer Group and Golf Course Formation (Morrowan) in the Ardmore basin, and thicknesses determined from outcrop measurements. From Hemish and Andrews (2001).

According to McBride (1986), and noted by this author from studied cores (Appendix 4), the Britt sandstone is very firm and generally well cemented, primarily with silica overgrowths and carbonate (calcite and dolomite). Authigenic clays within the sandstone include chlorite, kaolinite, and minor illite. Rock fragments include sedimentary and volcanic fragments and fossils. Heavy minerals include zircon, tourmaline, and epidote.

Boatwright Sandstone

The Boatwright sandstone occurs only in the south half of the Anadarko basin; to the north it changes to a carbonate facies in a manner similar to that of the Britt. Throughout much of its northern extent, the noncarbonate Boatwright facies consists mostly of shale with relatively thin (<50 ft), discontinuous, tight, nonproductive, and commonly "dirty" sandstones that make up distal marine-bar sequences. Only in the southeastern part of the play area does the Boatwright sandstone develop into relatively thick (>50 ft) and extensive marine bars that are productive. In these areas, Caddo and Grady Counties, Boatwright production is extensive. In the southeastern part of the trend, an average Boatwright well produces ~2.5 BCFG, rivaling production from the overlying Britt sandstone (~2.9 BCFG) (Table 4).

The distribution of Boatwright rocks is similar to that of the overlying Britt. South of a diagonal line extending from northeastern Dewey County to southwestern Roger Mills County, the Boatwright interval is chiefly shale and/or sandstone. North of this line, the Boatwright changes facies from shale to limestone. Here, the Boatwright carbonates are usually called *Chester* by industry people, but the real Chester limestone lies distinctly lower in the section, as shown on the regional cross sections. The transition from sandstone to carbonate is gradational over several miles. A distance of 50–75 mi separates predominantly carbonate strata to the north from prominent sandstone strata to the south. Although this study does not describe the carbonate facies in great detail, they do appear to represent a shallow-marine carbonate bank adjacent to the marine Boatwright shale. These relationships are shown on the regional sandstone-trend map of Plate 3 (in envelope) and on regional cross section B–B′ (Pl. 7, in envelope). Attention is drawn to the transition of the Boatwright interval from thick, massive carbonate to shale in wells 4 to 9.

The Boatwright sandstones in most parts of the southern Anadarko basin exhibit a distinctive coarsening-upward log profile. This implies a marine-bar origin similar to that of the overlying Britt and Cunningham. In an area east of Cement field (Ts. 2–6 N., Rs. 4–6 W.), however, the character of logs from some of the Boatwright wells indicates that individual sandstone units have sharp upper and lower contacts with shale, suggesting a similarity to the classic turbidites exposed in the Ardmore basin. Therefore, it is possible that some Boatwright sandstone units in the extreme southern part of the Anadarko basin,

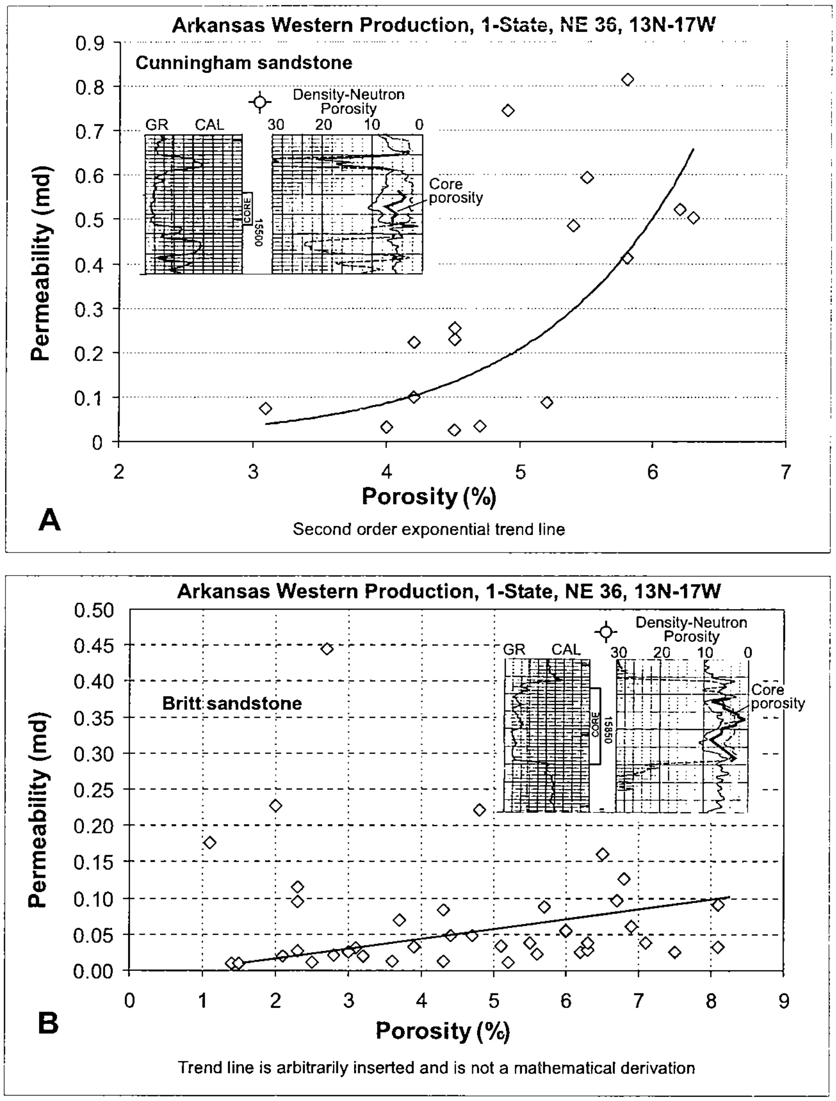

Figure 10. Core porosity and permeability data for the Springer Cunningham sandstone (*A*) and the Britt sandstone (*B*) in Arapaho field, Custer County, Oklahoma. Data provided by Walt Hendrickson, IHS Energy Group, Oklahoma City. *GR* = gamma ray; *CAL* = caliper.

as well as in the Ardmore basin, may have been deposited as turbidites.

Boatwright exposures on outcrop in the Ardmore basin have been interpreted to be both offshore bars and turbidites. In the subsurface, Boatwright sandstones are commonly tight or wet and nonproductive, but some trends contain secondary porosity sufficient for excellent hydrocarbon production. In these trends, the sandstone porosity is 6–12% and even higher. As with the overlying Springer sandstone units, the Boatwright is generally not a good reservoir with <6% porosity, regardless of depth. No core analysis was available to this investigation for characterization of the Boatwright sandstone in the deep Anadarko basin.

The Boatwright sandstone was described by McBride (1986), using Folk's (1974) classification scheme, and was based on only three intervals from the core of one well. From these limited samples, McBride determined that the Boatwright sand-grain size varied from fine to coarse. In other samples examined by the author, the grain size was more consistently fine to very fine. McBride's samples were subangular to subrounded and poorly sorted in contrast to the majority of samples examined by the author. Compositionally, the Boatwright described by McBride was very nearly pure quartz, which agrees with that for "clean" sandstone observed by the author. Therefore, the Boatwright plots close to the mature end of the QFR diagram of Figure 11.

According to McBride, calcite and dolomite and quartz overgrowths are the principal cementing agents in the Boatwright sandstone. Where present, authigenic clays within the sandstone include chlorite, kaolinite, and minor illite. Rock fragments and heavy minerals are similar in composition to those of younger Springer units.

DEPOSITIONAL ENVIRONMENTS

Depositional patterns of Springer sandstone sequences were determined by using the well logs in the regional grid of cross sections of this study and those of the IHS Energy Group. Unfortunately, the Springer does not crop out along the southern margin of the Anadarko basin, so interpretations of depositional environments in that basin are based on well logs and scattered cores.

Additionally, most significant exposures of the Springer Formation in the adjoining Ardmore basin were examined by the author. Gamma-ray profiles were made of several outcropping Springer members that are interpreted to represent the depositional environments of the Springer Formation. These gamma-ray profiles then were compared to logs of nearby wells to ensure some degree of quality control in the interpretation of depositional environments based solely on well-log characteristics. The surface exposures of the Springer are believed to be correlative in a general way with subsurface units in the adjoining Anadarko basin. By correlating depositional environments observed on outcrop with well-log characteristics, subsurface depositional environments are inferred for both basins.

Most Springer sandstone appears to have been deposited in a shallow-marine-shelf environment in water depths of <150 ft. These marine deposits are detached from any shoreline and therefore are called *offshore bars.*

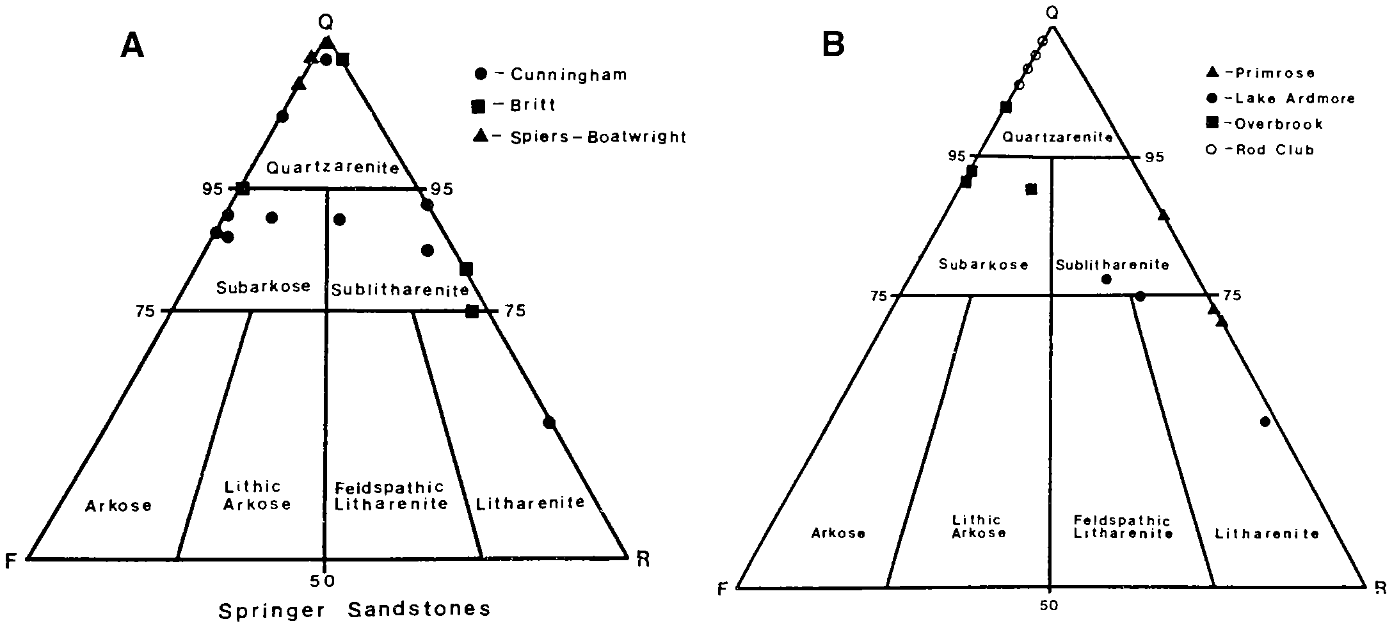

Figure 11. Composition of subsurface (*A*) and surface (*B*) Springer sandstones in the Anadarko basin and Ardmore basin, respectively. Classification is according to Folk (1974). From McBride (1986).

In the Springer, these types of bars are almost invariably oriented in a northwest–southeast direction, and many geologists stubbornly apply this "trendology" to every sandstone contained in the Morrow–Springer interval, being oblivious to different sandstone facies and environments of deposition.

Although most Springer sandstones in both the Anadarko and Ardmore basins occur as offshore bars, at least two other depositional environments characterize the Springer: sand-filled incised channels and turbidites. Offshore bars, channels, and turbidites each exhibit unique geometries and characteristics and can be recognized by their well-log signatures.

Detached (Offshore) Bars

Marine offshore bars are easily recognized in well logs, in core, and on outcrop. They are completely encapsulated in marine shale—above, beneath, and laterally. Bioturbation and trace fossils are abundant in the lower-bar facies. No deltaic constituents, such as delta-plain deposits (e.g., coal, lagoonal shale, splay sands) are in stratigraphic continuity directly above the bar sands. Additionally, offshore bars map as narrow, elongate sand bodies extending for miles.

Little commonly accepted terminology is used in describing specific zones or facies of shelf bars. The depositional processes that are responsible for the creation of an offshore bar, however, are similar to those of a subaqueous shoreface deposit. Therefore, terminology used in this study was "borrowed" from that applied to strandline deposits, knowing full well that offshore bars do not have a shoreface because they were deposited far from a shoreline.

A typical detached bar has certain characteristics that are easily recognized. The basal contact is gradational with marine shale, which underlies the bar. This gradational contact may be gradual over tens of feet vertically, or somewhat abrupt over only several feet vertically, but this transition is almost invariably present. Marine-bar sands having a sharp lower contact with shale are commonly the result of storm events rather than normal vertical accretion of a bar. Figure 12 shows the lower contact of the Overbrook Sandstone (Britt equivalent) near the

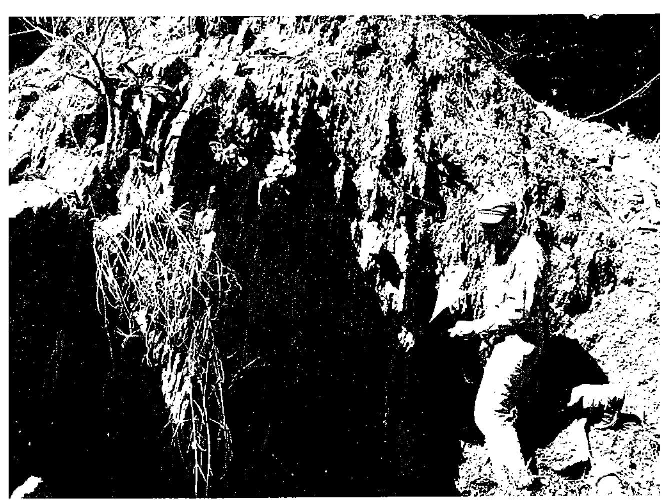

Figure 12. Basal contact of the Springer Overbrook Sandstone at City Lake spillway 3 mi north of Ardmore. The gradational transition from shale to sandy strata up-section (left) affects the degree of bed erosion so that the weathering profile gradually becomes more resistant up-section. This is what is meant by a coarsening (or "cleaning") upward profile recorded on well logs.

Figure 13. Above the basal contact of the Springer Overbrook Sandstone is a zone of very fine grained, thin-bedded sandstone interbedded with silty shale. These strata define the transition zone of an offshore-marine-bar complex. Thin sandstone beds almost invariably exhibit conspicuous ripple bedding and horizontal trace fossils. This section is at MGM Ranch, ~5 mi northwest of Ardmore.

Ardmore City Lake spillway. Behind the geologist (LeRoy Hemish, OGS) are beds of open-marine shale, and the lower-bar contact is directly in front of him. For several vertical feet the lower-bar facies consists of interbedded silty sandstone and shale, forming the *lower transition facies.*

In an up-section direction to the left, these strata gradually become increasingly more sandy, with discrete, thinly bedded, very fine grained sandstones interbedded with silty shale such as shown in Figure 13. These strata are typical of the Springer *transitional bar facies*, and the corresponding resistivity curve on a well log would gradually increase through this zone and the gamma-ray curve would gradually decrease. The transition zone of a bar typically exhibits abundant bioturbation and trace fossils in addition to ripple-bedded sandstone (Figs. 14, 15).

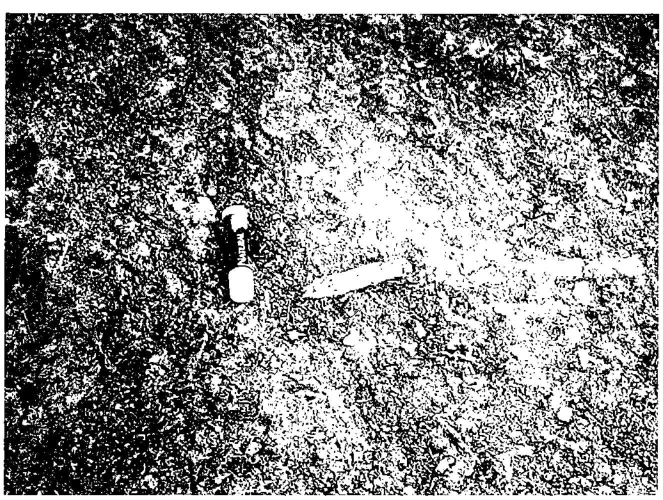

Figure 14. Trace fossils on a slab of Overbrook Sandstone at City Lake spillway 3 mi north of Ardmore. Burrows are typically horizontal. Bioturbation is also common in the strata. Lip balm tube is 2.5 in. long.

Figure 15. Mostly symmetrical ripple bedding in the marine-bar transition facies of the Overbrook Sandstone at MGM Ranch, 5 mi northwest of Ardmore. The photo is oriented so that the tops of the beds are at the top of the figure.

Figure 16. Flat-bedded, fine-grained sandstone in the main bar facies of the Overbrook Sandstone at City Lake spillway 3 mi north of Ardmore. The absence of interbedded shale indicates that this bar section is above the transition zone.

Stratigraphically higher in the bar, a point is reached at which there is very little or no interbedded shale, so the strata are essentially all sandstone. This point marks the *lower-bar facies,* which is roughly equivalent to the lower shoreface facies of strandline deposits. The lower-bar facies has cleaner sand, which is somewhat coarser grained (but still may be fine grained), and the bedding is horizontal and commonly rippled. Figure 16 shows this bar facies in the Overbrook Sandstone near the Ardmore City Lake spillway. There, the Overbrook is a relatively thick section of flat and/or ripple-bedded sandstone with no interbedded shale.

At the bar crest (unless it was eroded before preservation) would be the *upper-bar facies,* which characteristically exhibits high-angle cross-bedding. This zone would have received the most current (wave, tide) energy and probably would be the shallowest part of the bar. Figure 17 shows this facies in the Overbrook Sandstone at MGM Ranch. (See Hemish and Andrews, 2001, for more details concerning these exposures.) The upper contact of typical marine bars is sharp, as shown in Figure 18. So the textural profile of a detached bar commonly shows a coarsening upward characteristic through the transition facies, and then it may be somewhat blocky through the main bar facies (Figs. 16, 17), and the upper contact with shale is sharp (Fig. 18).

Figure 17. High-angle cross-bedding at the very top of the Overbrook Sandstone section at MGM Ranch, 5 mi northwest of Ardmore. This sedimentary structure is indicative of the upper-bar facies and lies stratigraphically above the horizontally bedded sandstone of the lower part of the main bar facies.

Turbidites

With some degree of certainty, it can be said that only the outcropping Rod Club Sandstone of the Ardmore basin and its correlative unit, the Boatwright(?) sandstone in the Anadarko basin, contain turbidite deposits. Both units also commonly occur in the form of offshore bars, as mentioned previously. In Figures 19 and 20 the Rod Club exhibits characteristics of both depositional environments.

Turbidite deposits occur in marine environments in which depositional stability is lost for a variety of reasons, causing sediments to flow catastrophically into the basins. Their distinguishing characteristics are sometimes confused with subaerial channel deposits, but certain stratigraphic associations and sedimentary structures usually can be used to identify turbidites accurately. Surface analogies were also useful in this study to help in identifying them on well logs.

Turbidite nomenclature and a depositional model are shown in Figure 21 (Walker, 1984). As can be seen in these figures, turbidite channels and sheet deposits are the most distinguishing parts of a turbidite fan. The turbidite deposits of the outcropping Rod Club Sandstone are similar to this model and occur both as channels and sheet deposits.

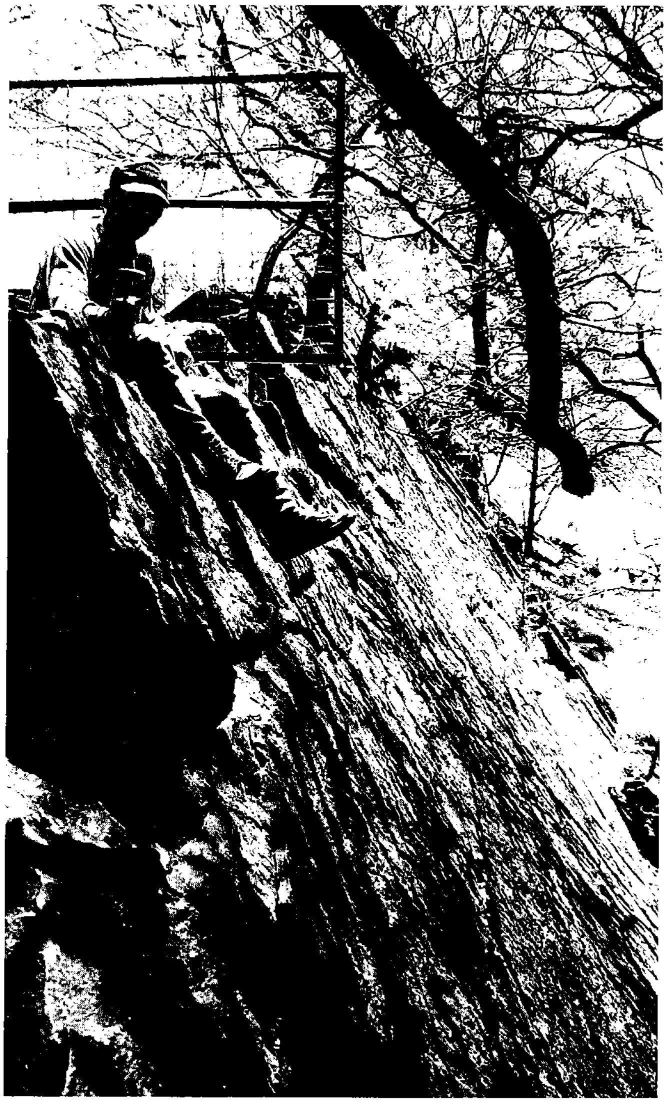

Figure 18. Upper contact of the Overbrook Sandstone is abrupt. Strata above this surface were eroded away, leaving a sandstone ridge extending for about 3 mi along the southwest flank of the Caddo anticline. OGS geologist LeRoy Hemish is sitting on the upper-bar facies, with high-angle cross-bedding (see Fig. 17).

Figure 19. Tabular beds of the Rod Club Sandstone along the northwest flank of the Caddo anticline having sharp upper and lower contacts with shale. Sedimentary structures, such as water-escape features, rip-up clasts, and massive bedding, are typical of classical turbidite deposits formed on a more steeply sloping oceanic shelf. This exposure is distinctly different than the Rod Club exposure at Goddard Ranch (Fig. 20).

Figure 20. Horizontal- and ripple-bedded Rod Club Sandstone at Goddard Ranch (~15 mi northeast of Ardmore). The section here exhibits a coarsening-upward textural profile indicative of an offshore-marine bar. Contrast this type of bedding with that of the Rod Club shown in Figure 19.

Turbidite channels of the Rod Club Sandstone appear as relatively thick, incised channels having sharp upper and lower contacts with shale. They are filled with very clean, moderately sorted, poorly cemented sand which has localized orangish-red iron staining. Rip-up clasts, shaly bedding stringers, and fossil wood fragments are also locally abundant in the sandstone. Bedding surfaces are often scoured into one another forming an amalgamation of different sandstone deposits. The sandstone often appears massive throughout 1–2-ft intervals, although high-angle cross-bedding is locally present. Some of these larger scaled features are shown in Figure 22.

Thinner sandstone beds of the Rod Club that are interpreted to be turbidites also have unique characteristics, including sharp upper and lower bedding contacts, tabular beds with extensive lateral continuity having little change in bed thickness (Fig. 19), water-escaped structures, shale rip-up clasts, and fossil wood fragments (Fig. 23). Bedding commonly is indistinct and appears massive on a small scale although localized areas have high-angle cross-bedding and convoluted (deformed) bedding.

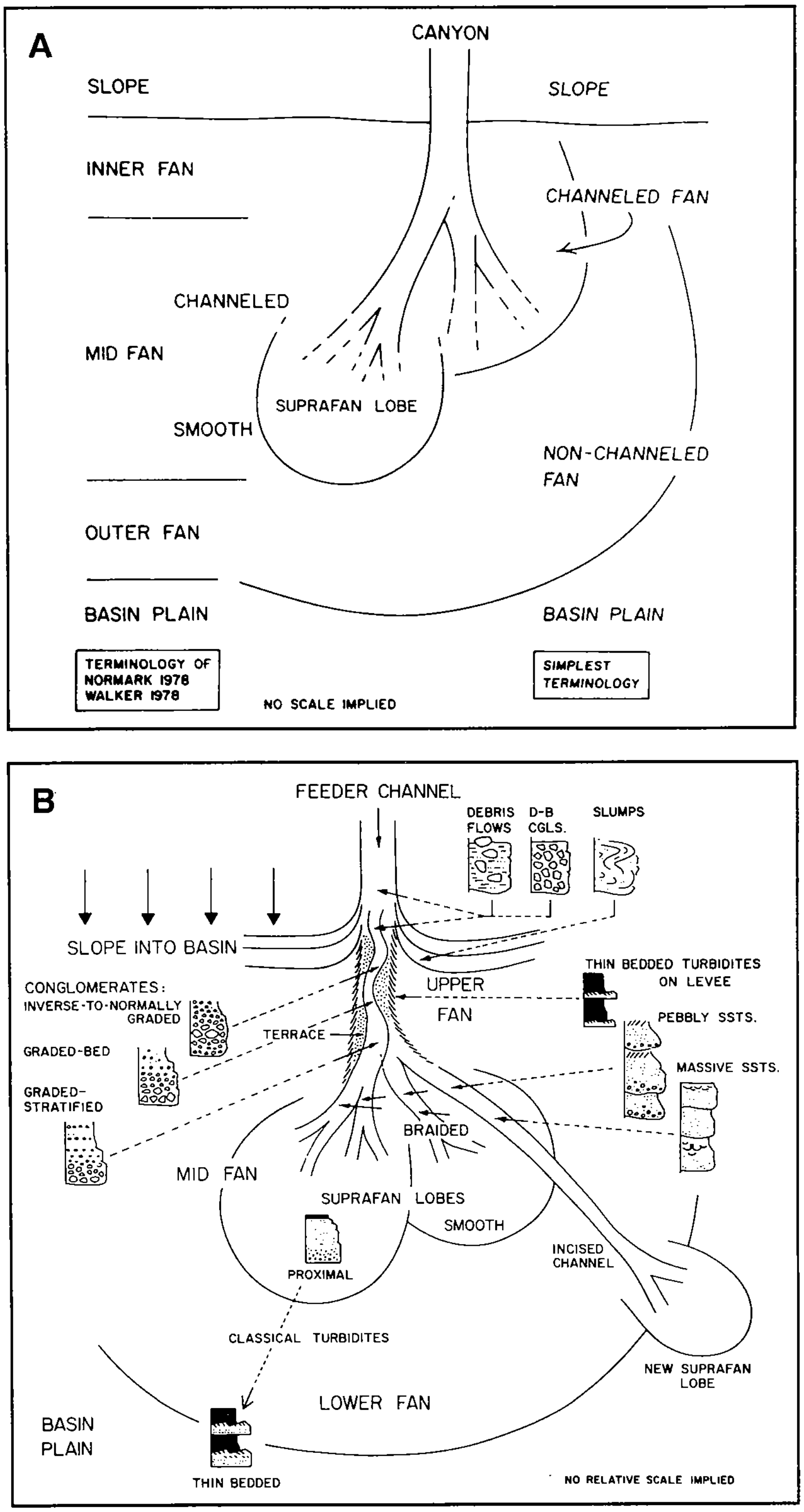

Figure 21. Simplified terminology of a turbidite fan (*A*), and a proposed model by Walker (*B*) incorporating a generalized stratigraphic section of turbidite facies. From Walker (1984).

Incised-Channel Deposits

In the Anadarko basin, both the Cunningham and Britt units contain anomalously thick sandstones in incised channels. No surface exposure of Springer Formation members in the Ardmore basin are known to have this depositional origin. Incised channels are formed in response to falling sea level. Valleys are eroded through previously deposited strata (usually marine shale), and fluvial deposits in the form of longitudinal bars fill these eroded valleys. Marine transgression (a rise in sea level) may coincide with, or occur shortly after, channel-sand deposition, so that parts of the incised-channel deposit may be reworked. However, because most sand is encased in older and more indurated strata, a rising ocean would have minimal effect on the deeply buried sand within the incised channel.

Certain well-log characteristics are indicative of incised channels. Gamma-ray logs in combination with porosity and/or resistivity logs are the tools of choice in identifying them. Almost all these logs show the sand to have a sharp basal contact with shale, and on gamma-ray logs a blocky or clean zone of unusual thickness is evident that is disproportionate to the thickness of other sandstones in the area. The upper contact of an incised-channel sand can also be sharp, but there is usually some fining upward in the textural profile that results from relatively rapid channel abandonment.

Distribution patterns mapped in the subsurface are also diagnostic of different depositional events. The Britt trend map (Pl. 2,

Figure 22. Thick-bedded and massive Rod Club Sandstone along the north flank of the Ardmore basin ~10 mi northwest of Ardmore. Note the contrast of this bed morphology with the tabular turbidite beds of the Rod Club exposed along the Caddo anticline (Fig. 19).

in envelope) shows two distinct sandstone trends, one to the northwest–southeast and the other basically north–south. The north–south trend represents an incised-channel complex ("Old Woman channel), and the northwest–southeast trend represents marine bars. Additionally, incised channels can be inferred from isopach mapping by their abrupt change in thickness of these deposits. Sandstones in incised channels can thicken to more than 100 ft in a lateral distance of less than half the channel thickness. Incised channels also exhibit great length and typically extend for many townships, with a width of only 1–2 mi or less. They invariably end in a marine environment, and their "beginnings" are usually eroded along basin margins, as is the case for the Britt.

SEDIMENT-SOURCE AREAS (PROVENANCE)

Cunningham Sandstone

Detritus in the Cunningham member of the Springer formation in the Anadarko basin appears to have come from the north–northeast, but no specific channel systems have been mapped separately in this study. Although the environment of deposition of the Cunningham sand bodies is overwhelmingly marine (offshore bars), numerous well logs show gamma-ray profiles indicative of channel deposits—i.e., sandstone having a sharp basal contact with shale. Some well logs indicative of channel deposition have been incorporated in the regional cross section B–B′ of Plate 7 (in envelope). Many such deposits probably formed in response to falling sea level and therefore are incised. Some of them thicken abruptly to more than 100 ft in areas that otherwise have little or no sandstone. This situation is particularly prevalent in Ts. 14–15 N., Rs. 16–17 W.

Sand carried into a marine environment by way of incised channels was redistributed on the shelf as detached marine bars, probably miles from the shoreline. The marine bars are not distributary-mouth bars and, as such, are not subaqueous delta-front deposits.

Britt Sandstone

The Britt sandstone has origins similar to those of the Cunningham, except that channel deposits are clearly evident throughout much of its northern extent. These deposits also are highly productive of gas and, as such, are mapped on Plate 2 (in envelope). The principal Britt channel system extends in a north–south direction very close to the Britt subcrop along the east-central part of the play map. This trend is often referred to as the "Old Woman" channel (Davis, 1974) and probably formed in response to sea-level changes in a falling-stage incised valley. The updip extent of the "Old Woman" channel is eroded at the subcrop. Most Britt sandstone reservoirs, however, occur as offshore marine bars that characteristically trend northwest–southeast (Pl. 2). As with the Cunningham, sands carried into the marine environment during Britt time were redistributed on the shelf as detached marine bars, probably miles from the shoreline.

The very fine grained and well-sorted Britt and Cunningham sandstones indicate relatively long-range transport. These same traits characterize the overlying Morrow sandstones, and their supply corridors are somewhat parallel to those in the underlying Springer. Therefore, Cunningham and Britt sediments appear to have come from areas far to the north and northeast (central Kansas uplift), because channels can be identified in the subsurface that trend in this direction.

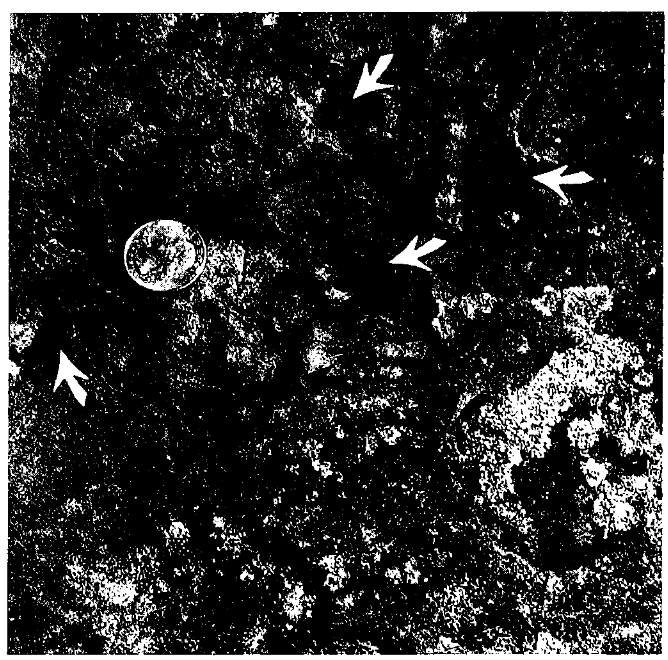

Figure 23. Shale rip-up clasts and fossil wood fragments in the turbidite facies of the Rod Club Sandstone along the northwest flank of the Caddo anticline. Sideritic/limonitic staining characterizes much of the Rod Club Sandstone in the Ardmore basin. Black arrows point to wood fragments; white arrows point to rip-up clasts.

Boatwright Sandstone

As previously mentioned, the Boatwright (approximately Rod Club equivalent) has two distinctly different environments of deposition—turbidites and off-shore bars. In certain parts of the Anadarko and Ardmore basins, both of these deposits occur simultaneously, although their stratigraphic relationship is unclear. As shown by the sandstone-trend map of Plate 3 (in envelope), the preponderance of Boatwright sandstone, regardless of facies, occurs in the very southeastern part of the Anadarko basin, and there are no south-trending sediment supply corridors (channels) recognized. Therefore, it seems likely that local tectonic events that occurred during the evolution of bordering geologic provinces to the south may have affected the distribution of Boatwright sandstone in both the Anadarko and Ardmore basins. The turbidites in particular have a relatively clear southern provenance due to their conspicuous channelized fan morphology in the Ardmore basin. However, the provenance of the Boatwright/Rod Club offshore bars is not so clear. Although more limited in areal extent, their distribution is very similar in nature to that of the younger Springer marine deposits (northwest–southeast bar trends). So it is possible that a different depositional event not related to turbidite deposition is responsible for the Boatwright offshore-bar deposits. And the provenance for these bar deposits is speculated to be from the south or southeast.

REGIONAL CROSS SECTIONS

Four regional cross sections were constructed to show the stratigraphy, nomenclature, facies, depositional environments, and character of the Springer Group: A–A′, B–B′, C–C′, and D–D′ (Pls. 6–9, in envelope).

Cross Section A–A′ (Plate 6)

Cross section A–A′ (Pl. 6, in envelope) is oblique to strike in a northwest–southeast direction and roughly parallel to the eastern subcrop limit of the Springer. Therefore, wells represented on this section are relatively shallow penetrations in the Anadarko basin and shelf areas of northwestern Oklahoma. Fifteen wells were selected in sandstone and carbonate trends where hydrocarbons are produced from the Springer. All wells include logs showing resistivity, conductivity, gamma-ray values, and some type of porosity. Many logs have spontaneous potential (SP), caliper, and other specific recordings as well.

Starting along the northern limit of the play at well 1, the Springer is about 220 ft thick and consists of Britt and Boatwright carbonate units. The Cunningham is not present this far north. This well is productive from the upper part of the Boatwright, which has porosity of about 6–10% in places as noted on the accompanying density–neutron log. The productive interval has a good SP deflection, indicating porosity and permeability.

Similar log characteristics are noted for well 2, except that the best zone is in the Britt, which is identified by a pronounced SP deflection. Low resistivity in the Britt, however, shows that it is wet. The accompanying porosity logs show a photoelectric (PE) value through the Britt and Boatwright of ~5, which means that it is a carbonate rock rather than sandstone.

The log of well 3 shows a thick incised Morrow channel cutting through the Springer section all the way down to the underlying Chester limestone. The Morrow sandstone can be identified by the log characteristics that show much lower resistivity and much higher porosity than can be found in the Springer carbonates.

Well 5 shows a similar incised Morrow channel in the Woodward trench. Deeply incised Morrow channel complexes such as these observed in wells 3 and 5 have locally removed all or parts of the Springer in north–south trends, as shown on the Boatwright trend map (Pl. 3, in envelope).

Well 6 has a productive Boatwright interval with high resistivity, a good SP trace, and porosity approaching 3%. The PE trace on the accompanying porosity log also shows a value of ~5, indicating a carbonate rock.

The subcrop limit of the Britt occurs between wells 6 and 7. Both carbonate units in well 7 have relatively thick, tight sections. Several miles southeast of well 7 the Britt interval changes facies and is composed of two sandstone beds in well 8. This is inferred from the much higher porosity in the Britt in well 8. Log shapes of the sandstone beds are not definitive in determining depositional environments, although the lower sand has a sharp basal contact with shale and fines upward, a trait common to channel deposits. The underlying Boatwright changes facies from carbonate (well 7) to predominantly shale in well 8. The updip limit of the Cunningham occurs several miles to the southwest of well 8.

The Cunningham is productive from this sandstone interval in well 9. The underlying Britt consists of two sandstone beds, the upper one of which is certainly some form of marine bar, whereas the lower sand exhibits non-marine traits, as seen in well 8.

At well 10, the Britt sandstone thickens abruptly to almost 100 ft in the "Old Woman" channel. This channel complex can be mapped for at least 50 mi to the south from its subcrop, and the sandstone in it produces gas from well 10. The overlying Cunningham is also productive from a much thinner sand in well 10, and the underlying Boatwright is predominantly shale in this part of the basin.

Wells 11 and 12 show the Cunningham interval thickening, with additional sandstone deposits interpreted to be channel-like by virtue of the very sharp basal contact and abrupt thickening locally. The log patterns can be compared to those of the underlying Britt and Boatwright sands that have the characteristic coarsening-upward log profile common to marine bars. Again, the Boatwright interval in both wells 11 and 12 is mostly shale.

The entire Springer interval thickens dramatically to ~980 ft in well 14 as compared to only ~220 ft in the first well. In well 14, the Cunningham interval is dominated by a very thick sandstone (~175 ft) having the typical blocky log signature that is sometimes characteristic of an incised-channel deposit. The underlying Britt and Boatwright intervals are mostly shale with poorly developed marine-bar deposits, having the usual coarsening-upward log profiles. Beneath the Boatwright interval is about 400 ft of Goddard shale, which rests conformably on the Mississippian Chester limestone.

The last well (15) in cross section A–A′ is in a much deeper part of the Anadarko basin, and the Springer section there thickens to ~1,700 ft. Notable in this well is the first occurrence of additional sandstones beneath the traditional Boatwright interval. Locally, as in this well, the upper Boatwright is often referred to as the *Spiers sand.* Much deeper in the Goddard shale interval is another thick sandstone that is productive of gas. This sandstone has no specific name and is simply called the *lower Goddard sand.* From wells 11 through 15, the Springer dips into the Anadarko basin at a higher gradient. The Springer was first penetrated in well 11 at about 11,444 ft and in well 15 at about 15,750 ft.

Cross Section B–B′ (Plate 7)

Cross section B–B′ (Pl. 7, in envelope) is very nearly a dip section that is oriented north–south. It ties with section A–A′ (Pl. 6) in the shallow Anadarko shelf and includes wells of increasing depth to more than 18,000 ft just north of the Mountain View fault. The last well in the cross section is in a fault block in the southernmost part of the Anadarko basin, where the Springer section is overturned. Fifteen wells in this cross section show the character of the Springer interval, specifically the gradual facies change in the Boatwright from carbonate in the north to shale in the south. Also shown is the abrupt facies change in the Britt interval from carbonate in the north to sandstone in the south. Well-log attributes in this section are the same as those in section A–A′ and show resistivity, conductivity, gamma-ray values, and some type of porosity. Many logs also have SP, caliper, and other specific recordings.

The first well in cross section B–B′ is actually north of the subcrop limit of the Springer, and only the Chester limestone is present at the Mississippian–Pennsylvanian unconformity. Thick, massive carbonates dominate the Chester at this locality. Only a few miles to the south, the Boatwright appears beneath the unconformity as a massive carbonate unit that produces gas in the Cedardale area (see detailed field study in Part V of this volume). The high resistivity, strong SP trace, and relatively low permeability are characteristic of this reservoir. The PE value of ~5 is indicative of carbonate rocks, as shown on the porosity log.

In well 2 the Springer is only ~145 ft thick. The updip limit of the Britt carbonate occurs at the unconformity only a few miles south of well 2.

Well 3, in the Cedardale area, produces from both the Britt and Boatwright carbonates in a stratigraphic updip trap.

The Springer Britt and Boatwright carbonates are also productive in well 4, and also exhibit a characteristically low average porosity, in this case generally <4%.

In well 5, about 3 mi to the south, the Springer thickens to more than 700 ft. The Britt carbonate thickens somewhat, whereas the Boatwright carbonate decreases slightly with a corresponding increase in shale.

In well 6, only ~5 mi south of well 5, the Britt carbonate increases to ~120 ft, whereas the Boatwright carbonate thins considerably. Note the lower half of the Boatwright interval, which is now mostly shale.

This same pattern continues 3.5 mi farther south in well 7, which shows the Boatwright to be mostly shale with only ~60 ft of carbonate (in comparison to ~160 ft in well 3).

Between wells 7 and 8, the updip limit of the Cunningham is crossed. In well 8, the Cunningham is composed almost entirely of sandstone. Note the PE value of about 2–3 in this interval and the high SP and porosity values in comparison to the thick Britt carbonate directly below. The Britt carbonate has a much higher PE value of ~5 and considerably lower porosity. The underlying Boatwright now has only about 30 ft of carbonate, the remainder of the interval being shale (the "Boatwright shale," as used in this report).

Well 9 is significant in showing the Britt interval to be composed of sandstone instead of carbonate. This is verified by PE values of about 2–3 and relatively high porosity comparable to that of the overlying Cunningham sandstone. The underlying Boatwright interval, however, consists of diminishing carbonate strata (PE value, about 4–5) and increasing shale.

In well 10 the Boatwright interval is essentially all shale. The overlying Britt interval is also mostly shale, owing to an abrupt facies transition from mostly sandstone in well 9.

In well 11 the Springer thickened at a much greater rate and is ~850 ft thick in comparison to only ~480 ft in well 10. Additional Cunningham and Britt sands are found in well 11, but the Boatwright continues to be dominated by shale, which is characteristic of much of this part of the basin.

This thickening trend continues in wells 12 and 13, and the lower half of the Cunningham interval in both wells has characteristics indicative of a progradational sequence—i.e., a marine sandstone facies overlain by possible channel sands.

The entire Springer interval has thickened considerably in well 14, but the section is mostly shale with only scattered marine sands in the Cunningham and Britt intervals. This well was drilled to 18,200 ft but did not fully penetrate the Springer, so the Boatwright is not shown.

A large fault, which is part of the Mountain View fault system, occurs between wells 14 and 15. This fault has displaced the Springer upward to the south, perhaps as much as 17,000 ft. This is the area of overturned Springer in which complex faulting has rotated the Springer interval so that the oldest sands are highest in the section. Many wells have been completed in this area for highly variable amounts of gas. Some wells appear to have very small reservoirs in apparently limited fault-block compartments. Others have larger reservoirs in larger structures. Note that in well 15 the Springer appears to have a normal section down to about 5,800 ft. There, a fault is interpreted, and the section is overturned, with Mississippian limestone overlying the younger Springer sandstones.

Cross Section C–C′ (Plate 8)

Cross section C–C′ (Pl. 8, in envelope) is a continuation of section A–A′ but extends deeper into the Anadarko basin to the southeast across the Cement area, through the Carter–Knox area, and ends just north of the main fault separating the Anadarko basin from the Ardmore basin. Well-log attributes consist of only resistivity–conductivity and gamma-ray–SP traces. No porosity logs are included because of the length of the logs. The last well in section A–A′ is the first well in section C–C′. All of the wells penetrate or very nearly penetrate the entire Springer section, so correlation of sandstone intervals can be more accurately envisioned and the basal contact can be seen. Faulting in many of the areas caused large problems in accurately representing the Springer interval, so wells were selected whose logs indicated the least amount of structural disturbance.

The first well in cross section C–C′ has a Springer interval about 1,700 ft thick. It consists of discrete marine sandstone intervals and intervening thick shale intervals in the Cunningham, Britt, Spiers–Boatwright, and Goddard units.

All these intervals thicken to the south in wells 2 and 3, where the sandstone facies become more apparent on well logs. In wells 1–3, the Springer rests on the Chester limestone in a manner similar to that throughout most of the Anadarko basin.

In well 4, however, the Springer rests on the Caney shale, a stratigraphic equivalent of the Chester limestone. The Caney has a characteristic log signature consisting of high gamma-ray values combined with high resistivity values. From this well southward into the Ardmore basin, the Springer is underlain by the Caney shale.

The Cement fault is crossed between wells 4 and 5. Wells to the south are upthrown at least 1,500 ft in comparison to wells north of the fault. In well 5 the Springer section expands to more than 3,400 ft—about twice the thickness of well 1. Additionally, all sandstones in well 5 appear to exhibit offshore-marine log characteristics, which include encapsulation by marine shale above and below, and a coarsening-upward log profile within the sandstone. On the basis of well-log correlations in adjacent areas, the sandstone also is laterally encased in shale. About 8.5 mi southwest of well 5, the Springer thickens to more than 4,500 ft, and the Springer intervals thicken to include many more sandstone zones. Most apparent are the sandstones below what is called the Britt sand, which include the Spiers–Humphreys, Sims, Flattop, Goodwin, and lower Goddard sands, in descending order.

The terminology used in the well 6 log shows affinity with that used in the Ardmore basin. Because the entire Springer section is represented, the reader can compare sandstone zones to see if they correlate with sandstone intervals found in the adjacent Ardmore basin.

A few miles east of well 6, the Springer thickens again at well 7 to ~4,700 ft, making this the thickest Springer section on the cross section.

Well 8 shows considerable thinning relative to well 7, particularly in the lower half of the Springer section. The large-scale change in thickness and incorporation of additional sandstone sequences make correlations difficult in this part of the basin, but readers can compare the entire Springer section to verify these stratigraphic changes and judge for themselves the overall accuracy.

The Chickasha fault is crossed between wells 8 and 9. This fault is downthrown to the east. Displacement is variable but can be more than 700 ft, as shown in this section. A general "feel" of displacement can be envisioned by comparing depths of adjacent correlative units in the logs. As in the previously discussed wells, the depositional origin of the sandstones is interpreted to be offshore-marine bars because log shapes are decidedly coarsening upward.

Well 10 is important because the Boatwright–Sims interval has a different log appearance. Instead of the usual coarsening-upward profile, the sandstone beds appear to *fine upward* and have sharp basal contacts.

This pattern becomes even more apparent in well 11, where a very thick sandstone occurs in the Sims interval with a sharp basal contact and a fining-upward textural profile. This is characteristic of channel deposits and might be a mid-fan turbidite channel deposit as shown in the diagram of Figure 21, if correlated to the outcrop. Also shown in well 11 is a suspected repeated Britt–Aldridge section in the interval between about 9,600 and 10,000 ft.

These stratigraphic features are also shown in well 12, but with a thinner lower Springer section.

The cross section ends at well 13, which shows considerable thinning in the lower part of the Springer and a reduction in sandstones. This well is the first well in cross section D–D′.

Cross Section D–D′ (Plate 9)

Cross section D–D′ (Pl. 9, in envelope) is a continuation of cross section C–C′ to the southeast and consists of 13 wells and two measured surface sections. It extends across the Doyle–Reagan fault separating the Anadarko basin from the Ardmore basin and continues through producing oil fields in the Ardmore basin. The section ends on outcrop along the flanks of the Caddo anticline northwest of the city of Ardmore. Well-log attributes consist of only the resistivity–conductivity traces with gamma-ray–SP traces where available. No porosity logs are included because of the length of the logs. The last well in section C–C′ is the first well in section D–D′. All of the wells penetrate or very nearly penetrate the entire Springer section, so correlation of sandstone intervals can be related to nomenclature used for both basins. Faulting in many of the areas near selected wells caused significant problems in the accurate correlation of the Springer Group, so log intervals were used that indicated the least amount of structural disturbance.

Wells 1 and 2 are on either side of the major fault separating the Anadarko from the Ardmore basin. This fault is informally called the Doyle fault or the Doyle–Reagan fault system, because no formal name has yet been assigned. Displacement along this fault is at least several hundred feet, as represented on the cross section, but it may be thousands of feet elsewhere. Stratigraphic units and interval thicknesses on either side of the fault do not correlate, which points to a complex problem. In some cases, it is easier to correlate Springer units several miles apart on one side of the fault than to make the same correlation just a short distance from one side of the fault to the other. Certainly, strata in well 2 are upturned because of faulting, and erosion of the upper part of the Springer has occurred there, as it has in other parts of the Ardmore basin.

Wells 3 and 4 show the full Springer section from the overlying Primrose to the underlying Caney shale. The Springer is ~3,200 ft thick in these wells. The sandstone units of the Springer Formation in these wells are, from highest to lowest, the Markham, Aldridge, Humphreys, and Sims. Below the Sims are the Goddard sands, which are often referred to as the *Flattop* and the *Goodwin*. All Springer sandstone sequences in well 4 appear to be detached marine bars except the Goodwin, which has characteristics of a channel deposit overlying marine sands and shale.

In well 5 the upper Springer Markham sand is missing by truncation at the Springer unconformity, whereas the remaining intervals are all present. Note that all sandstone sequences have a coarsening-upward log profile that is indicative of marine bars.

Well 6 shows all of the Springer sandstone units having distinct coarsening-upward log signatures and intervening shale intervals that are indicative of detached marine bars.

In well 7 the Markham sandstone is eroded, and both the Aldridge and Humphreys sandstones have shaled out, making correlations more difficult. The persistent occurrence of the Sims sandstone is usually a good marker to look for in well logs to help in correlations if other units are absent. This is particularly helpful when the entire Springer section is present.

Wells 8–10 show variations in the Springer section, and all the sandstones have marine log profiles. The expanded section in well 10 reflects deposition deeper in the center of the Ardmore basin.

Well 11 is difficult to correlate and is interpreted for both the upper and lower parts of the Springer to be absent. The typical double sand zone of the Humphreys interval and the single sand zone of the Sims in nearby wells are helpful in correlating this log. The marker bed in the lower Goddard section in wells 2–10 may also correlate with a resistivity spike at ~13,500 ft in well 1.

The well 12 log seems to have an expanded Springer section, probably owing to steeply dipping beds, inasmuch as the well is very near the outcrop, where the Springer beds dip steeply. Only two main sandstone zones occur in well 12, the Humphreys and the underlying Sims. They seem to correlate with the Overbrook and Rod Club Sandstones, respectively, on the basis of stratigraphic relationships seen at measured sections 13 and 14 (Meek, 1983).

Well 15 is east of the Caddo anticline, and the main sandstone zones seem to correlate with those in well 12, which is northwest of the anticline. At well 15 the upper Springer sandstone interval is relatively thick, and it is difficult to determine on the well log what is represented by the outcropping Lake Ardmore Member. Generally speaking, the Lake Ardmore Member seems to be correlative with the Aldridge sandstone in the subsurface. The underlying sandstone interval at the surface is the Overbrook Member, which seems to be correlative with the Humphreys interval in the subsurface. However, the log shape of the Humphreys in well 15 is distinctly different from any Overbrook sandstone examined at the surface, and instead is similar to that described for the Boatwright–Sims zone in cross section C–C′ (Pl. 8). This same log character seems to indicate a lithology similar to that of the Rod Club on outcrop, so it is possible that the correlations on this cross section are wrong. However, the underlying sandstone interpreted here to be the Sims appears at the proper stratigraphic interval within the Springer Group and seems to be correlative with the Sims–Rod Club zone identified in well 12.

STRUCTURE

The Springer play occurs mostly in the Anadarko basin of western Oklahoma but also extends into the smaller Ardmore basin to the southeast. Although emphasis is placed on the Anadarko basin in this study, it is necessary to address the major structural features that define both basins. Springer hydrocarbon accumulations are largely controlled by structural features in the southern part of the Anadarko basin and throughout the Ardmore basin. In many of these structurally complex areas, locations for exploratory wells are determined by detailed structure mapping using three-dimensional (3-D) seismic techniques. The base map used in this report for regional mapping, including the regional structure map (Pl. 5, in envelope), is modified from a geologic-province map of Oklahoma (Northcutt and Campbell, 1995).

The regional structure map (Pl. 5) was constructed from several data sources, including unpublished proprietary maps, thesis data, and formation tops retrieved from the Natural Resources and Information System (NRIS), a database developed at the University of Oklahoma. These data were supplemented locally by incorporating subsurface picks from numerous well logs used in this study. A contour interval of 1,000 ft was used in most areas in the Anadarko basin area to show the general configuration of the basin as well as the major structural elements in western Oklahoma. A 500-ft contour interval was used in the Anadarko shelf areas because the dip is considerably less. In the southernmost part of the Anadarko basin, and in the Ardmore basin, a 2,000-ft contour interval was used because of steep dips and faulting. The structure map was hand contoured and checked with well data where the three field studies (star symbols) and four cross sections were developed. Also shown on this map are locations of wells (solid squares) with Springer core descriptions (Appendix 4). The lines of regional cross sections A–A′, B–B′, C–C′, and D–D′ (Pls. 6–9, in envelope) are shown on the regional structure and sand maps.

As can be seen on the Springer structure map (Pl. 5), the regional dip throughout most of the Anadarko basin is only a few degrees to the south–southwest. In the Anadarko shelf areas of northwestern Oklahoma and the Panhandle, the regional dip is <1° to the south–southeast.

Deeper in the basin, the regional dip increases to 2–5°. Most of the shallow basin and shelf areas are devoid of structures of Springer age. Faults and folds of Springer and later (Pennsylvanian) age are pervasive in the extreme southern and southeastern parts of the Anadarko basin and throughout the Ardmore basin. This area has been enlarged as a separate map inset to Plate 5. It seems logical to assume that the major period of faulting occurred shortly after Springer deposition as units in the formation are eroded at the highest stratigraphic position within the Springer.

Several large, elongated folds occur just north of the Mountain View fault, which is part of the Wichita frontal fault zone in Washita and northern Beckham Counties. The most prominent of these folds are the Elk City and Cordell anticlines.

The Wichita frontal fault zone consists of a complex system of east–west-trending faults that define the extent of this study area in the southwestern part of the Anadarko basin. The most prominent of the fault traces is named the Mountain View fault. The Wichita uplift just south of the frontal fault zone is a mountain range where pre-Pennsylvanian strata are missing, so rocks of the Springer Group do not crop out along the basin edges. Complexly overturned Springer strata in the subsurface are being exploited for oil and gas just north of this fault complex, as shown.

Farther to the southeast, the complex Cement–Chickasha and Chitwood–Carter–Knox structures in southeastern Caddo and southern Grady Counties are much more complicated than shown, but in a general way the map shows major faults where large gas fields have been developed. Also shown is the Doyle fault complex, which is a western extension of the Reagan fault system. The Doyle fault separates the Anadarko basin to the north from the Ardmore basin to the south. As mentioned previously, sandstone units do not correlate across the Doyle fault, though they trend basically north to south. Therefore, some degree of lateral (strike-slip) movement appears to have occurred. In the Ardmore basin, several prominent faults are shown that control much of the production in the various fields in the Sho-Vel-Tum producing complex.

PRESSURE GRADIENTS AND GAS COMPRESSIBILITY

Gas reserves in the Springer Group are highly influenced by variable pressure conditions and also by reservoir characteristics of the specific Springer units, i.e., sandstone versus carbonate for the three informal members of this group—the Cunningham, Britt, and Boatwright—in the Anadarko basin. This discussion is not intended to compete with any reservoir-engineering text; rather, it is included to give the reader a general understanding of the subject.

In the shallower parts of the Anadarko basin, the initial "normal" pressure gradient is ~0.465 psi/ft, as plotted in Figure 24. Owing to partial pressure depletion, this gradient is currently even smaller for the Britt and Boatwright carbonate reservoirs in shallow parts of the Anadarko shelf, e.g., ~0.35 psi/ft (or less) in the Cedardale area (see Part V of this volume).

Deeper in the basin, however, the pressure gradient for the Springer–lower Morrow sandstones increases greatly to about 1.0 psi/ft, which is very high in comparison to formation pressures in reservoirs above and below the Morrow and Springer (Fig. 25). In areas where the Springer has a very high pressure gradient, it is considered to be *overpressured*, and gas reserves are greatly enhanced per unit volume of reservoir because of the com-

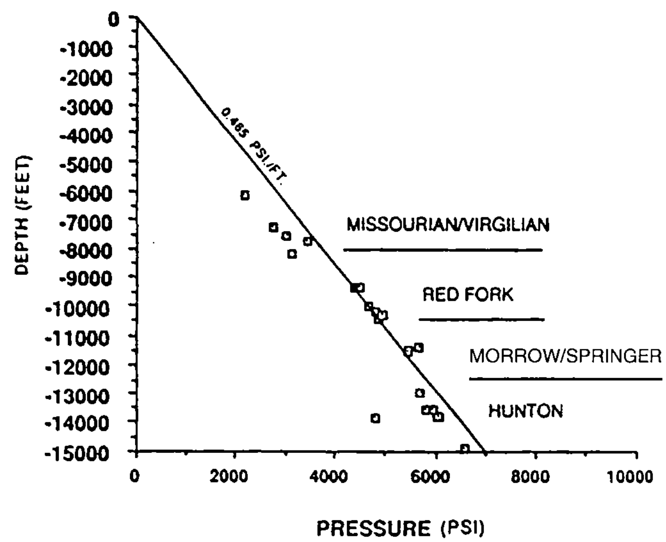

Figure 24. Pressure–depth profile from T. 17 N., R. 18 W., and T. 18 N., R. 18 W., of the shallow Anadarko basin. Note that all gradients plot along the projected 0.465 psi/ft "normal" gradient slope. From Al-Shaieb and others (1992).

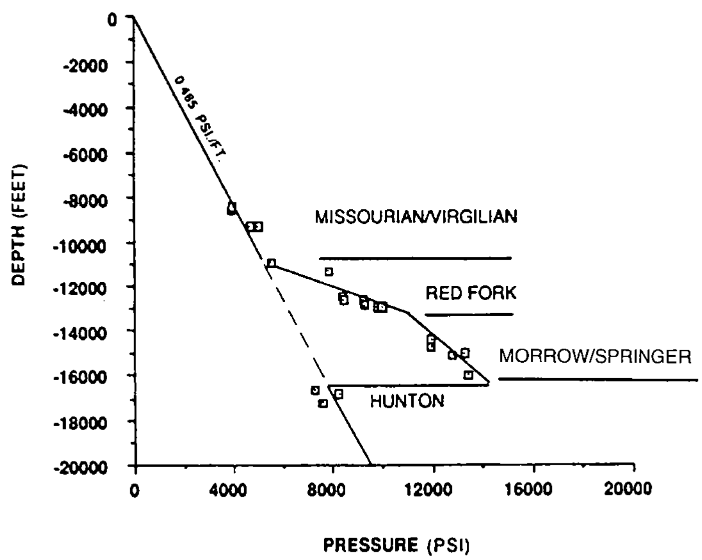

Figure 25. Pressure–depth profile in the deep Anadarko basin from Roger Mills County, Oklahoma. Deviation of curve to right (overpressuring) identifies the mega-compartment complex in the Red Fork and Morrow–Springer intervals. Hunton Group gradients cluster around the "normal" 0.465 psi/ft gradient. From Al-Shaieb and others (1992).

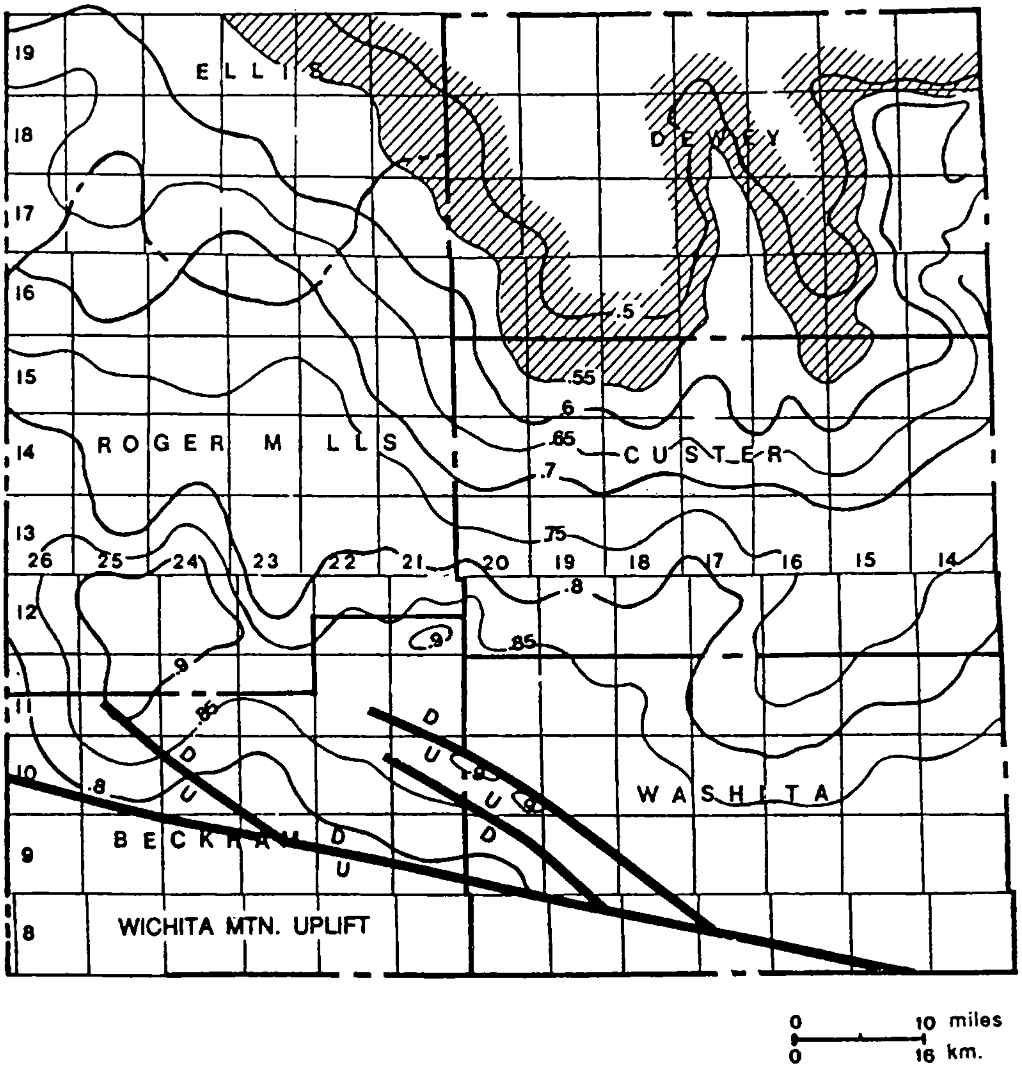

Figure 26. Pressure-gradient (psi/ft) contour map of the Morrow and Springer Group sandstones in the Anadarko basin. Transition zone from normal-pressure regime to overpressuring is shaded. From Al-Shaieb and others (1992).

pressed nature of the gas. Overpressuring is generally recognized where the pressure gradient exceeds 0.6–0.7 psi/ft. This elevated pressure must also be considered when drilling into the Springer in the deep basin, where "mudding up" to higher mud weights is required to prevent blowouts. A map showing pressure gradients in the Anadarko basin is given in Figure 26. Overpressuring in the Springer occurs only in the deep Anadarko basin and is a product of depth and compartmentalization from shallower reservoirs.

In gas-reserve calculations, the volume of gas produced is affected not only by reservoir characteristics (porosity, permeability, thickness, and lateral extent) but also by the amount of gas contained per unit volume of reservoir at depth (herein referred to as *gas formation volume factor*, or B_g). So a unit volume of reservoir at depth may contain more gas owing to compression than the equivalent reservoir volume at the surface. A large initial gas formation volume factor (B_g) is primarily responsible for the extremely large cumulative gas volumes reported for some deep Springer wells. This factor is multiplied directly by the gas-filled pore volume so that the volume of gas available at the surface is hundreds of times greater than in the reservoir (see gas-in-place formulas used in the two sandstone reservoir/engineering data tables for the Lookeba and Sickles North field studies: Tables 6 and 8, respectively).

In this publication, B_g is represented in standard cubic feet per reservoir cubic feet. All other factors being equal, B_g is inversely proportional to the compressibility factor, Z. Moreover, Z is affected by the specific gravity of gas (gas composition), reservoir temperature, and reservoir pressure. Therefore, all calculations hinge on the Z factor, which is the hardest to estimate and which changes during the life of a well. To some degree, the Z factor accounts for volumetric calculations of gas in place where the reservoir produces relatively small amounts of condensate.

At moderate depths in the Anadarko basin, Springer gas has a relatively high density or specific gravity (>0.65

g/cm^3), owing to the amount of heavier hydrocarbons in the gas. In these cases the gas is called *wet*, and the gas-filled reservoir tends to produce significant amounts of liquids (condensate) during pressure drawdown.

In the deeper part of the Anadarko basin, the gravity of Springer gas is less dense (<0.6 g/cm^3), and in these situations (e.g., Lookeba and Sickles North field descriptions, Parts II and III of this publication) the gas is called *dry*, and Springer reservoirs produce little or no condensate. In the two reservoir studies, the gas formation volume factor (B_g) and the compressibility factor (Z) range from ~392 and 1.44 in Sickles North field (depth, ~14,000 ft), to 376 and 1.42 in Lookeba field (depth, ~13,800 ft). The Springer carbonate reservoir in the Cedardale area has a much lower initial Z factor of about 150–200 at a depth of 7,30–7,800 ft.

SUMMARY OF REGIONAL SPRINGER MAPPING

The regional distribution of the Springer sandstones—Cunningham, Britt, and Boatwright—and their associated carbonate facies are shown on Plates 1–3 (in envelope). Also shown on these three plates are the interpretation of depositional facies, distribution of carbonate facies, major geologic provinces in western Oklahoma, the subcrop limit of Springer sandstone, field-study locations, core locations described in Appendix 4, and the lines of regional cross sections A–A′, B–B′, C–C′, and D–D′ (Pls. 6–9).

Plate 4 (in envelope) is a production-code map showing the allocation of Springer production based on work by Petroleum Information/Dwights Energydata, LLC (2000). On this map, Springer production is color coded in five different categories: Cunningham sandstone, Britt sandstone, Britt carbonate, Boatwright sandstone, and Boatwright carbonate. Also shown on the production-code map is Mississippian production along the northeast subcrop edge of the Springer.

Plate 5 (in envelope) is a regional map depicting the structure at the top of the Springer Group. Data used to construct this map were derived primarily from NRIS and supplemented locally by published and proprietary structure maps and by the field study maps of this publication.

Plates 6–9 (in envelope) are regional cross sections (A–A′, B–B′, C–C′, and D–D′) that illustrate the log character, facies relationships, and stratigraphy of the Springer Group. Correlations and log selection in the first three cross sections were based largely on work by Petroleum Information/Dwights Energydata, LLC (2000).

Plate 10 (in envelope) is a map showing oil and gas fields with production from the Springer Group. Included with Plate 10 is an alphabetical listing of field names and their geographic locations. Field names were determined by the Oklahoma Stratigraphic Nomenclature Committee of the Mid-Continent Oil and Gas Association. In many cases, Springer production is attributed to a general field boundary that has no geological relevance to sandstone in the Springer Group. In other cases, Springer production is found outside the formal field boundaries. These vagaries occur because the effort to formally define and extend field boundaries lags behind the extension of producing areas.

The sources of information used in completing this study included information from the private domain, theses, consultants, and personal investigations by the author. Approximately 2,000 well logs were used to construct the subsurface sandstone-trend maps of Plates 1–3. Outlines of published studies that contain either subsurface or surface mapping relevant to the Springer are shown on Plate 11 (in envelope).

Throughout this publication, references are made to various sand-size grades in the description of certain rock units; they are listed in Appendix 1. Similarly, various abbreviations and terms that are used in this publication are defined in Appendixes 2 and 3, respectively. Three cores are provided for examination by workshop attendees. Descriptions and facies interpretations of those cores, along with well logs and selected visual images, are given in Appendix 4. Production and reservoir data elements, including pressure, thickness, porosity, drainage area, and reserve estimations for each Springer reservoir, are summarized in an alphabetical listing of Springer fields in Appendix 5.

PART II

Lookeba Field

Lower Cunningham and Boatwright sandstone gas reservoirs in western part of T. 11 N., R. 11 W., and eastern part of T. 11 N., R. 12 W., northern Caddo County, Oklahoma

Richard D. Andrews
Oklahoma Geological Survey

INTRODUCTION

Lookeba field is in northern Caddo County, west-central Oklahoma (Fig. 27). The 42-section study area lies in the east-central part of the Anadarko basin about 16 mi east–southeast of Weatherford and about 8 mi south of I-40 (Pl. 1, in envelope). The study area also encompasses the southernmost part of Sickles North field, as shown on the generalized location map (Fig. 27). This was done in order to include all wells producing from the same Springer sandstone zones in the same map area, regardless of legal field boundaries. Producing zones within the study area include the younger Pennsylvanian Tonkawa, Marchand, Skinner, Red Fork, Atoka, and Morrow sandstones in addition to the underlying Upper Mississippian Chester limestone. However, this project investigates only the Springer Cunningham and Boatwright reservoirs, which produce gas from detached offshore-marine bars. Production limits are generally well defined on the basis of log interpretations.

Dry holes or nonproducing Springer zones are invariably tight or wet—a condition identified from porosity

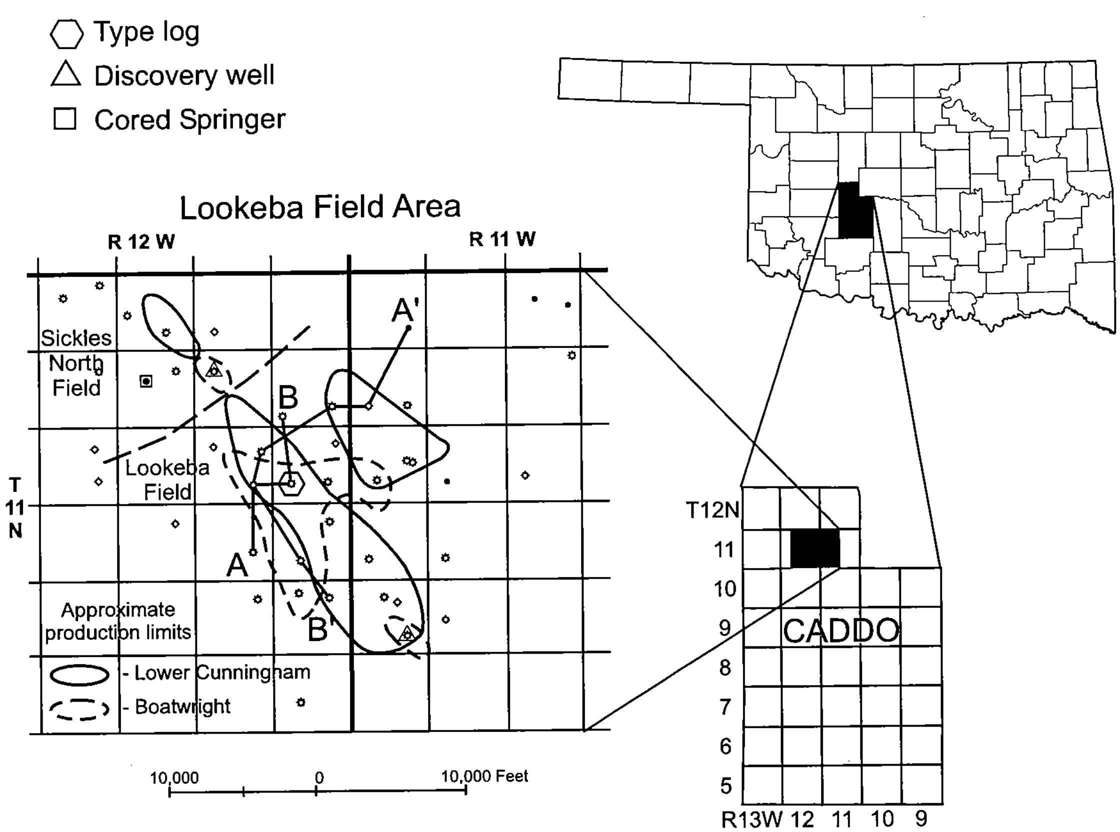

Figure 27. Generalized location map of Lookeba field and vicinity, northern Caddo County, Oklahoma. Lines of cross sections A–A′ (Fig. 30) and B–B′ (Fig. 31) are shown.

and resistivity logs. Some wells that are abandoned or were not completed in certain Springer zones appear to have bypassed gas potential. These wells are identified later in the field discussion. As a general rule, the Springer sandstones in Lookeba field occur as long, narrow sand bodies that trend northwest–southeast and are separated from each other by narrower zones of marine shale. All sandstones having at least 6% porosity are capable of gas production, and the larger bars tend to have water-wet downdip portions. Individual sandstone bars have pressure communication throughout most of their extent. Separate bars may have different reservoir pressures.

Springer Cunningham sediments in the study area probably were derived from incised-channel complexes extending southward from the north and northeast and then were reworked in a marine-shelf environment. The origins of Boatwright sandstones in the study area are not so clear. A southern source is supported by the preponderance of sandstone in the far southeast part of the Anadarko basin, and also because there are no recognized sediment supply corridors (channels) coming from the north. Gross-sandstone thicknesses are as much as 88 ft for the Cunningham and 31 ft for the Boatwright. However, because of authigenic clays and silica cementation, the net reservoir sandstone is usually much thinner. These values can be compared on the gross- and net-sandstone isopach maps prepared for each reservoir. Both the Cunningham and Boatwright sandstones exhibit similar definitive coarsening-upward well-log profiles. This characteristic is best illustrated on gamma-ray and resistivity logs. These similar-shaped log patterns are indicative of a relatively simple depositional setting, which is interpreted to be a shallow-marine shelf. Because of this, the detached offshore bars are easily correlated. This is unlike most of the Morrow sandstone units, which have highly variable well-log patterns because of their highly variable depositional environments. Figure 28 is a map identifying all wells in the study area that penetrated the Springer zones. Additional information in Figure 28 includes operators, well numbers, lease names, and completion dates.

Springer exploration began in this area in 1972 with the drilling of the No. 1 Senn well by Woods Petroleum in sec. 16, T. 11 N., R. 11 W., which is just east of the field. This well tested dry and penetrated little or no Springer sandstone. It is not clear if the Woods well identified the Springer as the primary objective, as so many other reservoirs were known in the general area at the time (including the Morrow). However, the Woods well certainly identified an effective updip seal in the Springer if sandstone occurred farther downdip to the southwest. A year later, in 1973, Apexco drilled the No. 1 Buell well about 4 mi to the west in sec. 11, T. 11 N., R. 12 W., and completed it in the Boatwright. This well is credited in this report as the Lookeba Springer discovery well. It was offset by two dry holes more than a year later in early 1975 that had little Springer sand, and again by another dry hole in late 1976. At this time, the Buell discovery well had offsets to the north, south, and west. Then in 1978, the field opener in the Springer Cunningham was completed about 4 mi to the southeast by Getty Oil in sec. 30, T. 11 N., R. 11 W., with their Lindley well. Nearly all of the remaining wells completed in the Springer were drilled during the 1980s.

An interesting development during the early history of this field was the drilling of the Woods No. 1 Car well in sec. 7, T. 11 N., R. 11 W. This well encountered a thick Cunningham sandstone that appeared to have gas potential. The Cunningham was perforated and apparently tested, but the well was abandoned in 1974. The well lies in the center of a small area productive from the Cunningham. This author believes there is still gas potential in the Car well.

The Apexco No. 1 Buell was the field opener for the Boatwright sandstone reservoir. It had a calculated open flow (COF) of 5.2 MMCFGPD from 6 ft of net pay (>6% porosity, or ϕ). Through February 2000 it produced more than 2.9 BCFG, about twice the volume of the next best Boatwright producer. The initial flowing tubing pressure (IFTP) is not known, but the initial bottom-hole pressure (IBHP) was the highest recorded pressure in the field (10,741 psi).

By comparison, the Getty Oil Lindley well, the field opener for the Cunningham sandstone, had initial production (IP) of 1,516 thousand cubic feet of gas per day (MCFGPD). The initial flowing pressure (IFP) of 3,430 psi is near the maximum recorded in the field. The production was commingled with that from a thin Boatwright sandstone. This well had 16 ft of net Cunningham sandstone (>6% ϕ) and 64 ft of gross sand. The lower part of the Cunningham sandstone interval is interpreted to extend into the water leg of the sand body downdip to the southeast. The well produced only 513 MMCFG and 195 barrels of condensate (BC) through February 2000.

The best producing wells in Lookeba field are the Cunningham wells that have thick net sandstones and were completed early in the history of the field. Cumulative production from individual wells systematically dropped off from a high of more than 10.4 BCFG (1980) to 1.8 BCFG (1987). Almost all edge wells were low-volume producers. Pressure depletion seems to be a big threat to additional infill wells particularly in the Cunningham. Porosity development in the Boatwright seems to be more variable, thereby enhancing compartmentalization.

As of February 2000, a total of 15 producing Springer wells were studied in this field area—11 productive from the Cunningham, one productive from the Britt, and six productive from the Boatwright. Four wells have multiple-zone completions in the Springer, and production is commingled. This makes it difficult to determine individual zone performance. Principal operators are or have been Apache (Apexco), Cotton Petroleum, and Sanguine. Produced gas has a relatively low specific gravity (about 0.57–0.58) and, as such, little condensate is produced. That which is recovered comes from wells in the far southeastern, structurally lowest part of the field. No significant amount of formation water is produced from any of the Springer reservoirs. Several wells found additional pay above the Springer within the study area, most commonly in the Marchand, which produces oil. Gas has been produced from scattered Cherokee and Morrow reservoirs, which are not currently a significant resource in the immediate area. The only production deeper than

Springer (Chester) is from the King Resources well in sec. 36, T. 11 N., R. 12 W.

Cumulative gas production to date from the Springer reservoirs evaluated in this study is ~30.6 BCFG (~26 BCFG from the Cunningham, and ~4.6 BCFG from the Boatwright). This does not include ~2.8 BCFG from a relatively small Cunningham reservoir less than 1 mi northeast of the main Lookeba field area.

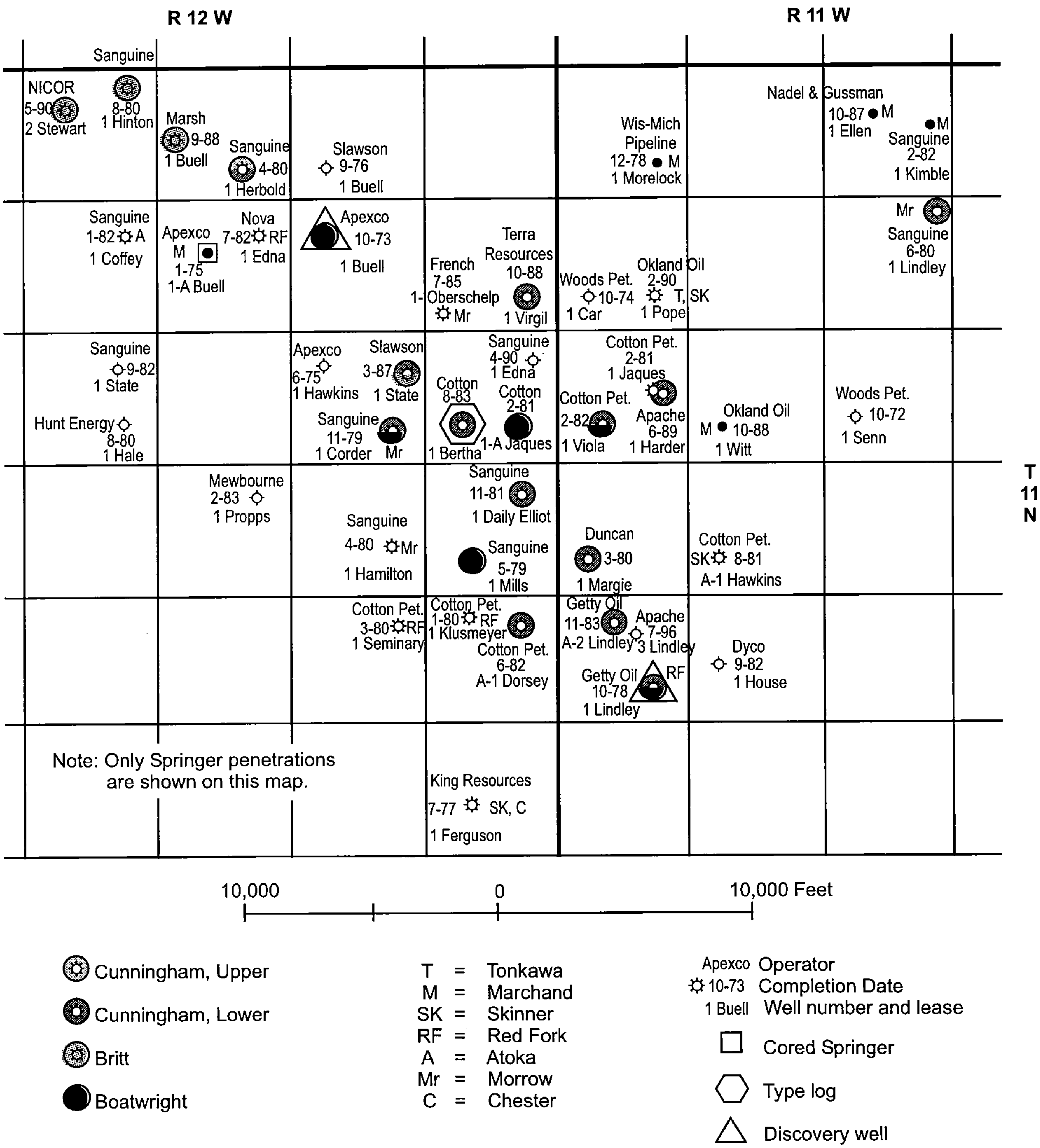

Figure 28. Well-information map, showing operators, well numbers, lease names, producing reservoirs, and completion dates in Lookeba field, Caddo County, Oklahoma.

STRATIGRAPHY

A typical log from Lookeba field, and the stratigraphic nomenclature, are shown in Figure 29. In this well, the Springer formation is about 330 ft thick and is informally divided into three sandstone units as accepted by most industry personnel: Cunningham, Britt, and Boatwright, in descending order. Additional informal subsurface names have been applied locally, and these are shown on regional cross sections B–B′ and C–C′ (Pls. 7, 8, in envelope). Each of the named Springer sandstone intervals contains more than one major sandstone zone, the upper and lower Cunningham being the most conspicuous examples. Beneath the Springer formation is a thick marine-shale unit that is correlative with the Goddard Formation in the Ardmore basin. The Goddard shale within the study area is about 200–250 ft thick. It overlies the Chester limestone, as noted on some of the well logs in the field cross sections.

As a general rule, the division between the three Springer sandstone intervals is quite simple, as noted on the type log (Fig. 29). A thin shale zone having a "hot" gamma-ray response typically occurs between the Cunningham and underlying Britt at 13,874 ft. Beneath the Britt, the top of the Boatwright interval in this field is picked at the top of the uppermost sandstone beneath the Britt shale. In many wells the gamma-ray response in the shale directly above the Boatwright sandstone is slightly "hot," as seen in the type log at about 13,950–13,954 ft. The base of the Boatwright interval is an arbitrary pick below the lowermost Boatwright sandstone where the strata are consistently shale. This pick has very low resistivity and a high density–neutron response. Every reservoir within the Springer formation has a "clean" gamma-ray response, a clearly identifiable SP response, a cross-plot porosity of at least 6%, and a resistivity of at least 50 ohm-m. These criteria are most evident in the lower Cunningham sandstone and are somewhat less apparent in the Boatwright sandstone.

The top of the Springer formation in Lookeba field is much more difficult to identify on well logs. It is usually recognized by a shale interval directly beneath the lower Morrow Primrose sandstone that has very low resistivity (high conductivity, as shown on the regional cross sections). This situation is somewhat complicated where the lower Morrow Primrose sandstone shales out, creating a situation in which the Springer–Morrow contact is a shale-on-shale contact. This is shown in wells 2 and 3 on cross section A–A′ (Fig. 30, in envelope). For many wells, the neutron-porosity response is highly sensitive to the types of clays in the Springer, causing a sharp inflection to the left. This is also seen on many of the well logs in the field cross sections. This inflection may be used along with the conductivity log in determining the Springer top.

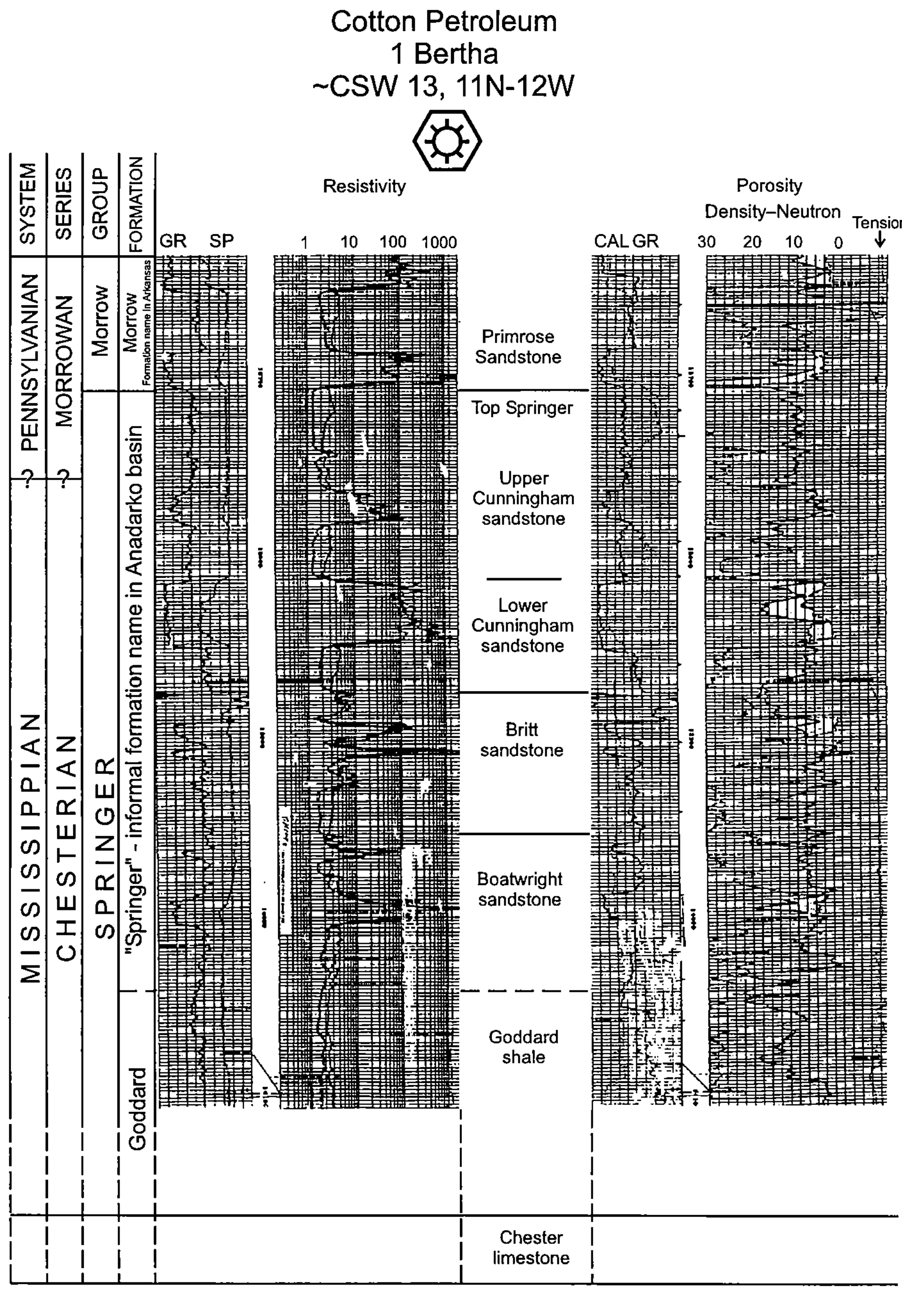

Figure 29. Type log for Lookeba field, showing formal and informal subsurface nomenclature of the Springer Group as used in the Anadarko basin of western Oklahoma. *GR* = gamma ray; *SP* = spontaneous potential; *CAL* = caliper.

Cunningham Sandstone

The Cunningham is the uppermost sandstone within the Springer Group. It occurs in two distinct sandstone zones, the upper and lower Cunningham. Together with shale, the Cunningham interval accounts for almost half the Springer formation in this study area. In most wells the upper Cunningham is very shaly and is not productive. For this reason, it is not mapped separately in this study. The lower Cunningham, however, is widespread and has the best consistent reservoir properties of any Springer sandstone in the field. The gross sandstone thickness is commonly 30–50 ft, and net thickness, using a 6% porosity cutoff, is commonly 20–30 ft. Cross-plot porosity is typically about 7–8% (unadjusted for limestone matrix), and it may be as high as 12%. In the absence of core data, permeability is estimated to be generally between 0.1 and 1.0 md. Porosity and permeability reductions owing to authigenic silica(?) cementation are the largest detriment to the productive nature of this reservoir. Conversely, many areas having porous sandstone have high water saturation and are not productive. This is generally the case for parts of Cunningham bars that are mapped to the east and west of Lookeba field. In productive zones, the Cunningham sandstone has a significant SP deflection on well logs.

On gamma-ray logs, the sandstone characteristically has either a blocky or a distinct coarsening-upward textural profile. The latter is due to interbedded shale layers lower in the section. Well logs showing a blocky log character have relatively sharp upper and lower contacts with shale. No logs show the distinctive fining-upward signature that is indicative of a channel deposit. Mapped patterns of the lower Cunningham sandstone show no divergence of trends between wells having blocky log shapes and those having distinctive coarsening-upward log shapes. Therefore, wells with both kinds of log characteristics are mapped together and indicate elongate northwest–southeast-trending sand bodies. The thick, blocky log patterns occur in the middle of the sandstone isopach trend, and the coarsening-upward log patterns occur along the periphery of sand bodies. The depositional facies vary from bar fringe to central bar. There appear to be no incised channels within the lower Cunningham zone in Lookeba field.

Britt Sandstone

The Britt sandstone is thin and tight and is productive in only one well, so it is not mapped. The character of this sandstone is shown on both field cross sections (Figs. 30, 31, in envelope). On trend to the northwest, the Britt sandstone is the principal reservoir in Sickles North field and is described and mapped in Part III of this volume.

Boatwright Sandstone

The Boatwright is the lowermost sandstone in the Springer formation. It also consists of upper and lower zones, although in this study they are separated by only about 15 ft and are mapped as one unit. The upper Boatwright sand is generally thin and tight and rarely accounts for net sandstone having porosity >6%; therefore, it is usually dry. The lower Boatwright sandstone zone is the principal reservoir in this interval, but the distribution of productive sandstone is greatly limited in comparison to the Cunningham.

Boatwright sandstone occurs primarily in T. 11 N., R. 12 W., in a single bar trend. Gross sandstone within this northwest–southeast trend is usually 10–20 ft thick, although locally it attains a maximum thickness of just over 30 ft. Net sandstone is greatly reduced, because the sandstone tends to shale out. Net sandstone is generally only about 4–10 ft thick, with a maximum of about 15 ft. Most wells having more than a few feet of net Boatwright sandstone are productive. An exception is the well in the SW¼ sec. 13, T. 11 N., R. 12 W. (see type log, Fig. 29). In this well, the Boatwright seems to have gas potential on the basis of formation evaluation.

Much of the Boatwright sandstone is shaly and tight. Locally, however, reservoir properties are similar to, or even better than, those of the Cunningham. In the few producing wells, porosity ranges from 5% to 12% and averages >8% (cross-plot porosity unadjusted for limestone matrix). Permeability in productive wells is probably similar to that in the Cunningham. The Boatwright sandstone has a moderate to weak SP-log deflection in productive zones.

Sandstones in the Boatwright interval invariably have a distinct coarsening-upward log profile characterized primarily by the gamma-ray log. Where both the upper and lower sandstone zones are present, both have this profile.

CROSS SECTIONS

The stratigraphy of the Springer formation is best shown by two detailed stratigraphic cross sections constructed through Lookeba field. Section A–A′ is a dip section (Fig. 30, in envelope), and section B–B′ is a strike section (Fig. 31, in envelope). Both cross sections use a common datum: the top of the "hot" shale, just beneath the Cunningham sandstone interval. Cross sections were laid out to show producing limits of principal reservoirs and reservoir facies rather than just the high-volume producers.

Cross Section A–A′ (Figure 30)

This section illustrates the producing characteristics and facies relationships in the lower Cunningham, and in the intervening areas that separate the three principal sand trends in the study area. The cross section is oriented in a southwest–northeast direction and is at right angles to the bar trends. Wells 1, 3, and 5 penetrated the central part of each respective bar trend, and wells 2 and 4 were drilled between the main bar trends, in the bar margin or interbar facies. Additionally, three wells in this cross section show the entire thickness of the Springer Group, including the Chester–Springer contact and the Goddard shale interval. Note that the Cunningham and Britt intervals thicken to the southwest in a basinward direction.

In well 1 the lower Cunningham, Britt, and Boatwright sandstones are all nonproductive because of low porosity and/or high water saturation. All three sands have some net porosity and were perforated and tested; the test results are not known. A bridge plug was installed above the Cunningham, and the well was completed in the Primrose. Note that the resistivity and SP deflection in porous zones in the Primrose is higher than that in the Springer.

Less than 1 mi north, at well 2, the lower Cunningham sandstone thins considerably and has a distinctive coarsening-upward textural profile. Although the Cunningham was perforated, it contains no net reservoir sand (>6% ϕ) and probably contributes very little to the cumulative production of the well. The underlying Boatwright sandstone is perforated in both the upper and lower zones and has better reservoir properties. The upper zone actually contains a thin zone with ~8% ϕ. The sandstones in the Britt zone are tight.

Well 3, about 0.4 mi farther north, is productive primarily from the lower Cunningham. A thin interval in the underlying Britt was also perforated, but the low porosity precludes this zone from having significant reserves. The lower Cunningham in this well has reservoir characteristics typical of the central bar facies—i.e., a relatively thick, clean sandstone having a blocky gamma-ray-log signature. Porosity varies from about 8% to 12%, and the deep resistivity is about 60–90 ohm-m in porous zones. This well was completed in 1987, 5 to 7 years after the initial wells were completed in the study area. Formation pressure in this well was found to be less than half the virgin reservoir in that bar, yet the well has made ~1.9 BCFG.

In well 4, less than 1 mi to the northeast of well 3, there is very little sandstone in any of the three Springer zones. The lower Cunningham thins appreciably, and the log character is indicative of a bar-margin facies. That zone was perforated but produced very little gas. Several hundred feet to the west of well 4, the lower Cunningham sand is probably absent, giving rise to an interbar facies as schematically drawn in the cross section. In well 4, the Britt interval is almost barren of sandstone, and the Boatwright interval contains only a thin, shaly remnant of the lower zone. About 250 ft of Goddard shale lies beneath the Boatwright sandstone and in turn is underlain by the Chester limestone.

About half a mile to the east at well 5, the lower Cunningham sandstone again thickens in the center of a third sand bar. The Cunningham in this well is interesting, because it was perforated, tested, and then abandoned very early in the development of Lookeba field. By log interpretation, however, this well should have produced gas. Reservoir characteristics are similar to those of many of the high-volume producers in the area. Porosity is between 10% and 13%, deep resistivity is as much as 55 ohm-m, and calculated water saturations are between 35% and 40% in the upper part of the sandstone, well within the accepted range of production. Productive wells have been completed to the west and south of this same sand body.

Well 6 is about 1.1 mi to the northeast of well 5 and is the last well in this cross section. Most notable in this well is the thinning of the Cunningham, Britt, and Boatwright intervals and the paucity of sandstone in any of them. This well demonstrates the discontinuous nature of the Springer sandstones to the northeast.

Cross Section B–B′ (Figure 31)

This cross section is oriented approximately north–south and illustrates the reservoir characteristics of the Boatwright sandstones.

Well 1 is at the northern edge of the field, where the Boatwright sandstone is ~9 ft thick with only a few feet of porosity. Overlying this, the Britt interval is shaled out, although the "hot" gamma-ray marker clearly identifies the contact with the overlying Cunningham interval. The lower Cunningham is distinct, with a 28-ft thickness and a deep resistivity of ~100 ohm-m, yet it is tight and nonproductive. A bridge plug was installed above the lower Cunningham after production testing, and the well was completed in a Morrow zone uphole (not shown).

Less than 1 mi south of well 1, well 2 penetrated the center of the productive Cunningham bar complex, as indicated by the blocky log signature. The Cunningham was completed flowing 1.32 MMCFGPD from a 37-ft sand (22 ft net). Cumulative production of nearly 5 BCFG is remarkable, because the formation pressure was partially depleted by an offset well drilled 2 years earlier in sec. 24. The relatively high porosity (10–12%), high resistivity (mostly >100 ohm-m), and large SP deflection are all indicators of an exceptional well. The Britt sandstone is tight and has no gas potential. The underlying Boatwright sandstone does have gas potential, as indicated by the high porosity and resistivity, but the operators probably opted for a single-zone completion in the more favorable Cunningham.

Well 3 is about half a mile west of well 2 and crosses section A–A′ (Fig. 30). Well 3 penetrated the western edge of production from both the Boatwright and Cunningham sandstones. At this location, the Boatwright produces from two zones having a combined gross thickness of ~26 ft and a net thickness of ~7 ft. Most of the porosity is just over 6%, so the reservoir by itself is marginal. This is also indicated by the negligible SP deflection in either perforated zone. As mentioned in the discussion of section A–A′, the lower Cunningham is tight and incapable of significant production. Additionally, the thinness of sandstone and the pronounced coarsening-upward textural profile indicate that this Cunningham interval is probably a bar-margin facies between the major bar complexes identified on the gross-sandstone isopach map of Figure 32. The relatively high resistivity in the Cunningham sandstone (~80 ohm-m) is probably due more to cementation than to hydrocarbon concentration. This is a normal situation in the case of tight reservoirs. Cumulative production from this well is 660 MMCFG, which is mostly attributable to the Boatwright reservoir, even though the Cunningham was perforated and its production commingled.

About 1.1 mi to the southeast, at well 4, the Boatwright sandstone occurs in two zones that are both perforated. Both zones have relatively good porosity of about 7–11%. They are reflected by a small SP deflection on the log, but cumulative production from these Boatwright zones is very low, at only 21 MMCFG. The deep resistivity in both zones is also relatively low (about 35–50 ohm-m), which translates to a water saturation (S_w) generally >49%, which accounts for the low production. The Britt interval is very shaly and contains no clean sandstone, as indicated by the suppressed resistivity log and the high apparent porosity on the neutron log. The overlying lower Cunningham sandstone is ~28 ft thick but is mostly tight despite the moderate SP deflection.

The last well in cross section B–B′, well 5, shows little sandstone in either the Boatwright or the Britt interval. The overlying lower Cunningham, however, is productive from ~8 ft of net sandstone (28 ft gross). The reduction in thickness from gross to net sandstone is primarily a function of cementation, which is an impediment to production in many clean marine-sand bodies. The low cumulative production of 16 MMCFG is due to a tight reservoir.

STRUCTURE

Lookeba field is in the east-central part of the Anadarko basin (Pl. 5, in envelope). In the deep subsurface, beds dip to the southwest at about 4.3° (~400 ft/mi). A detailed structure map of the study area (Fig. 33) shows the configuration of the top of the lower Cunningham (see type log, Fig. 29). As can be seen on this structure

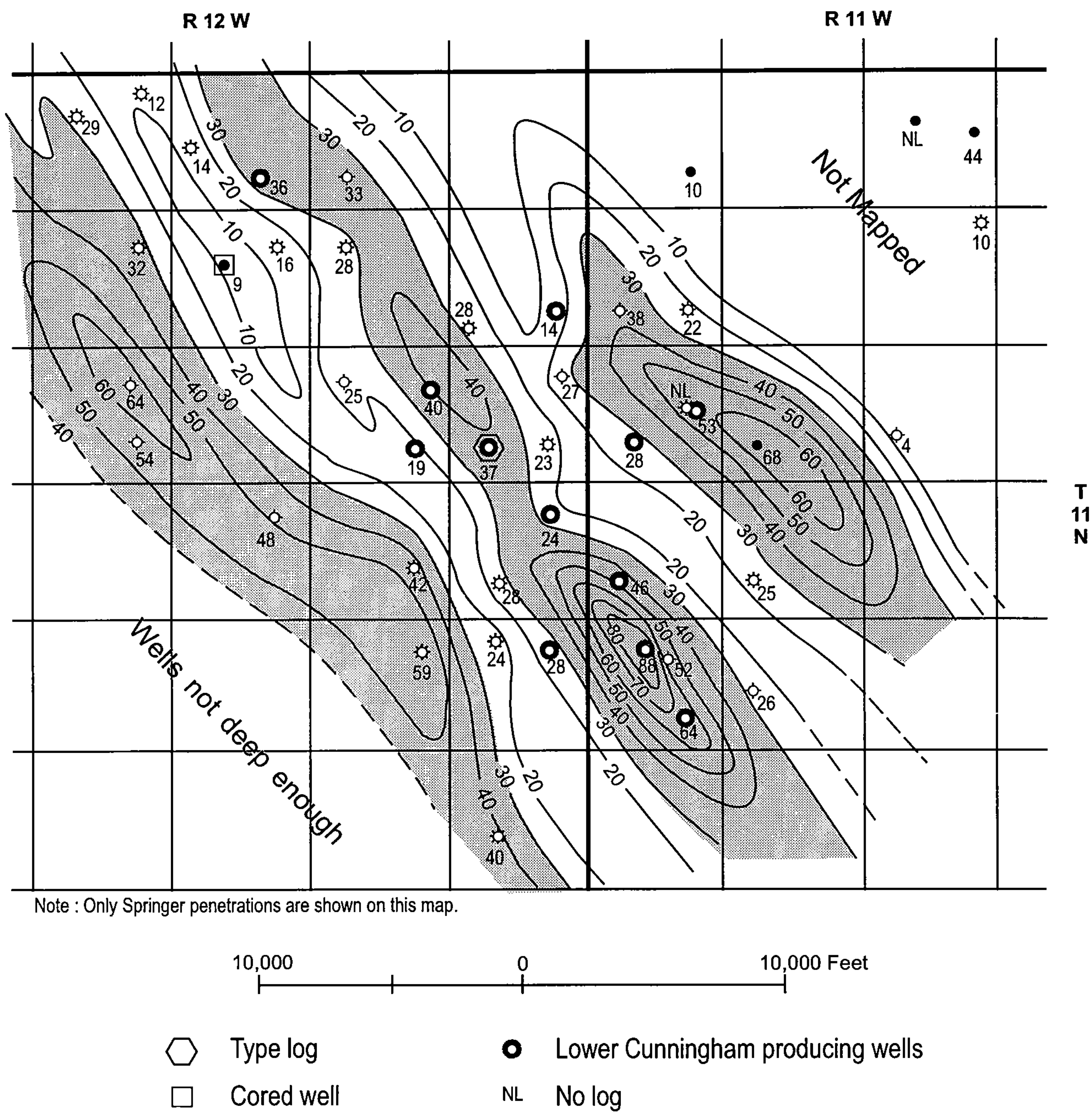

Figure 32. Gross-isopach map of the lower Cunningham sandstone in Lookeba field. Contour interval is 10 ft. See Figure 28 for well names. *NL* = no log.

map, the highest position of the lower Cunningham within Lookeba field is in the SE¼ sec. 11, T. 11 N., R. 12 W., at about −12,150 ft. The structurally lowest part of the field is in the S½ sec. 30, T. 11 N., R. 11 W., at about −12,800 ft. The vertical relief of the gas column, therefore, is about 650 ft. A structural trough extends through the field in a north–south direction. This trough is probably due to deep-seated faulting, but it is doubtful if the Springer has any displacement.

The regional structure at the top of the Springer Group in the Anadarko basin (Pl. 5, in envelope) shows a gentle southwest dip of ~2.3° in the Lookeba area and is uncomplicated by faulting or folding. Hydrocarbon trapping, therefore, is distinctly stratigraphic in this area.

SPRINGER SANDSTONE DISTRIBUTION AND RESERVOIR CHARACTERISTICS

Lower Cunningham Sandstone

Figure 32 shows the gross thickness of the lower Cunningham sandstone for all the wells in the study area. Many shallower wells completed in the Pennsylvanian Cherokee and Marchand sections are not shown on the map to avoid confusion in identifying only the deep pen-

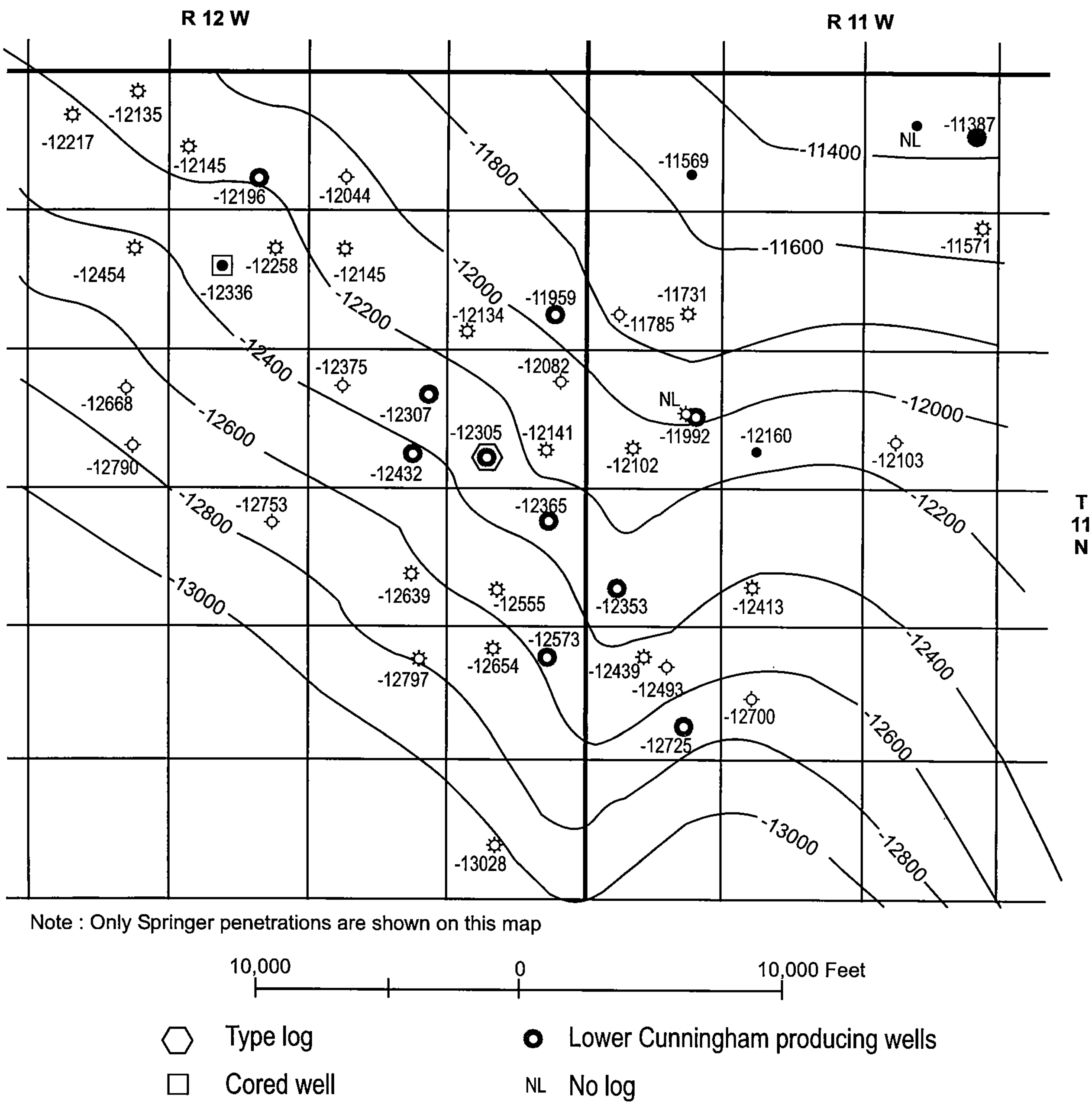

Figure 33. Structure map depicting the top of the lower Cunningham sandstone, Lookeba field. Contour interval is 200 ft. Datum is mean sea level. See Figure 28 for well names.

etrations. The gross-sand thickness is the total thickness of sandstone regardless of porosity, as interpreted from gamma-ray logs (determined from the 50% sand/shale line). The 20-ft-thickness line is approximately the limit of clean sandstone with developed porosity. This means that a considerable thickness of sandstone is not reservoir quality because it is too tight and that only the thickest part of the trend is a gas reservoir. Within the mapped area, the isopach map never reaches a zero thickness because thin, tight, dirty sandstone lenses that are not of reservoir quality persist over the entire mapped area. Areal-distribution patterns of the lower Cunningham sandstone show elongate bar trends oriented northwest–southeast. The thickest sandstone invariably occurs in the very center of the bar where the upper bar facies forms the bar crest. Three bar trends are mapped in the study area; a fourth occurs in the northeastern part of the area but is not mapped.

The gross thickness of the lower Cunningham sandstone ranges from ~10 ft to >80 ft. The least amount of sandstone occurs between major bar trends in the interbar areas. Poorly developed sandstones along the flanks of major bar trends are referred to in this report as bar margins. Where productive, the gross sandstone is usually >20 ft thick and averages ~37 ft. Thickness variations at right angles to the bar occur rapidly over short distances, whereas parallel to the bar, they are gradual.

The Cunningham sandstone interval almost invariably contains a significant amount of sandstone, indicating that much sand was transported onto the marine shelf during this time. Where the sandstone is relatively thick, the log signatures appear to be blocky due to the abrupt upper bar contact with shale, and a rapidly gradational lower bar boundary with shale. Close examination of some of these types of log signatures commonly reveals a subtle coarsening-upward textural profile at the very base, and then is constant upward. Some of the blocky log profiles look like incised-channel deposits, but their mapped geometry coincides with a marine-bar morphology. Interbar deposits invariably contain lesser amounts of sand and are characterized by a distinctive gradual coarsening-upward log profile. These log shapes are noted on both field cross sections A–A′ and B–B′ (Figs. 30, 31, in envelope). Because of the elongate, rather than lobate, nature of these bars, and the fact that typical delta-plain deposits (such as coal and bay-fill lagoonal and marsh shale) are absent, the bars are not delta-front deposits but shallow-marine (detached) bars.

The net-isopach map of the lower Cunningham sandstone (Fig. 34) shows the thickness of sandstone in wells having porosity >6%, which was judged to be the approximate lower limit of porosity in producing wells in Lookeba field. Porosity values were determined by visually averaging the cross-plot porosity on density–neutron logs, as described in a following section on formation evaluation. In producing Springer wells, the net-sand thickness generally ranges from only a few feet to ~30 ft. The maximum thickness in producing wells is 37 ft (in the NE¼ sec. 14, T. 11 N., R. 12 W.). Some wells produced very small amounts of gas from zero net feet (on logs), but this probably occurred because of more porous sandstone in close proximity to the well bore.

Throughout the mapped extent of the field, the average net sandstone thickness of the lower Cunningham is ~16 ft. The net-sand isopach map (Fig. 34) is similar in overall appearance to the gross-sand isopach map (Fig. 32), but with a significant reduction in sandstone thickness. This is due to clay-rich and tightly cemented zones within the lower Cunningham interval that are included in the gross-sandstone thickness. The difference between the gross- and net-sandstone thickness is usually about 10–20 ft for any given well; this constitutes a decrease of as much as ~75% from the gross-sandstone thickness in wells that have at least 20 ft of gross sandstone. However, a 25–50% reduction is more typical. The net- versus gross-sandstone relationship can easily be seen by comparing the gamma-ray and porosity responses on any of the logs shown on cross sections A–A′ and B–B′ (Figs. 30, 31, in envelope). In producing wells, most sandstone has porosity in the range of 5–12%, and no zones have more than ~12% porosity.

There appear to be gas–water contacts in two of the three lower Cunningham bar trends mapped in the study area. The bar trend farthest to the southwest has no identifiable gas–water contact; it may occur farther to the northwest outside the mapped area. The hypothetical gas–water contact was identified from well logs, using a variety of formation-evaluation techniques (explained later in a section on formation evaluation).

The reservoir limit is generally judged to be within the zero contour line in the net-isopach map, with some exceptions. The small, isolated net-sandstone "pod" mainly in sec. 3, T. 11 N., R. 12 W., contains dry holes with 7–8 ft of net sandstone. In this case, the limit of production was arbitrarily interpreted to coincide with an approximate contour interval of 7.5 ft.

Compartmentalization in the lower Cunningham sandstone appears to be minimal when considering reservoir pressures, as all wells brought on line after 1980 showed significant reservoir-pressure depletion. The net-sandstone isopach map supports this observation in that nowhere in any of the three sandstone bar trends does the reservoir "zero out," even though individual sandstone beds vary considerably in thickness and lateral extent. When calculating water saturation, however, there seems to be a wide variation in values within the same bar trend (explained later in the section on formation evaluation). This characteristic of Lookeba field is unnerving for the development geologist, and the variation of water saturation in producing areas is not always related to discontinuities within sandstone trends identified on the net-sand isopach map (Fig. 34).

Boatwright Sandstone

Figure 35 shows the gross thickness of the entire Boatwright sandstone interval. Gross sandstone in this study includes the total thickness of sandstone regardless of porosity, as interpreted from gamma-ray logs (determined from the 50% sand/shale line). The Boatwright interval commonly consists of two sandstone zones that are generally restricted to the northeastern half of T. 11 N., R. 12 W., and the western one-third of T. 11 N., R. 11 W. The

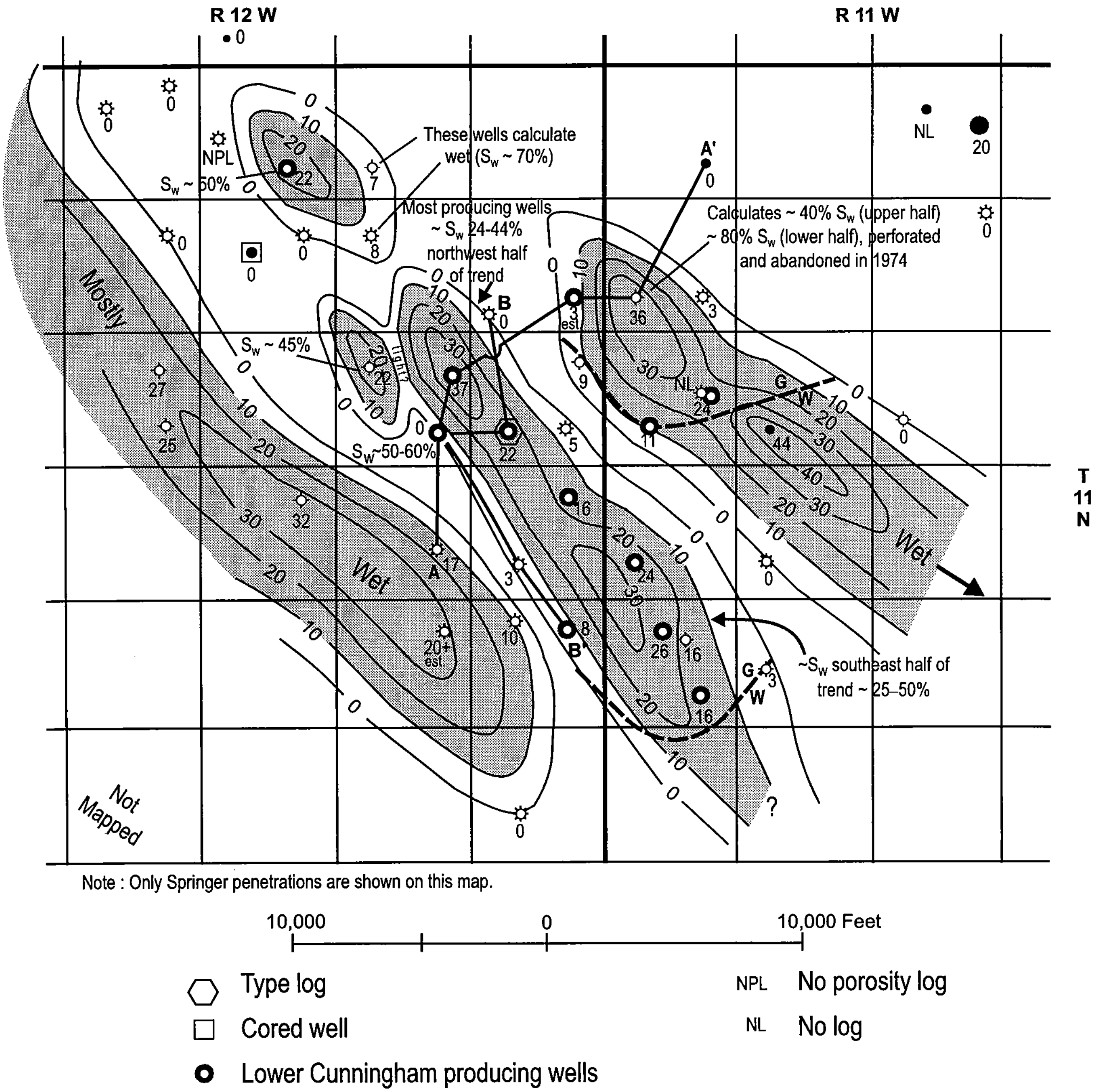

Figure 34. Net-isopach map of the lower Cunningham sandstone in Lookeba field. Net sandstone has a log porosity >6%. Contour interval is 10 ft. See Figure 28 for well names. *NL* = no log; *G* = gas; *W* = water; *NPL* = no porosity log.

Boatwright sandstone occurs in elongate northwest–southeast trends. Thickness variations are similar to those in the Cunningham sandstone: continuous sandstone is parallel to the bar trends, and rapid changes occur perpendicular to those trends.

Gross-sandstone thicknesses are generally in the range of about 10–20 ft, with a maximum of ~26 ft measured in two wells in secs. 14 and 24, T. 11 N., R. 12 W. Where productive, the average well thickness is ~16 ft. In the east-central part of T. 11 N., R. 12 W., the depositional trend of the Boatwright is discontinuous in all directions except to the northwest. In this direction it thins and is not productive, but the zone extends into Sickles North field.

On the basis of well-log interpretations, particularly gamma-ray profiles, the Boatwright sandstone was deposited in an offshore-marine environment as detached bars (not distributary-mouth bars). The bars exhibit a distinct coarsening-upward textural profile and a sharp upper contact with shale. The sandstone occurs in elongate bars that are encapsulated by marine shale. Porosity in these types of sand deposits is almost invariably in the upper part of the bar sequence. In the Boatwright sand-

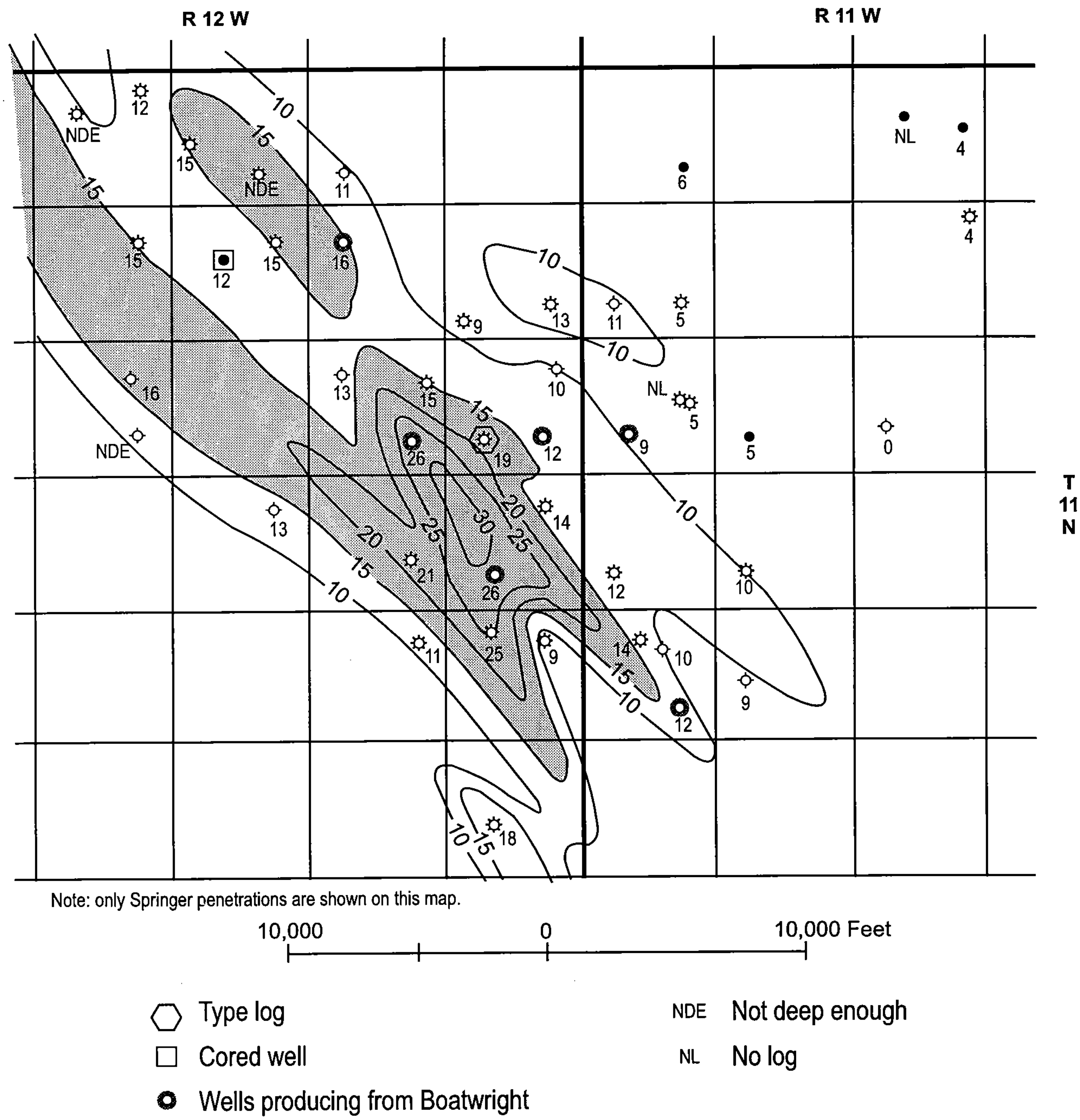

Figure 35. Gross-isopach map of the Boatwright sandstone in Lookeba field. Contour interval is 5 ft. See Figure 28 for well names. *NL* = no log; *NDE* = not deep enough.

stone of this field, however, porous zones are very thin, owing to the thinness of upper-bar facies (seen in the blocky part of the gamma-ray log at the top of the sandstone zone).

The net-sandstone isopach map of the Springer Boatwright interval (Fig. 36) shows the thickness of sandstone in wells having porosity >6%, again judged to be the approximate lower limit of porosity in producing wells within Lookeba field. Porosity values were determined by visually averaging the cross-plot porosity on density–neutron logs, as described in a later section on formation evaluation. In wells producing from the Boatwright, the net-sand thickness ranges from only a few feet to ~15 ft and averages a little less than 7 ft.

The net-sandstone isopach map (Fig. 36) has a somewhat different distribution pattern from that of the gross-sandstone isopach map (Fig. 35), because most of the Boatwright sandstone is tight. Some porosity occurs in scattered areas where the gross sandstone is thickest, but generally the porous Boatwright sandstone is discontinuous and compartmentalized. The thickest and most widespread occurrence of net Boatwright sandstone is in

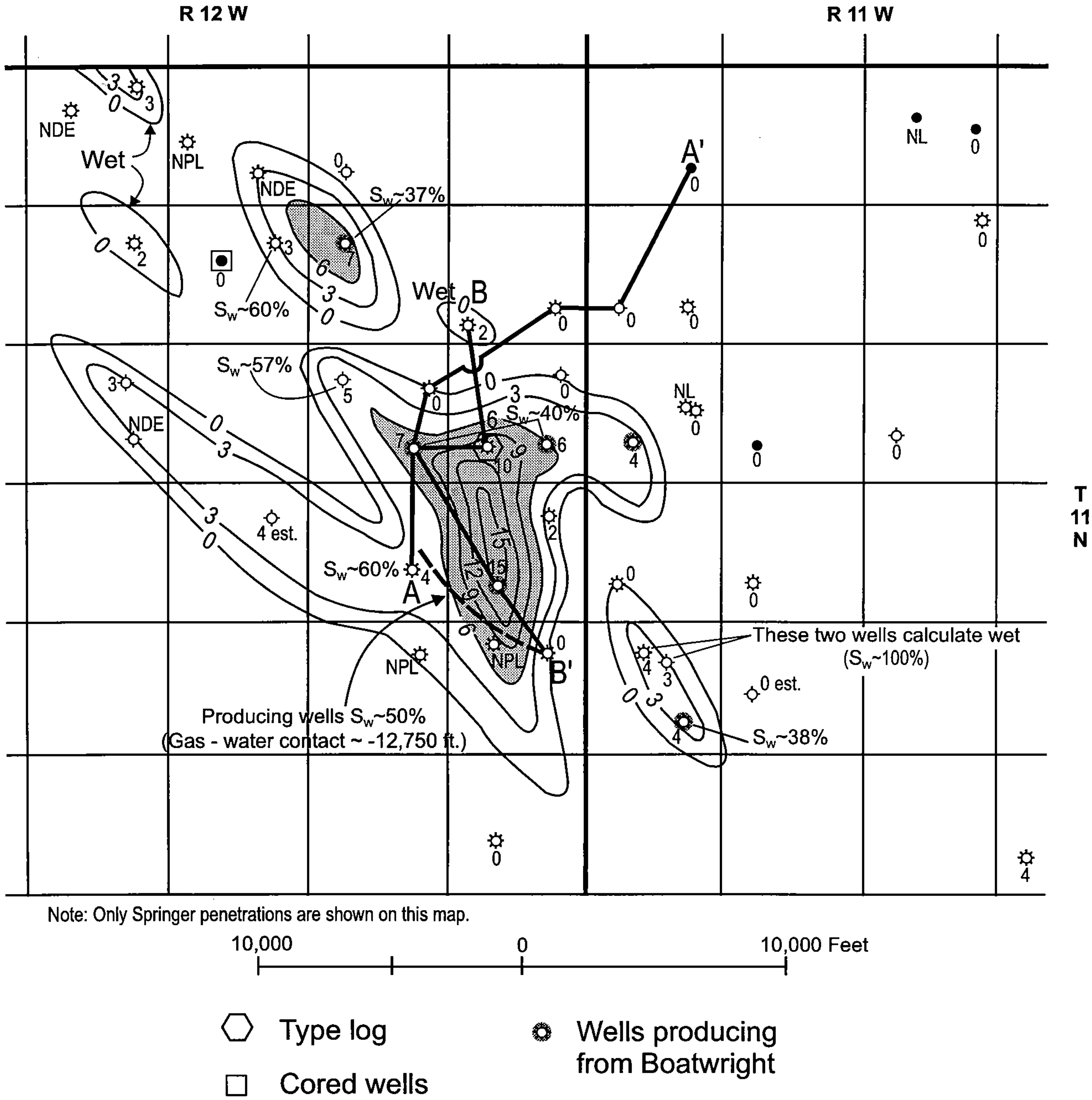

Figure 36. Net-isopach map of the Boatwright sandstone in Lookeba field. Net sandstone has a log porosity >6%. Contour interval is 3 ft. See Figure 28 for well names. *NL* = no log; *NDE* = not deep enough; *NPL* = no porosity log.

the east-central part of T. 11 N., R. 12 W., and the orientation of the principal sandstone trend there is more north–south than the predominant northwest–southeast trend depicted on the gross-sandstone map.

Differences between the net-sandstone thickness and the gross-sandstone thickness may be due to clay-rich and tightly cemented zones. This interpretation can sometimes be made from resistivity and gamma-ray logs; the resistivity in tightly cemented zones is considerably higher than in porous zones, and shaly zones rich in clay have higher gamma-ray values.

Differences between the gross- and net-sandstone thicknesses are much greater in the Boatwright sandstone than in the overlying Cunningham sandstone. Many wells with 15–20 ft of gross Boatwright sandstone have little if any net sandstone, a decrease of up to 100%. Where productive, most of the sandstone has porosity in the range of 5–12%, average ~8.5%, which is comparable to that of the Cunningham. Boatwright wells are not as good in comparison to Cunningham wells on a per-acre-ft basis, however, probably because of higher water saturations and restricted reservoir continuity in the Boatwright.

The Boatwright sandstone produces at three places in the study area: an isolated well in the NW¼ sec. 11; the main producing area, mostly in secs. 13 and 24, where the maximum net sandstone is 15 ft thick; and another area centered in sec. 30. Other pods of thin net sandstone are not productive. The pod of net sandstone in sec. 11 has produced about 2.9 BCFG from only 7 ft of net pay; that well is the best Boatwright producer in the study area. The volume of produced gas from that well greatly exceeds the reservoir volume identified in mapping, which means that the reservoir is either thicker and/or more extensive than indicated.

On the basis of S_w calculations from producing and nonproducing wells, the main producing bar in secs. 13 and 24 appears to have a single gas–water contact, as shown in Figure 36. A wide range of initial S_w values in those wells does not necessarily mean compartmentalization, however. Variations in clay content probably affect the measurement of true resistivity (R_t) in the reservoir (the clay suppresses the deep resistivity). This in turn can cause bound water to be included in the S_w equation. This commonly occurs in Morrow sandstones as well as in the Cunningham sandstone, as previously described.

A few wells in the main Boatwright sandstone bar complex are not completed in the Boatwright, most notably, the type well in the SW¼ sec. 13, T. 11 N., R. 12 W. This well appears to be at an optimal location but was not perforated, possibly because the well is producing from a better Cunningham section. Volumetric gas calculations (Table 6) indicate considerable underproduced gas from the Boatwright in the field.

The third area of Boatwright production comes from a single well in the SW¼ sec. 30, T. 11 N., R. 11 W. In this well, Boatwright gas is commingled with Cunningham gas, so the exact amount of Boatwright gas is unknown but probably is small, on the basis of reservoir size.

ENVIRONMENTS OF DEPOSITION OF CUNNINGHAM AND BOATWRIGHT SANDSTONES IN LOOKEBA FIELD

Depositional environments were interpreted from wireline-log signatures in order to understand the general depositional setting of sandstone within the Lookeba field study area. Logs from all wells in this area were used for interpretation, particularly gamma-ray and resistivity logs. Both reservoirs are interpreted to have been deposited by similar processes and similar marine environments.

Detached-Offshore-Bar Interpretation

The depositional environment of both the Boatwright and Cunningham sandstones in Lookeba field appears to be the marine shelf, several miles from shore. Water depths were relatively shallow, giving rise to a variety of bedding types including ripple and cross-bedding. The sandstones are generally very fine grained, are moderately well sorted, and consist mostly of quartz grains. Sandstone accumulations occur in elongate bars, several miles long and only about a mile wide. They are completely encased in marine shale above, below, and laterally and contain no associated deltaic deposits within each respective interval. Although some log shapes resemble incised-channel deposits (particularly for the Cunningham), there appears to be no downcutting or other fluvial characteristics. Additionally, the sandstone in each interval maps out in harmony regardless of log shape—i.e., there are not different trends based on different log shapes. Considering these subsurface characteristics and limited core analysis, the depositional environment of the Boatwright and Cunningham sandstones is interpreted to be that of an offshore bar, detached from the shoreline. Where the log shape is blocky, it is likely that a bar transition facies is poorly developed owing to an abundant sand supply, sporadic but localized strong currents, and rapid deposition. The Boatwright and Cunningham deposits do not form subaqueous distributary-mouth bars (not a delta front) as some geologists have interpreted in this field.

CORE ANALYSIS

No Cunningham or Boatwright sandstone cores are available from Lookeba field. One well was cored in the northwesternmost part of the study area but did not recover any Boatwright sandstone, and the Cunningham was poorly developed. Data for the Apexco No. 1-A Buell well, in the SE¼NW¼ sec. 10, T. 11 N., R. 12 W., are given in Figures 52 and 53 in the Sickles North field study (Part III of this volume).

A relatively thick, clean Cunningham sandstone section was recovered in cores from a well ~32 mi farther northwest of Lookeba field, in sec. 36, T. 13 N., R. 17 W., and the data are plotted in Figure 10. At that location the Cunningham is more deeply buried (~15,500 ft) than it is in Lookeba field (~13,800 ft). The increased depth of the Cunningham represented in Figure 10 probably accounts for lower porosity and permeability.

FORMATION EVALUATION

Correlation of the various Springer sandstones in Lookeba field is generally easy, owing to the relatively simple depositional environment of each Springer interval. The formation evaluation of the Springer sandstones is much more difficult, however, owing to the likelihood of clay problems, diagenetic alterations, and cementation, which tend to complicate calculations.

Springer sandstones may be relatively clean on the basis of gamma-ray-log responses, but consistently reliable values of water saturation (S_w) are elusive. In this study, a spreadsheet was created that incorporates representative values of deep, or true, resistivity (R_t) and crossplot porosity (ϕ) that can then be used to calculate S_w. Different formulas were used to calculate formation factor (F) in the tightly cemented rocks. The Archie formula of $1/\phi^2$ was finally used. Notation of formation-water resistivity (R_w) was made from service-company calculations, although their values (0.1 ohm-m) resulted in S_w values that were consistently too high. Experimentation with different R_w values indicates that a smaller number was necessary to characterize water-wet zones and hydrocarbon zones more realistically. Finally, an R_w value of 0.08 ohm-m was decided on. Unrealistic variations in S_w were still encountered in spreadsheet calculations, particularly for tight zones in which R_t was very high. But

TABLE 6. — Reservoir/Engineering Data for Springer Sandstones in Lookeba Field, Caddo County, Oklahoma

	Cunningham sandstone (exclusive of secs. 7 and 18, T. 11 N., R. 11 W.)	Boatwright sandstone (secs. 11, 13, 14, 24, T. 11 N., R. 12 W. + sec. 18, T. 11 N., R. 11 W.)
Discovery date (map area)	10/10/78 (Getty 1 Lindey, C SE¼ sec. 30, T. 11 N., R. 11 W.)	10/25/73 (Apexco 1 Buell, C NW¼ sec. 11, T. 11 N., R. 12 W.)
Reservoir size[a]	~3,260 acres (~5 mi^2)	~2,670 acres (~4.2 mi^2)
Reservoir volume	~56,000 acre-ft	~13,400 acre-ft
Depth	about 13,600–14,000 ft	~14,100 ft
Spacing (gas)	640 acres with increased density to 320 acres	
Gas–water contact	below about –12,765 ft (?)	below about –12,750 ft (?)
Porosity (in "clean" sandstone in producing areas)	about 5–12% (average ~7.5%)	about 5–12% (average ~8.5%)
Permeability	est. 0.1–1.0 md	probably = Cunningham
Water saturation (S_w) in producing wells Calculated using R_w = 0.08 ohm-m	about 25–53% (average ~35%)	average ~40%
Thickness (WPWA = where productive, well avg.)		
Net sandstone (WPWA), >6% ϕ	0–37 ft (average ~16 ft)	4–15 ft (average ~6.5 ft)
Gross sandstone (WPWA)	10–88 ft (average ~37 ft)	9–31 ft (average ~16.5 ft)
Reservoir temperature	about 200–215°F	about 210–240°F
Gas density	~0.58	~0.58
Z factor (compressibility)[b]	~1.42	~1.42
B_g (gas formation volume factor)[c]	~376 std cu ft per reservoir cu ft	~393 std cu ft per reservoir cu ft
Initial reservoir pressure (max. recorded BHP)	~10,114 psi	~10,741 psi
Initial pressure gradient	~0.73 psi/ft	~0.77 psi/ft
Cumulative field condensate (est. to 2/00)	~21,689 bbl (commingled)	est. <5% of Cunningham total
OGIP[d] (volumetric-field)	~42 BCF	~11.5 BCF
Cumulative field gas (est. to 2/00)	est. 26 BCF	est. 4.6 BCF
Average production per well	9 wells, ~2.9 BCF/well	6 wells, ~0.77 BCF/well
% gas recovery to date	62% (not including condensate)	43% (not including condensate)
Recovery MCF/ac-ft (field to date)	~460 MCF/ac-ft	~300 MCF/ac-ft

[a]Area within 0 ft net contour (Cunningham); 3 ft net contour (Boatwright).

[b]Compressibility factor (*Z*) estimated from standard reservoir engineering chart using T_{res} and P_{res} values listed in this table. T_{res} is in °Rankine (add 460° to reservoir temperature that is measured in °F), P_{res} = reservoir pressure.

[c]B_g calculated using the formula: $B_g = \frac{35.4 \times P_{res}}{T_{res} \times Z}$ The *Z* factor is stated above.

[d]Original gas in place (OGIP) determined from the following formula: Reserves (MCF) = 43.56 × area (acres) × sand thickness (ft) × porosity (%) × $(1 - S_w) \times B_g$.

these tight zones were nonproductive, so the resulting S_w calculations were not deemed important.

The true resistivity (R_t) of producing sandstones in the Springer formation typically ranges from ~50 to a little more than 150 ohm-m. A deep resistivity of <50 ohm-m almost invariably indicates that the zone is wet. With a typical porosity of 6–10%, the Springer probably will not produce significant gas with less than ~50 ohm-m of resistivity. On the other hand, where the deep resistivity is relatively high (greater than 100–200 ohm-m), and in the absence of net porosity, the Springer is usually tight because of cementation.

The characterization of permeability, and therefore porosity, by examining the separation between the shallow- and deep-resistivity curves is not always accurate, because some of the tight sands display relatively good separation. This indirect method of determining reservoir quality is based on the assumption that the amount of invasion of drilling fluids is proportional to the porosity and permeability of the reservoir, and that the amount of separation between the shallow- and deep-resistivity curves is affected by the degree of invasion. It is possible that overbalanced drilling enhances the degree of invasion in rocks that would otherwise be considered tight.

Porosity determinations using density–neutron logs were estimated by taking the cross-plot porosity of the two logs. By using this simple procedure, porosity values in the cleanest part of the producing sandstone intervals ranged from about 5% to 12% (average ~7.5%) for the Cunningham sandstone and 5% to 12% (average ~8.5%) for the Boatwright sandstone. Most wells were logged by using the density–neutron combination, and a matrix density of 2.71 g/cm^3 (limestone) was routinely used by logging companies. Therefore, porosity determinations in sandstone are theoretically a few percentage points higher than if a sandstone-matrix density of 2.65 g/cm^3 had been used. Porosity values in this study were pessimistically estimated to take this variation into account but were not systematically reduced by 2–3 percentage points as some evaluators do. Where only density porosity was available, values were attenuated by multiplying the indicated density porosity by a fraction, usually 0.65 or 0.7, so that the resulting porosity accounts for some of the normal gas effect (in producing wells) that causes the density porosity to be too high. The observed gas effect (crossover) in productive intervals may be 5–12 porosity units (see well 2, cross section B–B´, Fig. 31, in envelope). In nonproducing or tighter zones, the gas effect is much less (see well 3, cross section B–B´, Fig. 31).

In this study, S_w calculations for the Cunningham and Boatwright sandstones are extremely variable and range from ~25% to >100% (which of course is not correct). In producing zones, some calculations are unrealistically high (>50%), but overall, values seem to accurately reflect general reservoir conditions in regard to hydrocarbon versus water saturation. Clay problems are blamed for unrealistically high S_w values in sandstone having net porosity >6%. In these cases, S_w values are probably correct but include bound water rather than free (mobile) water. In a similar manner, cementation is blamed for unrealistically high S_w values in tight zones, because the formation factor (F) in the numerator of the S_w formula gets very large.

Calculations were made by using the equation $S_w = \sqrt{(F \times R_w)/R_t}$. The value for R_w that proved to best fit reservoir conditions was assumed to be 0.08 ohm-m at formation temperature. It is apparent that a range of R_w values might better characterize individual wells. The Archie equation for formation factor ($F = 1/\phi^2$) was used to reflect the highly cemented sandstone lithology, although the modified equation ($F = 0.81/\phi^2$) may also be used with satisfactory results in calculating S_w when adjusting R_w to 0.1 ohm-m. Using the modified Archie equation and $R_w = 0.08$ repeatedly resulted in calculated S_w values that were too low in water-wet zones. Values for R_t were taken directly from the deep-resistivity logs, but the resistivities may have been suppressed in some reservoirs because of bound water in interstitial clays. Porosity values also were taken directly from density–neutron, density, or sonic logs in a manner described above.

Reservoir characteristics of the Springer sandstones in Lookeba field are summarized in Table 6.

OIL AND GAS PRODUCTION

The estimated cumulative gas production from the Springer formation in Lookeba field is ~30.6 BCFG and 21,689 BO (condensate) from November 1973 through February 2000. The lower Cunningham sandstone accounts for most of this production (~26 BCFG and ~21,500? BO), whereas the Boatwright sandstone produced about 4.6 BCFG. An additional ~2.8 BCFG was produced from the lower Cunningham sandstone in a small unattached reservoir ~1 mi northeast of the main Cunningham reservoir. Figure 37 shows cumulative gas and oil production for each respective Springer reservoir. In some cases this value represents production commingled from both the Cunningham and Boatwright zones. Commingling makes reserve allocations for individual zones difficult to determine.

Figure 38 shows the date of first production, initial production (IP), tubing pressure, and bottom-hole pressure (BHP) for Springer wells in Lookeba field. By comparing the data in Figure 38 with those in Figure 37, it can be seen that wells completed earliest in the field are the largest producers and had the highest initial pressures. Liquid (condensate) production is mostly attributed to Cunningham wells in the structurally lowest part of the field (southeast).

On the basis of volumetric calculations, cumulative production from the lower Cunningham sandstone is ~62% of the original recoverable gas in place, which is estimated to have been 42 BCFG (Table 6). The percentage of recovered gas is probably a little on the low side, as most wells have reached depletion pressure of less than 1,000 psi. There is considerable room for error in reserve calculations because of assumptions made about areal extent, reservoir thickness, and especially S_w. The estimated recovery factor with regard to current cumulative gas production is ~460 MCFG/acre-ft for the lower Cunningham.

Production from the Boatwright sandstone represents only ~43% of the original recoverable gas in place, which is estimated to be 11.5 BCFG (Table 6). Most of the Boatwright wells have also reached pressure depletion. The estimated recovery with regard to current cumulative gas production from the Boatwright sandstone is ~300 MCFG/acre-ft. The lower recovery factor is probably due to the limited thickness and areal extent of porosity in the Boatwright sandstone.

The better wells in Lookeba field produce from the lower Cunningham sandstone. One well produced more than 10 BCFG, followed by four others with cumulative production varying from ~1.9 to 5 BCFG. Nine wells produce from the lower Cunningham for an average production of 2.9 BCFG/well. Good Boatwright wells produce only about 0.5 BCFG, except for one well in sec. 11 that has produced more than 2.9 BCFG. Six wells produce from the Boatwright for an average production of ~0.78 BCFG/well. Initial production rates for the lower Cunningham were 1–5 MMCFGPD, and even some of the

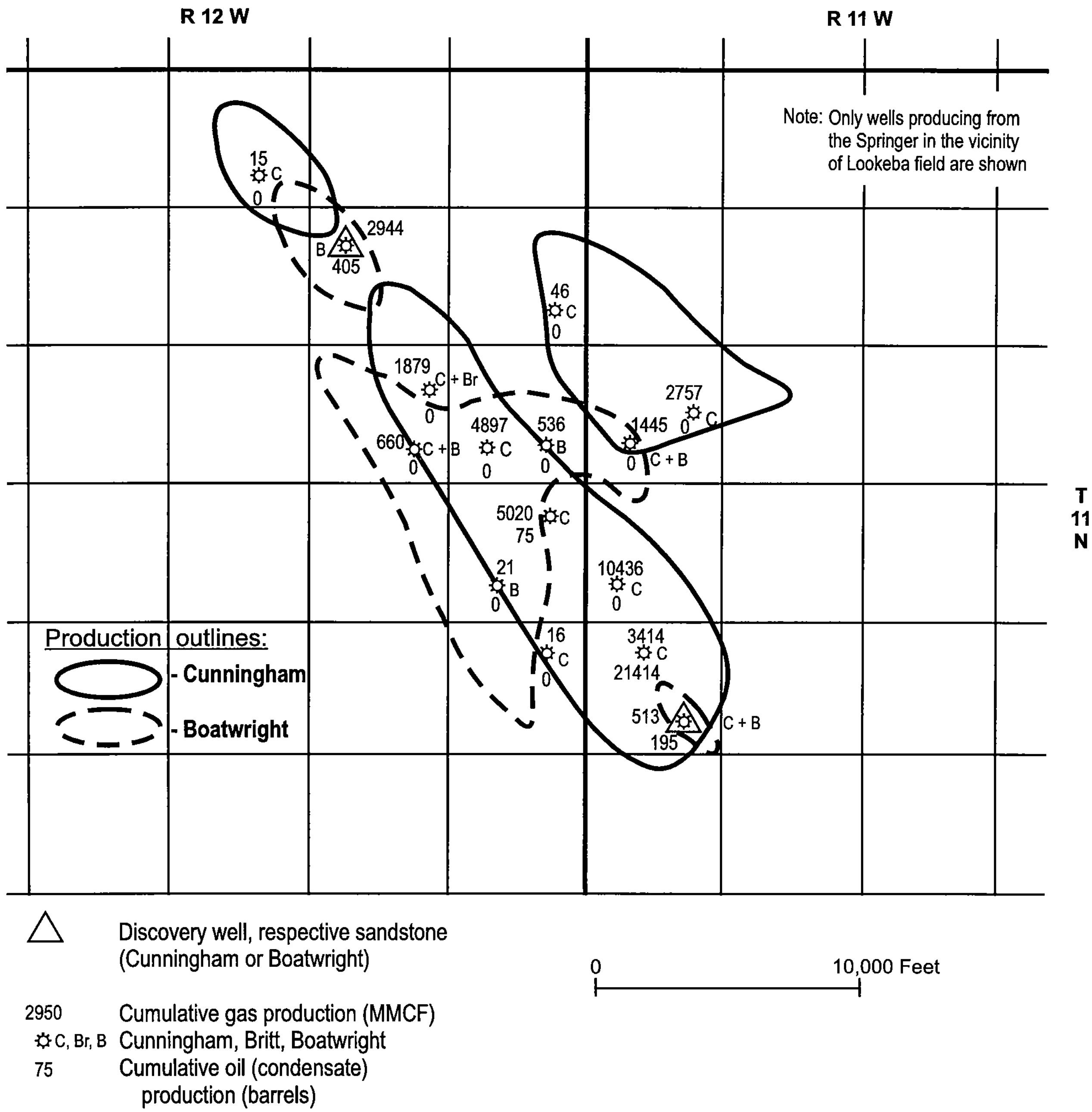

Figure 37. Map showing cumulative gas and oil (condensate) production for wells producing from the Cunningham and Boatwright sandstones in Lookeba field. Production is tabulated through February 2000. See Figure 28 for well names.

more recent wells had initial-production rates of >1 MMCFGPD. Initial Boatwright production was generally much less, <1 to ~2 MMCFGPD. Initial shut-in tubing pressures (SITP) are generally unavailable. Flowing tubing pressures (FTP) for both reservoirs, which are indirectly a function of reservoir quality (besides other factors), varied from several hundred psi to >4,000 psi, and many were in the range of 1,000–2,000 psi. The flowing pressure from very tight rocks is usually small in relation to the shut-in pressure.

PRODUCTION-DECLINE CURVES

Lower Cunningham Sandstone

Production- and pressure-decline curves for three lower Cunningham sandstone wells are shown in Figure 39. The upper plot shows the curves for the Sanguine No. 1 Elliott well in the C NE¼ sec. 24, T. 11 N., R. 12 W. This well has 16 ft of net sandstone with about 6–9% porosity, although some zones within the sandstone interval have <6% porosity. The reservoir thickens gradually to the

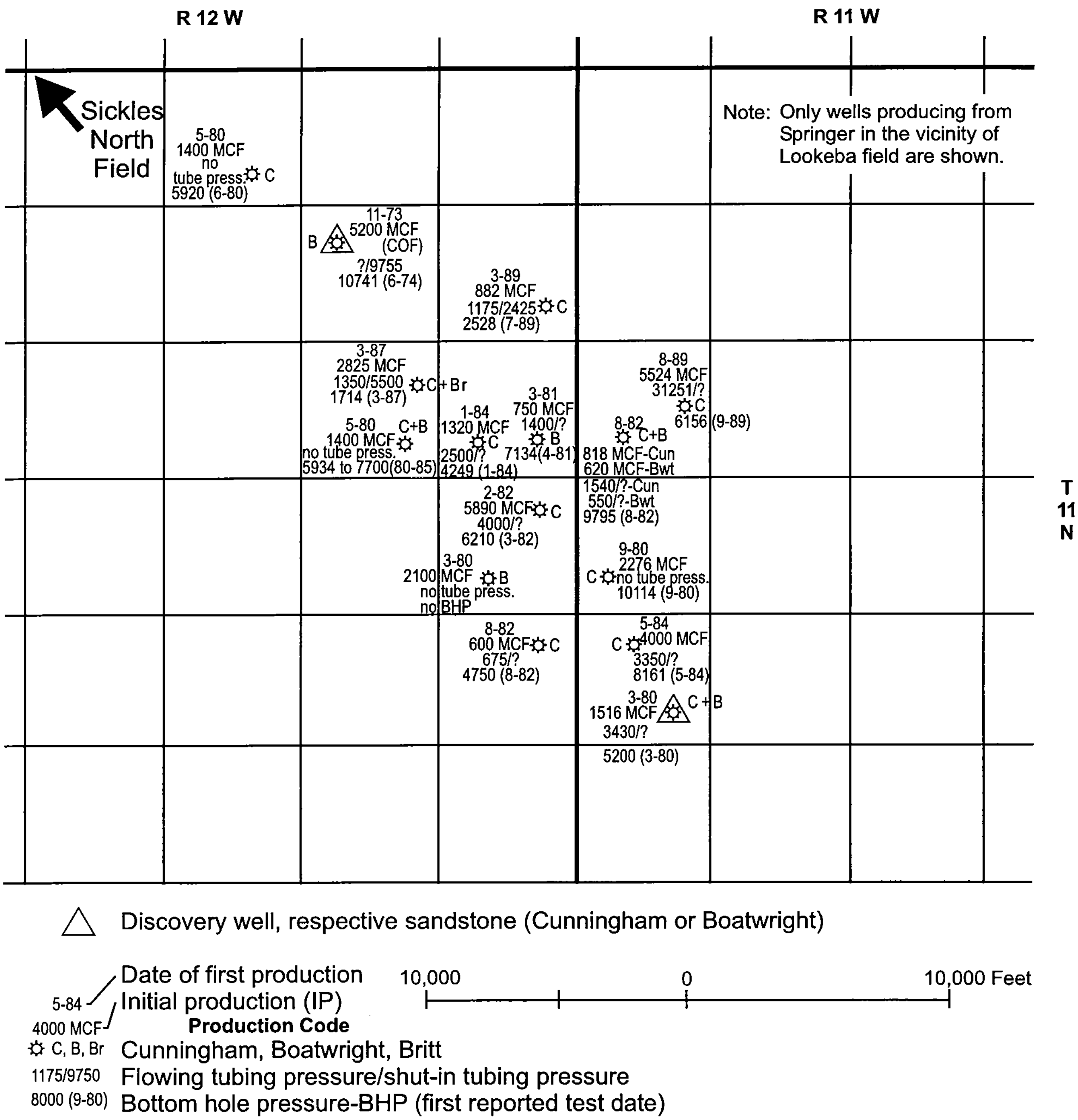

Figure 38. Map showing date of first production, initial production (IP), flowing tubing pressure (FTP), shut-in tubing pressure (SITP), bottom-hole pressure (BHP), and production code for wells producing from the Cunningham and Boatwright sandstones in Lookeba field. See Figure 28 for well names. *COF* = calculated open flow.

southeast and northwest to ~30 net ft of sandstone. The Elliott well is about a mile on trend to the northwest of a well drilled 1½ years earlier by Duncan. As a result, the formation pressure in the Elliott well was partially depleted, but the well still produced ~5 BCFG over 18+ years. The initial BHP in 1982 was ~6,210 psi, and by 1992 it had fallen to 864 psi. A northwest offset well was drilled in 1983 and encountered similar pressure depletion, though production was similar to that from the Elliott well, mainly because the reservoir is thicker.

Figure 39B shows the curves for the Duncan No. 1 Margie well in the C SW¼ sec. 19, T. 11 N., R. 11 W. This well produced ~10.4 BCFG from the lower Cunningham sandstone over ~20 years and is the most productive well in the field. It was completed in early 1980, with first production starting about 6 months later. The Margie well produces from 24 net ft of sandstone with about 6–10% porosity and had an initial BHP of 10,114 psi. By 1992, the BHP had fallen to 809 psi. Getty drilled a south offset (the A-2 Lindley) in the E½NW¼ sec. 30 in 1984, and its BHP had dropped only ~2,000 psi over the 4 years since the Margie well went on production.

Figure 39C shows the curves for the Getty No. A-2 Lindley well, referred to above. Cumulative production from this well is ~3.4 BCFG from 26 ft of net sandstone, with porosity ranging from about 6% to 8%. The gross sandstone thickness (88 ft) is considerable, but much of this is tight or wet. This well had an initial BHP of 8,161 psi in 1984, and a BHP of 4,556 psi during 1992, the last year pressure was recorded. This is still about 3,750 psi more than the offsetting Margie well drilled 4 years previously. Also shown is the annual oil (condensate) production, whose slow decline is similar to that of the gas.

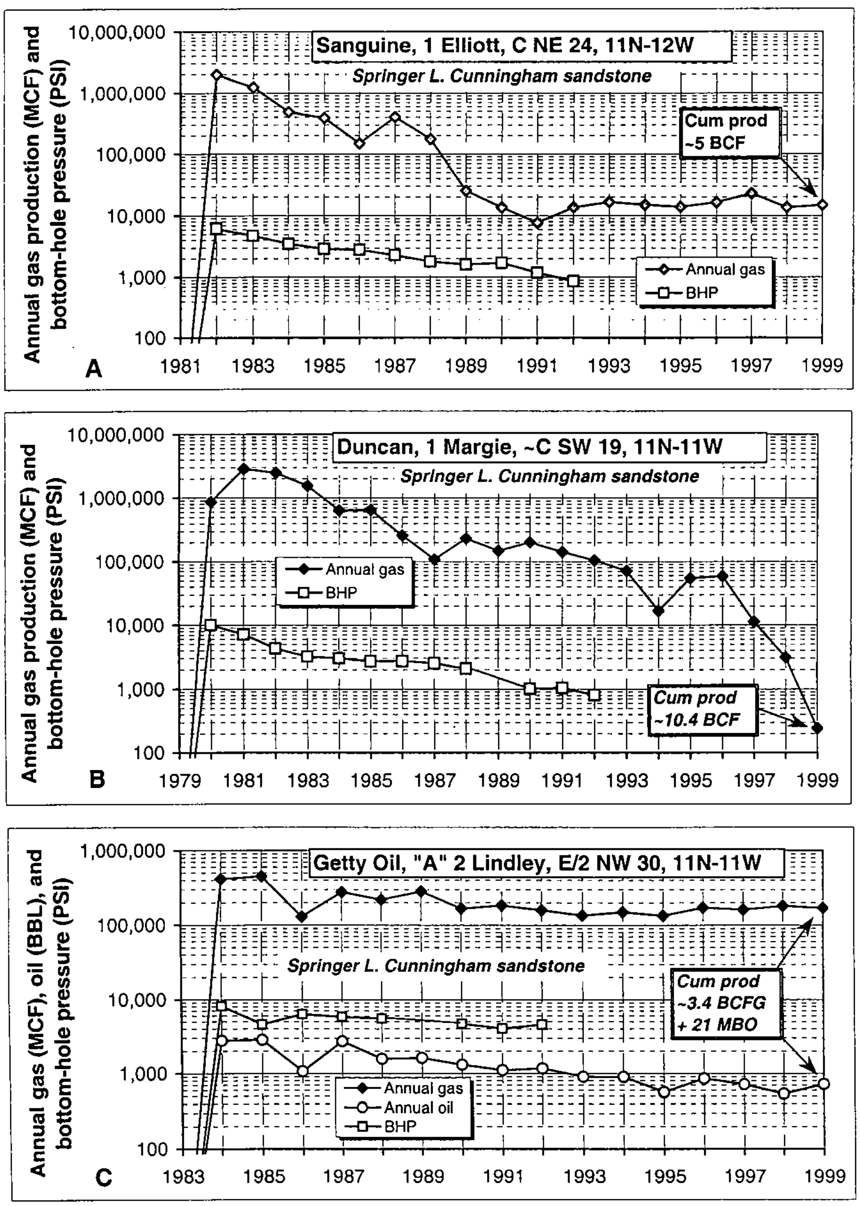

Figure 39. Production- and pressure-decline curves for three wells producing from the lower Cunningham sandstone in Lookeba field. Data are current through December 1999.

The production performance of the lower Cunningham sandstone is directly related to date of first production, reservoir quality, and thickness. All three wells have different decline rates over similar periods, which indicates reservoir heterogeneity and minimal interference from competing wells. These curves also illustrate the different degrees of depletion from one location to another throughout the field. Production and pressure data used to construct these curves are included in Table 7.

Figure 40 shows pressure versus cumulative gas production for the two Cunningham wells that have good pressure data. The visual BHP projection shows a common initial pressure but different decline rates over time. This is probably due in part to reservoir heterogeneity, as stated above. Trend lines have been inserted to clarify the decline patterns of different reservoirs.

Boatwright Sandstone

Production- and pressure-decline curves for two wells producing solely from the Boatwright sandstone are shown in Figure 41. The upper plot shows the production curve from the Apexco No. 1 Buell well in the C NW¼ sec. 11, T. 11 N., R. 12 W. Here, the reservoir consists of about 7 ft of net sandstone with 6–8% porosity, although the total gross-sandstone thickness is 16 ft. Cumulative production of ~2.9 BCFG is about 5 times more than the next highest Boatwright producer in the field. The Buell well is still producing gas after almost 27 years. This well was completed in late 1973, with a calculated open flow (COF) of 5,200 MCFGPD. The BHP of 10,741 psi was measured 7 months after production began, so the initial reservoir pressure was somewhat higher. The Buell is the only well completed in an isolated sandstone pod, and there are no offsets producing from the same reservoir.

Figure 41B shows the curves for the Cotton Petroleum No. 1-A Jacques well, in the N½SE¼ sec. 13, T. 11 N., R. 12 W. This well has produced ~536 MMCFG over ~20 years. It was initially completed in early 1981 for 750 MCFGPD from 6 ft of net pay having porosity ranging from about 6% to 9%. The gross-sandstone thickness is 12 ft, so half the sandstone thickness is tight. A month after production began, a BHP of 7,134 psi was recorded, which seems unrealistically low when considering that virgin pressure was probably similar to that of the Buell well (~11,000 psi). The Jacques well had no production competition from nearby wells prior to its completion, so it is doubtful if a pressure de-

TABLE 7. — Annual Springer Production and Pressure Data for Selected Wells in Lookeba Field, Caddo County, Oklahoma

	Boatwright production				Cunningham production						
	1 Buell C NW 11, 11N-12W		1 Jacques A SE 13, 11N-12W		1 Elliott C NE 24, 11N-12W		1 Margie ~C SW 19, 11N-11W		A-2 Lindley E/2 NW 30, 11N-11W		
Year	Gas (MCF)	BHP	Gas (MCF)	BHP	Gas (MCF)	BHP	Gas (MCF)	BHP	Gas (MCF)	Oil (bbl)	BHP
1974	358,598	10,741									
1975	463,377	5,711									
1976	230,156	3,679									
1977	177,362	2,691									
1978	147,110	3,907									
1979	82,982	3,786									
1980	110,041	2,982					867,752	10,114			
1981	131,244	3,105	73,156	7,134			2,842,102	7,132			
1982	104,178	1,028	35,336		1,993,025	6,210	2,482,018	4,261			
1983	32,428	3,013	36,931	5,115	1,247,236	4,767	1,535,243	3,188			
1984	84,567	2,601	18,985	5,822	489,088	3,504	636,282	2,999	417,235	2,778	8,161
1985	41,975	2,213	11,160	6,054	388,439	2,909	654,604	2,691	449,668	2,843	4,573
1986	70,279	2,707	5,510	7,873	148,737	2,821	259,685	2,714	129,671	1,073	6,368
1987	106,187	2,298	5,149	8,148	402,711	2,292	108,499	2,515	279,025	2,718	5,806
1988	101,648		27,788		175,490	1,801	233,139	2,080	219,758	1,582	5,531
1989	96,149	2,313	46,018		25,475	1,617	149,021		284,551	1,624	
1990	83,011	1,822	41,207		13,566	1,701	204,154	1,012	167,059	1,316	4,665
1991	67,216	1,747	27,018		7,695	1,184	142,571	1,046	182,803	1,113	4,056
1992	59,148	1,536	23,817		13,749	864	104,970	809	159,207	1,168	4,556
1993	66,383		33,594		16,724		71,013		135,019	909	
1994	51,295		31,693		15,065		16,818		149,753	904	
1995	55,231		17,675		13,903		55,084		133,913	564	
1996	51,570		25,239		16,445		58,826		171,922	854	
1997	47,339		28,066		22,969		11,299		161,611	714	
1998	46,006		23,623		13,606		3,097		180,515	535	
1999	68,980		23,671		14,800		243		170,391	719	
Cumulative production											
	2,934,460		535,636		5,018,723		10,436,420		3,392,101	21,414	

cline of ~4,000 psi could occur after just 1 month's production. About 1½ years later, Cotton drilled their No. 1 Viola well as an offset to the Jacques in the SW¼ sec. 18, T. 11 N., R. 11 W. It was dually completed in the Cunningham and Boatwright zones, with a BHP of 9,795 psi. This well encountered a much thinner Boatwright sandstone (4 net ft), yet the reported pressure was much higher than that of the Jacques well.

Boatwright production is scattered throughout Lookeba field and is commonly commingled with production from other Springer reservoirs, making single-zone production difficult to determine. The two production curves (Fig. 41A,B) represent only Boatwright production. Those curves are very different, reflecting reservoir heterogeneity. The reason for the rapid initial decline for the Jacques well is not known; speculation can include a faulty completion fluid loading, or curtailment. Thereafter, from 1989, a normal decline has occurred.

Pressure versus cumulative gas production (Fig. 40) is plotted for only one Boatwright well because of the lack of good pressure histories for other Boatwright wells. This curve can be compared to the pressure-versus-production trends of the two Cunningham wells previously described. Note that although all three wells project to a common initial BHP, they all have very different decline rates over time. To repeat, this is probably due to reser-

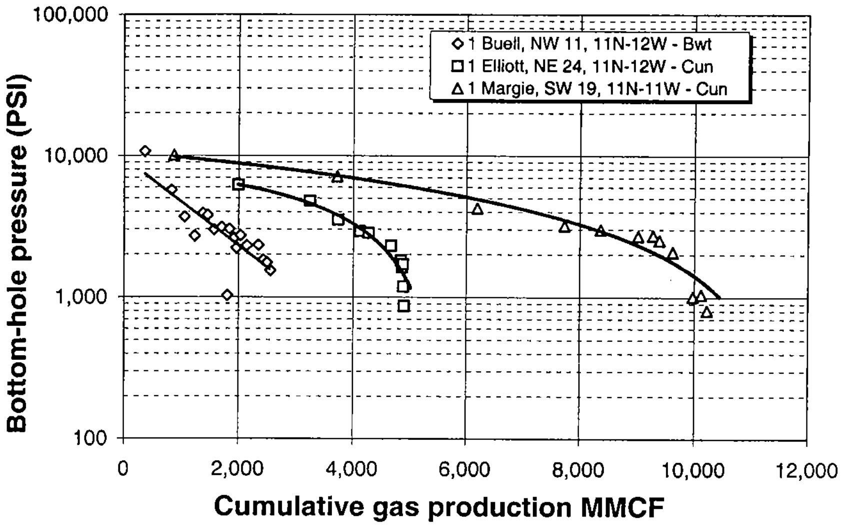

Figure 40. Graph showing relationship between pressure and cumulative gas production for three Springer wells having good pressure data in Lookeba field. Two produce from the lower Cunningham sandstone (*Cun*), and one produces from the Boatwright sandstone (*Bwt*).

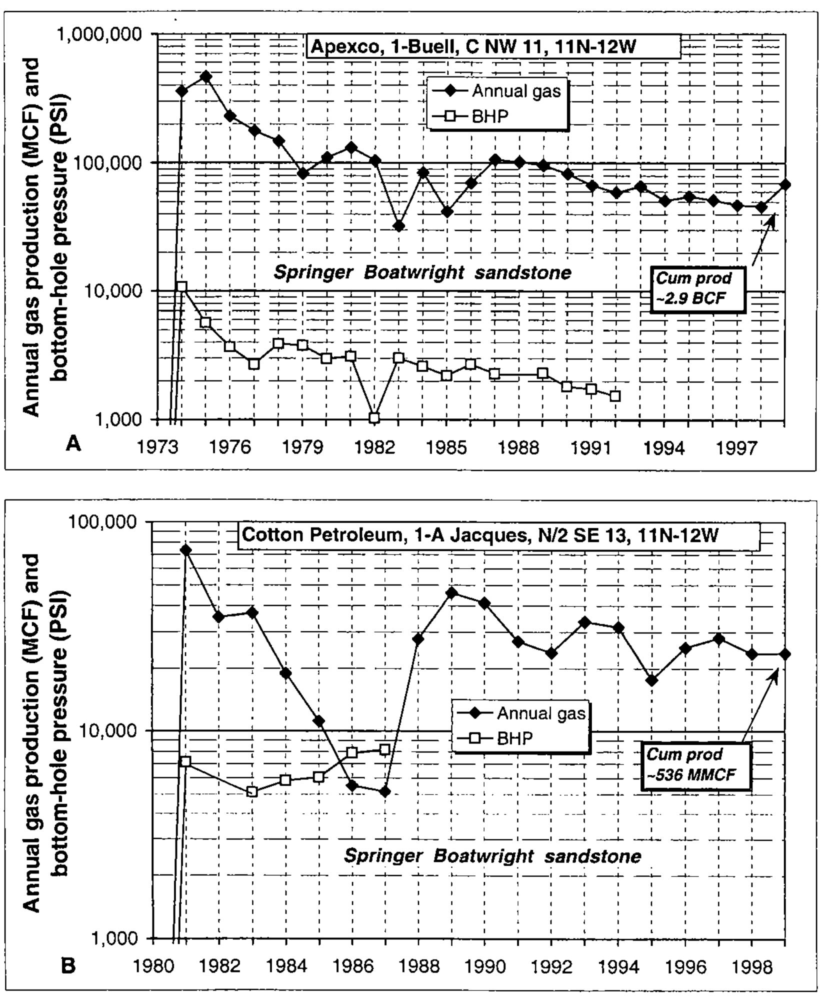

Figure 41. Production- and pressure-decline curves for two wells producing from the Boatwright sandstone in Lookeba field. Data are current through December 1999.

voir heterogeneity—i.e., variations in thickness, porosity, permeability, and lateral extent. The actual production and pressure data are presented in Table 7.

WELL-DRILLING AND COMPLETION PRACTICES

Wells in Lookeba field commonly are drilled with traditional water-based drilling fluids. The discussion of drilling techniques is beyond the scope of this study, but some important guidelines are noted for Springer wells in this area. Wells vary in depth from ~13,300 ft in the northern part of the field to almost 15,000 ft in the southern part. Most wells are only drilled to the base of the Boatwright sandstone. Another 200–250 ft would be necessary to reach the underlying Chester limestone, as a few wells did that are shown on field cross sections (Figs. 30, 31, in envelope).

Operators usually set 10.75-in. surface casing to about 1,500 ft, then set 7⅝-in. casing through the Cherokee section (to ~12,800 ft) and just above the Novi lime (the Novi lies beneath the Inola Limestone and about 200–300 ft above the Thirteen Finger lime within the Atoka Formation), then 4.5- to 5.5-in. liner to very near the bottom of the hole. Drilling mud weights are in the range of 9–10 ppg through the Cherokee section, then they increase to 15–16 ppg through the Morrow–Springer intervals. Sometimes, 2⅞- or 3.5-in. liner is used instead of the ~5-in. liner.

Completion reports indicate that many wells are acidized with 1,000–5,000 gal of 7.5% HCl. In all productive wells, the Springer sands are stimulated with a fracture treatment consisting of various treated gels (commonly water or acid gel). Amounts range from about 20,000 to 60,000 gal plus about 10,000–60,000 lb of sand.

Well-drilling costs for a conventional vertical well to a depth of ~14,000 ft, where overpressuring is anticipated, are estimated at $1.4 million for a dry hole and $2.0 million for a completed well having a single zone completion in the Springer (estimated costs as of February 2001). As in Sickles North field, wells usually take from 3 to 6 months, and sometimes up to a year, to drill and complete.

PART III

Sickles North Field

Britt and Boatwright sandstone gas reservoirs in northern part of T. 11 N., R. 12 W., southwestern part of T. 12 N., R. 12 W., and eastern part of T. 12 N., R. 13 W., northern Caddo County, Oklahoma

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INTRODUCTION

Sickles North field is in northern Caddo County, west-central Oklahoma (Fig. 42). The 64-section study area lies in the east-central part of the Anadarko basin about 16 mi east-southeast of Weatherford and about 2–4 mi south of I-40 (Pl. 2, in envelope). It is contiguous to the Lookeba field study area, previously described in Part II of this publication, which lies directly to the southeast. All the maps in both study areas adjoin one another but may differ slightly as to scale. As recognized by the Oklahoma Stratigraphic Nomenclature Committee of the Mid-Continent Oil and Gas Association, Sickles North field includes production from the Springer in addition to the younger Pennsylvanian Marchand, Deese, Red Fork, Atoka, and Morrow sandstones.

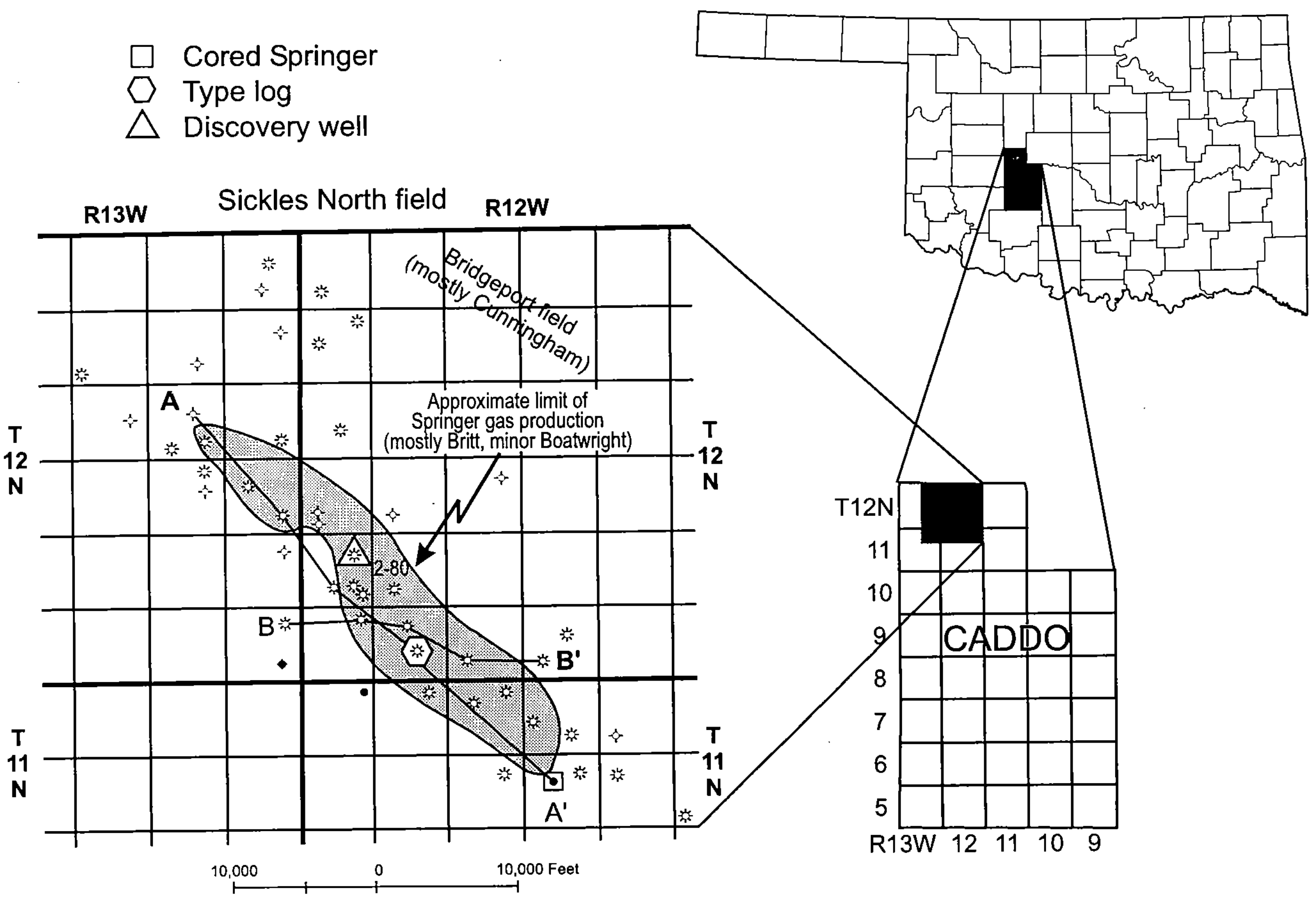


Figure 42. Generalized location map of Sickles North field in northern Caddo County, Oklahoma. Lines of cross section A–A′ (Fig. 45) and B–B′ (Fig. 46) are shown.

This study investigates only the Springer Britt and Boatwright reservoirs, which produce gas from detached offshore-marine bars. Many additional gas wells in the northeastern part of the study area produce from the Red Fork and Springer Cunningham sandstones in Bridgeport field. The productive limits of Sickles North field are generally well defined on the basis of log interpretations. With regard to both Springer producing zones, this field appears to be fully developed and is in the mature phase of production.

As a rule, the Springer sandstones in Sickles North field occur as long, narrow sand bodies (bars) that trend northwest–southeast and are separated from each other by narrower zones of marine shale. All sandstones with at least 6% porosity are capable of producing gas unless the downdip parts are water-wet. Individual bars generally have pressure communication throughout most of their extent. Bars that are separated by marine shale have independent reservoir-pressure regimes. Britt sediments in this study area probably were carried down incised-channel complexes from the north and northeast and were reworked in a marine-shelf environment, as indicated on the regional sandstone maps (Pl. 2, in envelope). The origins of the Boatwright sandstone are not so clear, but these sands are believed also to have come from the south and also redistributed as offshore bars. The known gross thickness of the Cunningham sandstone is 50 ft, and of the Boatwright, 28 ft. However, because of authigenic clays and silica cementation, the net reservoir sandstone is usually much thinner. These values can be compared on the gross- and net-sandstone isopach maps prepared for each reservoir.

Both the Britt and Boatwright sandstones have similar well-log shapes showing a definitive coarsening-upward textural profile. This characteristic is best illustrated on the gamma-ray and resistivity logs of wells accompanying this study. As with the Cunningham in Lookeba field, these similar-shaped log patterns are indicative of a relatively simple depositional setting that is interpreted to be a shallow-marine shelf. Because of this, sandstones within and between bar complexes are easily correlated. This contrasts with the overlying Morrow sandstone units, which exhibit widely varying log patterns that indicate variable depositional environments. A map identifying all wells used in this study is shown in Figure 43; note that only wells that penetrate the Springer in the vicinity of Sickles North field are shown. Additional information shown in Figure 43 includes operators, well numbers, lease names, and completion dates.

Sickles North field was probably discovered as development drilling moved northwestward from Lookeba field, which produces primarily from the Cunningham sandstone. The first well in this study area, the Apexco No. 1 Buell, was drilled in late 1973 and was the field opener for the Springer Boatwright reservoir in Lookeba field, to the southeast. Subsequent wells drilled in 1975 to the west and in 1976 to the north were dry in the Springer. Then, in early 1980, Sanguine drilled a northwest offset to the Buell well and completed it in the Cunningham. Subsequent offsets to this well during the 1980s found the Britt reservoir instead. The field opener for the Britt reservoir is attributed to the Walsh No. 1 Kimble, completed in February 1980 in the NE¼ sec. 30, T. 12 N., R. 12 W. This well produced from 17 net ft (23 gross ft) of sandstone (>6% porosity, or ϕ), with an initial production (IP) of 4,200 MCFGPD. Its cumulative production was only 254 MMCFG, however, because of its proximity to the gas–water contact. Most of the additional field wells were drilled during the latter part of 1980 and in 1981. Some wells were drilled as late as the 1990s (the latest well was drilled in 1994), but these later wells were not nearly as productive as the early wells. The principal operators in the field are Mustang, Cotton Petroleum, Sanguine, Apache, and Woods Petroleum.

The original spacing of wells drilled in the 1970s and early 1980s was 640 acres, but increased-density wells were drilled on 320-acre patterns during the middle to late 1980s and in the 1990s.

The cumulative production of individual wells varies greatly, from <1 BCFG to almost 5 BCFG; it averages >2 BCFG/well. As of July 1999, 17 wells had been completed in the Britt, and four in the Boatwright. There are no Cunningham gas wells within the limits of Britt gas production. The Sanguine No. 1 Herbold in the SE¼ sec. 3, T. 11 N., R. 12 W., produces from both the upper and lower Cunningham sands, but this well is ~0.5 mi southeast of Britt production. Four wells have dual completions in both the Britt and Boatwright zones, making individual zone performance difficult to determine. The gas has a relatively low specific gravity (about 0.57–0.58), and little condensate is produced. The condensate that is recovered comes primarily from wells completed late in the development history of the field. No significant amount of formation water is produced from any of the Springer reservoirs.

STRATIGRAPHY

A typical log from Sickles North field, and the stratigraphic nomenclature, are shown in Figure 44. In this well the Springer formation is about 350 ft thick and includes three sandstone units: the Cunningham, Britt, and Boatwright, in descending order. Additional informal subsurface names have been applied locally and are identified on regional cross sections B–B′ and C–C′ (Pls. 7, 8, in envelope). Each of the three Springer sandstone intervals contains more than one major sandstone zone, the upper and lower Cunningham being the most conspicuous example. Beneath the Springer formation is a thick marine shale that is correlative with the Goddard Formation in the Ardmore basin. The Goddard shale within the study area is about 200–250 ft thick. It overlies the Chester limestone, as noted on one well log in the field cross sections.

As a rule, the division between the three Springer sandstone intervals is quite simple, as noted in the discussion of Lookeba field. In the type log (Fig. 44), a thin shale zone having a "hot" gamma-ray response typically occurs between the Cunningham and the underlying Britt (at 13,928 ft). Beneath the Britt, the top of the Boatwright interval is picked at the top of the uppermost sandstone beneath the Britt shale. The base of the Boatwright sandstone interval is an arbitrary pick below the lowermost Boatwright sandstone where the underlying strata are consistently shale. On well logs, the Boatwright shale (or Goddard shale) exhibits very low resistivity and a high density–neutron response. Log characteristics of Springer reservoirs in this field include a "clean" gamma-ray re-

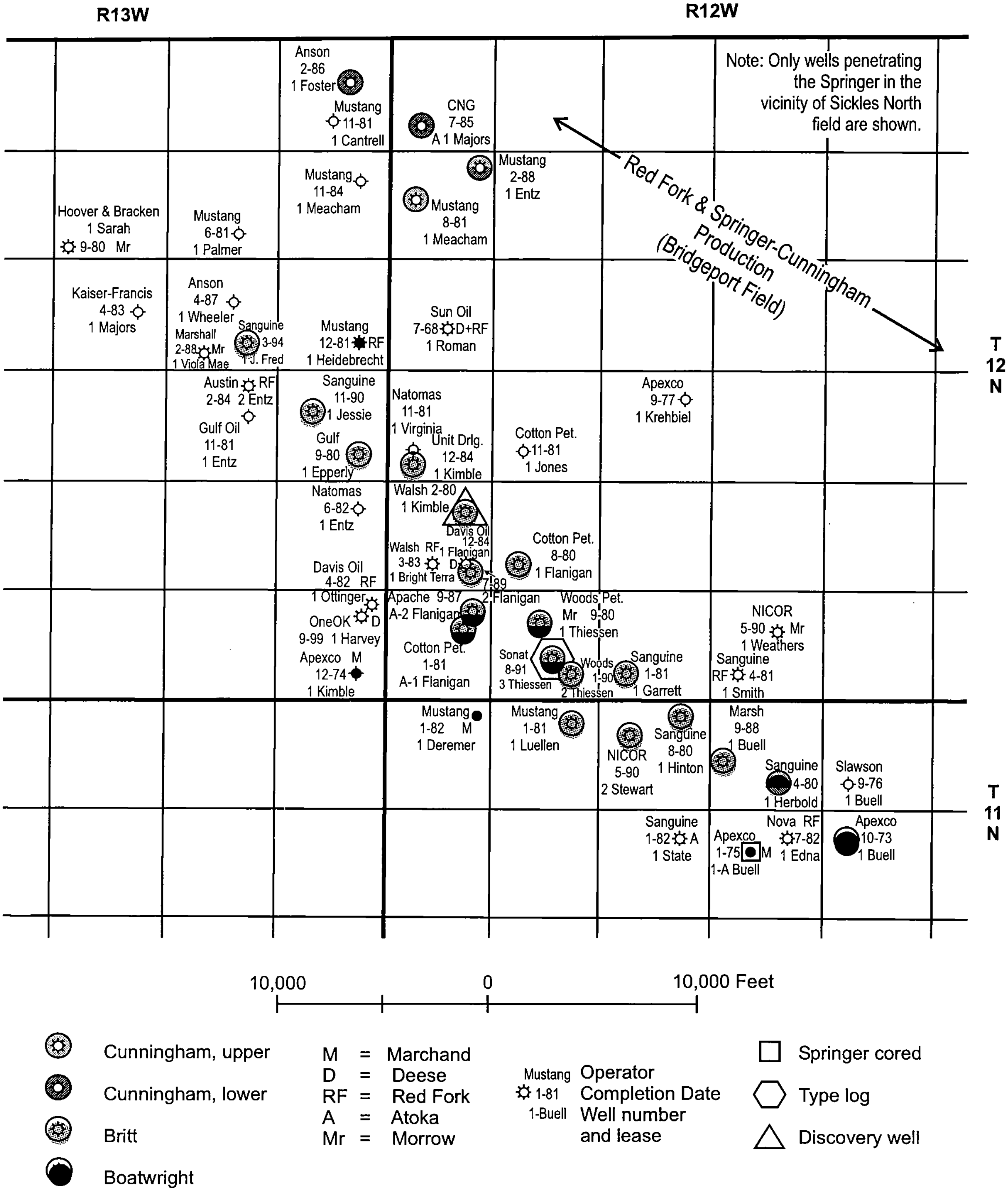


Figure 43. Well-information map, showing operators, well numbers, lease names, producing reservoirs, and completion dates in Sickles North field, northern Caddo County, Oklahoma.

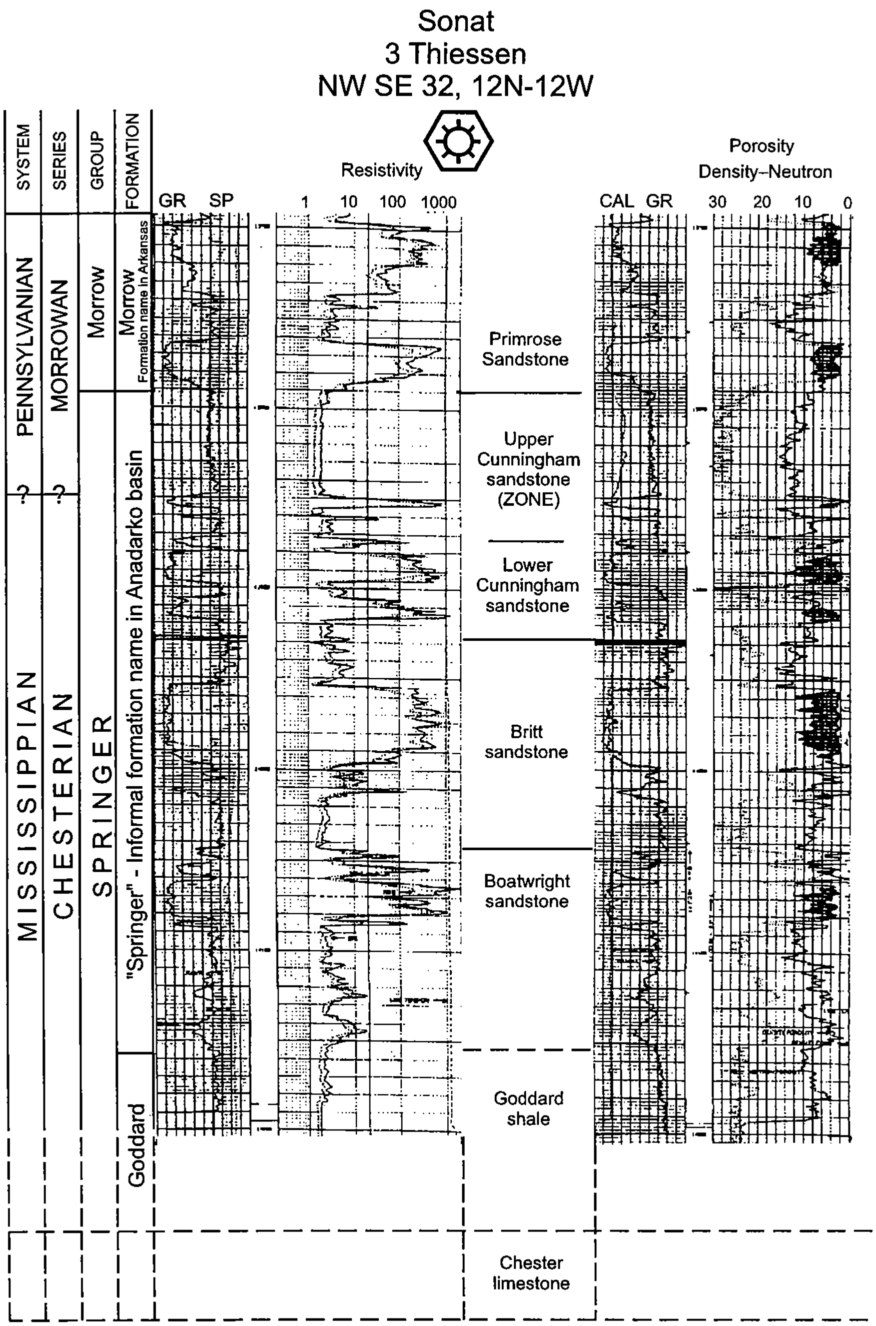


Figure 44. Type log for Sickles North field, showing formal and informal subsurface nomenclature of the Springer Group as used in the Anadarko basin of western Oklahoma. *GR* = gamma ray; *SP* = spontaneous potential; *CAL* = caliper.

sponse, a clearly identifiable SP response, a cross-plot porosity of at least 6%, and a resistivity of at least ~50 ohm-m. These criteria are most evident in the Britt sandstone, and are less so in the Boatwright sandstone.

The top of the Springer formation in Sickles North field is much more difficult to identify on well logs. It is usually recognized by a shale interval directly beneath the lower Morrow Primrose Sandstone, which has very low resistivity (high conductivity, as shown on the regional cross sections). This situation is somewhat complicated where the Primrose shales out, creating a shale-on-shale contact for the Springer–Morrow boundary. This is evident particularly in well 2 on both cross sections A–A′ and B–B′ (Figs. 45, 46, in envelope). In many cases, the neutron-porosity response is highly sensitive to the types of clays in the Springer and has a sharp inflection to the left.

Cunningham Sandstone

The Cunningham includes two distinct sandstone zones, the upper and lower, and together with shales they occupy an interval that is almost one-third the thickness of the Springer formation in this area. In most wells, the upper Cunningham is very shaly and is not productive. It is not mapped separately in this study. The lower Cunningham is relatively thick (at least 60 ft) locally but is tight or becomes shaly. It is nonproductive and is not mapped separately in this study.

Britt Sandstone

The Britt sandstone is the principal and most widespread reservoir in Sickles North field. The sandstone trend is that of an offshore-marine-bar complex extending tens of miles to the southeast into Lookeba field, where the Britt becomes tight or is mostly shale, and to the northwest, where the Britt is tight or wet. Perpendicular to the main bar trend, in a northeast–southwest direction, sandstone in the Britt interval thins to only a few tight feet, forming the stratigraphic trapping mechanism for this field. Within the main part of the bar trend, the Britt commonly has a gross-sandstone thickness of 30–50 ft. However, the net reservoir thickness, using a 6%-porosity cutoff, is usually only 10–20 ft. Cross-plot porosity is typically about 5–10% (unadjusted for limestone matrix) and averages about 7% in producing areas. Core data from a nonproducing Britt interval southeast of the field (see later discussion) had permeability measurements in the range of <0.1 to 0.3 md. Porosity and permeability reductions from authigenic-silica(?) cementation are the largest detriment to the productive nature of this reservoir. Conversely, many areas with porous sandstone have high water saturations and are not productive. This is generally the case for the southwest (downdip) part of Sickles North field. On well logs, a significant SP deflection through the Britt sandstone is a good indication of reservoir-grade porosity and permeability.

As seen on gamma-ray logs, the Britt sandstone invariably has a distinct coarsening-upward textural profile. The transition from shale to sandstone at the bottom is rapid rather than gradual, so there is little development of a bar transition facies. The upper sandstone contact with overlying marine shale is invariably sharp. No log signatures have a distinctive fining-upward shape that would indicate a channel deposit. Mapped patterns of the Britt sandstone show elongate northwest–southeast-trending sand bodies; the thickest or central part of the bar trend is characterized by a rapid vertical transition from shale to sandstone, whereas the edge wells tend to have a gradual coarsening-upward transition. Therefore, depositional facies vary from a central bar complex to bar-fringe deposits.

Boatwright Sandstone

The Boatwright is the lowermost sandstone unit in the Springer formation. The Boatwright interval contains only one main sandstone zone, but this can be composed of several thin sandstone beds with thin shale interbeds. The remainder of the Boatwright interval consists of a thin-bedded to a laminated, silty, sandy, and shaly section that has somewhat higher resistivity than the baseline shale. This zone is probably a bar transition zone that might have developed locally into cleaner sandstone.

The Boatwright sandstone is widespread, and there is seldom less than 5 ft of gross sandstone anywhere within the study area. A maximum thickness of 28 ft is found in one well in the NW¼SE¼ sec. 32, T. 12 N., R. 12 W. The Boatwright seldom develops reservoir porosity >6%, and only four productive wells in secs. 31 and 32 encountered at least 6 ft of net sandstone.

Much of the Boatwright sandstone is shaly and tight. Locally, however, reservoir properties are similar to, or even better than, those of the Britt. In the four producing wells, porosity ranges from 5% to 11% but averages only ~6% (cross-plot porosity unadjusted for limestone matrix). Permeability in those wells is probably lower than that in the Britt.

CROSS SECTIONS

The stratigraphy of the Springer interval is best shown on the detailed stratigraphic cross sections constructed through Sickles North field. Cross section A–A′ (Fig. 45, in envelope) is a strike line, and cross section B–B′ (Fig. 46, in envelope) is oblique to strike. Both sections use the "hot" gamma-ray marker bed between the Cunningham and Britt intervals as a common datum. Cross sections were laid out to show producing limits of principal reservoirs and reservoir facies instead of merely showing the high-volume producers.

Cross Section A–A′ (Figure 45)

This section illustrates the productive characteristics and the water-wet zones in the Britt sandstone, in addition to facies relationships in the underlying Boatwright zone. The cross section is oriented in a northwest–southeast direction and is parallel to the bar trend. Wells 2 and 4 are productive in the Britt and were drilled within the central bar complex. Well 1 was drilled along the northern fringe of the bar and encountered the bar-margin deposits. Well 3 is wet in the Britt, and well 5 is south of the limits of Britt production, where the interval is either tight or wet.

In well 1 the lower Cunningham and Britt sandstones are both dry, primarily because of low porosity. A thin porous streak in the lower Cunningham at ~13,490 ft is obviously wet; note the very low deep resistivity in that zone (<30 ohm-m). The relatively thin nature of the Britt and the coarsening-upward textural profile on the gamma-ray and resistivity logs indicate that bar-margin facies prevail at this location. The underlying Boatwright interval contains very little sand, and that which is present is dirty, as indicated by the suppressed gamma-ray deflection to the left. The basal contact of the Boatwright with the Goddard shale is most evident on the resistivity log.

About 1.8 mi to the southeast at well 2, the Britt sandstone shows the typical rapid transition from the underlying shale to sandstone. This well is in the central bar complex and has >30 ft of gross sand. The best porosity (about 6–9%) is in the upper part of the bar and is perforated. The corresponding deep resistivity is generally 60–100 ohm-m, and the well produced ~2.2 BCFG. Both the overlying lower Cunningham and underlying Boatwright intervals are shaly and are not of reservoir quality.

In well 3, about 1.2 mi farther southeast, the upper Britt sandstone is even thicker than in well 2, but the entire sandstone interval is wet, as indicated by the low deep resistivity of <35 ohm-m in most of the sandstone section. The good SP deflection, however, indicates that this is a relatively porous and permeable sandstone. The lower Britt is thin and tight. The overlying lower Cunningham sandstone is thick but is wet where porous. The underlying Boatwright comprises several feet of gross sandstone, but it is all shaly or tight.

The type log section for Sickles North field is from well 4, which is about 1.4 mi southeast of well 3. At this location, all three Springer intervals have relatively thick, porous sandstones. The upper Britt sandstone is ~44 ft thick and displays the characteristic rapid basal transition from shale to sandstone and sharp upper contact with shale. It is the principal reservoir in Sickles North field. Most of the upper Britt is perforated; net sandstone is ~17 ft, with porosity >6%. In the underlying Boatwright interval, the sandstone reaches a maximum field thickness of about 25 ft, but all but about 7 ft is tight. The Boatwright was perforated but contributes little to the field's production. As in well 1, the contact with the Goddard shale is evident from the gamma-ray and porosity logs. Above the Britt, the lower Cunningham is moderately well developed, with several feet of net sandstone. It was not perforated, however, because the resistivity log indicated that it was wet.

Well 5 is about 2.5 mi southeast of well 4 and is just outside the productive limits of both the Britt and Boatwright sandstones. The Britt is relatively thick at this locality, but the upper half is tight, and the lower several feet appears to be wet. The Boatwright sandstone at well 5 is very shaly and no longer has reservoir porosity. The Cunningham is also mostly shale.

Well 5 was included in cross section A–A′ because it was cored through most of the Springer sandstone intervals and across the Morrow–Springer contact. Discussion of this core is in a later section of this field study.

Cross Section B–B′ (Figure 46)

This section is oriented west to east across the center of Sickles North field. It is intended to show the relationship between the interbar and bar-center facies of the Britt sandstone as well as the character of the Boatwright sandstone, both of which produce in this area.

Just beyond the western limit of Sickles North field, well 1 shows the typical interbar facies of the upper Britt interval that is nonproductive. The upper Britt and lower Cunningham sands were perforated and tested, but little or no gas was recovered. The lower Britt is unusually well developed in this well but is also nonproductive because of high water saturation. The underlying Boatwright sandstone is very thin and tight and is dry.

At well 2, about 1 mi to the east, the upper Britt sandstone has thickened to ~37 ft and has relatively good porosity. The deep resistivity in this well of 60 to >100 ohm-m is typical of an exceptional well, which has produced >4.8 BCFG. The gradational basal contact and sharp upper contact with shale is again typical of the offshore-bar concept adopted in this study. The underlying Boatwright also has porosity developed in a ~6-ft interval that was also perforated. The overlying Cunningham interval is largely shale, best interpreted from the gamma-ray and resistivity log traces.

The Britt and Boatwright sandstones in well 3, about 0.6 mi east of well 2, have similar thicknesses and log characteristics. As in well 2, the Britt in well 3 is part of the central bar complex, indicated by the rapid gradational lower contact and sharp upper contact with shale. High deep resistivities of 60 to almost 200 ohm-m in the presence of porosity indicate a productive section. The statigraphically higher Cunningham sands, although numerous, are not productive because of high water saturation or low porosity.

Well 4, nearly 1 mi farther east, is close to the eastern margin of Sickles North field. At this locality the upper Britt sandstone thins from ~44 ft in well 3 to slightly >30 ft in well 4. The high deep resistivity of ~100 ohm-m in a relatively thick porous zone is indicative of a highly productive well. To date, it has made almost 5 BCFG. The underlying Boatwright sandstone in this well is thin but appears to have gas potential by virtue of the relatively high porosity (~11%) and corresponding deep resistivity of ~50 ohm-m. This sand probably was not perforated because of the more favorable Britt reservoir. The Cunningham interval at well 4 contains several sandstone zones that appear tight.

Well 5 was drilled just east of the productive limits of the field. The relatively thin, gradually coarsening-upward log profile of the Britt sandstone is indicative of bar-margin or interbar facies. Some porosity is noted in the upper part of this bar, and limited gas potential may be present in this zone. The same is true in the underlying Boatwright sand, which was perforated and tested. Results are not known, but the relatively low deep resistivity corresponding to porosity may indicate relatively high water saturation, which is probably the case for the overlying Britt sand as well. The overlying lower Cunningham sand has cross-plot porosity of <6%, so it is doubtful that this zone has much gas potential.

STRUCTURE

Sickles North field is in the east-central part of the Anadarko basin and is structurally on strike with Lookeba field (Pl. 5, in envelope). In the deep subsurface, beds dip to the southwest between 2.4° and 3.7° (<200 to ~300 ft/mi). A detailed structure map of the study area (Fig. 47) shows the configuration of the top of the "hot" shale marker between the Britt and Cunningham intervals (see type log, Fig. 44). The highest position in Sickles North field is in the SE¼ sec. 14, T. 12 N., R. 13 W., at about –11,950 ft. The structurally lowest part of the field is in the NE¼ sec. 5, T. 11 N., R. 12 W., at about –12,350 ft. The vertical relief of the gas column, therefore, is about 400 ft. A pronounced structural trough extends through the center of the field in a north–south direction. This trough is probably due to deep-seated faulting, but it is doubtful that the Springer has any fault displacement.

The regional dip at the top of the Springer Group in the Sickles North field area is about 2.3° to the southwest (Pl. 5, in envelope) and is uncomplicated by faulting or folding. Hydrocarbon trapping appears to be strictly stratigraphic within the area.

SPRINGER SANDSTONE DISTRIBUTION AND RESERVOIR CHARACTERISTICS

The principal reservoir in Sickles North field is the upper Britt sandstone, whereas the Boatwright sandstone is a distant secondary objective. Isopach maps consisting of gross- and net-sandstone thicknesses for both these reservoirs are included in the study.

Upper Britt Sandstone

Figure 48 shows the combined gross thickness of the upper and lower Britt sandstones. Usually, this value represents only the upper Britt, as the lower unit is mostly absent. Only Springer wells within and close to the Sickles North field area are included in this and other geologic maps. The gross-sand thickness is the total thickness of sandstone regardless of porosity, as interpreted from gamma-ray logs (determined from the 50% sand/shale line). Usually less than half the gross Britt sandstone has net porosity >6%. This means that for the Britt to be prospective in this study area, it must be at least 20–30 ft thick to have significant porosity. Gross sandstone of lesser thicknesses are generally dirty and tight because there is not enough sand in the central bar facies to constitute a reservoir.

The upper Britt does not reach a zero thickness on the gross-isopach map, because thin, tight, dirty sandstone lenses persist over the entire mapped area. The thickest

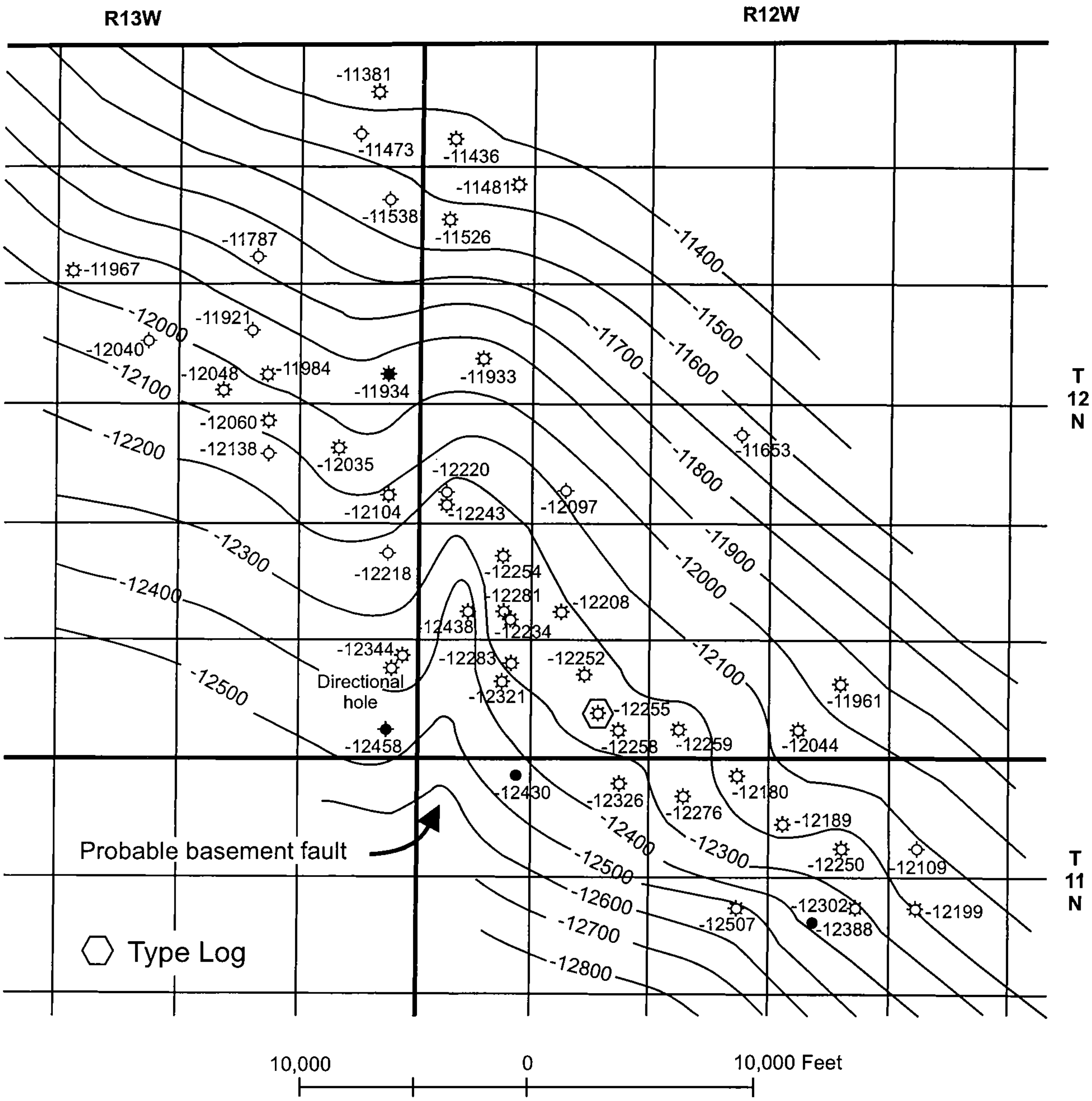


Figure 47. Structure map depicting the top of the Britt interval (gamma-ray marker), Sickles North field. Contour interval is 100 ft. Datum is mean sea level. See Figure 43 for well names.

sandstone occurs in the central bar complex, where it is also the cleanest sandstone. Only one major Britt bar complex produces in North Sickles field. Another minor trend occurs in the northeasternmost part of the study area in Bridgeport field, but this is not mapped.

The gross thickness of the Britt sandstone within Sickles North field ranges from about 10 to 50 ft. The thinnest sandstone occurs along the northeast and southwest margins of the bar trend. The log and stratigraphic appearance of the bar-margin facies have a distinctly gradual coarsening-upward profile, as seen in wells 1 and 5 in cross section B–B´ (Fig. 46, in envelope). Where productive, the gross sandstone is usually >20 ft thick and averages ~39 ft. Thickness variations occur over short distances at right angles to the bar trends. Parallel to the bar trends, thickness variations are generally gradual.

Like the Cunningham in Lookeba field, the Britt interval usually contains a large amount of sandstone, indicating that much sand was transported onto the marine shelf during late Springer time. Where the sandstone is relatively thick, log signatures have the following characteristics that reflect the textural profile of the sandstone sequence: a rapid transition over a 5–10-ft interval from shale to sandstone at the base, overlain by a thick (about 20–40-ft) sandstone sequence having a relatively clean or blocky log response, and finally a sharp upper contact with shale. The resulting profile, therefore, characterizes the sand-grain size as coarsening upward. Wells 2–4 in

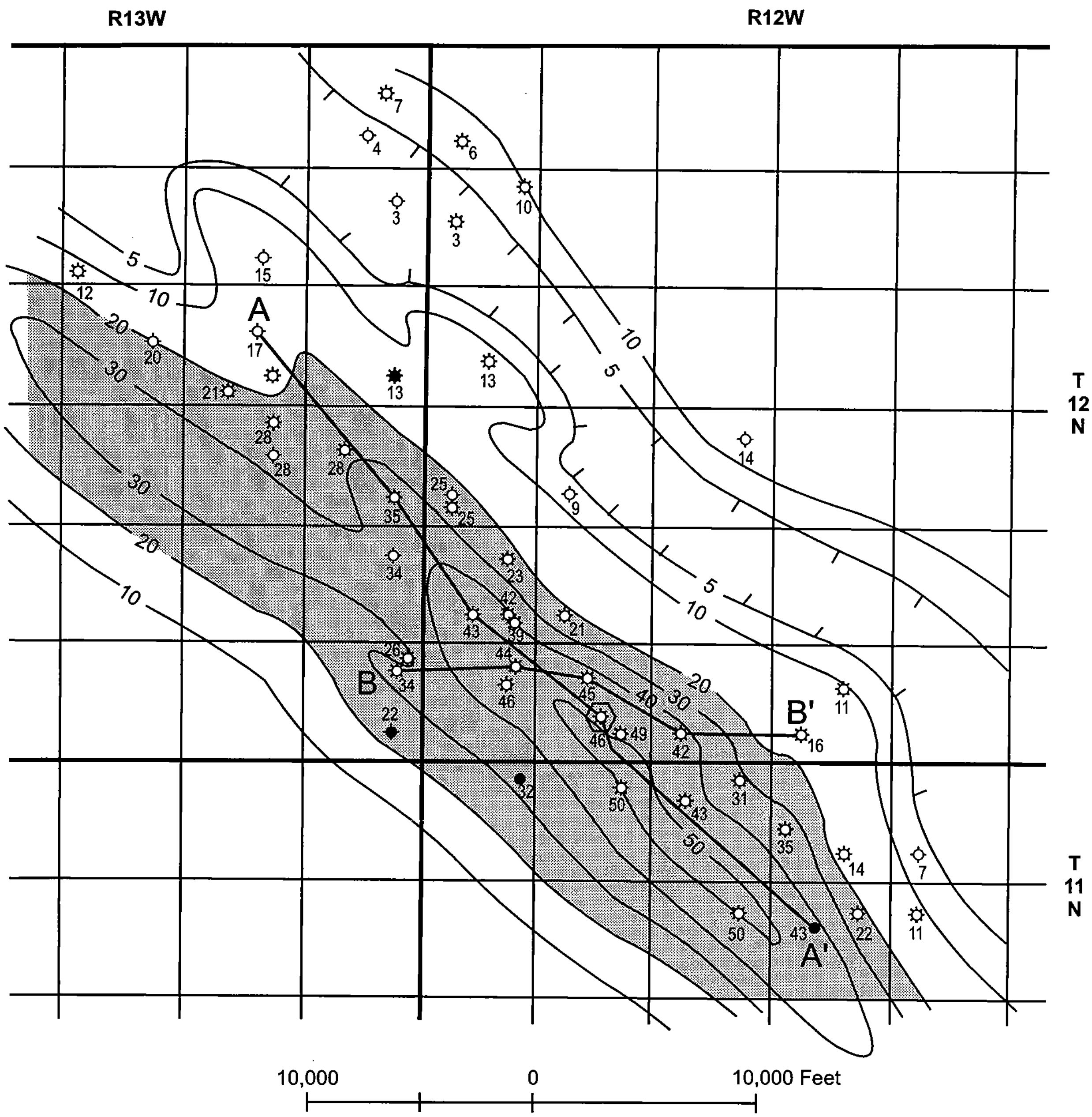


Figure 48. Gross-isopach map of the Britt sandstone in Sickles North field. Contour interval is 10 ft unless otherwise noted. See Figure 43 for well names. Hachures indicate a trend <5-ft thick.

both cross sections (Figs. 45, 46, in envelope) show these log signatures. The bar margin and interbar facies have a more gradual upward-coarsening profile over the entire sandstone interval.

The upper Britt sandstone is a shallow-marine-bar complex encapsulated in marine shale. No bay-fill, coal, or delta-plain deposits are associated with it. The net-sandstone isopach map of the Britt sandstone (Fig. 49) shows the thickness of sandstone in wells having porosity >6%, which was judged to be the approximate lower limit of porosity in producing wells within Sickles North field. Porosity values were determined by visually averaging the cross-plot porosity on density–neutron logs, as described in a later section on formation evaluation. In producing Britt wells, the net-sand thickness generally ranges from only a few feet to a little less than 20 ft. The maximum net-sandstone thickness in producing wells is 28 ft (SE¼NW¼ sec. 32, T. 12 N., R. 12 W.).

Throughout the area mapped, the average net-sandstone thickness is ~14 ft. The net-sand isopach map (Fig. 49) is similar in overall appearance to the gross-sand isopach map (Fig. 48), but with a significant reduction in sandstone thickness. This is due to clay-rich and tightly cemented zones within the Britt interval that are included in the gross-isopach thickness. The difference in thickness between the gross and net sandstone in wells within

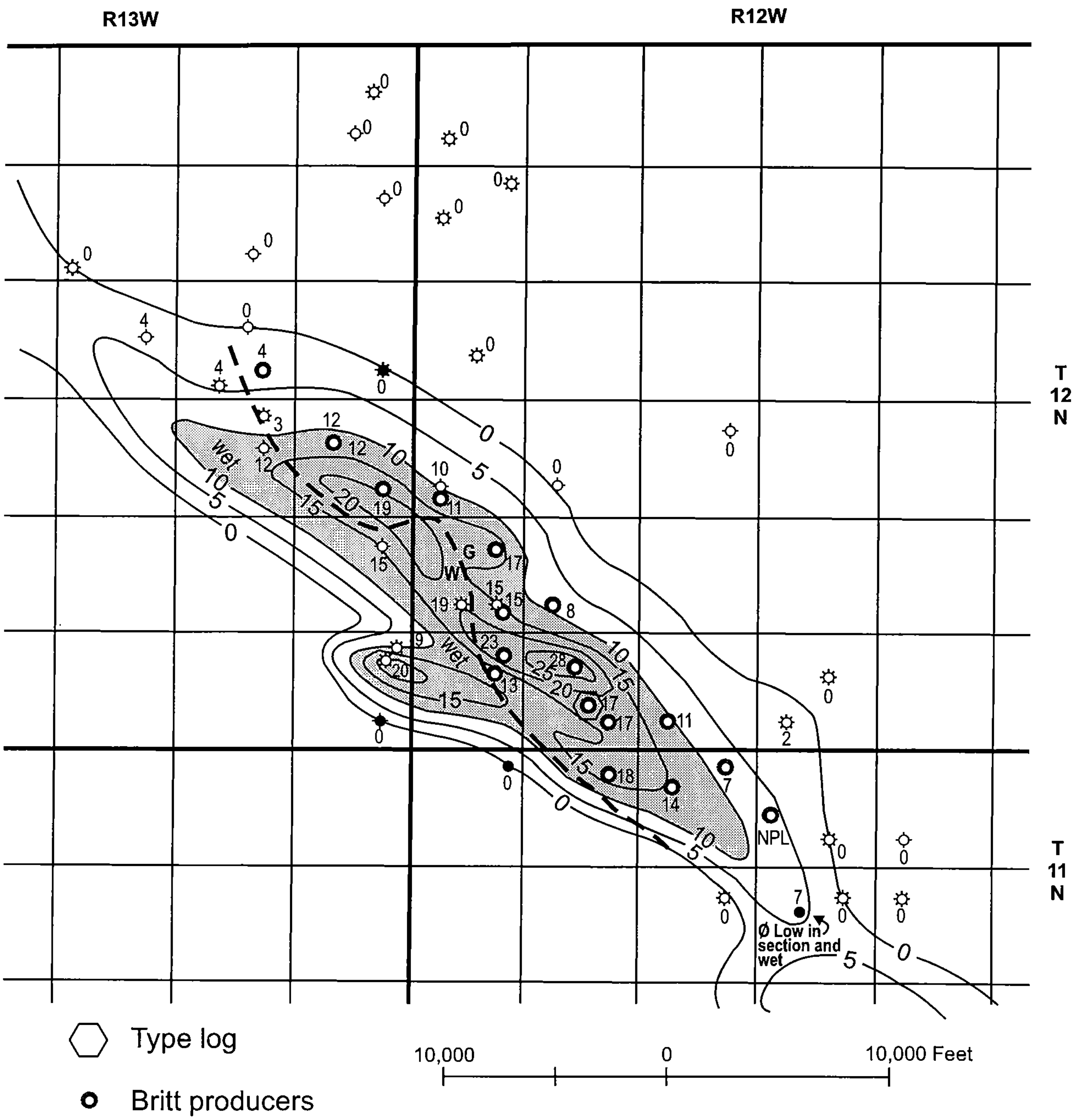


Figure 49. Net-isopach map of the Britt sandstone in Sickles North field. Net sandstone has a log porosity >6%. Contour interval is 5 ft. See Figure 43 for well names. *G* = gas; *W* = water.

the shaded area on the gross-sandstone map (within the 20-ft contour interval) is usually about 15–25 ft; mostly, this constitutes a decrease of 50% from the original gross-sandstone thickness in wells that have at least 20 ft of gross sandstone. In some cases this reduction is more than 90% in wells with relatively thick gross-sandstone sections along the southeastern part of the bar trend. Porosity reduction below 6% is the primary reason for hydrocarbon trapping in this area. The net-versus-gross-sandstone relationship can easily be seen by comparing the gamma-ray and porosity responses on any of the logs shown in cross sections A–A′ and B–B′ (Figs. 45, 46, in envelope). Net sandstone has porosity in the range of 6–10%, and there are no exceptionally high porous zones in any wells.

Water-saturation calculations indicate a gas–water contact within the Britt bar trend, as shown on the net-sandstone isopach map (Fig. 49). The gas–water contact was identified from logs of wells that were either nonproductive or had zones that calculated wet, using a variety of formation-evaluation techniques. The hypothetical position of a 3-ft contour line on the net-sandstone isopach map (Fig. 49) seems to be the productive limit of Sickles North field, except in the southeastern part of the field, where 7 ft of net porosity was indicated for the lower part of the Britt, which appears to be wet.

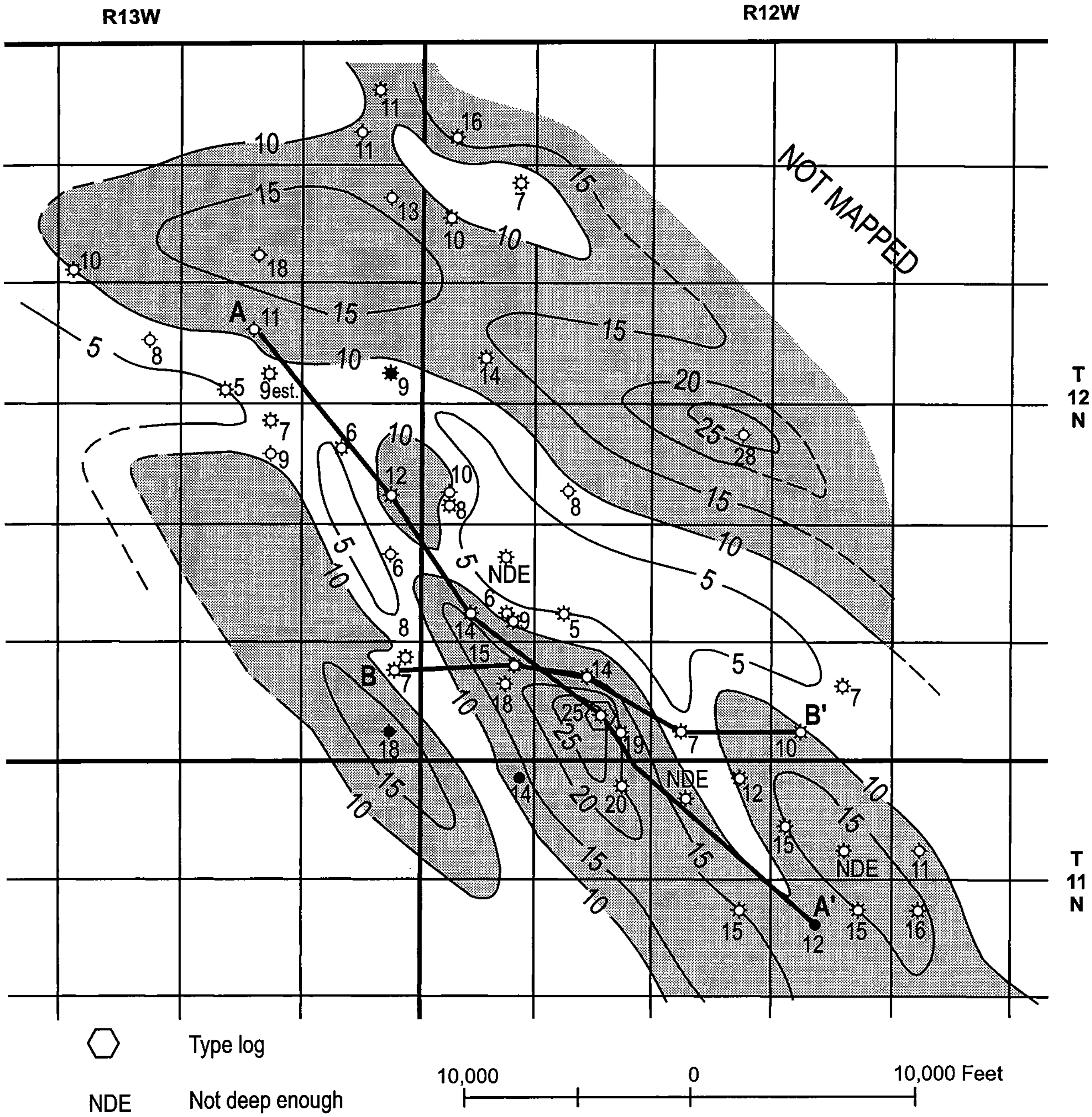


Figure 50. Gross-isopach map of the Boatwright sandstone in Sickles North field. Contour interval is 5 ft. See Figure 43 for well names.

Compartmentalization in the Britt sandstone is not prevalent when considering reservoir pressures, as all wells that were brought on line after the initial few wells (following 1980) were completed had significant pressure depletion. The net-sandstone isopach map supports this observation, for nowhere within the limits of the zero contour are there separate pods of sandstone that "zero out." However, because of reservoir heterogeneity between and within beds that make up the total net-sandstone assemblage, some areas in the field probably have very little pressure communication and therefore exhibit characteristics of partial compartmentalization.

Boatwright Sandstone

Figure 50 shows the gross thickness of the Boatwright sandstone interval in all the wells drilled through that zone in the vicinity of Sickles North field. Gross sandstone in this study is the total thickness of sandstone, regardless of porosity, as interpreted from gamma-ray logs (determined from the 50% sand/shale line). The interval in which the Boatwright sandstone occurs is usually 80–100 ft thick, and there is usually only one sandstone present, which is at the top of this interval. This sandstone zone can be composed of several thin beds separated by shale, but they are all in the same stratigraphic position in the same bar, so they are all considered to be aggregates of the same bar. The Boatwright sandstone is distributed in an elongate northwest–southeast trend that persists to the southeast into the Lookeba field study area. Thickness variations are similar to those of the overlying Britt sandstone, where sandstone is most continuous parallel to the bar trends and most variable at right angles to them.

Where the Boatwright sandstone is present, its gross thickness is generally in the range of 5–15 ft, and only two wells had more than 20 ft (interpreted in secs. 21 and 32, T. 12 N., R. 12 W.). Where it is productive, the average gross-sand thickness is ~9 ft. The two most conspicuous sand trends are in the central part of T. 12 N., R. 12 W., and in the southwestern part of T. 12 N., R. 12 W. The latter trend is the only one that is productive in Sickles North field; it contains a zone of porous and permeable sandstone. Sandstone in the center of T. 12 N., R. 12 W., is tight.

As with the other Springer sandstones described in this study, the Boatwright in Sickles North field appears to occur in a series of elongated offshore-marine bars. Textural profiles are decidedly coarsening upward, with sharp upper contacts with shale. Marine shale completely encapsulates the sandstone, and there are no associated deltaic deposits. These sand bodies cannot, therefore, be considered distributary-mouth bars but instead are interpreted as detached offshore bars. Porosity in these kinds of sand deposits is usually in the upper part of the bar and stands apart from the rest of the upward-coarsening bar sequence. But in the Boatwright of this field, porosity zones are very thin owing to the thinness of the upper-bar facies (the blocky part of the gamma-ray log at the top of the sandstone zone).

The net-sandstone isopach map of the Boatwright (Fig. 51) shows no resemblance to the gross-isopach map (Fig. 50) because most of the Boatwright sandstone is tight. Scattered areas having some net porosity occur where the gross sandstone is thickest. This is not to say that there is no sandstone between areas with net sandstone, but only that areas of porous sandstone are discontinuous.

Criteria used for delineating net porosity are the same as those used for the Britt. A cutoff of <6% is judged to be the approximate lower limit of porosity in producing wells in Sickles North field. The productive Boatwright net-sand thickness ranges from only a few feet to a maximum of 7 ft and averages a little less than 5 ft. A porosity cutoff much above 6% would reduce the areal extent of the reservoir to practically nothing.

The thickest and most widespread occurrence of net Boatwright sandstone is in the southeastern part of the mapped area. This trend continues into Lookeba field, where the Boatwright is a considerably better and more widespread reservoir. As with the other sandstones described in this study, net-sandstone trends are parallel to the gross trends in a northwest–southeast direction. Differences between the net- and gross-sandstone thicknesses may be due to clay-rich and tightly cemented zones. This interpretation can sometimes be made from resistivity and gamma-ray logs; the resistivity in tightly cemented zones is considerably higher than in porous zones, and shaly zones rich in clay have higher gamma-ray values. These differences are much greater in the Boatwright sandstone than in the overlying Britt sandstone. Many wells having 10–15 ft of gross Boatwright sandstone contain little or no net sandstone, a decrease of up to 100%. Where productive, most of the sandstone has porosity in the range of 5–11%, but averages only ~6%. Boatwright wells in this field do not produce nearly as well on a per-acre-ft basis in comparison to the Britt, probably because of the generally dirty, thin, and spatially limited reservoir.

An unknown amount of gas is produced from four Boatwright wells in secs. 31 and 32, T. 12 N., R. 12 W., because production is commingled with gas produced from a much larger Britt reservoir. Judging from the single-zone completions of the Boatwright sandstone in adjoining Lookeba field, the combined cumulative production from all four wells in Sickles North field is probably <2 BCFG from a very thin reservoir. This estimate is only slightly less than the calculated gas in place, which means that little gas potential remains for the Boatwright in this area. No gas–water contact is evident in this small gas-producing sand pod. Boatwright production in sec. 11, T. 11 N., R. 12 W., was previously discussed in the Lookeba field study.

One well in the trend previously described appears to have limited untapped gas potential in a thin Boatwright sand. The well was drilled in the SW¼ sec. 33, T. 12 N., R. 12 W., where water saturation in a 3-ft zone is only ~36%. This zone may be isolated, or it could adjoin the producing sandstone pod in secs. 31 and 32 to the west.

DEPOSITIONAL ENVIRONMENTS OF BRITT AND BOATWRIGHT SANDSTONES

Depositional environments were interpreted from wireline-log signatures and map patterns in order to understand the general depositional setting of sandstone within the Sickles North field study area. Also, one core from the Apexco well in the NW¼ sec. 10, T. 11 N., R. 12 W., was examined from which interpretations were made (see Appendix 4). Logs from all Springer wells in this area were used for interpretation, particularly gamma-ray and resistivity logs. Both reservoirs are interpreted to have been deposited by similar processes and in similar marine environments.

Detached-Offshore-Bar Interpretation

The depositional environment of both the Britt and Boatwright sandstones in Sickles North field appears to be the same as that of the Cunningham as described in Lookeba field to the southeast: the sands were deposited in a shallow-marine shelf environment. The sand was transported and deposited several miles offshore in water depths most certainly less than 150 ft and probably much less. The shallow nature of deposition gave rise to a variety of sedimentary structures common to this environment, such as ripple bedding, cross-bedding, burrowing, bioturbation, and possibly storm effects. The sandstones are generally very fine grained, moderately well sorted, and consist mostly of quartz grains that are tightly cemented with silica as the primary cementing agent. Sands accumulated in elongate bars several miles long and about a mile wide. These sand bodies are completely encased in marine shale above, below, and laterally and have no associated deltaic deposits within each respective interval. Considering these characteristics and limited core analysis, the depositional environment of the Britt and Boatwright sandstones is interpreted to be that of an offshore bar, detached from the shoreline. Where the log shape has an abrupt transition from shale to sand along the basal contact, and then blocky in an upward direction, it is likely that a bar-transition facies was poorly developed, owing to both an abundant sand supply and rapid bar development. The Britt and Boatwright deposits do not form subaqueous distributary-mouth bars (not a delta front), as some geologists have interpreted in this study area.

CORE ANALYSIS

One core is available that adequately represents the main producing reservoir in this area, the Britt sandstone. This core is described in Appendix 4 and includes the Morrow–Springer contact. For comparison, core-porosity

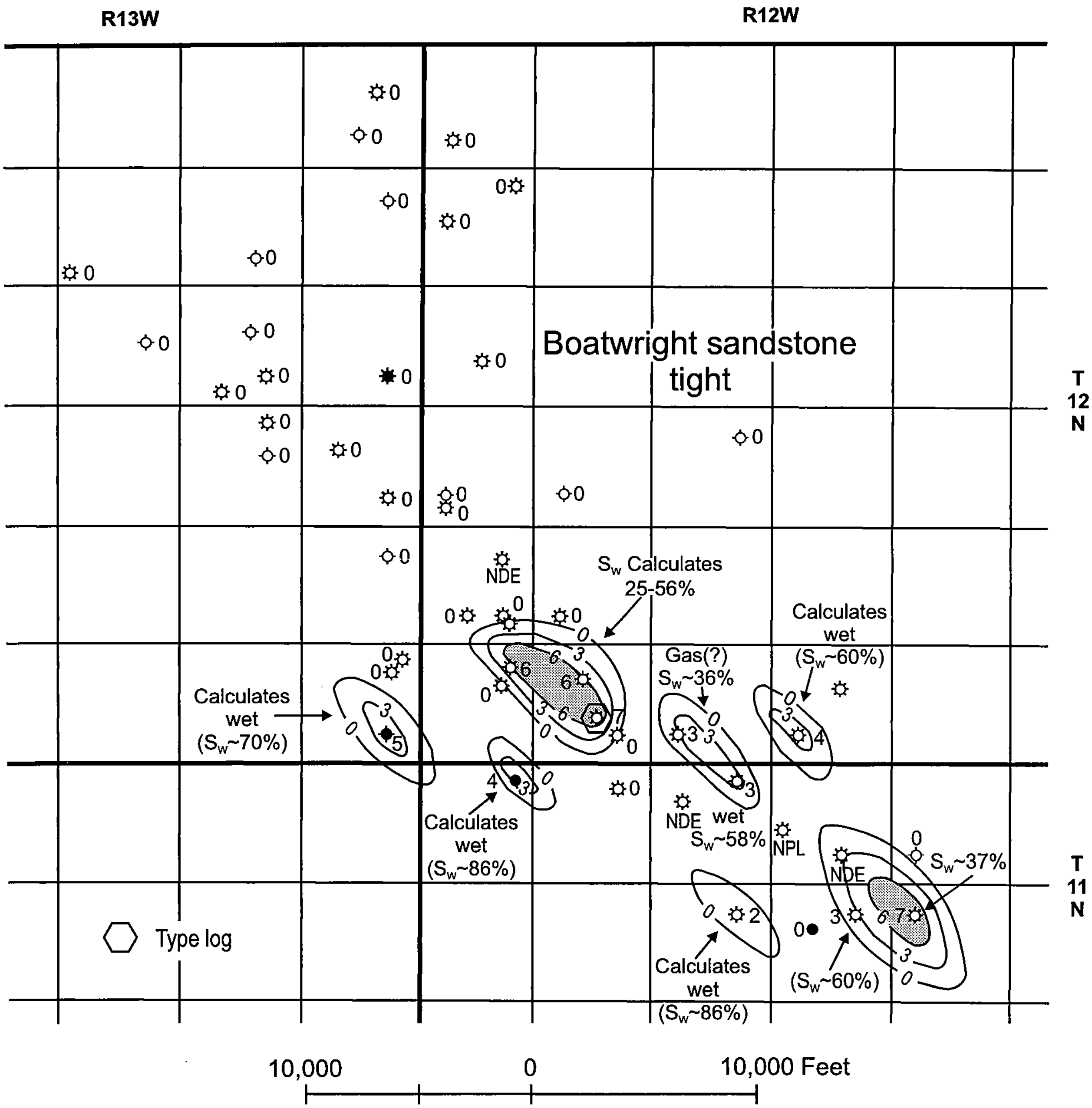


Figure 51. Net-isopach map of the Boatwright sandstone in Sickles North field. Net sandstone has a log porosity >6%. Contour interval is 3 ft. See Figure 43 for well names. *NDE* = not deep enough; *NPL* = no porosity log.

measurements from the Apexco No. 1-A Buell well, in the SE¼NW¼ sec. 10, T. 11 N., R. 12 W., are plotted adjacent to the well-log tracks in Figure 52. Most of the cored section above the Britt and below the Morrow—the Cunningham section—is shaly, and porosity values do not represent a clean sandstone. The core porosity in the Britt interval, however, is comparable to that of the well log. The track directly left of the core-porosity plot shows the intervals that were sampled for palynomorph assemblages. On the basis of palynomorph interpretation, the basal Morrow section is definitely Pennsylvanian in age, and the uppermost Springer section may also be Pennsylvanian.

A graphic presentation of porosity and permeability data from the Apexco No. 1-A Buell well is presented in

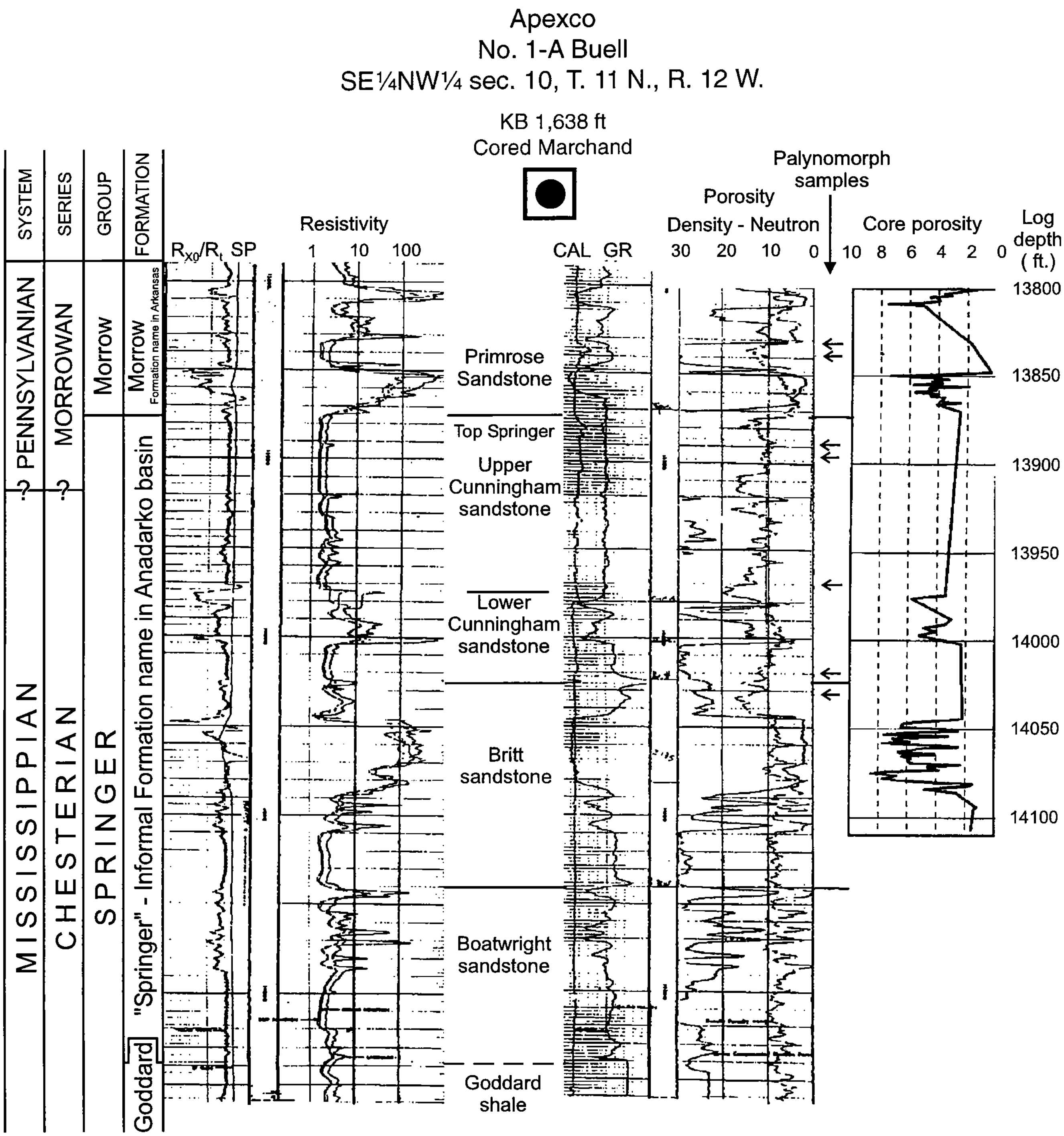


Figure 52. Comparison of log porosity with core porosity of Morrow and Springer sandstones in the Apexco No. 1-A Buell well. Palynomorph-sample locations are shown to the left of the core-porosity plot. Core data provided by Apache Corp., Oklahoma City. *CAL* = caliper; *GR* = gamma ray; R_{xo}/R_t = resistivity of flushed zone divided by deep (true) resistivity; *SP* = spontaneous potential.

Figure 53. Data for shaly zones were omitted. It can be seen from these core data that the Britt sandstone is generally tight in the area southeast of the field, although a few zones had better permeability of up to 0.3 md. The corresponding porosity-versus-permeability trend line for the Britt may be correct in predicting higher permeability values for sandstone having the highest porosity. Therefore, in areas producing from the Britt a few miles to the northwest, it is predicted that the upper permeability values (0.1 md) predominate over the low-end values (0.05 md), as shown in this graph. In the Buell well, the Cunningham was poorly developed, so permeability values do not represent a clean, productive sandstone. The Boatwright was not recovered in this well. The Primrose Sandstone in the Buell well is considered representative of that unit and is correlative through the general area, making the Springer–Morrow contact reliable, as interpreted from well logs by this author.

FORMATION EVALUATION

The Britt and Boatwright sandstones in Sickles North field are easily correlated because each sandstone sequence was deposited in a stable setting, which occluded multiple depositional environments. Formation evaluation of the Springer sandstones is much more difficult, however, owing to interstitial clay, diagenetic alterations, and cementation, which interfere with water-saturation calculations and the determination of true resistivity and porosity.

Springer sandstones can be relatively clean, on the basis of gamma-ray-log responses, but consistently reliable values of water saturation (S_w) are elusive. In this study, a spreadsheet was created that incorporated representative values of deep, or true, resistivity (R_t) and cross-plot porosity (ϕ) that can be used to calculate S_w. Different formulas were used to calculate formation factor (F) in the tightly cemented rocks. The Archie formula of $1/\phi^2$ was finally used. The determination of R_w was made from service-company calculations on some logs, although their value (0.1 ohm-m) resulted in S_w values that were consistently too high unless a modified F formula was utilized. Experimenting with different R_w values seemed to indicate that a smaller number was necessary to more realistically characterize water-wet zones as well as hydrocarbon zones. Finally, an R_w of 0.08 ohm-m was decided on. Unrealistic variations of S_w were still encountered in spreadsheet calculations, particularly for tight zones where R_t was very high. But those zones were tight and nonproductive, so the resulting S_w calculations were not deemed important.

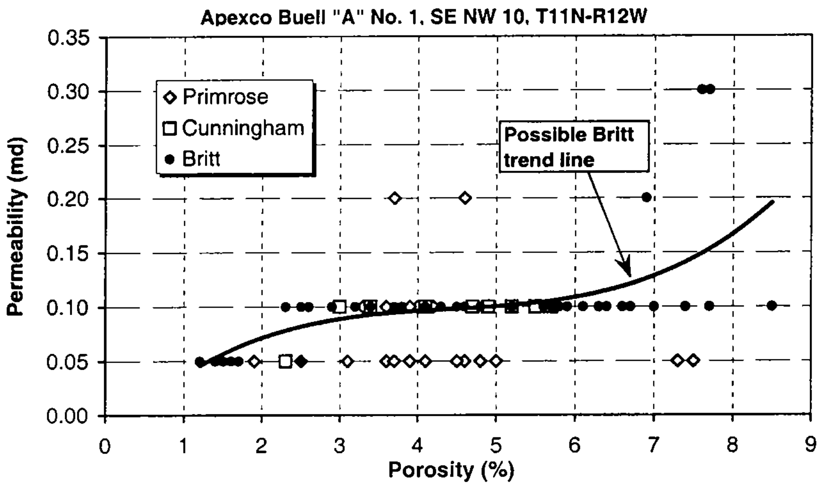
The R_t of the Britt and Boatwright sandstone in producing zones typically ranges from ~50 ohm-m to almost 200 ohm-m. A deep resistivity of <50 ohm-m almost always indicates that the zone is wet. With a typical porosity of 6–10%, the Springer probably cannot produce significant gas with less than ~40 ohm-m of resistivity in this study area. On the other hand, where the deep resistivity is relatively high (greater than 100–200 ohm-m) and the porosity is relatively low (<6%), the Springer is usually tight from cementation.

The characterization of permeability, and therefore porosity, by examining the separation between the shallow- and deep-resistivity curves has mixed results in the Britt sandstone (the Boatwright is generally too thin to utilize this technique effectively). In most zones where the Britt has good porosity, the separation is at least 150 ohm-m (wells 2, 4, cross section B–B´, Fig. 46, in envelope). However, highly productive zones in the Britt have very little separation between the shallow- and deep-resistivity measurements, yet they have good porosity (well 3, both cross sections, Figs. 45, 46, in envelope). This indirect method of determining reservoir quality is based on the assumption that the amount of invasion of drilling fluids is proportional to the porosity and permeability of the reservoir, and that the amount of separation between the shallow- and deep-resistivity curves is affected by the degree of invasion. It is possible that overbalanced drilling enhances the degree of invasion in rocks that would otherwise be considered tight.

Porosity determinations using density–neutron logs were made by taking the cross-plot porosity of the two logs. By using this simple procedure, porosity values in the cleanest part of the producing sandstone interval ranged from about 5% to 10% (average ~7%) for the Britt sandstone and 5% to 11% (average ~6%) for the Boatwright sandstone. Most wells were logged by using the density–neutron combination tool, and a matrix density of 2.71 g/cm^3 (limestone) was routinely used by logging companies. Therefore, porosity determinations are theoretically a few percentage points higher in sandstone than if a sandstone-matrix density of 2.65 g/cm^3 had been used. Porosity values used in this study were pessimistically estimated to take this variation into account but were not systematically reduced by 2–3% percentage points, as some evaluators do. Where only density porosity was available, values were attenuated by multiplying the indicated density porosity by a fraction, usually 0.65 or 0.7, so that the resulting porosity accounts for some of the normal gas effect (in producing wells) that causes the density porosity to be too high. The observed gas effect (crossover) in productive intervals may be 5–11 porosity units (see well 2, cross section B–B´, Fig. 46, in envelope). In nonproducing or tighter zones, the gas effect is much less (see well 5, cross section A–A´, Fig. 45, in envelope).

In this study, S_w calculations for the Britt and Boatwright sandstones are extremely variable and range from ~25% to >100% (which of course is not correct). In producing zones, S_w values are in the range of 25–57% for the Britt and 25–61% for the Boatwright. Some calculations are unrealistically high in producing zones (>50%), but overall, values seem to accurately reflect general reservoir conditions with respect to hydrocarbon versus water saturation. Clay problems are blamed for unrealistically high S_w values in sandstone having net porosity >6%. In these situations, S_w values are probably correct but include bound water rather than free (mobile) water. In a similar manner, cementation is blamed for unrealistically high S_w values in tight zones, because the formation factor (F) in the numerator of the S_w formula gets very large.

Calculations were made by using the equation $S_w = \sqrt{(F \times R_w)/R_t}$. The value for formation-water resistivity (R_w)



Note: No trend lines adequately fit these data

All measured values less than 0.1 md are represented as 0.05 md

Figure 53. Graph showing core porosity and permeability data for the Morrow Primrose and the Springer Cunningham and Britt sandstones in Sickles North field. Data provided by Apache Corp., Oklahoma City. See Figure 52 for wireline-log representation of cored interval.

that proved to best fit reservoir conditions was assumed to be 0.08 ohm-m at formation temperature. It is apparent that a variation of R_w values may better characterize individual sandstone zones in different wells because of minor variations in formation water chemistry. The Archie equation for formation factor ($F = 1/\phi^2$) was used to reflect the highly cemented sandstone lithology, although the modified equation ($F = 0.81/\phi^2$) may also be used with satisfactory results in calculating S_w when adjusting the R_w to 0.1 ohm-m. The calculated S_w values were too low in water-wet zones when the modified Archie equation and $R_w = 0.08$ were used. Values for R_t were taken directly from the deep-resistivity logs, but the resistivities may have been suppressed for some reservoirs because of interstitial clays, thereby causing S_w values to be too high. Porosity values were also taken directly from density–neutron, density, or sonic logs in the manner described above. Reservoir characteristics of the Springer sandstone in Sickles North field are summarized in Table 8.

OIL AND GAS PRODUCTION

The estimated cumulative production from the Springer formation in Sickles North field is ~36 BCFG and 11,770 BO (condensate) from October 1980 through February 2000. The Britt sandstone accounts for almost all of this production (~34+ BCFG and ~11,000? BO). The Boatwright sandstone probably accounts for <2 BCFG, but the exact amount cannot be determined because of commingled production. For wells from which production has been commingled, estimated single-zone production is based on reservoir quality, thickness, and extent. Figure 54 shows cumulative gas and oil production for each respective Springer well in Sickles North field. Some values represent commingled production from the Britt and Boatwright, which makes reserve allocations for individual zones difficult to determine. Production figures for a few Cunningham wells in the northern part of the study area are also provided for comparison. Condensate production is mostly attributed to Britt wells completed late in the development history of the field, regardless of structural position.

Figure 55 shows the date of first production, initial production (IP), tubing pressure (TP), and bottom-hole pressure (BHP) for wells that produce from the Britt and Boatwright sandstones in the vicinity of Sickles North field. By comparing the date of first production (Fig. 55) to cumulative production (Fig. 54), it can be seen that wells completed early in the field's history are the largest producers and had the highest initial pressures.

Because of such factors as areal extent, reservoir thickness, and especially S_w, there is considerable room for error in reserve calculations. On the basis of volumetric calculations, production from the Britt sandstone is ~82% of the original recoverable gas in place, which is estimated to have been ~42 BCFG (Table 8). The percentage of recovered gas seems reasonable in view of current reservoir pressures <1,000 psi and decline-curve slopes that have flattened out over time. Estimated recovery for the Britt, based on current cumulative gas production, is ~705 MCFG/acre-ft. Initial-production rates varied from ~0.5 to almost 6 MMCFGPD and averaged 1–2 MMCFGPD. Wells had flowing pressures of <1,000 psi to as high as 6,600 psi.

The Boatwright sandstone probably has produced >75% of the original recoverable gas in place, which is estimated at ~2.1 BCFG (Table 8). The ultimate recovery, based on current cumulative gas production, is certainly <560 MCFG/acre-ft, although this is speculative, owing to the vagueness of estimated Boatwright gas produced from commingled wells. The lower recovery per acre-feet in comparison to the Britt is due to the limited thickness and areal extent of porosity in the Boatwright sandstone.

There are no exceptional Boatwright producers in Sickles North field, and it is doubtful if more than one well would produce >0.5 BCFG from the Boatwright alone. Initial flowing pressures (IFP) are generally unavailable, although a few commingled wells indicated pressures of 2,450 to 7,000 psi, the latter of which seems high. An initial BHP representative of the Boatwright alone is not known, so it is assumed to be greater than or equal to the highest measured value for the overlying Britt.

PRODUCTION-DECLINE CURVES

Britt Sandstone

Production-decline curves for three wells that produce solely from the Britt sandstone in Sickles North field are shown in Figure 56. The upper plot shows the production

TABLE 8. — Reservoir/Engineering Data for Springer Sandstones in Sickles North Field, Caddo County, Oklahoma

	Britt sandstone	Boatwright sandstone
Discovery date (map area)	2/18/80 (Walsh 1 Kimble, C NE¼ sec. 30, T. 12 N., R. 12 W.)	9/2/80 (Woods Pet. 1 Thiessen, SE¼NW¼ sec. 32, T. 12 N., R. 12 W.)
Reservoir size[a]	~5,260 acres (~8.2 mi^2)	~600 acres (~1 mi^2)
Reservoir volume	~49,680 acre-ft	~2,678 acre-ft
Depth	about 13,600–14,000 ft	~14,100 ft
Spacing (gas)	640 acres with increased density to 320 acres	
Gas–water contact	–12,100 to –12,300 ft	none observed
Porosity (in "clean" sandstone in producing areas)	about 5–10% (average ~7%)	about 5–11% (average ~6%)
Permeability	about 0.1–0.3 md	probably lower than Britt
Water saturation (S_w) in producing wells Calculated using R_w = 0.08 ohm-m	about 25–57% (usually 30–40%)	about 25–61% (average ~48%)
Thickness (WP = where productive)		
Net sandstone (WP), >6% ϕ	0–28 ft (average ~14 ft)	0–7 ft (average ~4.5 ft)
Gross sandstone	0–50 ft (average ~39 ft)	0–28 ft (average ~9 ft)
Reservoir temperature	about 200–215°F	about 200–220°F
Gas density	~0.58	~0.58
Z factor (compressibility)[b]	~1.44	~1.44
B_g (gas formation volume factor)[c]	~392 std cu ft per reservoir cu ft	~392 std cu ft per reservoir cu ft
Initial reservoir pressure (max. recorded BHP)	~10,627 psi	~10,627 psi
Initial pressure gradient	~0.75 psi/ft	~0.75 psi/ft
Cumulative field condensate (est. to 2/00)	11,770 bbl (commingled)	est. <5% of Britt total
OGIP[d] (volumetric-field)	~41.6 BCF	~2.1 BCF
Cumulative field gas (est. to 2/00)	est. 34+ BCF	prob. <2 BCF
% gas recovery to date	82% (not including condensate)	unknown, probably >75%
Recovery MCF/ac-ft (field to date)	~705 MCF/ac-ft	prob. <560 MCF/ac-ft

[a]Area within 0 ft net contour (Boatwright); ~2 ft net contour (Britt).

[b]Compressibility factor (Z) estimated from standard reservoir engineering chart using T_{res} and P_{res} values listed in this table. T_{res} is in °Rankine (add 460° to reservoir temperature that is measured in °F), P_{res} = reservoir pressure.

[c]B_g calculated using the formula: $B_g = \frac{35.4 \times P_{res}}{T_{res} \times Z}$ The Z factor is stated above.

[d]Original gas in place (OGIP) determined from the following formula: Reserves (MCF) = 43.56 × area (acres) × sand thickness (ft) × porosity (%) × (1 – S_w) × B_g.

curve from the Gulf Oil No. 1 Epperly well, in the C SE¼ sec. 24, T. 12 N., R. 13 W. This well was one of the earliest completed in the field in 1981. It encountered 19 ft of net (35 ft of gross) sandstone with 6–8% porosity, although some zones within the gross-sandstone interval have <6% porosity. The Epperly well was drilled where the Britt sandstone is the thickest in the northwestern part of the field. This well probably had virgin pressure of a little more than 10,000 psi, although the earliest test showed a BHP of only 8,539 psi on the day of first production. The well produced over a 12-year period, until 1992, when it became inactive. During that period, more than 2.2 BCFG and 233 BO (condensate) was produced. Note the relatively stable pressure recorded during most of the well's productive life. The initial production was 2,200 MCFGPD, with a flowing pressure of 2,565 psi. The most recent BHP recorded, in 1991, was 4,221 psi. Mechanical problems probably caused this well to be prematurely abandoned.

An offset well less than a mile to the northwest in the same section as the Epperly well was drilled by Sanguine late in 1991, 10 years after the Epperly well was completed. The production curve for this well, the Sanguine No. 1 Jessie (SE¼NW¼ sec. 24, T. 12 N., R. 13 W.), is shown in Figure 56B. This well produced ~3.9 BCFG over ~9 years from 12 ft of net (28 ft of gross) sandstone and is one of the best producers in the field. The Jessie well had an

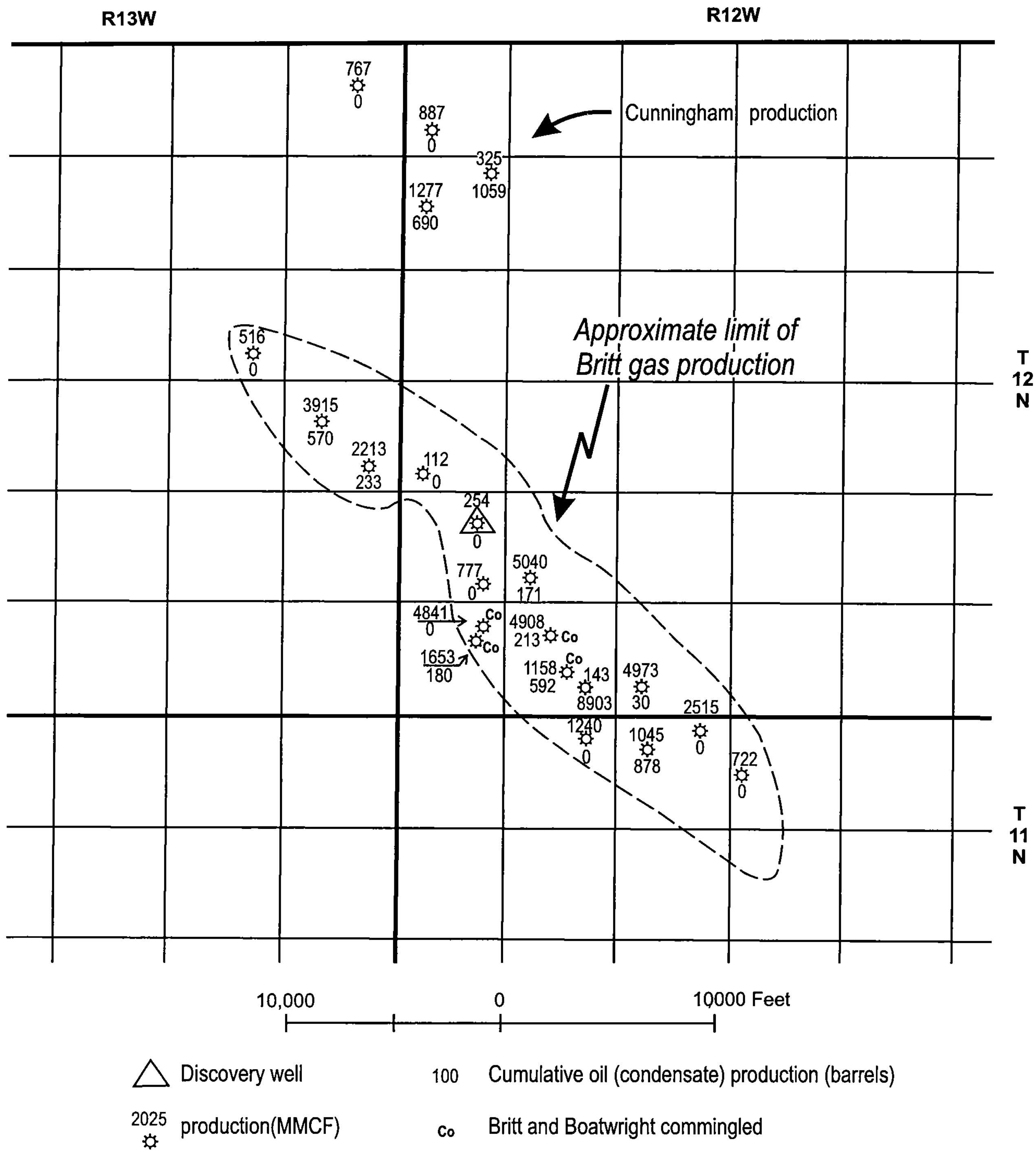
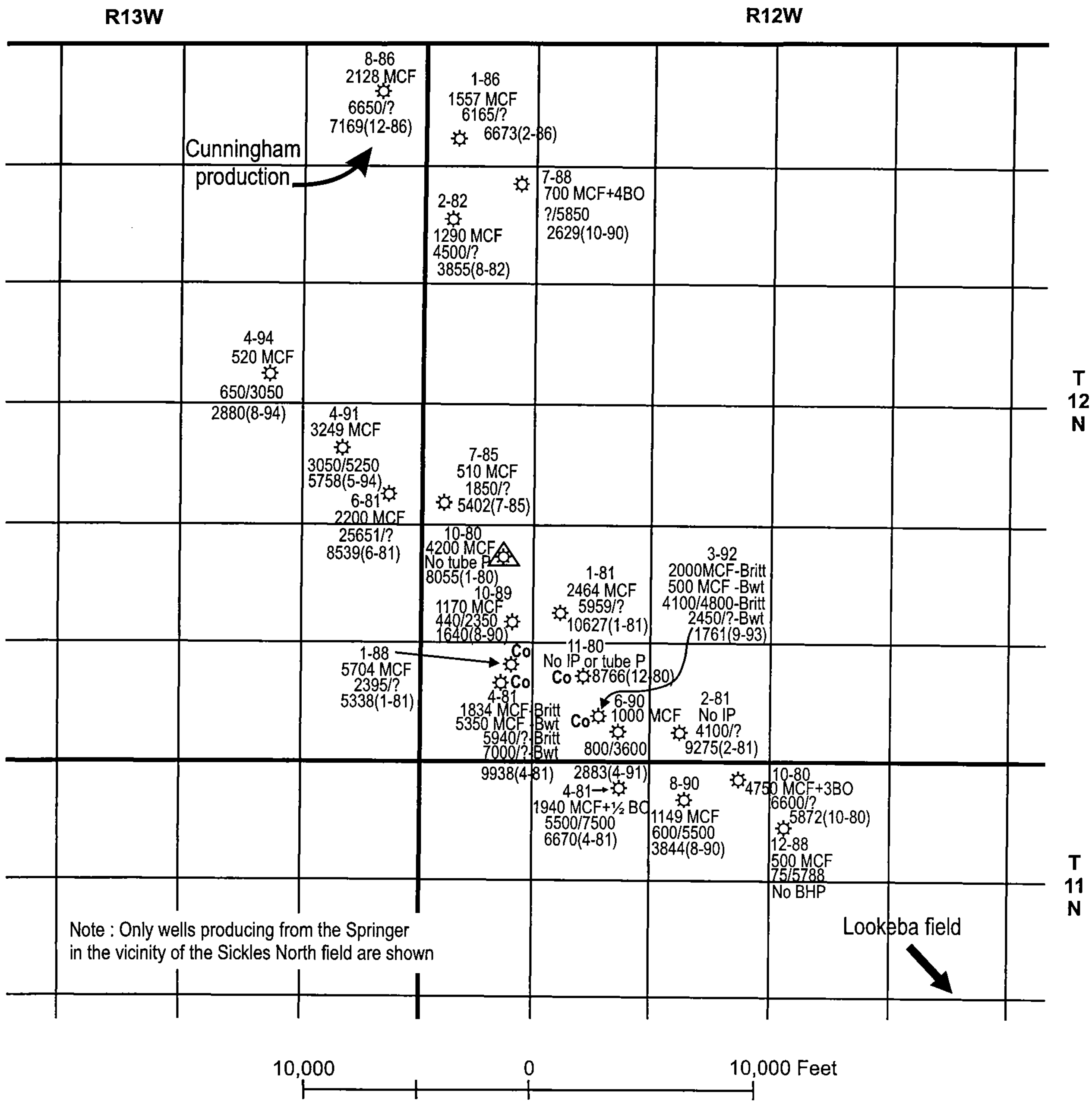


Figure 54. Map showing cumulative gas and oil (condensate) production for wells producing from the Britt and Boatwright sandstones in Sickles North field. Production tabulated through February 2000. See Figure 43 for well names.

initial flowing pressure of 3,050 psi and initial production of 3,249 MCFGPD, which is considerably more than the Epperly well (Fig. 56A). The initial BHP of the Jessie well is not known, so the degree of pressure depletion (if any) likewise is not known. The pressure curve in this graph indicates at least partial depletion, yet the earliest measured BHP (1991) in the Jessie well was still considerably higher than that measured in the abandoned Epperly well in 1991. The enhanced gas production recovered from the Jessie well supports the concept of development drilling, because reservoirs like these are apt to show some degree of compartmentalization.



△ Discovery well
4-91 Date of first production
2050 MCF Initial production
3050/5250 Flowing tubing pressure / shut-in tubing pressure
5700(6-81) Bottom hole pressure (BHP) and first reported test date
Co Britt and Boatwright commingled

Figure 55. Map showing date of first production, initial production (IP), flowing tubing pressure (FTP), shut-in tubing pressure (SITP), bottom-hole pressure (BHP), and production code for wells producing from the Britt and Boatwright sandstones in Sickles North field. Production is from the Britt sandstone except where indicated. See Figure 43 for well names.

Figure 56C shows a third Britt producer, the Cotton Petroleum No. 1 Flanigan well, completed in 1980. This well had competition from two wells that came on line a few months before it was completed. Yet cumulative production from this well is ~5 BCFG from only 8 ft of net (21 ft of gross) sandstone, with porosity ranging from about 6% to 10%. The Flanigan well probably had a virgin BHP of ~10,600 psi, as was presumed to be the case for the earlier wells completed directly to the south and northwest. The very high production from the Flanigan well is surprising, considering the reservoir thickness. This well showed a relatively small pressure decline until 1989; thereafter, it fell rapidly to ~1,035 psi. The above-average porosity in conjunction with higher than average perme-

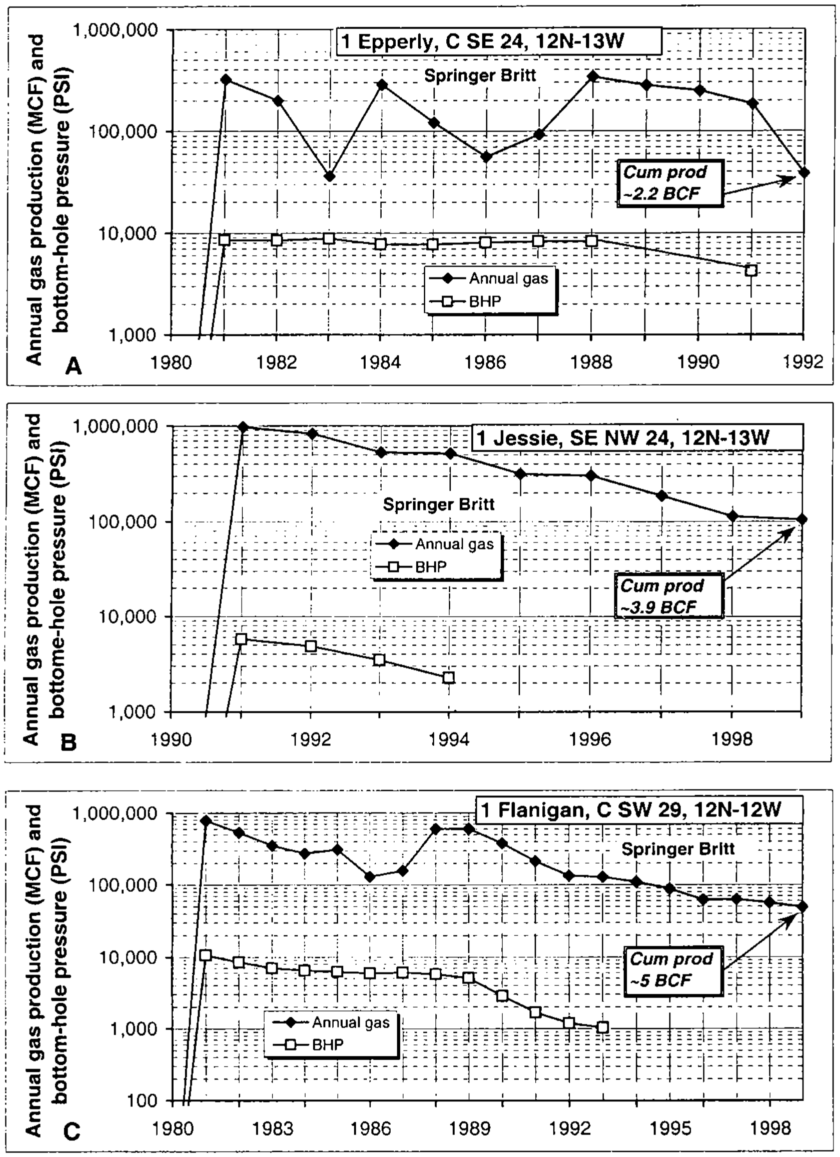


Figure 56. Production- and pressure-decline curves for three wells producing from the Britt sandstone in Sickles North field. Data are current through December 1999.

ability in the Flanigan well may account for the unusually high production. Nearby offsets to the south and southwest produced ~5 BCFG from a much thicker reservoir of >20 ft.

The three production curves for the Britt wells (Fig. 56) show a variety of reservoir characteristics and dates of first production. Although wells drilled into the thicker reservoirs and completed early in the history of the field have produced the most gas, the curves show that thinner reservoirs and wells completed later can also achieve above-average production. All three wells have different production- and pressure-decline rates over time, which indicates minimal interference from competing wells and reservoir heterogeneity. These production curves also illustrate the different degrees of depletion from one area to another throughout the field. Production and pressure data used to construct these three graphs are included in Table 9.

Figure 57 shows the trends of pressure versus cumulative gas production for five Springer wells in Sickles North and Lookeba fields—two producing from the Britt, two from the Cunningham, and one from the Boatwright. The five wells were selected because of their good pressure data. The visual projection of BHPs shows that these wells had a common initial reservoir pressure but different decline rates, probably owing in part to reservoir heterogeneity. Trend lines have been inserted to clarify the decline patterns of the different reservoirs. Most notable is the rapid decline of the Boatwright reservoir and the slower decline of the Cunningham reservoir, with the Britt somewhere in between.

Boatwright Sandstone

There are no production histories with good pressure data for the Boatwright reservoir in Sickles North field. Thus, no decline curves for that reservoir are given in this study. Two decline curves for the Boatwright sandstone are shown for single-zone completions in Lookeba field to the southeast (Fig. 41). Those wells probably represent some of the better Boatwright production in the immediate area.

Figure 57 shows pressure versus cumulative gas production plotted for one Boatwright well. This curve can be compared to the pressure-versus-production trends for the two Cunningham and two Britt wells. Note that although all five wells project to a similar initial BHP, they all have very different decline rates over time. Again, this is due to reservoir heterogeneity.

WELL-DRILLING AND COMPLETION PRACTICES

Wells in Sickles North field are drilled with traditional water-based drilling fluids in a manner similar to that in Lookeba field. The discussion of drilling techniques is beyond the scope of this study, but some important guidelines are noted for Springer wells in this study area. Wells vary in depth from ~13,800 ft in the northern part of the field to ~14,400 ft in the west-central part of the field. Most wells do not fully penetrate the Springer Group and, as such, are drilled only to the base of the Boatwright sandstone. Drilling another 200–250 ft would be necessary to reach the underlying Chester limestone.

Operators usually set 10.75-in. surface casing to about 1,500 ft, then set 7⅞-in. casing through the Pennsylvanian Cherokee section (at ~12,400 ft) and just above the

TABLE 9. — Annual Springer Britt Production and Pressure Data for Selected Wells in Sickles North Field, Caddo County, Oklahoma

	Britt production					
	1 Epperly C SE 24, 12N-13W		1 Jessie SE NW 24, 12N-13W		1 Flanigan C SW 29, 12N-12W	
Year	Gas (MCF)	BHP	Gas (MCF)	BHP	Gas (MCF)	BHP
1981	323,215	8,539			780,206	10,627
1982	200,684	8,480			533,010	8,471
1983	36,204	8,819			354,374	7,005
1984	286,652	7,721			274,287	6,483
1985	121,340	7,701			310,822	6,238
1986	56,334	8,066			131,129	5,937
1987	93,032	8,280			157,472	6,090
1988	341,585	8,264			601,405	5,773
1989	280,769				603,549	5,089
1990	249,570				379,988	2,841
1991	184,610	4,221	973,256	5,758	214,645	1,677
1992	38,589		829,629	4,842	134,255	1,190
1993			531,787	3,474	129,356	1,035
1994			518,260	2,264	110,065	
1995			316,550		88,266	
1996			302,021		61,847	
1997			186,442		62,755	
1998			113,337		56,466	
1999			105,171		49,135	
Cumulative production						
	2,212,584		3,876,454		5,033,032	

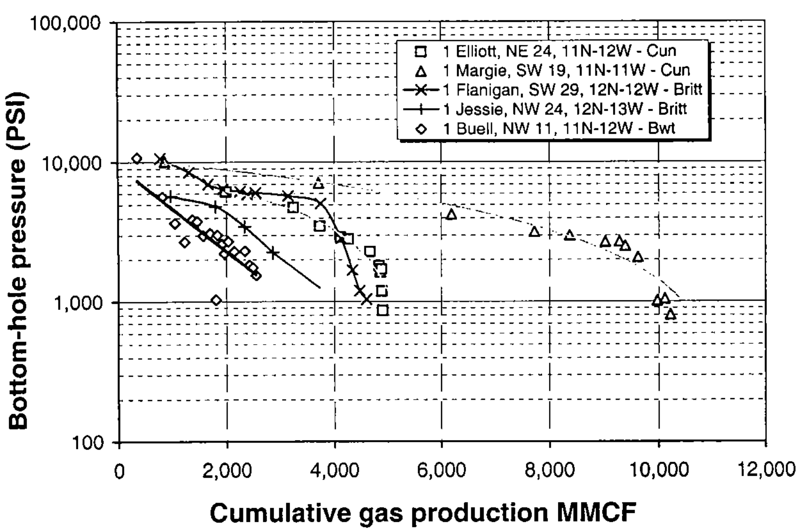


Figure 57. Graph showing relationship between pressure and cumulative gas production for five Springer wells having good pressure data. Two produce from the lower Cunningham sandstone (*Cun*), two produce from the Britt sandstone, and one produces from the Boatwright sandstone (*Bwt*) in the Lookeba and Sickles North field areas.

Novi lime (the Novi lies beneath the Inola Limestone and about 200–300 ft above the Thirteen Finger lime within the Atoka Formation), then 4.5- to 5.5-in. liner to very near the bottom of the hole. Sometimes, 2⅞-in. or 3.5-in. liner is used instead of the ~5-in. liner. Drilling mud weights are in the range of 9–10 ppg through the Cherokee section, then they increase to 15–16 ppg through the Morrow–Springer intervals. Many wells are acidized with 1,000–7,000 gal of 7.5% HCl. In all productive wells, the Springer interval is stimulated with a fracture treatment consisting of various treated gels (commonly water or acid gel). Amounts range from about 20,000 to 80,000 gal plus about 10,000–60,000 lb of sand. Well-drilling costs for a conventional vertical well to a depth of ~14,000 ft, where overpressuring is anticipated, are estimated at $1.4 million for a dry hole and $2.0 million for a completed well having a single zone completion in the Springer (estimated costs as of February 2001). As in Sickles North field, wells usually take from 3 to 6 months, and sometimes up to a year, to drill and complete.

PART IV

Springeran–Chesterian Relationships in the Anadarko Basin and Shelf of Northwestern Oklahoma and Texas Panhandle

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INTRODUCTION

It has long been apparent to those working the Anadarko basin and shelf areas of Oklahoma and Texas that the nomenclature used is typically erratic, and the resulting production allocation less than precise. A correlative and equivalent formation may be called various names, and there are many instances of nomenclature being vague, too broad, or incorrect. The IHS Energy Group has undertaken a regional stratigraphic-correlation program to rectify these problems.

As part of this regional study, the logs from every producing well within most of the Anadarko basin and shelf were reviewed to verify the actual producing reservoirs. Approximately 35,000 wells in northwestern Oklahoma and the panhandles of Oklahoma and Texas were examined (Fig. 58). Regional cross sections were constructed and used to determine the stratigraphic relationships and to develop a stratigraphic-nomenclature system that could be used across the area with accuracy, detail, and consistency. Although the entire stratigraphic section has been scrutinized, the Springer Group of Late Mississippian and Early Pennsylvanian age demonstrates most effectively a carbonate platform and slope system and its stratigraphically equivalent basinal clastic system.

Some units of the Springer Group have often been misidentified either as the overlying Pennsylvanian Morrow sandstone or the underlying Mississippian Chester limestone. Historically, the first carbonate encountered below the Morrow–Springer clastic section has been called the *Chester limestone*. In this volume, the Springer Group is considered to consist of the Boatwright, Britt, and Cunningham stratigraphic units, in ascending order (Fig. 59). In the past, the Cunningham in Oklahoma was invariably classified as a sandstone. More recently, extensive correlations indicated that the Boatwright and/or Britt in certain areas developed a carbonate facies that often had been referred to the "Chester limestone." These correlations in both Oklahoma and Texas, from the deep Anadarko basin through the slope and onto the shelf, indicate that the Springer clastics of the deep basin are stratigraphically equivalent to Springer carbonate facies on the slope and shelf and not to the Chester. As seen on well logs, a highly conductive Boatwright shale directly above the true Chester limestone provides a reliable regional marker at the base of the Springer Group. The Cunningham was observed to develop a rare carbonate facies in Texas that was nonproductive.

Regional cross sections are presented that show these facies changes and trapping mechanisms, along with lithofacies and production maps that delineate trends.

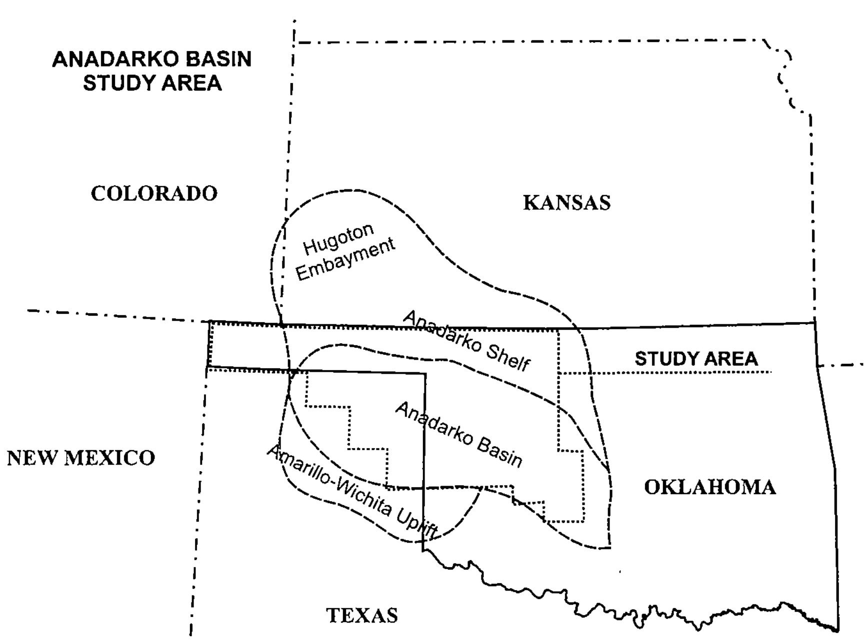

Figure 58. Map of Anadarko basin and shelf study area in western Oklahoma and Oklahoma and Texas Panhandles.

SYS	SERIES	GROUP	UNIT	SANDSTONE	CARBONATE	EQUIVALENT
PENNSYLVANIAN	VIRGILIAN	Shawnee/Cisco	Topeka Ls Pawhuska Ls Hoover Ss Elgin Sd Oread Ls Heebner Sh Endicott Ss	Hoover Endicott	Pawhuska Oread Ls	
		Douglas/Cisco	Lovell Ls Haskell Ls Tonkawa Ss	Tonkawa	Douglas Group	
	MISSOURIAN	Lansing/Hoxbar	Avant Ls Cottage Grove Ss	Cottage Grove	Lansing Group	
		Kansas City/Hoxbar	Dewey Ls Hogshooter Ls Layton Ss Checkerboard Ls Cleveland Ss	Layton Cleveland Culp	Kansas City Group Melton	Marchand Upper Marchand Lower
	DES MOINESIAN	Marmaton	Big Lime Oswego		Big Lime Oswego	Marmaton Wash
		Cherokee	Cherokee Marker Prue Ss Verdigris Ls Skinner Ss Pink Ls Red Fork Ss Inola Ls Mona	Prue Skinner Red Fork Cherokee Wash Middle Cherokee Wash Lower/ Mona	Verdigris Pink Inola	Prue Wash Skinner Wash Red Fork Wash Bartlesville, Tussy
	ATOKAN	Atoka	Atoka 13 Finger Ls	Atoka	Atoka 13 Finger	
	MORROWAN	Morrow	Morrow Primrose	Upper Morrow Morrow Lower Morrow Primrose		
MISSISSIPPIAN	SPRINGERAN	Springer	Cunningham Britt Boatwright	Cunningham Britt Boatwright	Britt Boatwright	
	CHESTERIAN	Chester	Chester Ls		Chester	
		Manning	Manning Ls		Manning	
	MERAMECIAN	Meramec	Meramec Chat Meramec Ls		Meramec Chat Meramec	
	OSAGEAN	Osage	Osage Ls			
	KINDERHOOKIAN	Kinderhook	Kinderhook Sh			
SIL./DEV.	CHATTANOOGIAN		Woodford Sh Misener Ss	Misener		
	ULSTERIAN	Hunton	Hunton Group		Hunton (Frisco) Hunton (Bois d'Arc) Hunton (Haragan) Hunton (Henryhouse) Hunton (Chimney Hill)	
	NIAGARAN ALEXANDRIAN					
ORDOVICIAN	CINCINNATIAN	Sylvan	Sylvan Sh Maquoketa		Maquoketa	
	CHAMPLAINIAN	Viola	Viola Group		Viola (Fernvale) Viola (Trenton)	
		Simpson	Simpson Dense Bromide Ss Tulip Creek Ss McLish Ss Oil Creek Ss Joins	Bromide Tulip Creek McLish Oil Creek Joins		
	CANADIAN	Arbuckle	Arbuckle Group		Arbuckle	
CAMB	CROIXAN					

Figure 59. Stratigraphic-nomenclature chart for the Anadarko basin and shelf of western Oklahoma. From Hendrickson and others (1996b, fig. 2).

PURPOSE

It was the purpose of this study to ensure that hydrocarbon production in the study areas was accurately allocated to a common and consistent stratigraphic nomenclature. This nomenclature was developed through regional correlations and substantiated by a dense framework of contiguous cross sections.

Hendrickson and others (1996a,b), Williams and others (1996), and Smith and others (1996) previously discussed correlation and allocation projects with specific results. Smith and others (1996) reported that certain Springer sandstones were observed to undergo facies changes into carbonates. In the areas of Springer carbonate deposition, these carbonates had been identified as Mississippian Chester. This chapter includes a condensed cross section previously presented as a poster session at a workshop in Oklahoma City on Silurian, Devonian, and Mississippian geology and petroleum resources in the southern Midcontinent that was held in March 1999 and sponsored by the Oklahoma Geological Survey. These cross sections demonstrate the relationships of the Springer sandstones, Springer carbonates, and the Chester limestone. These correlations have resulted in notable reserves having been reallocated from what was originally called Mississippian Chester to what is herein identified as Boatwright and Britt carbonates. The production map of Plate 4 (in envelope) indicates the areas of Boatwright and Britt production (specific as to sandstone and carbonate areas) as well as the areas of true Chester production.

METHODOLOGY

The producing formation or formations in a well are originally defined by means of the completion report (Form 1002A) filed with the Oklahoma Corporation Commission in which both the perforated interval(s) and the producing formation(s) are listed. The operator is responsible for seeing that the producing formation is identified as fully and correctly as possible, but no exacting standards or mechanisms are in place to ensure that this is done. As a result, the nomenclature for the Anadarko basin and shelf area is erratic and less than precise.

During a recent effort by IHS Energy Group to standardize reservoir nomenclature, the authors generated more than 15,000 mi of geologic cross sections to demonstrate the stratigraphic sequences and relationships throughout the Anadarko basin and shelf area. Figure 59 shows the stratigraphic section used in this study to designate reservoir and formation names. Figure 60 is an index map of the study area showing the network of nearly 3,000 mi of drafted cross sections, which are only a small part of the total used in the project. Also indicated are the lines of the cross sections included in this chapter (A–A′, B–B′, C–C′, and D–D′, Figs. 61–64), which demonstrate the facies changes that have resulted in certain units within the Springer Group, as herein defined, being erroneously identified as the underlying Chester.

The producing formation(s) and zone(s) defined by the operator on the completion card and/or Form 1002A were compared to those of the IHS regional cross sections. If there was a difference between the two, the no-

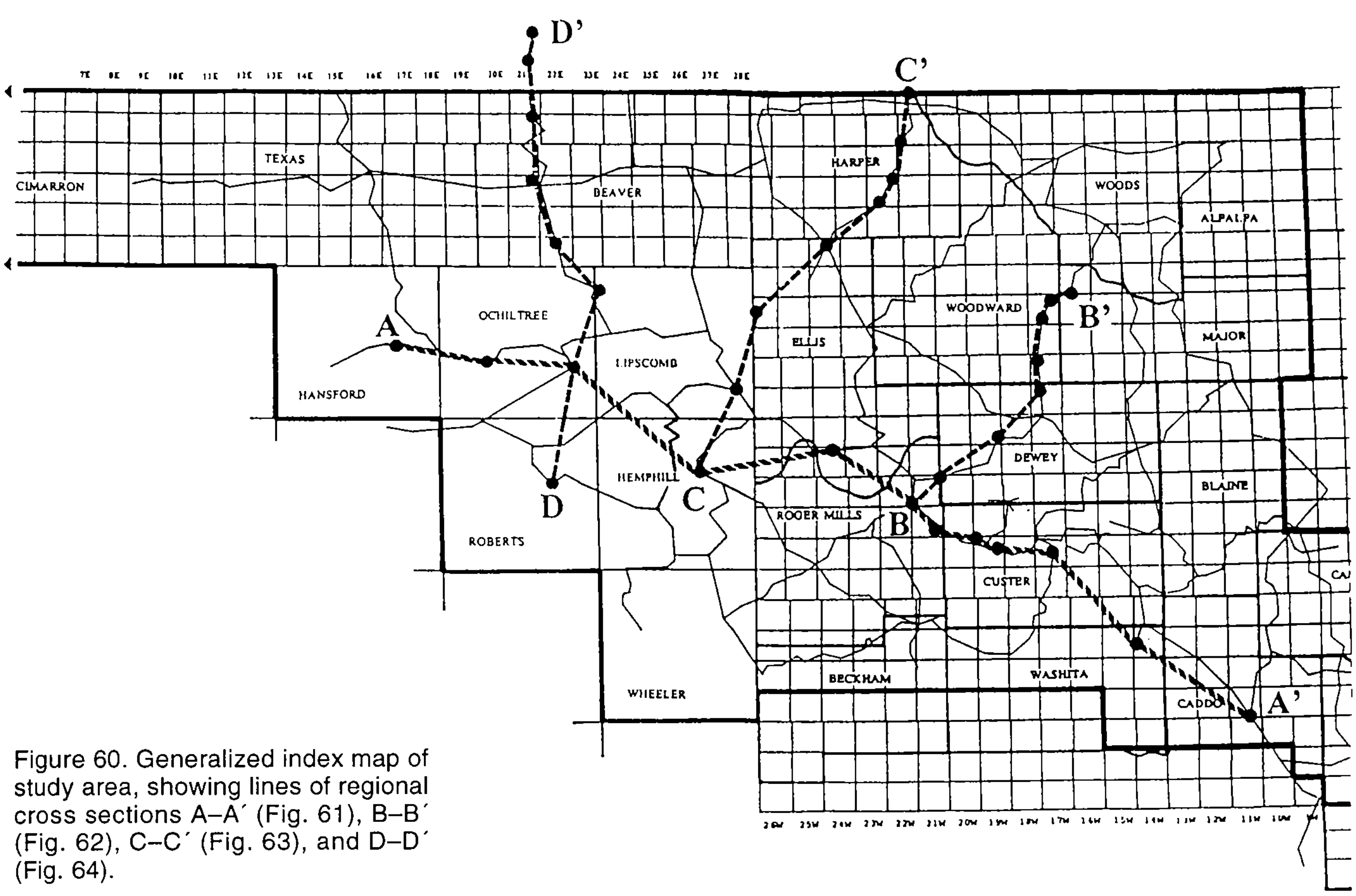

Figure 60. Generalized index map of study area, showing lines of regional cross sections A–A′ (Fig. 61), B–B′ (Fig. 62), C–C′ (Fig. 63), and D–D′ (Fig. 64).

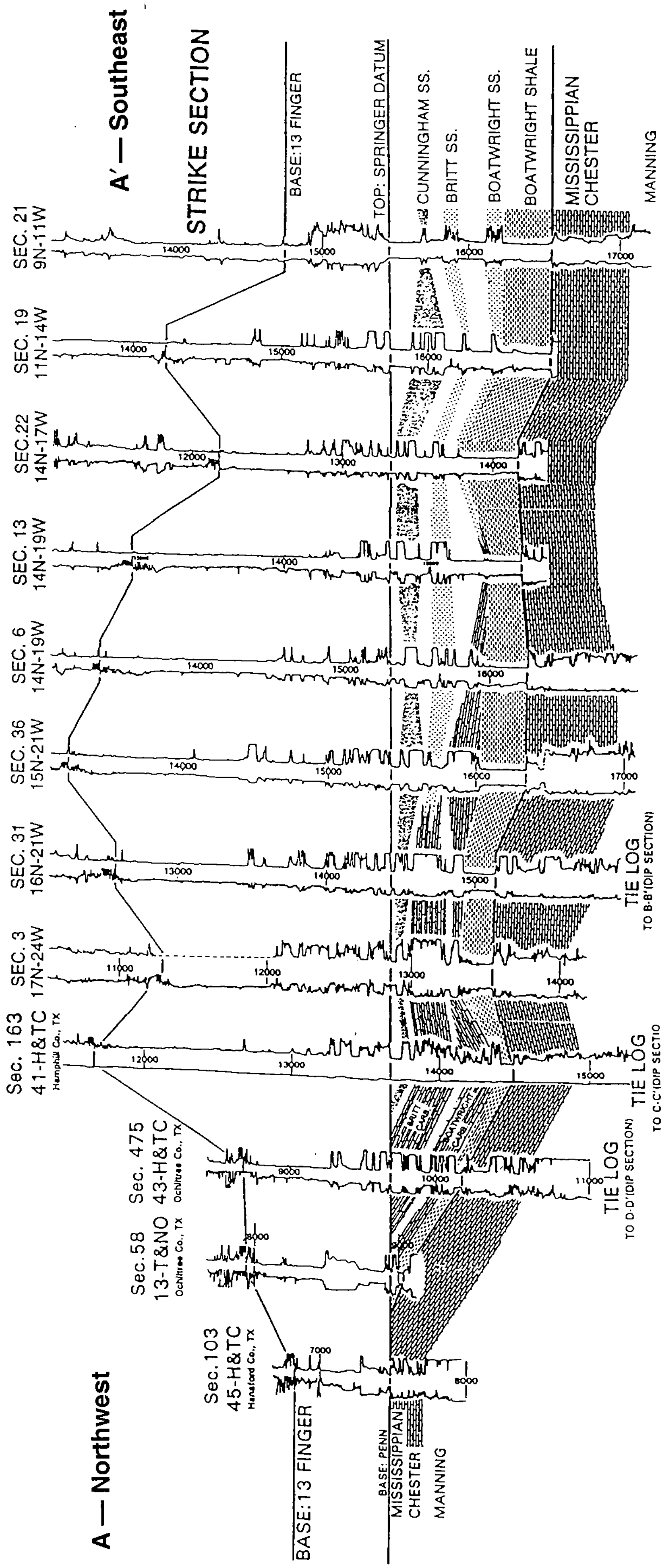

Figure 61. Stratigraphic cross section A–A′. Line of section shown in Figure 60.

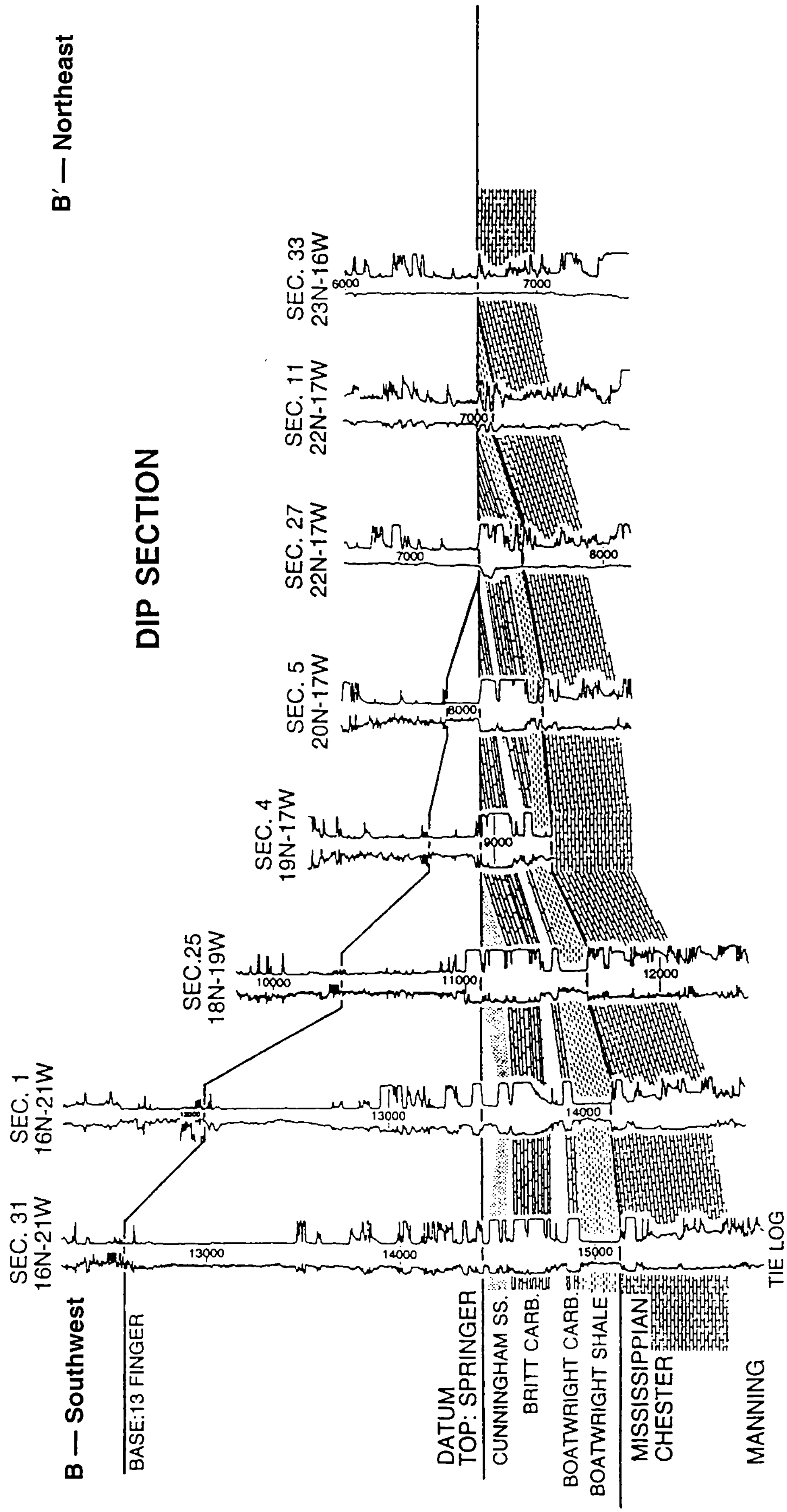

Figure 62. Stratigraphic cross section B–B′. Line of section shown in Figure 60.

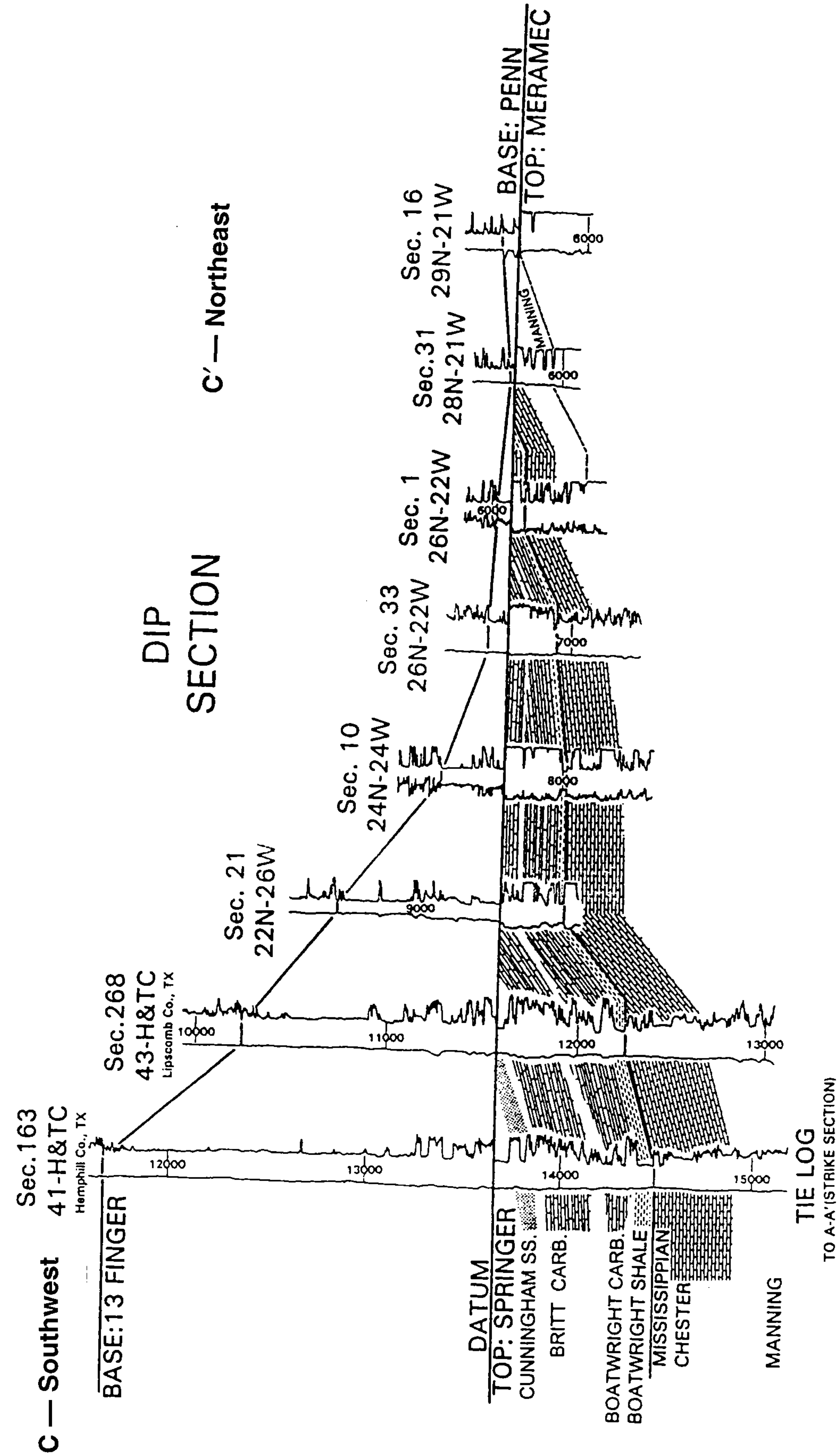

Figure 63. Stratigraphic cross section C–C′. Line of section shown in Figure 60.

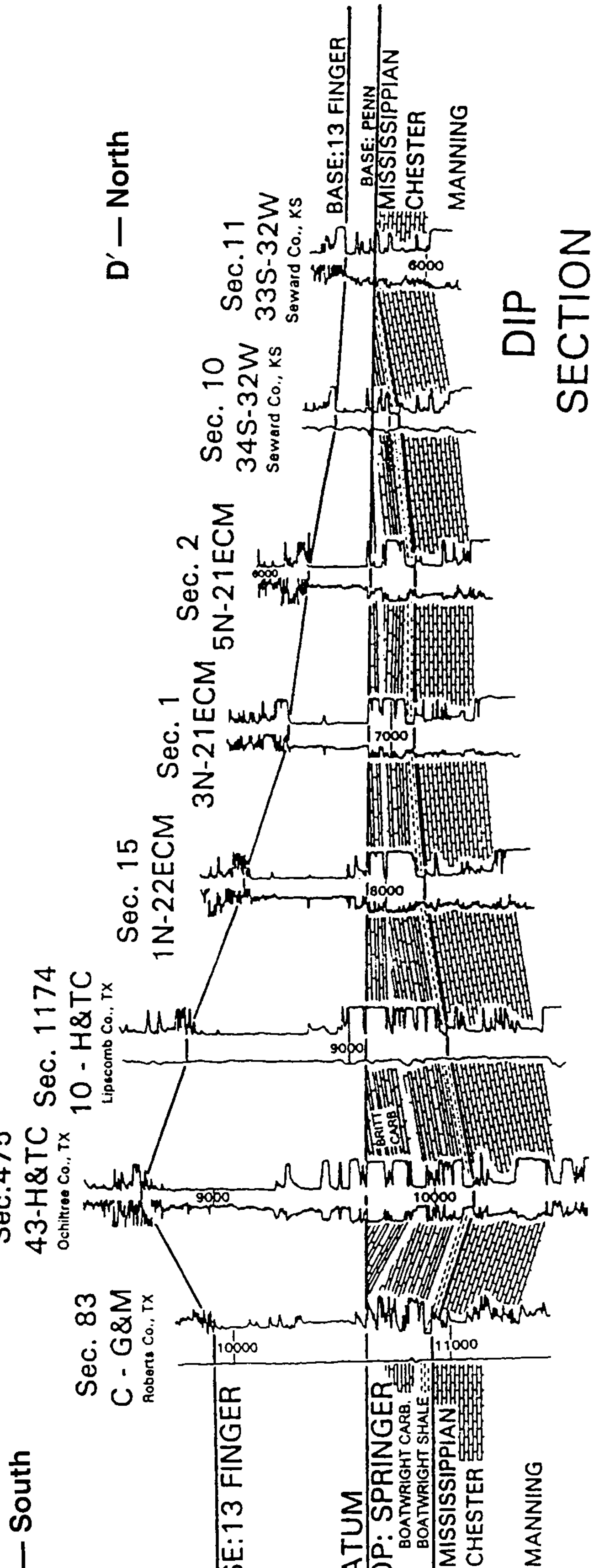

Figure 64. Stratigraphic cross section D–D′. Line of section shown in Figure 60.

menclature on the regional cross sections was used. Almost 40% of the producing formations as originally defined on completion cards were either too vague, too broad, or incorrect and were consequently reassigned corrected reservoir names. Furthermore, about 15% of the perforated intervals required correction because of reporting errors, typographical errors, or a failure to record the perforated intervals.

RESULTS

The overall results of this study have been twofold. First, the development of a dense framework of regional cross sections demonstrates the stratigraphic sequences and relationships found within the Anadarko basin and shelf area. Second, an improvement in the accuracy, detail, and consistency in the allocation of production is reflected in the IHS production database, which should be of substantial benefit to anyone using production data for the study area.

Additionally, and discussed in some detail, the relationships and facies of the Springer and Chester Groups have been clarified. Regional correlations from the deep part of the Anadarko basin northwestward demonstrate that the Boatwright and Britt undergo a facies change from sandstone to carbonate. Although these carbonates have been identified as Chester, they are distinct from the true Chester because the intervening Boatwright shale is everywhere present and correlative, overlying the true Chester. This shale is present independently of the facies (sandstone or carbonate) of the Boatwright and Britt. The Cunningham sand was deposited over the south half of the study area, and no carbonate facies has been observed there for this unit.

Cross section A–A´ (Fig. 61) is an approximate strike section over the southeastern two-thirds of its extent. The northwestern one-third of the cross section becomes a dip section as the beds emerge from the Anadarko basin at its westernmost extent. The southeasternmost well of the cross section, the Arkla No. 1-21 Clancy Estate, was drilled in the Eakly–Weatherford trend, an area of notable Boatwright and Britt sandstone production, and produces from the Boatwright sandstone between 16,115 and 16,220 ft. The thick Boatwright shale in the well extends from 16,220 to 16,550 ft, at which depth the true Chester was encountered. Over the extent of this cross section, the Boatwright shale thins from 330 ft in the southeast to 225 ft in the northwest. From the No. 1-21 Clancy well, the cross section extends northwestward to where the Boatwright sandstone first thins and then changes into thin carbonates. Northwestward, these thin carbonates coalesce into a massive carbonate section >200 ft thick (T. 15 N., R. 21 W.), which in turn thins into a regionally persistent Boatwright carbonate bed ~40 ft thick at the northwestern end of the cross section. Similarly, the Britt sandstone, present in the southeastern part of the cross section, undergoes a facies change to a massive carbonate section (T. 16 N., R. 21 W.). This lithologic change takes place farther northwest than was observed for the Boatwright. The Boatwright and Britt carbonates are shown to be continuous through northwestern Oklahoma and across the northeastern part of the Texas Panhandle to the point at which they are truncated.

Cross section B–B´ (Fig. 62) is a dip section that intersects the strike section (A–A´) in T. 16 N., R. 21 W. From the southwestern end of section B–B´, the Boatwright and Britt carbonates can be correlated to the northeast to the point at which they are systematically truncated—first the Britt, and then the Boatwright. These units are carbonates throughout this cross section because the section is northwest of the area where both units undergo the facies change from sandstone to carbonate. The Boatwright shale thins from 215 ft in the southwest to 60 ft toward the northeast, where an intervening limestone member that developed within the Boatwright shale accounts for 20 ft of the 60-ft gross thickness. As with the overlying Boatwright, Britt, and Cunningham members, the Boatwright shale is ultimately truncated just southwest of the last well of the cross section. In the absence of truncation, however, the Boatwright shale is a regionally continuous and correlative marker bed between the underlying true Chester and the overlying Boatwright and Britt.

Cross section C–C´ (Fig. 63) is another dip section, which intersects cross section A–A´ in Section 163, Block 41, H&TC Survey, Hemphill County, Texas, and traces the Boatwright shale, Boatwright carbonate, Britt carbonate, and Cunningham sandstone intervals to the northeast to the point at which they are successively truncated in a manner identical to that on sections A–A´ and B–B´.

Cross section D–D´ (Fig. 64) is yet another dip section and ties to cross section A–A´ in Section 475, Block 43, H&TC Survey, Ochiltree County, Texas. The cross section's southwesternmost log is from Roberts County, Texas, and shows the Britt carbonate truncated, and the Boatwright carbonate emerging from the Anadarko basin toward its southwestern extent. Although the tie log shows the Cunningham sandstone truncated, a full section of Boatwright and Britt carbonates near the thickest part of the Anadarko basin is represented. The cross section progresses northeastward across Lipscomb County, Texas, and the panhandle of Oklahoma and ultimately ends in Seward County, Kansas, where the Boatwright and Britt carbonates, as well as the Boatwright shale, are successively truncated.

Owing to the constraints of space, the cross sections presented here have no horizontal scale, and the wells represented are widely spaced. The cross sections are a distillation of thousands of miles of cross sections that were constructed by the IHS Energy Group. Logs included on these sections were chosen to demonstrate specific points. In some parts of the cross sections, correlations may not appear to be irrefutable; however, many additional logs were used in the correlation process between any two logs in these cross sections. The well-to-well correlation of individual sandstone members is not intended to be taken literally but is only graphic in nature and meant to illustrate lithology.

The reallocated-production database has been completed for the northwestern part of Oklahoma, including the Oklahoma Panhandle. The Oklahoma and Texas Panhandle portions of the database could not be completed

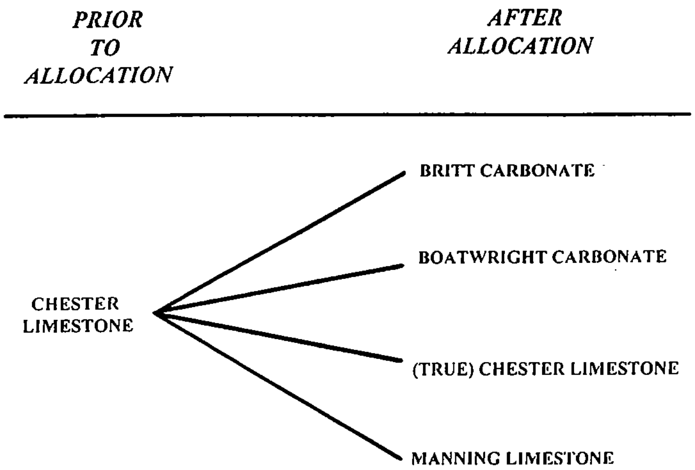

Figure 65. Diagram depicting Springer carbonate production prior to this study, and after reallocation.

in time for this publication but will be available shortly. Plate 4 (in envelope) is a map of northwestern Oklahoma, indicating wells that have produced from the Springer Group, as herein defined. In general, production from Springer sandstones is limited to the southeastern quarter of the study area, with the exception of the Cunningham, which produces over the south half, having never developed a carbonate facies. Two northeast–southwest boundary lines that delineate the approximate facies change from sandstone to carbonate for both the Britt and Boatwright (Pls. 2, 3, in envelope) are indicated, with sandstone deposition to the southeast and carbonate deposition to the northwest. As the Britt and Boatwright carbonates are successively truncated, the productive trends of these two units are indicated where they are found in subcrop.

Plate 4 (in envelope) also shows wells having production from the true Mississippian Chester limestone. In the southeastern part of the indicated Chester production, a full section of Chester is approximately 300 ft thick just this side of the point at which its subcrop begins, whereas at the northwestern limit of the study area a full section is usually 150 ft thick. The observed thinning is depositional in nature and not the result of erosional truncation. Hydrocarbon trapping in the Chester occurs at, and/or slightly downdip of, the point where the Chester first subcrops. This is because producible Chester hydrocarbons are generally limited to the upper parts of the unit. Where a well encounters the Chester near its ultimate truncation, the upper, potentially productive parts have been truncated, and the remaining lower parts typically are not productive.

SUMMARY AND CONCLUSIONS

Production within the study area has been allocated by IHS Energy Group to conform to a standardized nomenclature system and has been used to generate a new database called Intelligent Reservoirs. For this effort, an extensive network of cross sections was generated to enhance the accuracy, detail, and consistency of the allocation process, and nearly 3,000 mi of cross sections have been drafted to support the database.

The stratigraphic and facies relationships of the Springer and Chester Groups have been demonstrated. For the Boatwright and Britt carbonates, the definition of these individual units and their separation from the true Mississippian Chester limestone (Fig. 65) gives additional, and heretofore unavailable, detail and insight into the reservoir production data. Additionally, an understanding of these relationships is necessary for the accurate mapping of these units within the study area.

It is anticipated that the increased accuracy, detail, and consistency of the allocated production, as well as the stratigraphic and facies relationships developed by this study, will aid in future exploration and exploitation.

PART V

Cedardale Area

Boatwright and Britt carbonate production in parts of Ts. 22–23 N., Rs. 17–19 W., Woodward County, Oklahoma

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INTRODUCTION

A gas-producing area with completions in the carbonate facies of the Boatwright and Britt members of the Springer Group (Upper Mississippian–Lower Pennsylvanian) was evaluated to demonstrate the producing characteristics and identify trapping mechanisms. Additionally, this area was selected because of the inaccurate nomenclature reported for Springer carbonate completions, most of which were attributed to the underlying Chester, as shown on completion forms filed with the Oklahoma Corporation Commission.

As shown in Figure 66, the study area includes parts of Ts. 22–23 N., Rs. 17–19 W. Although the true Chester is productive in this area, it is not evaluated in detail in this report. A map showing the locations of Springer carbonate completions and Chester completions is provided as Plate 4 (in envelope). The study area includes parts of the Cedardale Northeast and Cedardale Northwest fields.

Within the study area, gas was first commercially produced from the Boatwright carbonate in 1962. Five years later, in 1967, gas was commercially produced from the Britt carbonate. In 1962, Boatwright gas was first sold from the No. 1 Garvie well in sec. 26, T. 22 N., R. 17 W.

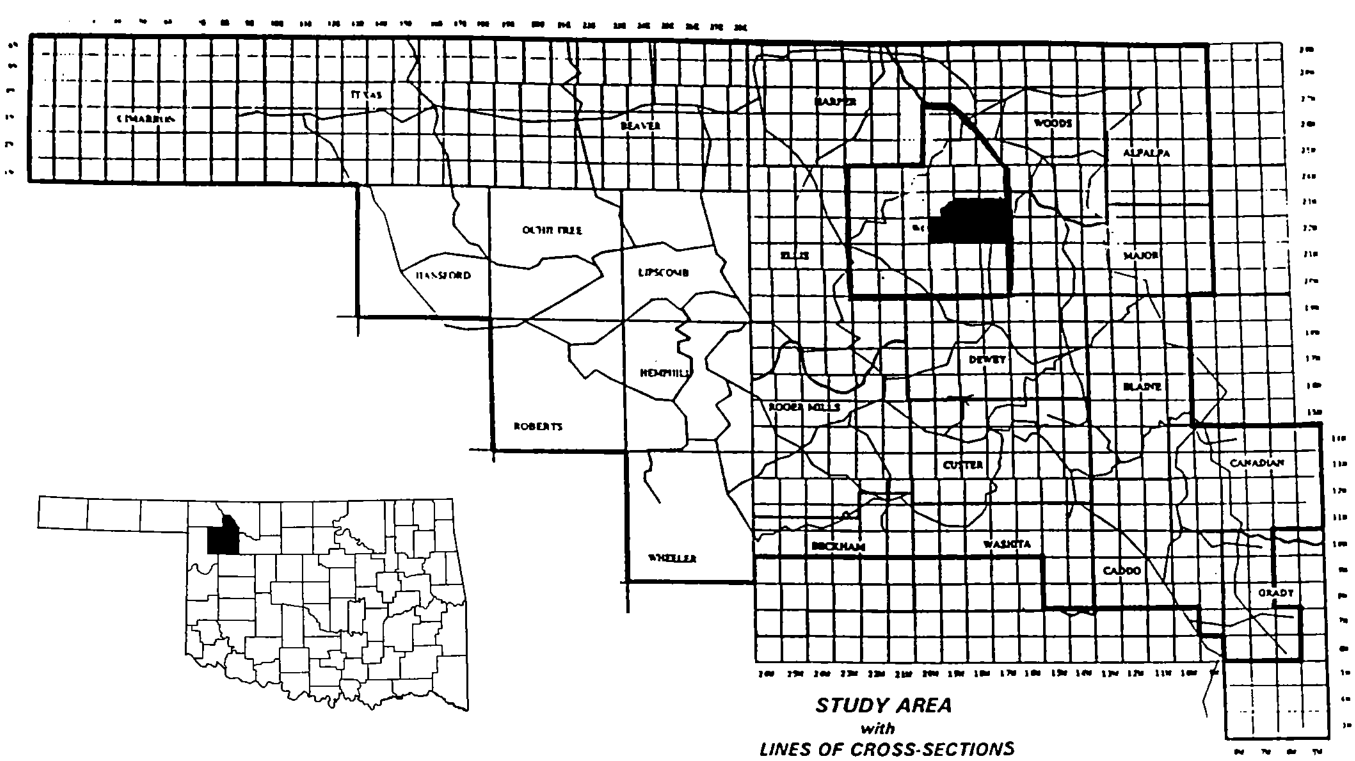


Figure 66. Index map of Oklahoma, showing the grid of regional cross sections completed by the IHS Energy Group and the Cedardale study area in Woodward County.

The first 10 single-zone Boatwright completions have produced an average of 2.3 BCFG/well from an average depth of 7,050 ft. In 1967, Britt gas was first sold from the No. 1 Otto Roberts well in sec. 26, T. 22 N., R. 18 W. The first 10 single-zone Britt completions have produced an average of 2.7 BCFG/well from an average depth of 7,550 ft.

As of December 1999, the study area had produced more than 189 BCFG from 166 completions in Boatwright and Britt carbonate reservoirs. Within that population, 76 wells have produced nearly 84 BCFG from single-zone completions in the Boatwright carbonate, and 31 wells have produced >51 BCFG from single-zone completions in the Britt carbonate. Additionally, production from 15 wells that were completed in the Boatwright and Britt was commingled, yielding an additional 12.4 BCFG. In comparison, 49 completions were attempted in the Chester limestone, of which only four were single-zone completions. These four single-zone Chester completions have produced <2 BCFG. The average recovery from the underlying Chester is far less than from the Britt or Boatwright carbonate; thus, it is important to make a clear distinction between the Chester and Springer reservoirs.

STRATIGRAPHY

Much of the nomenclature used in the study area is misleading because of misidentification and improper correlation of the Chester–Springer boundary. The miscorrelation does have a reasonable explanation, however. The area was originally drilled from the shallow shelf toward the deeper basin. Early workers correctly identified the unconformity between the Pennsylvanian Morrow clastic section and the underlying Mississippian Chester carbonate section. In a basinward direction, however, increasingly younger Mississippian carbonate strata (Springer) are present below the Morrow unconformity. Thus, as a carbonate section was typically observed below the Morrow section, the transition from one carbonate unit to a series of younger carbonate units was not formally recognized. Workers did acknowledge younger "Chester" intervals and labeled them "Chester A" and "Chester B." Usually the "Chester A" can be correlated with the Boatwright, and the "Chester B" with the Britt. The terms *upper Chester* and *lower Chester* were also used. The lower Chester is correlative with the top of the true Chester. The upper Chester is correlative with the top of the Springer carbonate section (either the Britt or Boatwright), whichever subcrops below the Morrow unconformity. Several papers concerning the identification of carbonates within the Springer Group have been published in the last 5 years (see Selected References, this volume). For further discussion of these stratigraphic relationships, see Part IV of this volume.

As previously stated, the first carbonate encountered below the clastic section of the Morrow Group or Cherokee Group in the study area was termed *Chester.* An angular unconformity exists below the Morrow Group that truncates the Britt carbonate in the western part of the study area and truncates most of the Boatwright carbonate in the eastern part. The Boatwright shale is everywhere present in the lowermost part of the Boatwright interval. As demonstrated in the dip cross section through the Cedardale area (section A–A′, Fig. 67, in envelope), the Boatwright shale is an excellent persistent marker for identifying the top of the underlying true Chester. The top limestone section of the Chester is consistent throughout the study area, except that it becomes more porous to the east.

The strike cross section (B–B′, Fig. 68, in envelope) illustrates the consistency of the Boatwright interval. A remnant lower Morrow sandstone overlying the erosional surface of the Britt carbonate is also shown. It appears that porosity develops near the weathered surface in the Britt interval. Diagenetic processes involving fresh water percolating through the Britt carbonates and partially dissolving the rock likely enhanced porosity in certain areas below the unconformity surface. The lines of both cross sections are shown in Figures 70 and 72–74.

A type log for the Britt carbonate is provided as Figure 69. This well encountered approximately 17 ft of reservoir section with porosity >10%. This zone of high porosity is 20 ft below the unconformity surface. The porosity may have been derived from diagenetic enhancement where ground water entered a porous zone when it was exposed as an erosional surface. This well has produced 4.5 BCFG and 6,759 BO from the Britt carbonate. This type log is from a well in the same section as the tie well for both cross sections.

Variations in the thickness of the Britt interval, as shown on the Britt isopach map (Fig. 70), are interpreted as having been caused by erosional scours during late Springeran or early Morrowan time. The thickness of the Britt ranges from 0 to 102 ft within the study area. Wells producing from the Britt are also shown on the map. It appears that the Britt must be at least 30 ft thick to be productive. The best wells are proximal to (but not within) the erosional scours. Thus, erosion down to a certain point in the section allowed surface waters to percolate into the subsurface and enhance porosity away from the erosional surface itself. Additionally, in many wells, rocks at the erosional surface have sufficient porosity to be productive.

A type log for the Boatwright interval is shown in Figure 71. This example does not show the entire Boatwright interval, as the contact with the overlying Morrow section is erosional. The type log for the Britt (Fig. 69) shows a normal section of Boatwright without an erosional contact. The type log for the Boatwright illustrates a typical section with multiple zones of porosity. This example has three distinct porous intervals. The top porosity zone appears to be at the unconformity surface. The excellent porosity in this zone was probably enhanced by weathering. The second porosity zone is about 20 ft below the unconformity surface and was probably enhanced by diagenetic processes involving ground water percolating downdip from the outcrop. About 40–50 ft below the erosional surface of the Boatwright is the third porosity zone. This well has produced 8.2 BCFG from all three zones.

A Boatwright isopach map (Fig. 72) shows small, gradual variations in the thickness of the section where it was not eroded. In the southernmost part of the study area, a full section of Boatwright typically consists of 220+ ft of

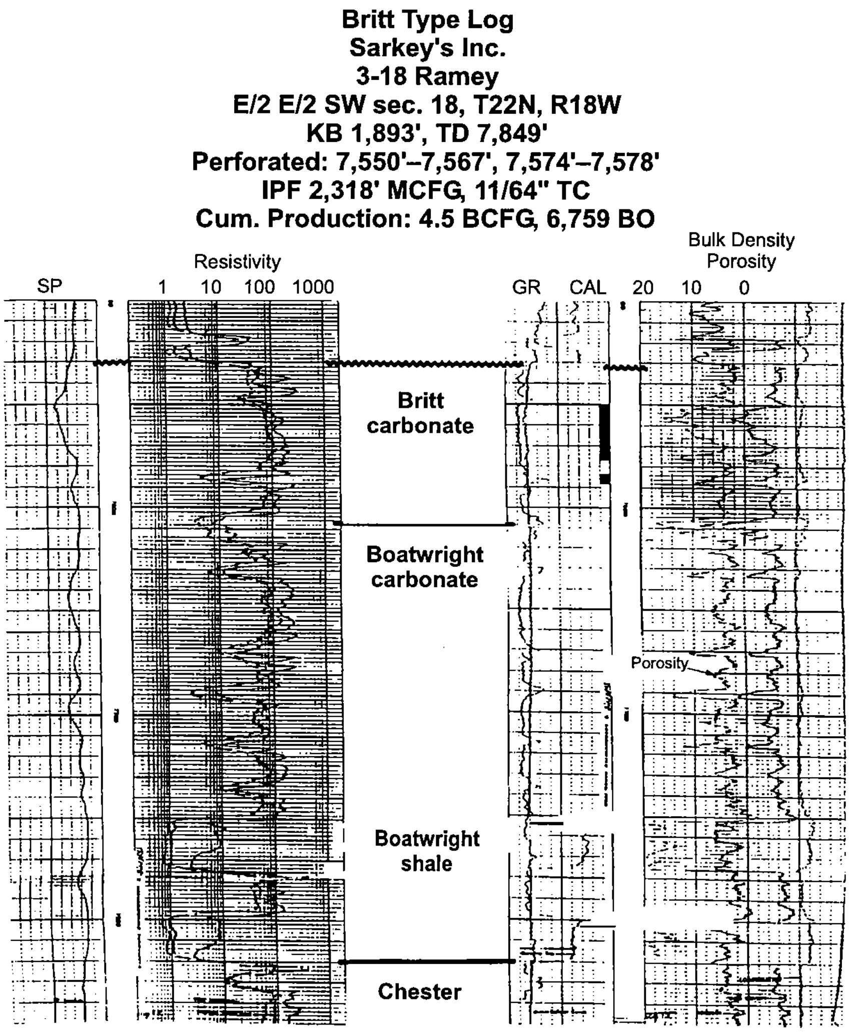


Figure 69. Type log for the Britt carbonate in the Cedardale area, showing informal subsurface nomenclature of the Springer Group as used in the Anadarko basin of western Oklahoma. *GR* = gamma ray; *SP* = spontaneous potential; *CAL* = caliper.

limestone and shale. In the northern part of the study area, the interval might thin to 180 ft or less. The basal 60- to 70-ft part of the Boatwright is characterized by two shale intervals (the Boatwright shale) separated by a 20-ft-thick limestone (see cross sections and type logs). Most Boatwright wells are completed in porous zones within a total interval of at least 80 ft.

The Boatwright shale is extremely useful in determining the Boatwright–Chester contact. As shown on the isopach map (Fig. 72), most of the productive Boatwright wells were drilled where the top of the Boatwright is an erosional contact or within 3 mi downdip of the contact. Although many wells have been completed within the area of the full Boatwright section, these wells tended to account for significantly lower cumulative production, which is typically commingled with that from other formations. These observations suggest the importance of weathering and diagenetic processes in the development of porosity in the Boatwright.

As with the Britt, variations in the thickness of the eroded Boatwright are interpreted to have been caused by erosional scours during late Springeran or early Morrowan time. These scours (Fig. 72) are aligned with the scours seen in the Britt (see Fig. 70). The thickness of the Boatwright ranges from 22 to 234 ft in the study area. Like the Britt, the best Boatwright wells are proximal to the erosional scours. As shown in Figure 72, only two of the 28 single-zone Boatwright completions that have produced more than 1.0 BCFG are in the axis of the trough of the erosional scours. Thus, it appears that weathered rock was eroded away within the axis of the erosional scours, leaving the more resistant rock with a lower reservoir potential. This erosion allowed surface waters to percolate laterally downdip into the subsurface and enhance porosity away from the erosional surface itself. Many of the completions within the Boatwright are, however, in the weathered zone beneath the erosional surface.

STRUCTURE

Because the top of the Britt carbonate covers only half the study area and is an erosional surface, no structure map of the Britt was prepared. The Boatwright likewise was not used to depict structure, because its top is also an erosional surface over half the area. However, sufficient Chester penetrations exist to generate an accurate structure map depicting the top of the Chester (Fig. 73). This map shows a southwesterly dip into the Anadarko basin of about 100–125 ft/mi. A system of up-to-the-basin faults is present in the eastern part of the study area. The faults appear to have about 50–100 ft of throw, with splinter faults dying off away from the fault system. No corresponding thick intervals of the Boatwright are present on the downthrown sides of the faults, or corresponding thin intervals on the upthrown sides. This suggests that the faulting occurred after erosion of the Boatwright carbonate. No relationship was detected between the observed Chester structure and trapping mechanisms in the Britt or Boatwright. Several areas do appear favorable, however, for deep-seated structures that may not have been adequately tested. It is apparent to the authors that using the first carbonate encountered below the clastic Morrow section for a structural datum would provide a misleading interpretation of the deeper structure.

PRODUCTION

Smith (1996) first identified the significance of identifying the "correct" carbonate reservoir, as the Springer completions typically produce nearly twice as much gas as do Chester completions within the same depth range.

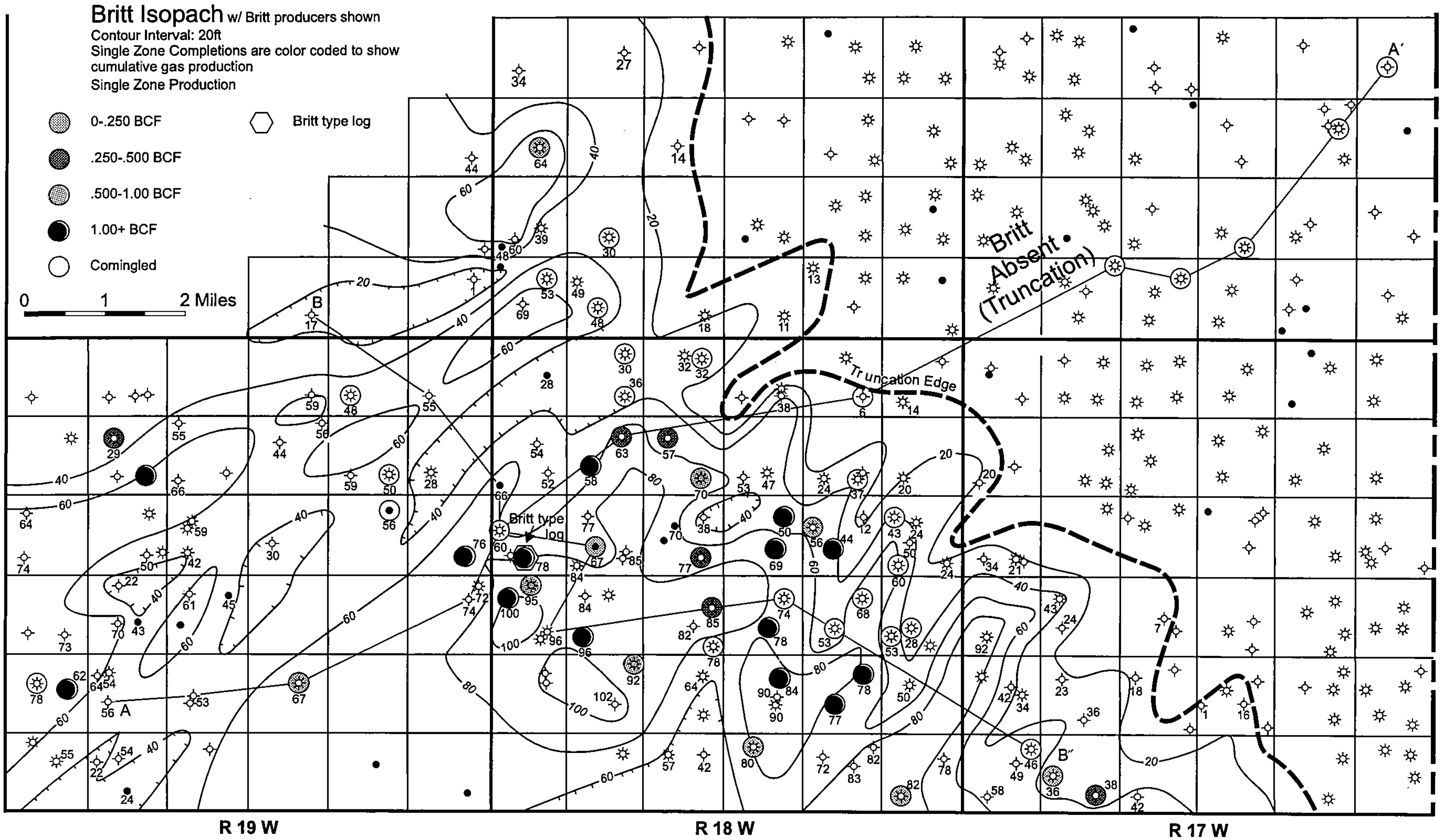
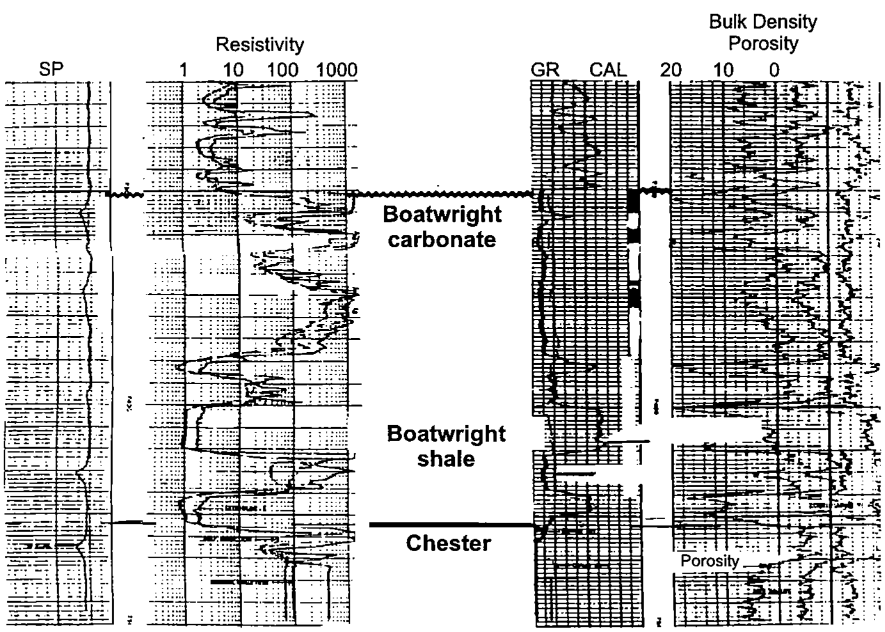


Figure 70. Britt carbonate isopach map (total gross thickness of all carbonate in Britt interval) in the Cedardale area, showing cumulative gas production from wells producing from the Britt zone. Contour interval is 20 ft. Cross sections A–A´ and B–B´ shown in Figures 67 and 68.

TABLE 10. — State-Reported "Chester" Single-Zone Completions and Cumulative Gas and Oil Production

Reservoir name (IHS)	Population	Gas cum. (BCF)	Oil cum. (bbl)
"Chester"	154	164.978	232,946
What those 154 completions really are:			
Atoka/Boatwright carbonate/Chester	4	0.990	6,473
Boatwright carbonate	71	74.143	95,024
Britt carbonate	27	45.744	49,511
Britt carbonate/Boatwright carbonate	14	11.437	9,728
Britt carbonate/Boatwright carbonate/ Chester	1	0.203	639
Britt carbonate/Boatwright carbonate/ Red Fork	1	0.457	79
Boatwright carbonate/Chester	28	29.464	67,554
Cottage Grove/Red Fork	1	0.744	0
Chester	4	1.696	2,445
Chester/Manning	1	0	1,493
Oswego	2	0.101	0
Total	154	164.978	232,946

Boatwright Type Log
Texas Oil and Gas Corp.
1 Garvie
N/2 S/2 SE sec. 25, T22N, R17W
KB 1,813', TD 7,481'
Perforated: 7,301'–7,310', 7,318'–7,324'
7,342'–7,344', 7,346'–7,354'
IPF 4,600' MCFG, 23/64" TC
Cum. Production: 8.2 BCFG, 8,671 BO



Smith reports that more than 1.2 TCFG produced from Springer carbonates was misallocated as having been produced from the underlying Chester in nearly 750 completions. The report by Smith includes most of the Oklahoma portion of the Anadarko basin but does not include the Oklahoma or Texas Panhandle.

Using the nomenclature originally reported to the State agencies, 177 wells were completed in the "Chester." Of these, 154 completions were reported to be single-zone "Chester" completions. As shown in Table 10, these wells have a cumulative production (as of December 1999) of 165 BCFG and 233,000 BO. After examination of logs of these wells, using the Boatwright shale to identify the base of the Springer section and the top of the Chester, the identification of producing formations was corrected. Of the 154 "Chester" single-zone completions originally reported to the State, only four are actually single-zone Chester completions. Some of the wells do not produce from either Springer carbonates or from the Chester; they appear to have been misreported.

Cumulative oil and gas production from the Boatwright and/or Britt is shown in Table 11. To date, the average single-zone Boatwright completion has produced 1.1 BCFG and 1,767 BO. The average single-zone Britt completion has produced about 50% more gas (1.65 BCFG). Ultimate-recovery calculations (shown in Table 15) suggest a similar outcome: Britt completions should ultimately produce 38% more gas than Boatwright completions. Interestingly, commingled completions involving only the Britt and Boatwright produce an average of 0.82 BCF, 75% below a single-zone Boatwright completion and ~50% below an average Britt completion. Typically, the Boatwright is less productive away from the Boatwright unconformity surface.

Figure 71 *(left)*. Type log for the Boatwright carbonate in the Cedardale area, showing informal subsurface nomenclature of the Springer Group as used in the Anadarko basin of western Oklahoma. *GR* = gamma ray; *SP* = spontaneous potential; *CAL* = caliper.

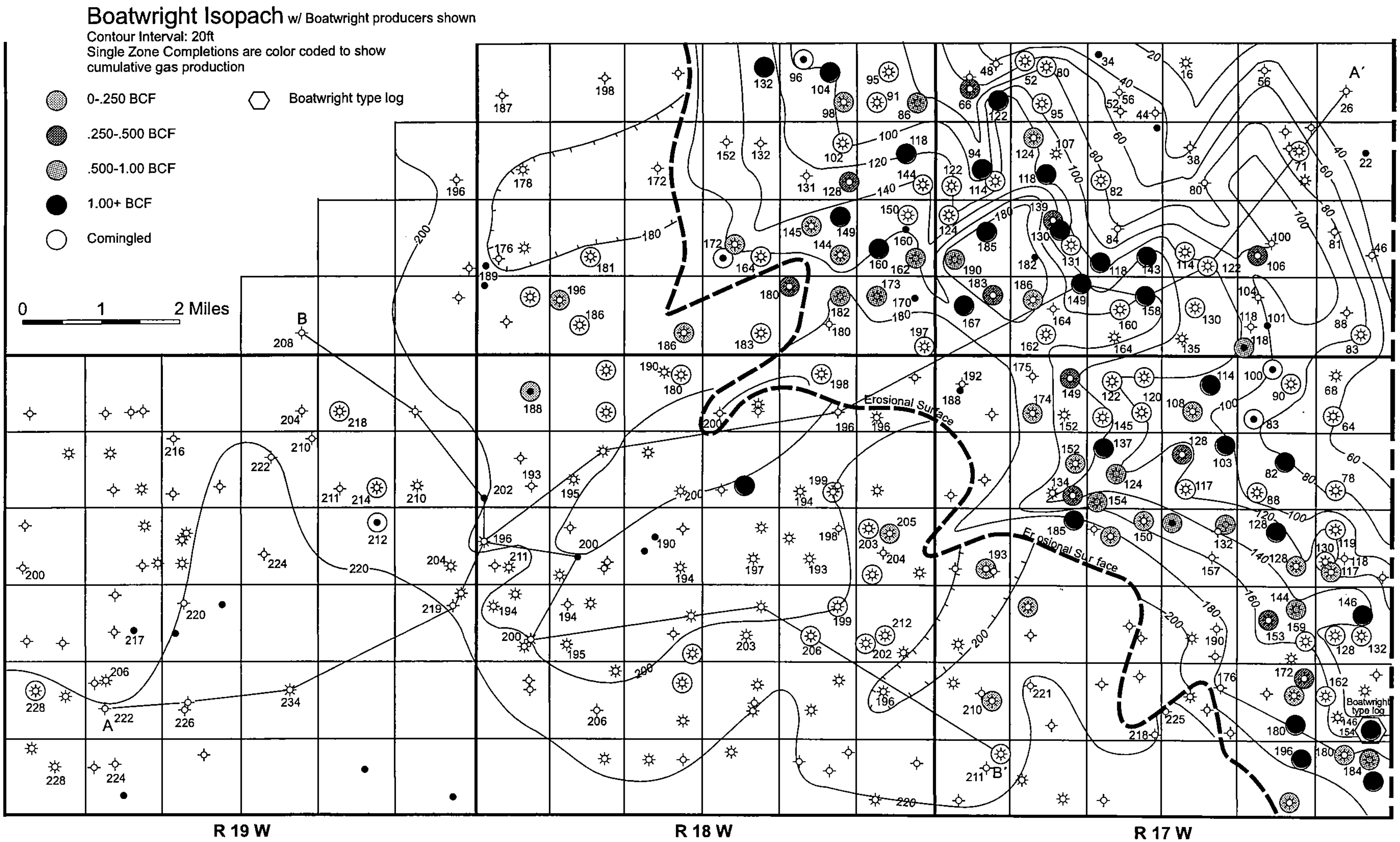


Figure 72. Boatwright carbonate isopach map (total gross thickness of all carbonate in Boatwright interval) in the Cedardale area, showing cumulative gas production from wells producing from the Boatwright zone. Contour interval is 20 ft. Cross sections A–A′ and B–B′ shown in Figures 67 and 68.

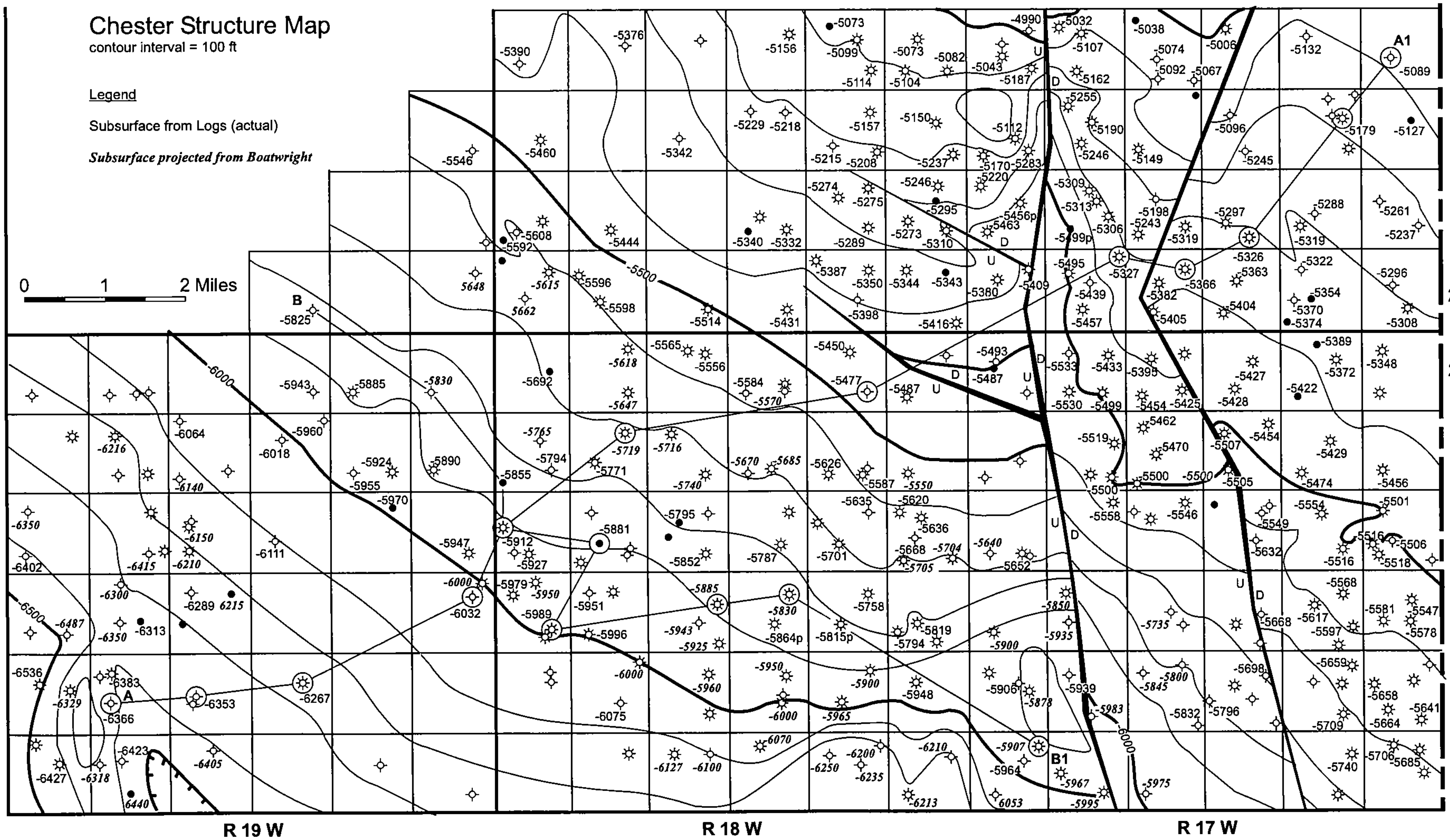


Figure 73. Structure map depicting the top of the Chester limestone in the Cedardale area. Contour interval is 100 ft. Datum is mean sea level. Hachures indicate depression. Cross sections A–A′ and B–B′ shown in Figures 67 and 68.

TABLE 11. — Springer Carbonate Production in Cedardale Area

Reservoir name (IHS)	Population	Gas cum. (BCF)	Oil cum. (bbl)
Boatwright carbonate	76	83.914	134,305
Britt carbonate	31	51.275	67,086
Britt carbonate/Boatwright carbonate	15	12.368	9,728
Total	122	147.558	211,119

TABLE 12. — Average Reservoir Parameters of Springer Carbonates in Cedardale Area

Average reservoir parameters	Reservoir name (IHS)	
	Boatwright	Britt
Depth	7,146 ft	7,520 ft
Perforated interval (thickness, porosity)	29 ft, 6.3%	18 ft, 7.7%
7%+ cutoff (thickness, porosity)	11 ft, 8.8%	12 ft, 9.4%
7%+ cutoff "single-zone completions"	14 ft, 8.9%	16 ft, 9.7%
4%+ cutoff (thickness, porosity)	25 ft, 6.6%	22 ft, 7.4%
Saturated interval (thickness, porosity)	62 ft, 4.5%	42 ft, 5.3%
Water saturation (%) (min./avg./max.)	8/34/82	8/36/70
Avg. initial pressure (psi)	2,391	2,673
Avg. initial pressure gradient (psi/ft)	0.336	0.352
Avg. drill-pattern spacing (acres)	252	292

RESERVOIR CHARACTERISTICS

Reservoir characteristics of the Britt and Boatwright carbonates were investigated through detailed log analysis. To develop a good data set for understanding the reservoirs in producing wells, 96 single-zone completions were evaluated, plus an additional 81 wells from which Britt or Boatwright production was commingled with a second reservoir. Table 12 shows the average producing-reservoir parameters within the study area. Although not as thick, the Britt has better porosity and pressure than the Boatwright. However, the difference is small enough so that the reservoir parameters favor the Boatwright to produce more gas than the Britt. Curiously, when one compares the results of single-zone completions in the two reservoirs, on average the Britt produces 38% more gas.

An examination of the reservoir parameters of single-zone completions with good pressure data reveals that the reservoir volume using the 7% porosity-cutoff data favors the Britt by 24% (see Table 12). The higher pressures observed in the Britt, coupled with increased reservoir volume, suggest that single-zone Britt completions should outperform Boatwright completions by 39%. Indeed, this explains the observation that single-zone Britt completions do outperform single-zone Boatwright completions by 38%. In the study area, there are more commingled completions than single-zone completions.

Table 12 describes average reservoir parameters, except initial pressure, regardless of how the well was ultimately completed. What does this imply about the Boatwright's capacity in light of the fact that the overall population is significantly influenced by commingled completions? Are there numerous underperforming Boatwright completions masked by virtue of having been commingled with another reservoir?

Table 13 shows the variations in thickness and average porosity observed in the completions within the study area. The Boatwright typically is thicker than the Britt; however, porosity tends to be better developed in the Britt. This observation explains why wells with the highest cumulative production are those completed in the Boatwright. Probably due to a combination of higher pressure and more "producible" reservoir-quality rock (7%+ cutoff for single-zone completions), the average cumulative production for the entire population does favor the Britt.

Table 13 also provides insight to the productive capability of the reservoirs. Operators tend to perforate an average of 29 ft of Boatwright, although an average of 25 ft has porosity of 4% or greater. Operators prefer a different perforation tactic when dealing with the Britt. They tend to perforate 18 ft of Britt where the average well has 12 ft of porosity of 7% or greater, and perforate 22 ft of porosity of at least 4%. It appears that operators perforate the midpoint (between 12 and 22 ft) in Britt completions, which might equate to a midpoint in porosity criteria of 5.5% (between the 7% and 4% cutoffs). As shown on the type log (Fig. 69) and on the cross sections, porosity observed within the Britt section is not typically homogeneous but is discontinuous and laminated. Using 4% porosity as a cutoff, not quite as liberal as for the Boatwright, operators might realize an additional reservoir volume of 16%. Does this difference in perforation patterns prevent Britt completions from realizing additional reserves? Conversely, are operators of Boatwright completions wasting money by perforating intervals that would not contribute reserves?

Using the Perfect Gas Law (or Ideal Gas Law), the volume of a tank (reservoir) can be determined if two things can be quantified: the amount of gas produced per pound of pressure drawdown, and the initial pressure. Using a pressure-decline method (the amount of gas produced per pound of pressure depletion between the first gas test and the most recent gas test), a recoverable-gas reserve base can be established. Because it does not contribute to the amount of gas produced per pound of pressure depletion, nonmobile gas would not be calculated in a Perfect Gas Law equation. Similarly, stranded (although

TABLE 13. — Thickness and Porosity of Springer Carbonate Reservoirs in Cedardale Area

	Reservoir name (IHS)	
	Boatwright	Britt
Observed well thickness (ft)		
Perforated thickness (min./avg./max.)	4/29/101	2/18/52
7%+ porosity thickness	11	12
4%+ porosity thickness	25	22
Saturated thickness (min./avg./max.)	12/63/119	10/41/84
Observed well porosity (%)		
Perforated porosity (min./avg./max.)	1.5/6.2/17.1	3.0/7.8/15
7%+ average porosity	8.8	9.4
4%+ average porosity	6.6	7.4
Saturated porosity (min./avg./max.)	1.5/4.5/13.0	2.5/5.3/11.7

mobile) gas would not be a factor in a Perfect Gas Law calculation.

A second method for calculating reserves for pressure depletion is presented: MCFG/psi. For this method, the ultimate recovery from each well is calculated, using a production-rate decline that is divided by the original reported pressure. The results of both methods are provided in Table 14.

Table 15 shows the ultimate potential gas in place for the completions in the study area. Using the parameters describing the perforated interval(s) of each well, the completions in the Boatwright should produce ~185 BCFG, and those in the Britt, ~48 BCFG. The 4% porosity-cutoff data yield a calculated gas in place of 189 BCFG for the Boatwright and ~73 BCFG for the Britt. Although it may not be economically producible, there is considerable saturated gas in the Boatwright carbonate—325 BCFG. The saturated gas in place in the Britt carbonate is not much different from that calculated for the 4% porosity cutoff—86 BCFG. Using a pressure-decline method (the amount of gas produced per pound of pressure depletion between the first gas test and the most recent gas test), a recoverable gas reserve of 245 BCFG can be established for the Boatwright, and nearly 85 BCFG for the Britt. The data confirm the assertion that gas will not be recovered from nonperforated gas-bearing intervals. Thus, the nonperforated intervals with porosity >4% (described earlier) in the Britt do not contribute to the production stream. Using a pressure-decline method, the calculated reserves are indeed between the volumetric calculations for the 4% and 7% cutoffs, which agrees with a typical completion technique.

TABLE 14. — Two Methods for Calculating Recovery per Pressure Depletion from Springer Reservoirs in Cedardale Area

	Reservoir name (IHS)	
Recovery per pressure depletion	Boatwright	Britt
Average of pressure decline (psi)	755	791
Average of MCFG/psi	669	558

Table 15 also shows the average reserve calculations for single-zone completions having good pressure data, using various volumetric criteria and pressure-decline methods. In volumetric calculations for single-zone completions, the Britt calculates as having more gas in place per well than does the Boatwright. The pressure-decline method agrees with the volumetric calculations. However, the MCFG/psi method shows more reserves per completion for the Boatwright than for the Britt. The populations used to generate the values are statistically valid. Because these calculations are influenced by the total amount of gas produced (influenced by humans), this curious observation suggests that either one of two hypotheses may be true: some Britt completions may be prematurely abandoned, or the production-decline rates will level off—i.e., these wells will have longer lives than originally projected. Using the pressure-decline technique as a reasonable ratio, operators may inadvertently leave 0.39 BCFG per prematurely abandoned completion, or underestimate the life and reserves of their wells if a production-decline method is used to forecast future production. Identifying the producing zone correctly obviously plays a significant role in the valuation of a property.

Contrary to the statistics generated by single-zone completions, commingled intervals within the Britt and Boatwright alter the reservoir statistics such that the average Boatwright completion has greater reservoir capacity than does the average Britt completion. However, most of the commingled Britt or Boatwright completions are lackluster. The reservoir characteristics of the average commingled Britt zone are significantly poorer than those of the average single-zone Britt completion. Although having poorer reservoir characteristics, single-zone and commingled-zone Boatwright completions are not as dramatically different as are those of the Britt completions. In general, thicknesses observed in commingled zones are comparable to the single-zone completions. Porosities in the commingled completions are less than those in single-zone completions. Observed water saturation and initial pressure also decreased in commingled completions. The average commingled well producing from both the Britt and Boatwright does not produce as much gas as a single-zone completion from the Boatwright (poorer of the two). Adding the characteristics of the commingled zones to the overall population of reservoir parameters helps demonstrate the high degree of lateral discontinuity in reservoir quality. The reservoir encountered by the drill bit may not be the same reservoir quality 100 ft from the wellbore.

For each single-zone completion having good pressure data, an area of drainage was calculated using several different parameters. Initial-pressure and water-saturation values were constant for each calculation. "Perforated drainage areas" were calculated using ultimate-recovery values for each completion and the perforated-thickness and perforated-porosity values. "Saturated drainage areas" were calculated using ultimate-recovery, saturated-thickness, and saturated-porosity values for each completion. In contrast, the Perfect Gas Law was utilized to determine effective reservoir size, generating different calculations for drainage (gas recovered per pound of pressure depletion multiplied by initial pressure).

P/Z calculations (reservoir pressure divided by compressibility factor) for perforated, 7% cutoff, 4% cutoff, and saturated intervals were generated, using the appropriate thickness and porosity while water saturation, initial pressure, and reservoir size were held constant. The authors believe that the *P/Z* calculations are more reliable than using the ultimate-recovery method for determining drainage area. The results of the calculations are presented in Table 16. For both reservoirs, the average producing area is about 250 acres. The average Britt completion is likely to drain 152–231 acres, whereas the average Boatwright completion is likely to drain 154–298 acres. It is likely that most Britt and Boatwright production is contributed by reservoirs with porosity of at least 4%.

TABLE 15. — Ultimate Potential Gas in Place for Springer Carbonate Reservoirs in Cedardale Area

	Reservoir name (IHS)	
	Boatwright	Britt
All wells — Gas-in-place calculations		
Sum of perforated gas in place (BCF)	185.06	48.38
Sum of 7%+ gas in place (BCF)	104.40	52.54
Sum of 4%+ gas in place (BCF)	188.84	72.84
Sum of saturated gas in place (BCF)	325.08	86.00
Sum of pressure decline gas in place (BCF)	245.14	84.53
Sum of MCF/psi gas in place (BCF)	217.22	59.66
Single-zone completions — Gas-in-place calculations		
Perforated gas in place (BCF)	1.94	2.12
7% porosity cutoff gas in place (BCF)	1.72	3.07
4% porosity cutoff gas in place (BCF)	2.42	3.65
Saturated gas in place (BCF)	3.51	4.40
Average pressure-decline gas in place	1.79	2.11
Average MCF/psi gas in place	1.59	1.49
Average ultimate recovery (BCF)	**1.26**	**1.74**

TABLE 16. — Calculated Drainage Areas for Single-Zone Completions in Springer Carbonate Reservoirs in Cedardale Area

	Reservoir name (IHS)	
Calculated drainage area (acres)	Boatwright	Britt
Average spacing	249	251
Perforated drainage area	427	459
P/Z perforated drainage area	298	231
P/Z 7% cutoff drainage area	210	244
P/Z 4% cutoff drainage area	154	152
P/Z saturated drainage area	133	113
Saturated drainage area	304	165

RESERVOIR HETEROGENEITY

A typical well log characterizes a very small part of the reservoir, which may not be indicative of the areal extent of the reservoir's drill (spacing) pattern. The lateral continuity of porosity and the thickness of porosity in the Boatwright, as determined from well logs, is highly suspect. As shown in Tables 13 and 15, two porosity-cutoff criteria were used to investigate the parts of the reservoir that appear to have contributed gas to the production stream.

Nine Boatwright completions with less than half the average 7% porosity-cutoff thickness and below the average 4% porosity-cutoff thickness were identified as "thin" (see Table 17). Although these wells have less than average reservoir capacity, eight of the nine completions have produced more gas than the average Boatwright completion. These eight "overproducing" completions did not benefit from excessive reservoir pressure. On the other end of the thickness spectrum, nine Boatwright completions with double the average 7% porosity-cutoff thickness and two additional Boatwright completions with double the average 4% porosity-cutoff thickness were identified as "thick" (Table 17). With twice the reservoir capacity, only four of the 11 completions have produced more than double the average Boatwright completion. Surprisingly, five of the 11 "thick" completions have produced less than half the gas produced by an average Boatwright completion. These underperforming completions did not undergo pressure depletion. The eight overproducing completions and the five underperforming completions demonstrate the variability of reservoir quality away from the wellbore.

TABLE 17. — Variability of Thickness versus Ultimate Recovery for Springer Carbonate Reservoirs in Cedardale Area

Reservoir		7% Cutoff Thk. (ft)	7% Cutoff Por. (%)	4% Cutoff Thk. (ft)	4% Cutoff Por. (%)	Ult. rec. (BCF)[a]
Boatwright	thin	0		8	4.5	**1.600**
Boatwright	thin	0		14	4.0	**1.678**
Boatwright	thin	0		22	6.0	**2.397**
Boatwright	thin	1	7.0	9	5.0	0.988
Boatwright	thin	2	7.0	5	6.1	**2.770**
Boatwright	thin	2	7.0	9	5.3	**1.820**
Boatwright	thin	3	8.0	12	6.0	**2.670**
Boatwright	thin	3	9.0	22	5.8	**3.849**
Boatwright	thin	4	8.0	14	6.3	**2.952**
Boatwright	thick	9	7.5	52	5.8	0.275
Boatwright	thick	14	8.0	52	6.0	0.041
Boatwright	thick	22	8.9	51	7.3	0.124
Boatwright	thick	24	8.7	55	7.1	0.773
Boatwright	thick	26	8.5	52	7.0	0.984
Boatwright	thick	27	9.0	50	7.4	**6.152**
Boatwright	thick	30	13.0	30	13.0	**5.471**
Boatwright	thick	30	10.0	42	8.7	**3.083**
Boatwright	thick	36	9.5	44	8.7	**2.675**
Boatwright	thick	38	9.3	57	8.3	0.013
Boatwright	thick	40	7.0	54	6.6	0.472
Britt	thin	0		5	4.0	0.586
Britt	thin	1	7.0	6	6.0	0.140
Britt	thin	1	7.0	6	5.0	0.729
Britt	thin	3	8.0	12	5.3	1.060
Britt	thin	5	10.0	10	8.0	0.006
Britt	thin	6	7.0	6	7.0	0.096
Britt	thin	6	7.0	10	6.4	0.472
Britt	thin	12	11.0	14	10.0	0.005
Britt	thick	20	11.0	50	7.0	**4.828**
Britt	thick	30	12.0	32	11.7	0.692
Britt	thick	30	14.0	44	11.0	**1.770**
Britt	thick	30	11.7	53	9.0	0.004
Britt	thick	34	9.0	50	7.9	**3.427**
Britt	thick	39	14.1	58	11.3	**5.040**

[a]Ultimate recoveries in boldface type indicate above-average production.

It appears that an abundance of reservoir capacity, as observed on well logs, does not guarantee a good Boatwright producer. Conversely, excellent wells producing 0.988–3.849 BCFG have been completed in zones <4 ft thick with at least 7% porosity, and in zones <22 ft thick with at least 4% porosity. The Boatwright reservoir encountered by the bit may be significantly different from the reservoir that is in communication with the wellbore. How many wells having these "dismal" characteristics have been plugged or overlooked?

A similar comparison was made in evaluating "thin" and "thick" Britt completions (see Table 17). None of the "thin" Britt completions produced like the average Britt completion. However, one completion did produce 1 BCFG from a zone only 12 ft thick exceeding 4% porosity, of which only 3 ft had at least 7% porosity. Another completion produced 0.73 BCFG from a 6-ft zone with an average porosity of 5%. Two of the "thick" Britt completions produced below the average, yet one had low initial pressure, making it somewhat predictable. One "thick" Britt completion did produce more than the average, yet it should have produced significantly more gas than it did on the basis of reservoir quality. There can be numerous explanations for this underperformance. Unlike the Boatwright, the data do suggest that the results of a Britt completion are more predictable for "thin" or "thick" intervals.

SUMMARY

The Britt and Boatwright carbonates are often misidentified as the underlying Chester. The Boatwright shale is an excellent marker for separating the Springer carbonates from the Chester carbonates, because it can be correlated throughout the Anadarko basin regardless of the clastic or carbonate lithology of the Springer. The Springer carbonates produce significantly more gas per completion than do the completions in the true Chester. In this study area, on average, the Britt produces 4 times more gas than the Chester, and the Boatwright produces 3 times more gas than the Chester.

Structural position does not appear to play much of a role in the productivity of the Springer carbonates. The truncation of the Springer carbonates beneath the Morrow is the dominant trapping mechanism. In both reservoirs, weathering of the unconformity surface enhanced porosity.

Downdip from the unconformity surface, it appears that ground-water percolation improved porosity within the reservoirs through diagenesis. Although both reservoirs are heterogeneous, the Boatwright is extremely so—to such a degree, in fact, that predicting productivity on the basis of reservoir thickness and porosity calculated from well logs is unreliable.

In the study area, several wells have produced >5 BCFG, with the best completion accounting for >8.2 BCFG. The average completion yields a gross return on investment of 6 to 1 from the Britt and 4 to 1 from the Boatwright. Considerable potential remains within the trend; however, the difficulty in predicting accurate results may discourage would-be attempts at in-fill drilling.

FUTURE POTENTIAL

There is considerable potential for the development of additional reserves in the truncation trend of the Springer carbonates. In several places, producible gas may have been overlooked because of poor completion practices, confusion in nomenclature leading to undrilled locations within fields, large gaps in the overall truncation trend, heterogeneity within reservoirs, and possible nonperforated (undrained) intervals in existing wells. Although the study area represents but a small part of the Springer carbonate trend, certain points warrant further investigation.

Operators tend to be willing to perforate potential reservoir rock with porosity <4% in the Boatwright. They do not appear to perforate the Britt in the same manner. *Perhaps significant reserves are being overlooked in the Britt because operators are not perforating as much of the reservoir section.* Because the trapping mechanisms and processes for improved reservoir porosity are similar for the Britt and Boatwright, one might expect the Britt to behave in a similar fashion to the Boatwright.

As shown for single-zone completions (Table 15), the pressure-decline method, which invokes the Perfect Gas Law, indicates an average completion reserve equal to the volumetric calculation for the perforated interval (2.11 BCFG versus 2.12 BCFG). The average ultimate recovery equals 82% of these two gas-in-place calculations (1.74 BCFG). On average, a volume of 0.95 BCFG is not produced when a 7% cutoff is used to select the perforated interval. Could a large percentage of this nonperforated gas be captured? In comparison, an average single-zone completion in the Boatwright will recover 1.26 BCFG. This represents 70% of the pressure-decline reserves and 73% of the volumetric calculation using the 7% porosity cutoff. The pressure-decline method calculates an average gas in place that is only 8% less than the volumetric calculation for the perforated interval. If the Britt does behave in a similar fashion to the Boatwright, and if the operators perforated all the 7%+ porosity, the average ultimate recovery of the Britt might increase by 0.500 BCFG to 2.25 BCFG per completion.

As mentioned in this report, MCF/psi calculations are based on ultimate recovery divided by initial pressure, a calculation that can be altered by premature abandonment. In comparison, the pressure-decline method is not as easily influenced by premature abandonment. Table 14 shows the calculations for recovery per pound of pressure depletion. Calculations for the average Boatwright and Britt completions are provided in Table 15. If the ratio observed between the two calculations for Boatwright completions provides a reliable indication, an average of 0.380 BCFG per single-zone Britt completion is being prematurely abandoned. These "abandoned" reserves may require in-fill wells to produce at rates acceptable to operators.

The use of incorrect names as reported to the State makes the Cedardale area appear to be adequately drilled out. Errors and confusion in nomenclature suggest, however, that undrilled locations remain within fields at present, as shown on the production map (Fig. 74). More interestingly, the truncation trend of the Springer carbonates covers a huge area in northwestern Oklahoma and the Oklahoma Panhandle, yet there are large gaps in production in the overall truncation trend (Pl. 4, in envelope). An examination of the ultimate recovery per completion by year shows a steady decline (see Fig. 75). According to the graph, an average completion should make just over 0.600 BCFG from the Boatwright—if currently drilled. Additionally, the average initial pressure gradient encountered by wells has fallen from 0.450 psi/ft to a current level of 0.215 psi/ft (see Fig. 76). Thus, the average 7,000-ft completion drilled in 1962 encountered 3,250 psi, whereas currently a similar well might encounter ~1,550 psi. Using the average recovery per pound of pressure depletion (Table 14) and an abandonment pressure of 150 psi, one might expect to recover just over 1.0 BCFG from a well drilled today. To achieve the 0.600 BCFG as indicated by Figure 75, only 800 psi of pressure depletion would be required. A careful examination of potential areas of depletion should allow for the identification of potential in-fill locations that could provide an ultimate recovery ranging from 0.600 to 1.0 BCFG.

As discussed, reservoir heterogeneity is extreme within the Boatwright interval. The thickness and porosity of the reservoir as identified in well logs are not laterally continuous. Wells with only *half* the average amount of reservoir have produced twice as much gas as the average well, and conversely, wells with *twice* the average thickness have failed to produce half the gas produced by the average well. These observations suggest that the reservoir encountered in a wellbore is not representative of the reservoir drained by the well. Thus, wells were probably drilled within the truncation trap of the Boatwright carbonate whose well logs did not look favorable, so perhaps the operators decided not to test the reservoirs. In fact, logs indicate that several wells in the study area were not tested that seem similar to the average productive well.

Reservoir quality in the Britt carbonate does appear to correspond with ultimate recovery. However, considering that the trapping mechanism and processes which improve porosity appear to be identical to those for the Boatwright carbonate, one would presume similar heterogeneity (as documented for the Boatwright) to be the norm. It seems reasonable that within the truncation trend of the Britt carbonate, extreme reservoir heterogeneity may provide opportunities for increased in-fill drilling.

Using pressure-drawdown results in conjunction with the amount of gas produced between tests, it appears that the Boatwright is either capable of delivering gas at the lower porosity or that the reservoir is heterogeneous and zones of higher porosity are nearby. The authors believe that reservoir heterogeneity is the main factor to be considered. As already noted, reservoir thickness and porosity are not reliable predictors of ultimate recovery from a Boatwright completion. It appears that a pre-completion estimate of reservoir performance based on well-log information is unreliable.

WELL-DRILLING AND COMPLETION PRACTICES

Most wells were drilled with an overbalanced mud system, and most used a chemical-based mud, although the range of observed mud weights, pH, and water loss was

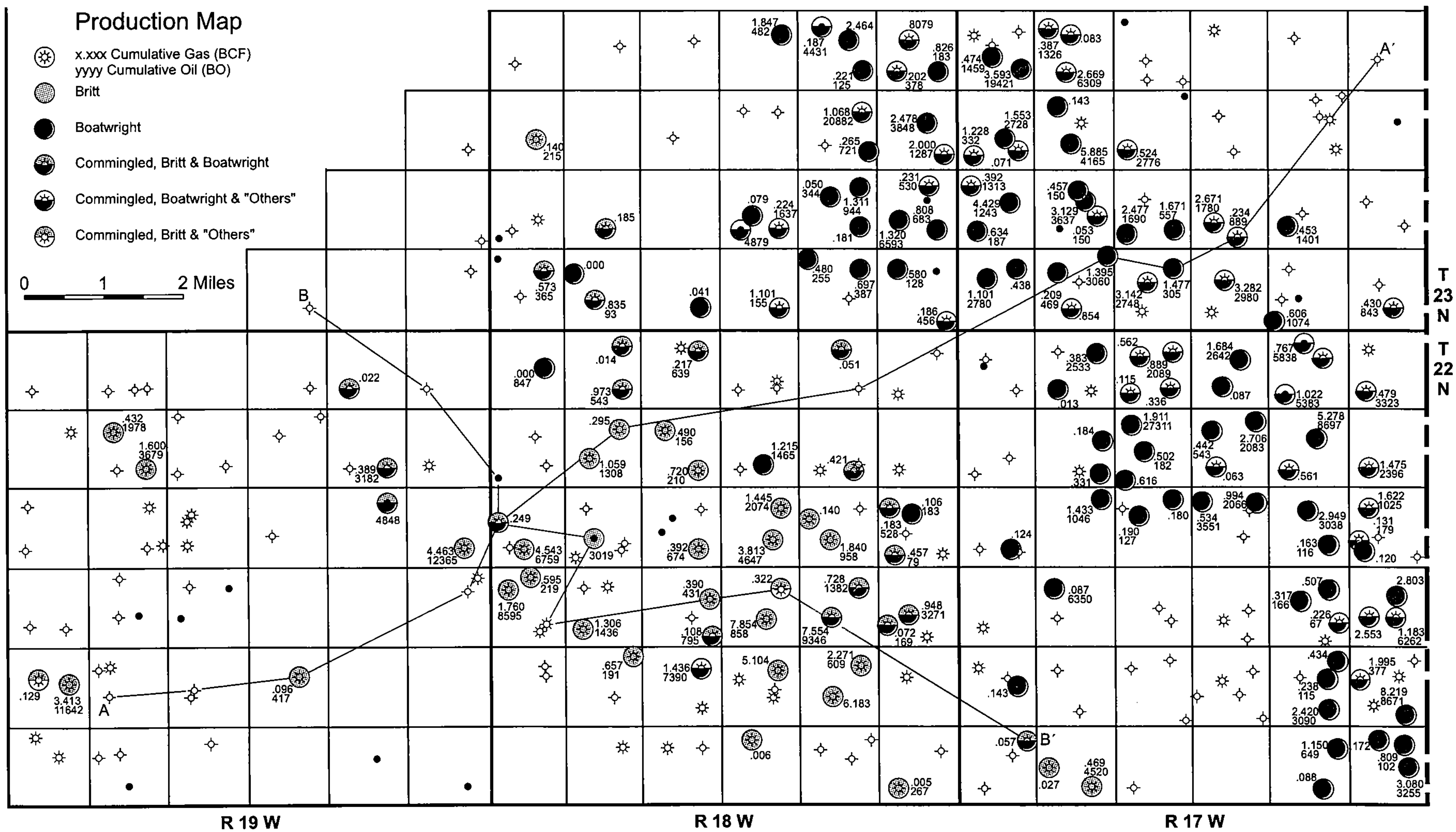


Figure 74. Map showing Springer carbonate production from wells completed only in the Britt and Boatwright carbonates, in addition to wells having commingled production. Cross sections A–A′ and B–B′ shown in Figures 67 and 68.

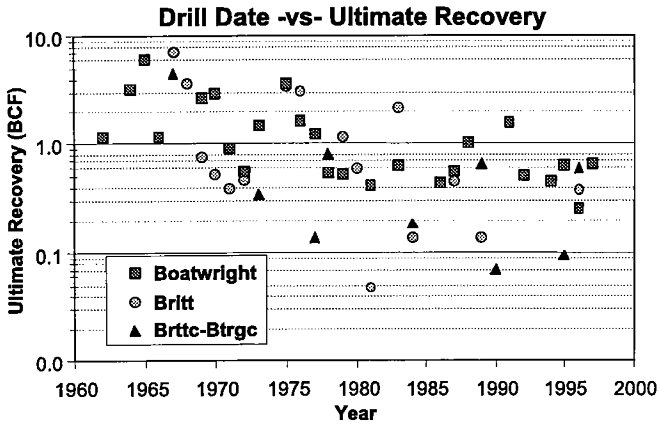


Figure 75. Graph showing relationship between ultimate gas recovery and drilling date for wells producing from Springer carbonate reservoirs in the Cedardale area. *Brttc* = Britt carbonate; *Btrgc* = Boatwright carbonate.

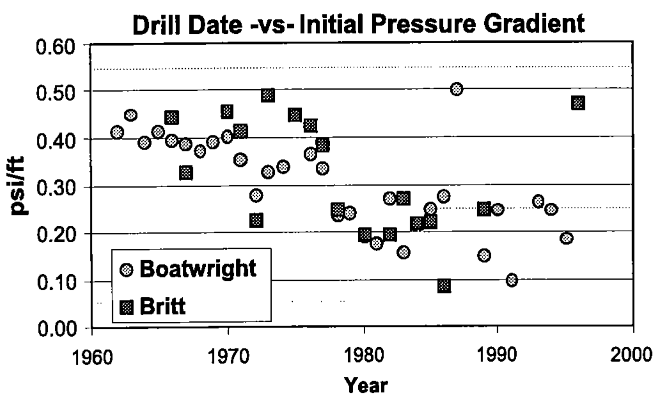


Figure 76. Graph showing relationship between initial pressure gradient and drilling date for wells in the Cedardale area.

broad. Typically, a mud weight of 9.2 ppg was used, yielding an average overbalance of 850 psi for the Boatwright and 1,500 psi for the Britt. The average mud pH was 9.0 for the Britt and 9.1 for the Boatwright. Mud water loss averaged 9.8 ml in the Britt and 9.4 ml in the Boatwright. No analysis on the impact of mud weight, mud pH, or mud water loss on ultimate recovery was made.

No consensus of completion practices could be established. Most wells were given some sort of acid treatment to clean the perforations and producing zone near the wellbore. Many wells were fracture stimulated on completion, but stimulation data are scant.

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SELECTED REFERENCES
FOR THE SPRINGER GROUP

Al-Shaieb, Zuhair; Puckette, James; Ely, Patrick; and Tigert, Vanessa, 1992, Pressure compartments and seals in the Anadarko basin, *in* Johnson, K. S.; and Cardott, B. J. (eds.), Source rocks in the southern Midcontinent, 1990 symposium: Oklahoma Geological Survey Circular 93, p. 210–228.

Andrews, R. D., 1999, Morrow gas play in the Anadarko basin and shelf of Oklahoma: Oklahoma Geological Survey Special Publication 99-4, 133 p.

Asquith, G. B., 1984, Depositional and diagenetic history of the upper Chester (Mississippian) oolitic reservoirs, north-central Beaver County, Oklahoma, *in* Hyne, N. J. (ed.), Limestones of the Mid-Continent: Tulsa Geological Society Special Publication 2, p. 87–92.

Ball, M. M.; Henry, M. E.; and Frezon, S. E., 1991, Petroleum geology of the Anadarko basin region, Province (115), Kansas, Oklahoma, and Texas: U.S. Geological Survey Open-File Report 88-450-W, 36 p.

Billingsley, H. R., 1956, Sholom Alechem oil field, Stephens and Carter Counties, Oklahoma, *in* Hicks, I. C., and others (eds.), Petroleum geology of southern Oklahoma, a symposium: American Association of Petroleum Geologists, Tulsa, v. 1, p. 294–310.

Blatt, Harvey; Middleton, Gerard; and Murray, Raymond, 1980, Origin of sedimentary rocks: Prentice-Hall, Englewood Cliffs, New Jersey, 782 p.

Boyer, R. C., 1983, Depositional environments and diagenetic history of the Springer Formation, Ardmore basin, Oklahoma: University of Texas at Dallas unpublished M.S. thesis, 189 p.

Briggs, Garrett, 1963, A paleocurrent study of Upper Mississippian and Lower Pennsylvanian rocks of the Ouachita Mountains and Arkoma basin, southeastern Oklahoma: University of Wisconsin unpublished Ph.D. dissertation.

Brown, R. L.; and Northcutt, R. A., 1993, Springer marine sandstone, Anadarko basin, Oklahoma, *in* Bebout, D. G.; White, W. A.; Hentz, T. F.; and Grasmick, M. K. (eds.), Atlas of major Midcontinent gas reservoirs: Bureau of Economic Geology, University of Texas, Austin, p. 53–54.

Brownlee, D. E., 1981, Stratigraphic and structural investigation of the Eola klippe, Garvin County, Oklahoma: University of Oklahoma unpublished M.S. thesis, 133 p.

Davis, H. G., 1974, High pressure Morrow–Springer gas trend, Blaine and Canadian Counties, Oklahoma: Shale Shaker, v. 24, no. 6, p. 104–118.

Dionisio, L. C., Jr., 1975, Structural analysis and mapping of the eastern Caddo anticline, Ardmore basin, Oklahoma: University of Oklahoma unpublished M.S. thesis, 83 p.

Donovan, T. J.; Roberts, A. A.; and Dalziel, M. C., 1981, Epigenetic zoning in surface and near-surface rocks resulting from seepage-induced redox gradients, Velma oil field, Oklahoma; a synopsis: Shale Shaker, v. 32, no. 3, p. 1–7.

Dutton, K. D.; Bemis, Robert; Johnson, Rodney; and White, J. L., 1984, Shale production from the Britt Formation in northwest Caddo County, *in* Proceedings of 1984 deep drilling and production symposium, Amarillo, Texas: Society of Petroleum Engineers, Dallas, p. 115–124.

Elias, M. K., 1956, Upper Mississippian and Lower Pennsylvanian formations of south-central Oklahoma, *in* Hicks, I. C., and others (eds.), Petroleum geology of southern Oklahoma, a symposium: American Association of Petroleum Geologists, Tulsa, v. 1, p. 56–134.

Folk, R. L., 1974, Petrology of sedimentary rocks: Hemphill Publishing Co., Austin, 181 p.

Ghazal, R. L., 1975, Structural analysis and mapping of the western part of the Caddo anticline, Carter County, Oklahoma: University of Oklahoma unpublished M.S. thesis, 61 p.

Goldstone, W. L., Jr., 1922, Differentiation and structure of the Glenn Formation of Oklahoma: American Association of Petroleum Geologists Bulletin, v. 6, p. 5–23.

Haiduk, J. P., 1990, Facies analysis, paleoenvironmental interpretation, and diagenetic history of Britt sandstone (Upper Mississippian) in portions of Caddo and Canadian Counties, Oklahoma: Shale Shaker, v. 40, no. 5, p. 118–136. [Also Oklahoma State University unpublished M.S. thesis, 1987, 188 p.]

Harlton, B. H., 1956, West Velma oil field, *in* Hicks, I. C., and others (eds.), Petroleum geology of southern Oklahoma, a symposium: American Association of Petroleum Geologists, Tulsa, v. 1, p. 221–233.

Hemish, LeRoy; and Andrews, R. D., 2001, Stratigraphy and depositional environments of the sandstones of the Springer Formation and the Primrose Member of the Golf Course Formation in the Ardmore basin, Oklahoma: Oklahoma Geological Survey Guidebook 32, 37 p.

Hendrickson, W. J.; Smith, P. W.; and Williams, C. M., 1996a, Regional correlations and reservoir characterization studies of the Pennsylvanian System in the Anadarko basin area of western Oklahoma and the panhandle of Texas, *in* Swindler, D. L.; and Williams, K. P. (eds.), Transactions of the 1995 American Association of Petroleum Geologists, Midcontinent Section Meeting: Tulsa Geological Society, p. 100–108.

Hendrickson, W. J.; Smith, P. W.; Williams, C. M.; and Woods, R. J., 1996b, A regional correlation and production allocation project within the Oklahoma portion of the Anadarko basin and shelf with a specific discussion of the Springer and Chester Groups: Shale Shaker, v. 47, no. 2, p. 31–41.

Hendrickson, W. J.; Hogan, J. V.; Smith, P. W.; Willey, C. E.; and Woods, R. J., 2000, Springeran/Chesterian relationships within the Anadarko basin and shelf of northwestern Oklahoma and the Texas Panhandle, *in* Merriam, D. F. (ed.), Transactions of the 1999 American Association of Petroleum Geologists, Midcontinent Section Meeting: Kansas Geological Survey Open-File Report 99-28, p. 184–191.

Henry, J. D., 1987, Sterling field; 2, A look at the structure of Sterling field: Oil and Gas Journal, v. 85, no. 19, p. 62–64.

Herbaly, E. L., 1950, Regional analysis of the Springer stratigraphic interval: Northwestern University unpublished M.S. thesis.

Hester, T. C.; Schmoker, J. W.; and Sahl, H. L., 1990, Log-derived regional source-rock characteristics of the Woodford Shale, Anadarko basin, Oklahoma: U.S. Geological Survey Bulletin 1866, p. D1–D38.

Hoard, J. L., 1956, Tussy sector of the Tatums field, Carter and Garvin Counties, Oklahoma, *in* Hicks, I. C., and others (eds.), Petroleum geology of southern Oklahoma, a symposium: American Association of Petroleum Geologists, Tulsa, v. 1, p. 186–206.

Jackson, J. A. (ed.), 1997, Glossary of geology [4th edition]: American Geological Institute, Alexandria, Virginia, 769 p.

Jacobson, C. L., 1954, Petrology of Springer oil bearing sandstone (Oklahoma): Oil and Gas Journal, v. 52, no. 50, p. 206–208.

Keighin, C. W.; and Flores, R. M., 1989, Depositional facies, petrofacies, and diagenesis of siliciclastics of Morrow and Springer rocks, Anadarko basin, Oklahoma, *in* Johnson, K. S.

(ed.), Anadarko basin symposium, 1988: Oklahoma Geological Survey Circular 90, p. 147–161.

——— 1993, Petrology and sedimentology of Morrow/Springer rocks and their relationship to reservoir quality, Anadarko basin, Oklahoma [abstract], *in* Johnson, K. S.; and Campbell, J. A. (eds.), Petroleum-reservoir geology in the southern Midcontinent, 1991 symposium: Oklahoma Geological Survey Circular 95, p. 25.

Keith, B. D.; and Zuppann, C. W., 1993, Mississippian oolites and modern analogs: American Association of Petroleum Geologists Studies in Geology 35, p. 243–259.

Kleehammer, R. S., 1991, Conodont biostratigraphy of Late Mississippian shale sequences, south-central Oklahoma: University of Oklahoma unpublished M.S. thesis, 135 p.

Lane, H. R.; and Straka, J. J. II, 1974, Late Mississippian and Early Pennsylvanian conodonts, Arkansas and Oklahoma: Geological Society of America Special Publication 152, 144 p.

Lovick, G. P., 1977, Petrography and sedimentation of the Upper Mississippian sandstones of the Goddard Formation and the Rod Club and Overbrook Members of the Springer Formation in the Ardmore basin, Oklahoma: University of Texas at Arlington unpublished M.S. thesis, 66 p.

Lyday, J. R., 1991, Berlin field; genesis of a recycled detrital dolomite reservoir, deep Anadarko basin, Oklahoma [abstract]: Houston Geological Society Bulletin, v. 33, no. 5, p. 28.

Manger, W. L.; and Sutherland, P. K., 1992, Analysis of sections presumed to be complete across the Mississippian–Pennsylvanian boundary, southern Midcontinent, *in* Manger, W. L.; and Sutherland, P. K. (eds.), Recent advances in Middle Carboniferous biostratigraphy—a symposium: Oklahoma Geological Survey Circular 94, p. 69–80.

McBride, M. H., 1986, A petrologic and diagenetic study of outcropping and subsurface Springer and lower Morrowan sandstones, Ardmore and Anadarko basins, Oklahoma: University of Tulsa unpublished M.S. thesis, 160 p.

McCaslin, J. C., 1976, Drilling programs link Oklahoma gas fields: Oil and Gas Journal, v. 74, no. 8, p. 151.

——— 1978, Oklahoma's Springer trend is one of the busiest: Oil and Gas Journal, v. 76, no. 15, p. 98–99.

——— 1982a, Deep drilling brisk in Anadarko basin: Oil and Gas Journal, v. 80, no. 3, p. 157–159.

——— 1982b, Texaco drilling deep Cyril basin wildcat: Oil and Gas Journal, v. 80, no. 29, p. 203–204.

Meek, F. B., 1983, The lithostratigraphy and depositional environments of the Springer and lower Golf Course Formations (Mississippian–Pennsylvanian) in the Ardmore basin, Oklahoma: University of Oklahoma unpublished M.S. thesis, 212 p.

Meek, F. B.; Elmore, R. D.; and Sutherland, P. K., 1988, Lithostratigraphy and depositional environments of the Springer and lower Golf Course Formations, Ardmore basin, Oklahoma, *in* Hayward, O. T. (ed.), South-Central Section of the Geological Society of America: Geological Society of America, Boulder, Centennial Field Guide, v. 4, p. 189–194.

Monaghan, P. T., 1985, The stratigraphy of the Mississippian–Pennsylvanian shale sequence of southern Oklahoma: Baylor University unpublished B.S. thesis.

Northcutt, R. A.; and Campbell, J. A., 1995, Geologic provinces of Oklahoma: Oklahoma Geological Survey Open-File Report 5-95, scale 1:750,000.

Parker, E. C., 1956, Camp field, Carter County, Oklahoma, *in* Hicks, I. C., and others (eds.), Petroleum geology of southern Oklahoma, a symposium: American Association of Petroleum Geologists, Tulsa, v. 1, p. 174–185.

——— 1959, Structure and lithology of the Springer in southeast Velma–Camp area, *in* Mayes, J. W., and others (eds.), Petroleum geology of southern Oklahoma, a symposium: American Association of Petroleum Geologists, Tulsa, v. 2, p. 227–248.

Peace, H. W. II, 1964, The Springer Group of the southeastern Anadarko basin in Oklahoma: University of Oklahoma unpublished M.S. thesis, 37 p.

——— 1965, The Springer Group of the southeastern Anadarko basin in Oklahoma: Shale Shaker, v. 15, no. 5, p. 81–99.

Peace, H. W., 1989, Mississippian facies relationships, eastern Anadarko basin, Oklahoma: University of Oklahoma unpublished M.S. thesis, 117 p.

Pollastro, R. M.; and Schmoker, J. W., 1989, Relationship of clay-mineral diagenesis to temperature, age, and hydrocarbon generation—an example from the Anadarko basin, Oklahoma, *in* Johnson, K. S. (ed.), Anadarko basin symposium, 1988: Oklahoma Geological Survey Circular 90, p. 257–261.

Reedy, H. J.; and Sykes, H. A., 1959, Carter–Knox oil field, Grady and Stephens Counties, Oklahoma, *in* Mayes, J. W., and others (eds.), Petroleum geology of southern Oklahoma, a symposium: American Association of Petroleum Geologists, Tulsa, v. 2, p. 198–219.

Reeves, S. R.; Kuuskraa, J. A.; and Kuuskraa, V. A., 1998, Emerging U.S. gas resources; 3, Deep gas poses opportunities, challenges to U.S. operators: Oil and Gas Journal, v. 96, no. 18, p. 133–145.

Rice, D. D.; Threlkeld, C. N.; and Vuletich, A. K., 1989, Characterization and origin of natural gases of the Anadarko basin: Oklahoma Geology Notes, v. 49, p. 47–52.

Rutledge, R. B., 1956, The Velma oil field, Stephens County, Oklahoma, *in* Hicks, I. C., and others (eds.), Petroleum geology of southern Oklahoma, a symposium: American Association of Petroleum Geologists, Tulsa, v. 1, p. 260–281.

Schramm, M. W., Jr., 1963, Paleogeologic and quantitative lithofacies analysis of the Simpson Group, Oklahoma: University of Oklahoma unpublished Ph.D. dissertation, 84 p.

Sheriff, R. E., 1991, Encyclopedic dictionary of exploration geophysics [3rd edition]: Society of Exploration Geophysicists, Tulsa, 384 p.

Shirley, Kathy, 1997, Anadarko still yielding big plays: American Association of Petroleum Geologists Explorer, v. 18, no. 9, p. 1, 16–17.

Smith, P. W., 1996, Anadarko basin statistical study: gas well recovery -vs- depth in the Anadarko basin of western Oklahoma: Gas Research Institute, Chicago, Final Report GRI-96/0196, 65 p.

Smith, P. W.; Hendrickson, W. J.; and Williams, C. M., 1996, Regional correlations and reservoir characterization studies of the Springer Group in the Anadarko basin area of western Oklahoma, *in* Swindler, D. L.; and Williams, K. P. (eds.), Transactions of the 1995 American Association of Petroleum Geologists, Midcontinent Section Meeting: Tulsa Geological Society, p. 116–126.

Smith, P. W.; Hendrickson, W. J.; Williams, C. M.; and Woods, R. J., 1997, Effects of depth on reservoir characteristics and production in Morrow and Springer well completions in the Anadarko basin, *in* McMahan, Greg (ed.), Transactions of the 1997 American Association of Petroleum Geologists, Midcontinent Section Meeting: Oklahoma City Geological Society, p. 207–224.

——— 2000, Stratigraphic relationships of Springer and Chester Groups within the Oklahoma portion of the Anadarko basin and shelf: a clarification, *in* Johnson, K. S. (ed.), Platform carbonates in the southern Midcontinent, 1996 symposium: Oklahoma Geological Survey Circular 101, p. 197–207.

Smith, P. W.; Hendrickson, W. J.; and Woods, R. J. [in press], Significance of accurate carbonate reservoir definition and delineation: Chester and Springer carbonates, *in* Johnson, K. S. (ed.), Silurian, Devonian, and Mississippian geology and petroleum of the southern Midcontinent, 1999 symposium:

Oklahoma Geological Survey Circular.

Straka, J. J. II, 1969, Age and correlation of the Goddard (Mississippian) and Springer (Mississippian–Pennsylvanian) Formations in southern Oklahoma as determined by conodonts: University of Iowa unpublished Ph.D. dissertation, 283 p.

——— 1972, Conodont evidence of age of Goddard and Springer Formations, Ardmore basin, Oklahoma: American Association of Petroleum Geologists Bulletin, v. 56, p. 1087–1099.

Sundberg, K. R., 1994, Surface geochemistry applications in oil and gas exploration: Oil and Gas Journal, v. 94, no. 23, p. 47.

Sutherland, P. K., 1981, Mississippian and Lower Pennsylvanian stratigraphy in Oklahoma: Oklahoma Geology Notes, v. 41, p. 3–22.

Sutherland, P. K.; and Grayson, R. C., Jr., 1992, Morrowan and Atokan (Pennsylvanian) biostratigraphy in the Ardmore basin, Oklahoma, *in* Sutherland, P. K.; and Manger, W. L. (eds.), Recent advances in Middle Carboniferous biostratigraphy—a symposium: Oklahoma Geological Survey Circular 94, p. 81–99.

Swanson, D. C., 1979, Deltaic deposits in the Pennsylvanian upper Morrow Formation of the Anadarko basin, *in* Hyne, N. J. (ed.), Pennsylvanian sandstones of the Mid-Continent: Tulsa Geological Society Special Publication 1, p. 115–168.

Taff, J. A., 1903, Tishomingo folio, Indian Territory: U.S. Geological Survey Geological Atlas of the United States, Folio 98, 8 p.

Taylor, J. A., 1951, The Lower Pennsylvanian Primrose sandstone of Oklahoma: University of Oklahoma unpublished M.G.E. thesis, 140 p.

Tomlinson, C. W., 1929, The Pennsylvanian system in the Ardmore basin: Oklahoma Geological Survey Bulletin 46, 79 p.

——— 1959, Best exposures of various strata in Ardmore basin, *in* Mayes, J. W., and others (eds.), Petroleum geology of southern Oklahoma, a symposium: American Association of Petroleum Geologists, Tulsa, v. 2, p. 302–333.

Tomlinson, C. W.; and McBee, W., 1959, Pennsylvanian sediments and orogenies of Ardmore district, Oklahoma, *in* Mayes, J. W., and others (eds.), Petroleum geology of southern Oklahoma, a symposium: American Association of Petroleum Geologists, Tulsa, v. 2, p. 2–52.

Van Wagoner, J. C.; Mitchum, R. M.; Campion, K. M.; and Rahmanian, V. D., 1990, Siliciclastic sequence stratigraphy in well logs, cores, and outcrops: concepts for high-resolution correlation of time and facies: American Association of Petroleum Geologists Methods in Exploration 7, 55 p.

Walker, R. G. (ed.), 1984, Facies models [2nd edition]: Geoscience Canada Reprint Series 1, 179 p.

Wang, H. D., 1993, A geochemical study of potential source rocks and crude oils in the Anadarko basin, Oklahoma: University of Oklahoma unpublished Ph.D. dissertation, 296 p.

Wang, H. D.; and Philp, R. P., 1997, Geochemical study of potential source rocks and crude oils in the Anadarko basin, Oklahoma: American Association of Petroleum Geologists Bulletin, v. 81, p. 249–275.

Weaver, C. E., 1958, Geologic interpretation of argillaceous sediments; Part 2—Clay petrology of Upper Mississippian–Lower Pennsylvanian sediments of central United States: American Association of Petroleum Geologists Bulletin, v. 42, p. 272–309.

Westheimer, J. M., 1956, The Goddard Formation, *in* Hicks, I. C., and others (eds.), Petroleum geology of southern Oklahoma, a symposium: American Association of Petroleum Geologists, Tulsa, v. 1, p. 392–396.

Williams, C. M.; Hendrickson, W. J.; and Smith, P. W., 1996, Regional correlation and reservoir characterization studies of the Morrow Group in the Anadarko basin area of western Oklahoma, *in* Swindler, D. L.; and Williams, K. P. (eds.), Transactions of the 1995 American Association of Petroleum Geologists, Midcontinent Section Meeting: Tulsa Geological Society, p. 109–115.

Williams, C. M.; Hendrickson, W. J.; Smith, P. W.; and Woods, R. J., 1997, A regional stratigraphic correlation, reservoir characterization and production allocation project within the Anadarko basin and shelf of Oklahoma with emphasis on the Springer Group, *in* McMahan, Greg (ed.), Transactions of the 1997 American Association of Petroleum Geologists, Midcontinent Section Meeting: Oklahoma City Geological Society, p. 25–35.

Appendixes

Appendix 1

Various Size Grade Scales in Common Use

(from Blatt and others, 1980)

Udden–Wentworth	*ϕ values*	*German scale*† *(after Atterberg)*	*USDA and Soil Sci. Soc. Amer.*	*U.S. Corps Eng., Dept. Army and Bur. Reclamation*‡
		(Blockwerk)		
Cobbles		——200 mm——	Cobbles	Boulders
			——80 mm——	——10 in.——
——64 mm——	−6			Cobbles
		Gravel		——3 in.——
Pebbles		(Kies)		
				Gravel
——4 mm——	−2		Gravel	
				——4 mesh——
Granules				Coarse sand
——2 mm——	−1	——2 mm——	——2 mm——	——10 mesh——
Very coarse sand			Very coarse sand	
——1 mm——	0		——1 mm——	
Coarse sand		Sand	Coarse sand	Medium sand
——0.5 mm——	1		——0.5 mm——	
				——40 mesh——
Medium sand			Medium sand	
——0.25 mm——	2		——0.25 mm——	
Fine sand			Fine sand	Fine sand
——0.125 mm——	3		——0.10 mm——	
Very fine sand				
			Very fine sand	——200 mesh——
——0.0625 mm——	4	——0.0625 mm——		
			——0.05 mm——	
Silt		Silt		
			Silt	Fines
——0.0039 mm——	8			
		——0.002 mm——	——0.002 mm——	
Clay		Clay	Clay	
		(Ton)		

†Subdivisions of sand sizes omitted.

‡Mesh numbers are for U.S. Standard sieves: 4 mesh = 4.76 mm, 10 mesh = 2.00 mm, 40 mesh = 0.42 mm, 200 mesh = 0.074 mm.

Appendix 2

Abbreviations Used in Text and on Figures, Tables, and Plates

ac-ft	acre-foot
B	barrel(s)
bbl, BBL	barrel(s)
BC	barrels of condensate
BCF	billion cubic (of gas)
BCFG	billion cubic feet of gas
B_g	gas formation volume factor
BHP	bottom-hole pressure
BLW	barrels of load water
BO	barrels of oil
BOPD	barrels of oil per day
BP	bridge plug
BW	barrels of water
BWPD	barrels of water per day
CAL	caliper
CAOF	calculated absolute open flow
CIBP	cast-iron bridge plug
COF	calculated open flow
cum.	cumulative
D&A	dry and abandoned
DF	derrick floor
DST	drillstem test
F	formation factor
FTP	flowing tubing pressure
G	gas
GCM	gas-cut mud
GL	ground level
GOR	gas/oil ratio
GR	gamma ray
HCl	hydrochloric acid
IPF	initial production flowing
IPP	initial production pumping
ISIP	initial shut-in pressure
KB	kelly bushing
MCF	thousand cubic feet (of gas)
MCFG	thousand cubic feet of gas
MCFGPD	thousand cubic feet of gas per day
MMBO	million barrels of oil
MMCF	million cubic feet (of gas)
MMCFG	million cubic feet of gas
MMCFGPD	million cubic feet of gas per day
md	millidarcy(s)
NDE	not deep enough
NL	no log
NPL	no porosity log
NRIS	Natural Resources and Information System (a database)
O&GCM	oil- and gas-cut mud
OGIP	original gas in place
P	pressure (usually reservoir pressure)
P&A	plugged and abandoned
PE	photoelectric (well-logging survey)
ppg	parts per gallon
P_{res}	reservoir pressure
psi, PSI	pounds per square inch
R_t	deep, or true, resistivity
R_w	formation-water resistivity
R_{xo}	resistivity of flushed zone
SITP	shut-in tubing pressure
SP	spontaneous potential
std cu ft	standard cubic feet
SW	salt water
S_w	water saturation
TC	tubing choke
TCF	trillion cubic feet (of gas)
TCFG	trillion cubic feet of gas
TD	total depth
trc	trace
T_{res}	reservoir temperature
W	water
wtr.	water
WP	where productive
WPWA	where productive, well average
Z	compressibility factor
ϕ	porosity

Appendix 3

Glossary of Terms

(as used in this volume)

Definitions modified from Jackson (1997), Sheriff (1991), and Van Wagoner and others (1990).

bioturbation— The churning and stirring of a sediment by organisms.

carbonate— A sediment or sedimentary rock formed by precipitation from aqueous solution of carbonates of calcium, magnesium, or iron; e.g., limestone and dolomite. In referring to rocks, the term "carbonates" also includes those composed of clastic and biogenic grains that are predominantly calcite and/or dolomite in composition.

channel deposit— An accumulation of clastic material, commonly consisting of sand, gravel, silt, and clay, in a trough or stream channel where the transporting capacity of the stream is insufficient to remove material supplied to it.

detached bar— Informal terminology used to describe a marine sand deposit commonly occurring on the shallow continental shelf that is separated from the mainland (or shoreline) by an expanse of mud (shale). This terminology is used to differentiate from other marine sand deposits that occur adjacent to shorelines, such as distributary-mouth bars.

delta front— A narrow zone where deposition in deltas is most active, consisting of a continuous sheet of sand, and occurring within the effective depth of wave erosion (10 m or less). It is the zone separating the *prodelta* from the *delta plain*, and it may or may not be steep.

delta plain— The level or nearly level surface composing the landward part of a large delta.

diagenesis— All changes that affect sediments after initial deposition, including compaction, cementation, and chemical alteration and dissolution of constituents. It does not include weathering and metamorphism of preexisting sediments.

distributary-mouth bar— The subaqueous (marine) part of the delta composed mostly of sand transported to the delta front by a network of delta plain channels (distributary channels). The distributary mouth bar occurs adjacent to the coastline and therefore is considered "attached."

facies— (a) A mappable, areally restricted part of a lithostratigraphic body, differing in lithology or fossil content from other beds deposited at the same time and in lithologic continuity. (b) A distinctive rock type, broadly corresponding to a certain environment or mode of origin.

fluvial— (a) Of or pertaining to a river or rivers. (b) Produced by the action of a stream or river.

incised valleys— Entrenched fluvial systems that extend their channels basinward and erode into underlying strata.

isopach— A line drawn on a map through points of equal true thickness of a designated stratigraphic unit or group of stratigraphic units.

millidarcy (md)— The customary unit of measurement of fluid permeability, equivalent to 0.001 darcy.

offshore bar— A low, elongate sand ridge, built chiefly by wave action, occurring at some distance from, and extending generally parallel with, the shoreline. Syn.: longshore bar.

permeability— The capacity of a porous rock, sediment, or soil for transmitting a fluid; it is a measure of the relative ease of fluid flow under unequal pressure. The customary unit of measure is the *millidarcy.*

porosity— The ratio of the aggregate volume of interstices in a rock or soil to its total volume. It is usually stated as a percentage.

prodelta— The part of a delta that is below the effective depth of wave erosion, lying beyond the *delta front*, and sloping gently down to the floor of the basin into which the delta is advancing and where clastic river sediment ceases to be a significant part of the basin-floor deposits. Consists entirely, or almost entirely, of clay and silt that became predominantly shale upon diagenesis.

progradation— The building forward or outward toward the sea of a shoreline or coastline (as of a beach, delta, or fan) by nearshore deposition of river-borne sediments or by continuous accumulation of beach material thrown up by waves or moved by longshore drifting.

regression— The retreat or contraction of the sea from land areas, and the consequent evidence of such withdrawal (such as enlargement of the area of deltaic deposition).

strandline— The ephemeral line or level at which a body of standing water, e.g., the sea, meets the land; the shoreline.

subaerial— Said of conditions and processes, such as erosion, that exist or operate in the open air on or directly adjacent to the land surface; or of features and materials, such as eolian deposits, that are formed or situated on the land surface. The term is sometimes considered to include fluvial.

transgression— The spread or extension of the sea over land areas, and the consequent evidence of such advance.

truncation— An act or instance of cutting or breaking off the top or end of a geologic structure or landform, as by erosion.

turbidite— A sediment or rock deposited from, or inferred to have been deposited from, a turbidity current.

unconformity— A substantial break or gap in the geologic record where a rock unit is overlain by another that is not next in stratigraphic succession, such as an interruption in the continuity of a depositional sequence of sedimentary rocks.

valley fill— Sediment deposited in a valley or trough by any process; commonly, fluvial channel deposition is implied.

Appendix 4

Core Descriptions, Well Logs, and Digital Images of Select Rock Intervals for the Following Wells:

1. **Apexco No. 1-A Buell**
   SE¼NW¼ sec. 10, T. 11 N., R. 12 W.
   Lower Morrow Primrose and Springer Cunningham and Britt sandstones
   Detached offshore-marine bars
   Prepared cored interval: 13,797.5–13,873 ft
   13,969–14,091.3 ft

2. **Hadson Petroleum Corp. No. 1-23 Frick**
   NE¼SW¼ sec. 23, T. 4 N., R. 6 W.
   Springer Cunningham sandstone
   Detached offshore-marine bar
   Prepared cored interval: 9,522–9,616 ft

3. **Shell Oil Co. No. 1-19 Coulter**
   SW¼NE¼ sec. 19, T. 21 N., R. 17 W.
   Springer carbonates: Britt and Boatwright
   Marine carbonate bank
   Prepared cored interval: 7,893–8,009 ft

Apexco No. 1-A Buell

SE¼NW¼ sec. 10, T. 11 N., R. 12 W.

Core of lower Morrow and upper to middle Springer
Detached offshore-marine-bar sandstone and marine-shelf shale

Log depth: about 1–14 ft lower than core depth — Described by: Richard D. Andrews

Note: vfg = very fine grained; fg = fine grained; mg = medium grained; cg = coarse grained

Core depth (*in feet*)	Lithology and sedimentary structures
13,736–13,797.5	Not described, mostly lower Morrow shale.
13,797.5–13,800.8	Shale and interbedded vfg sand and silt.
13,800.8–13,801	Sandstone, vfg, elongate and rounded mud clasts 0.25–0.75 in. @13,800.8 ft.
13,801–13,802	Sandstone, vfg, thinly bedded, with interbedded shale laminations. Highly bioturbated, destroying most bedding.
13,802–13,809	Sandstone, vfg to fg, very clean, firm, tight, quartz framework, light buff color, mostly silica cement, slight effervescence. Numerous elongate shale clasts up to ~0.75 in. long, but most are only a few millimeters. Bedding is mostly horizontal.
13,809–13,817	Shale and interbedded vfg/silty sandstone consisting of thin horizontal and wavy beds.
13,817–13,827	Interbedded vfg sandstone and/or siltstone with shale. Thin beds have wavy to horizontal surfaces and are possibly partially destroyed by bioturbation.
13,827–13,829	Sandstone, vfg, silica cement, tight, little or no calcite cement, burrowed, bioturbated.
13,829–13,841	Shale, black, fissile, no fossils.
13,841–13,844	Sandstone, vfg, bedding destroyed by bioturbation.
	Lower Primrose Sandstone
13,844–13,862	***Main bar facies:*** vf to fg, mostly quartz grains tightly cemented with silica, little or no effervescence with acid. Minor porosity possibly due to alteration of rock(?) fragments. Numerous mg, white, accessory grains that may be crinoid fragments effervesce with acid. Bedding is contorted (soft-sediment deformation), upper half of section grading downward to wavy bedding having interlaminations of black shale. Reddish sideritic clasts and broken shale laminations at 13,853 ft, stylolites at 13,850 (A) ft, 13,859 (C) ft, and 13,861 (C) ft. Mud clasts attributed to storm rip-up(?) are most conspicuous at the base of 13,852 (B) ft and at 13,855 (D) ft and 13,858 (A) ft.
13,862–13,869.5	***Bar transition:*** Interbedded vfg sandstone and/or siltstone with shale.
	BASE MORROW, TOP SPRINGER
13,869.5–13,873	***Open-marine shale:*** black, fissile.

Core depth (in feet)	Lithology and sedimentary structures
13,873–13,969	Not described, 96 ft consists mostly of black fissile shale, as below.
13,969–13,972	Shale, black, fissile.
13,972–13,974	Sandstone, dark gray, vf to fg, minor calcite cement, fair to good porosity, bedding mostly indistinct owing to bioturbation.
13,974–13,979	Shale, black, fissile, some reddish sideritic(?) nodules.
	Top Cunningham sandstone
13,979–13,985	Interbedded vfg sandstone and/or siltstone with shale, thin bedding is horizontal or wavy.
13,985–13,994	Mostly sandstone, vf to fg, silica cement, tight, localized mud/shale clasts to 2 in. long, although most clasts are <0.25 in. Interbedded shale and lenses of vfg sandstone 13,989–13,991 ft. Mud clasts (storm rip-up?) occur at 13,993.5 ft.
13,994–14,033	Shale, black, fissile, with numerous pyrite lenses and laminations in upper part.
	Top Britt sandstone
14,033–14,061	***Main bar facies:*** sandstone, fg, quartz framework, strongly calcitic above 13,048 ft, silica cement below. Poor to fair porosity, bedding is mostly indistinct or massive, some horizontal. Stylolites occur at 14,057 (C) and 14,061 (A) ft, and possible soft-sediment deformation at 14,053 (B) ft. Sharp upper contact of sandstone with shale.
14,061–14,074	***Bar transition(?):*** sandstone, vf to fg, minor calcite cement, and interbedded shale. Interval is strongly bioturbated, as bedding is largely destroyed. Mud clasts, shell(?) remnants, and broken crinoid(?) fragments occur at 14,071 (B) ft.
14,074–14,077	Interbedded shale and sandstone/siltstone. **Base of Britt bar**
14,077–14,078	Crinoidal packstone with brachiopod(?) fragments.
14,078–14,082	Siltstone and shale, bioturbated.
14,082–14,087	Crinoidal packstone with fg to vfg quartz(?) grains.
14,087–14,091	Shale, black, fissile, with sandy/silty laminations.
14,091–14,103	Not described, 12 ft consists mostly of shale and interbedded vfg sandstone.

Apexco No. 1-A Buell

(SE¼NW¼ sec. 10, T. 11 N., R. 12 W.)

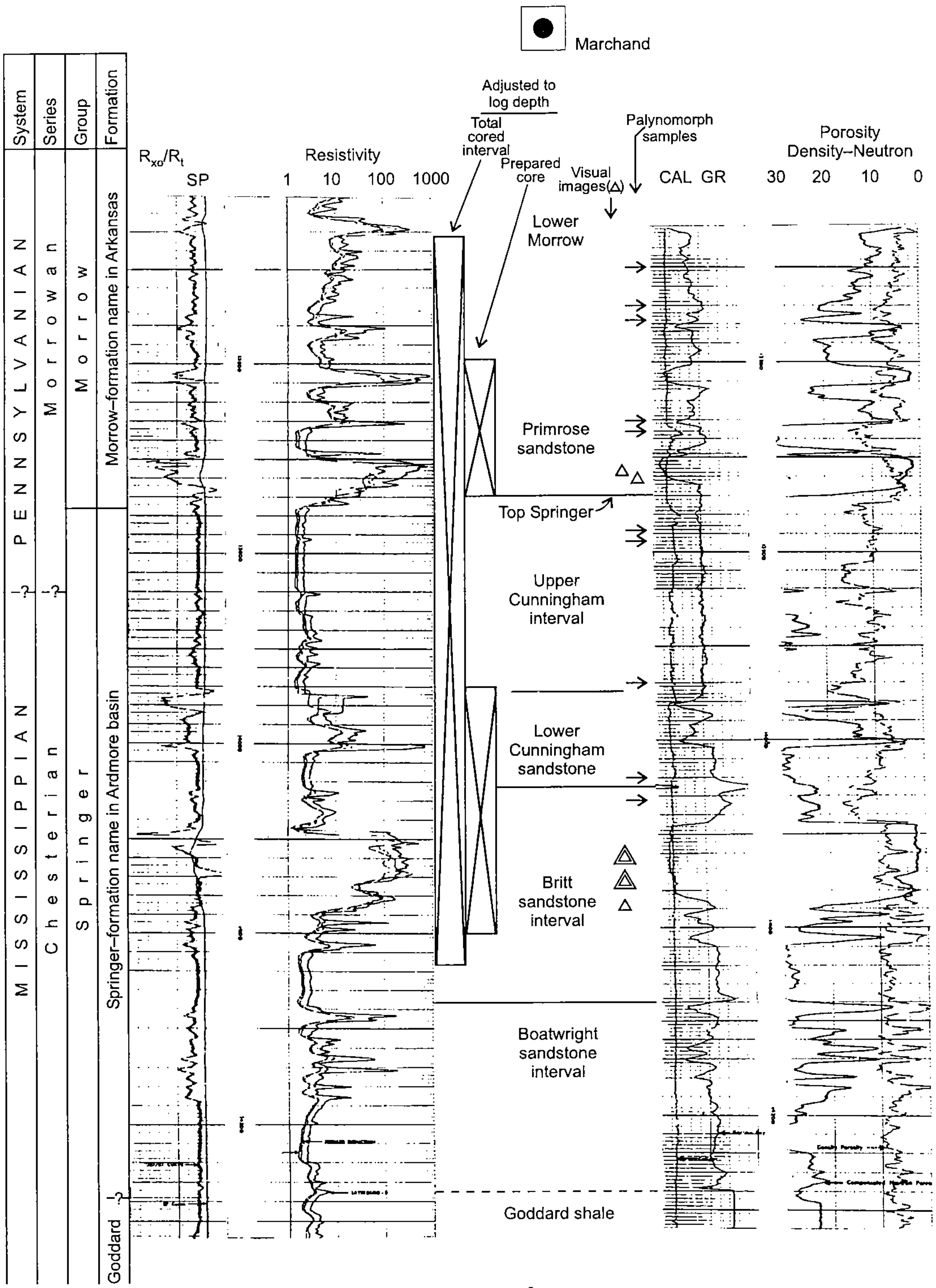
Formations cored: Lower Morrow Primrose and Springer Cunningham, Britt

Depositional environment (Springer): Detached offshore-marine bars

Core depth: 13,736–14,103 ft

Log depth: about 13,737–14,117 ft ± a few feet

KB: 1,638 ft



T.D.: 14,250 ft

Completion date: 1/12/75

Perforated: Marchand @ 9,730–9,786 ft

IPF 212 BOPD

Apexco No. 1-A Buell

(SE¼NW¼ sec. 10, T. 11 N., R. 12 W.)

LOWER PRIMROSE SANDSTONE

Core depth: 13,852 ft
Log depth: ~13,855 ft

Main (central) bar complex: A very fine to fine-grained quartz framework with numerous accessory white clasts, medium grained, and possible broken crinoid(?) fragments. Sample shows soft-sediment deformation (flowage) as defined by the swirly black-shale laminations. The bottom side of the sample shows a zone of eroded mud clasts. These sedimentary features indicate rapid deposition and framework instability, possibly caused by sudden deposition following a high-energy event such as a storm. The sandstone has a small amount of visible porosity, though it is tightly cemented primarily with silica.

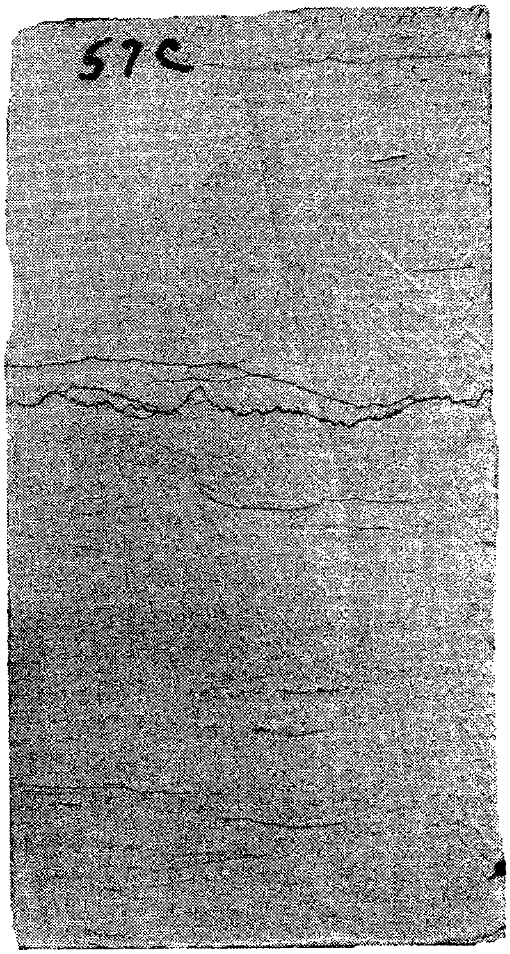
Core depth: 13,853 ft
Log depth: ~13,856 ft

Lower part of central bar complex: Consists of very fine grained sandstone and locally, interbedded shale. The sandstone is tightly cemented with silica, as there is little or no effervescence with acid. Bioturbation has destroyed much of the bedding integrity of the thin shale beds throughout the sample so that they now appear as eroded clasts. Several elongate and rounded mud clasts are somewhat orange in color, probably owing to iron oxide or carbonate (siderite) cementation. Several feet below this interval, the Primrose grades into the bar-transition zone, which is seldom considered a reservoir owing to its high shale content.

Apexco No. 1-A Buell

(SE¼NW¼ sec. 10, T. 11 N., R. 12 W.)

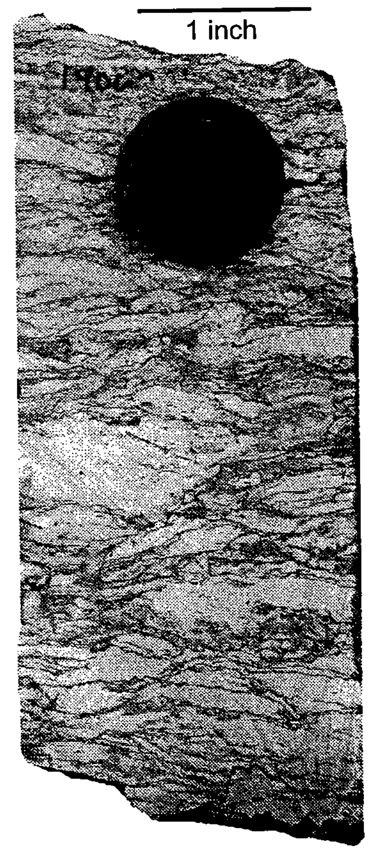
SPRINGER BRITT SANDSTONE



1 inch

Core depth: 14,057 ft
Log depth: ~14,065 ft

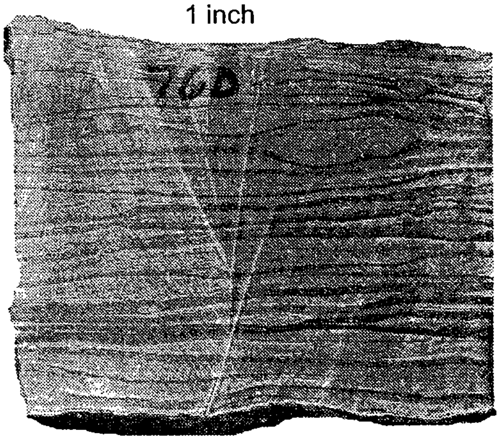
Main (central) bar complex: Consists of fine-grained quartz framework sandstone. This interval is tightly cemented with silica and has poor to fair porosity, which is about average for the Springer sandstone at this depth. This same zone is productive in many nearby wells. Faint shale laminations seem to define ripple bedding. In the center of the sample, the most conspicuous shale "parting" defines a stylolite, one of several noted in this cored interval. Stylolites usually indicate high pressure and stress.



Core depth: 14,062 ft
Log depth: ~14,075 ft

Bar transition—upper part: Consists of very fine grained sandstone and interbedded shale. Original bedding is destroyed by bioturbation, which obscures bedding surfaces and bed thicknesses. The high amount of interbedded shale precludes these types of strata from being good reservoirs.

1 inch



Core depth: 14,076 ft
Log depth: ~14,090 ft

Bar transition—lower part: Consists of interbedded shale and very fine grained sandstone/siltstone lenses. This section contains considerable shale and has little evidence of bioturbation. Below these strata, the section grades into shale.

Hadson Petroleum Corp. No. 1-23 Frick

NE¼SW¼ sec. 23, T. 4 N., R. 6 W.

Core of Springer Cunningham sandstone
Detached offshore-marine-bar sandstone

Log depth: about 2–3 ft lower than core depth

Described by: Richard D. Andrews

Note: vfg = very fine grained; fg = fine grained; mg = medium grained; cg = coarse grained

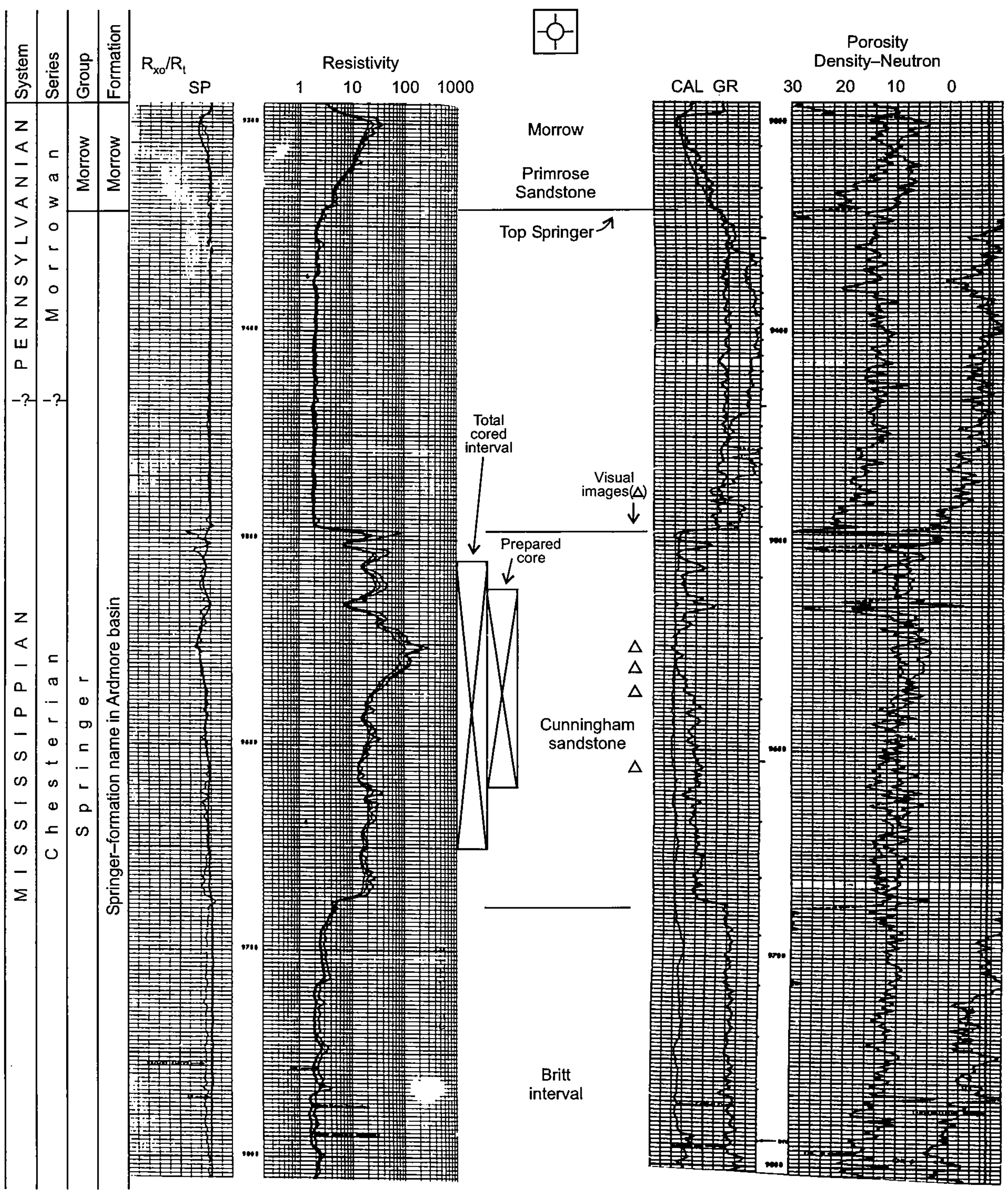
Core depth *(in feet)*	Lithology and sedimentary structures
9,510–9,522	Not described.
9,522–9,525.5	Sandstone, vfg, with interbedded shale. Sandstone is tight, slightly calcitic, and composed mostly of quartz framework. Bioturbation has destroyed most bedding, including black-shale interlaminations.
9,525.5–9,525.7	Ironstone, possible sideritic.
9,525.7–9,529.8	Mostly black shale with interlaminations of silty, vfg sandstone.
9,529.8–9,536	***Bar top:*** vfg to fg sandstone having small (mostly <0.5 in.) rounded to elongate mud clasts at 9,530, 9,531.5, 9,532, 9,533, and 9,536 ft. Sandstone is highly bioturbated, making bedding indistinct. Sandstone is composed mostly of quartz framework and is tightly cemented primarily with silica, although faint effervescence occurs with acid.
9,536–9,560	***Main reservoir facies:*** consists of fg to vfg sandstone, mostly quartz framework and silica cement, although minor calcite cementation is present. The thin bedding is wavy, possibly rippled, and has minor bioturbation. The inclination is probably due to structure or inclination of hole. Numerous black-shale interlaminations occur, defining bedding. Elongate shale clasts and rounded sideritic mud clasts(?) occur at 9,540 and 9,541.5 ft.
9,560–9,603	***Lower part of bar facies:*** consists of sandstone, vfg, mostly quartz framework and silica cement, minor calcite cementation. Becomes increasingly bioturbated with depth, causing original bedding (ripples?) to become indistinct. Black-shale laminations also increase with depth. Inclination of beds is probably due to structure, as above. At ~9,562 ft, vertical burrowing is most prominent.
9,603–9,615	***Bar transition:*** sandstone as above, but progressive increase of interbedded black shale and bioturbation with depth. Incorporation of larger amounts of black shale in the bioturbated strata causes a darker coloration of this interval.
9,615–9,650	Not described, consists of 35 ft of bioturbated, vfg sandstone/siltstone and interbedded shale.

Hadson Petroleum Corp. No. 1-23 Frick

(NE¼SW¼ sec. 23, T. 4 N., R. 6 W.)

Reservoir cored: Springer: Cunningham sandstone
Depositional environment (Springer): Detached offshore-marine bars

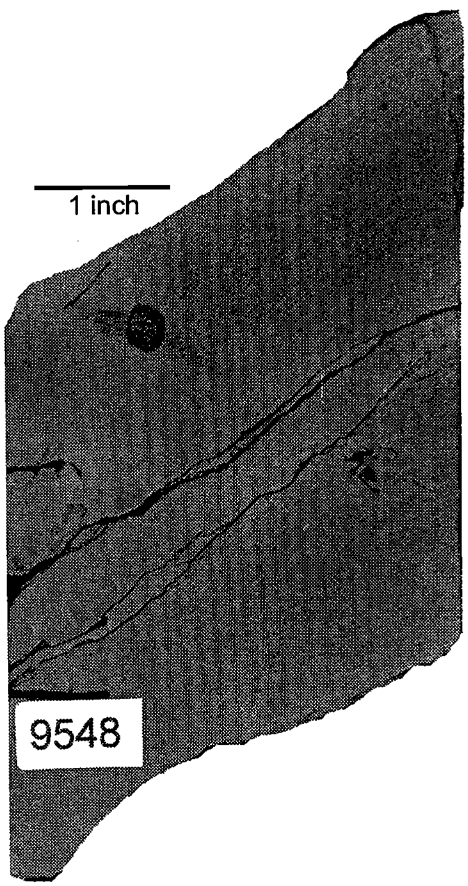
Core depth: 9,510–9,650 ft
Log depth: about 9,510–9,650 ft ± a few feet
KB: 1,638 ft



T.D.: 9,675 ft
P&A: 7/3/79

Hadson Petroleum Corp. No. 1-23 Frick

(NE¼SW¼ sec. 23, T. 4 N., R. 6 W.)



Core depth: 9,547.6–9,548.1 ft
Log depth: about 9,548–9,548.5 ft

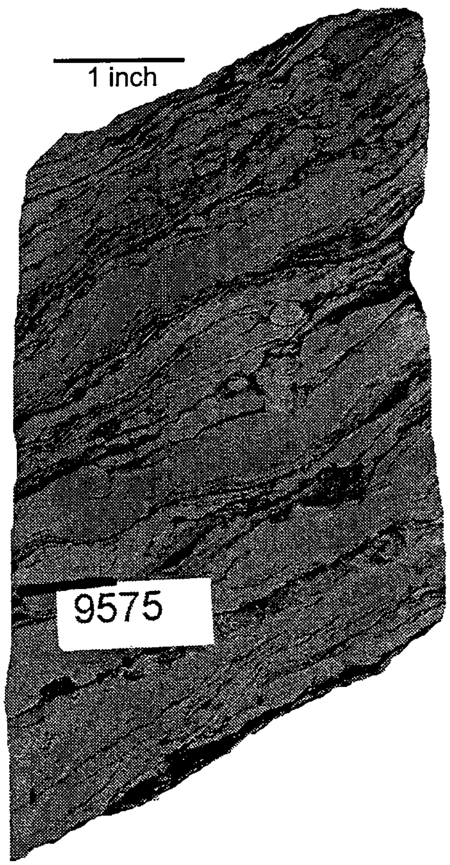
Main (central) bar facies, lower part: The fine to very fine grained sandstone occurs in beds only a few inches thick and has conspicuous ripple marks on bedding surfaces (exemplified by black shale laminations). This indicates that deposition occurred in the lower part of the main (central) bar complex, above the transition zone but below the upper bar facies, which characteristically has thicker bedding, cross-bedding, or both. The upper-bar facies is not present in this bar sequence at this location. The distinct bedding and lack of biogenic structures indicate that sedimentation was relatively aggressive and depositional energy moderately high. Compare these strata to successively lower strata of the same bar sequence in the following figures. The main (central) bar complex is the primary reservoir facies for these types of marine deposits and is easily identified from well logs as provided in this Appendix. Strata such as these occur where the resistivity in the accompanying well log is >100 ohm-m and where the gamma-ray log is the cleanest (lowest values to left). Note that the inclination of beds is probably due to structural dip rather than cross-bedding.

Core depth: 9,562 ft ± a few inches
Log depth: about 9,564 ft ± a few inches

Vertical burrowing in lower part of central bar complex: The very fine grained sandstone has some evidence of biogenic activity in the form of narrow, vertical tubes. These are best illustrated in the central part of the sample and are roughly at right angles to bedding, which appears inclined owing to structural dip. Most bedding surfaces are clearly identifiable, although some are a little "fuzzy" from initial stages of bioturbation. The minimal amount of bioturbation in this sample indicates that these strata were relatively insulated from the more aggressive period of sedimentation and the higher energy environment affecting the overlying sandstone depicted in the previous illustration. With depth, biogenic sedimentary structures become increasingly more abundant.

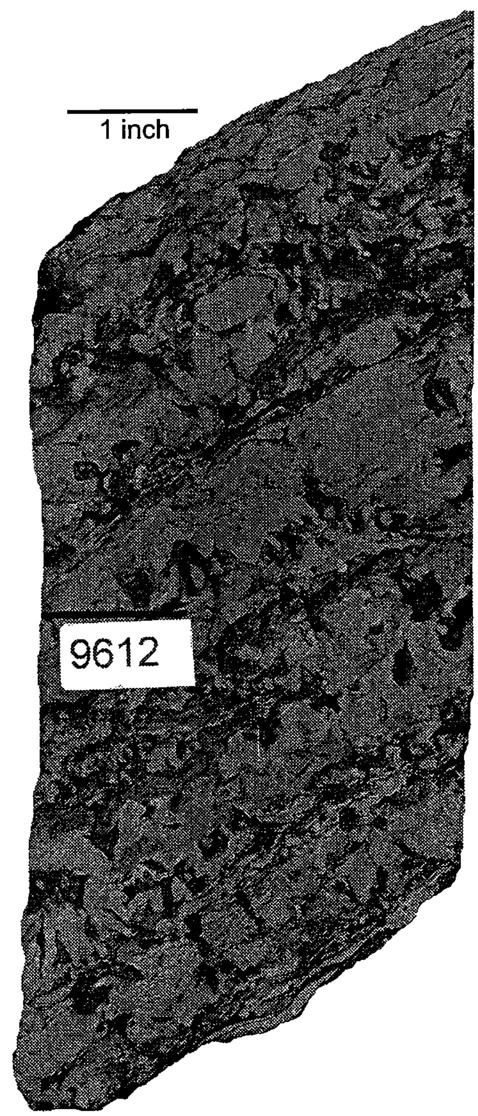
Hadson Petroleum Corp. No. 1-23 Frick

(NE¼SW¼ sec. 23, T. 4 N., R. 6 W.)



Core depth: 9,574.75–9,575.1 ft
Log depth: about 9,575–9,575.5 ft

Deformed bedding caused by moderate bioturbation: Thin, very fine grained sandstone beds ~0.5 in. thick are set apart by laminations of black shale. The wavy nature of bedding surfaces was probably due originally to ripples on bedding surfaces. However, the distinctness of individual sandstone beds and shale interlaminations was partially altered by burrowing organisms that lived in the once soft and undisturbed strata. The abundance of sandstone versus shale, and the smaller degree of bioturbation, indicate that these strata were deposited stratigraphically higher in the bar sequence, in comparison to the interval depicted in the following interval at a depth of ~9,612 ft. Strata depicted in this image occur where resistivity is about 20–60 ohm-m. Again, note that the inclination of beds is probably due to structural dip rather than cross-bedding.



Core depth: 9,611.75–9,612.25 ft
Log depth: about 9,614–9,614.5 ft

Advanced bioturbation and burrowing in the lower part of the bar transition facies: Zones and patches of very fine grained sandstone are enveloped by darker clay-rich material that once composed interlaminations and thin beds of shale. The total disintegration of bedding and the amorphous appearance of sandstone is typical of strata that have been "chewed" to pieces by marine organisms. Particularly in the bottom left corner of this sample, vertical columns of sand define burrows of organisms. Bioturbation commonly occurs in marine sediments but is particularly abundant where sedimentation is not very aggressive, such as in an offshore-bar environment, particularly in the deeper water facies of the lower-bar and bar transition zones. Areas of rapid deposition, such as an active delta front, are not especially conducive for bioturbation, and, therefore, the degree of burrowing and bioturbation is useful in distinguishing delta-front environments from more passive, detached offshore-marine-bar environments. Strata such as these occur where resistivity in the well log is about 10–30 ohm-m.

Shell Oil Co. No. 1-19 Coulter

SW¼NE¼ sec. 19, T. 21 N., R. 17 W.

Core of Springer Britt and Boatwright carbonates
Marine carbonate bank (limestone)

Log depth: about 0–4 ft lower than core depth

Described by: Richard D. Andrews

Note: vfg = very fine grained; fg = fine grained; mg = medium grained; cg = coarse grained

Core depth *(in feet)*	Lithology and sedimentary structures
7,893–7,899.5	Shale, dark gray.
7,899.5–7,902.5	Packstone with crinoid and shell fragments and possibly mud clasts.
7,902.5–7,903	Mudclast conglomerate with crinoid fragments at base.
7,903–7,908.8	Shale, black, fissile.
	Top Britt carbonate
7,908.8–7,920	Packstone/grainstone(?) with mg to cg carbonate clasts that are mostly unidentifiable to the eye. Texture is mostly uniform with massive or indistinct bedding, although locally, horizontal bedding is present. Color is light gray.
7,920–7,937.5	Crinoidal/oolitic packstone/grainstone(?) with relatively large crinoid fragments 0.25–0.5 in., although most fragments are <0.1 in. Stylolites at 7,925.8 and 7,930.4 ft. Conspicuous porosity at 7,934.7 to 7,937.5 ft. *Abundant* oolites (<1 mm) at 7,933–7,938 ft. Porosity best developed in oolitic zones, although some oolitic zones are tightly cemented with calcite.
7,937.5–7,941	Crinoidal wackestone/mudstone, dark gray, with "rafted" larger crinoid fragments generally <0.25 in. suspended in a fg and clay-rich carbonate matrix with common thin horizontal bedding.
7,941–7,949.3	Crinoidal packstone, mg to cg, light gray, massive bedding.
7,949.3–7,954.5	Crinoidal wackestone, dark gray, thin wavy bedding prevalent, although thick bedding and graded bedding (with crinoid fragments) occurs at ~7,954 ft.
7,954.5–7,970	Crinoidal packstone/wackestone consisting mostly of mg to cg fragments partially surrounded by a greenish-gray clay-rich matrix. Some intervals have crinoid fragments >0.5 in. Shaly layers define horizontal bedding that is otherwise indistinct in the carbonate strata.
7,970–7,971	Shale, dark gray.
7,971–7,972.4	Crinoidal packstone/wackestone.
7,972.4–7,981	Mostly shale, dark gray, thin horizontal bedding grading into interbedded shale and crinoidal wackstone/mudstone.
7,981–7,986	Crinoidal wackestone/mudstone, dark gray to black having indistinct bedding.
	Top Boatwright carbonate
7,986–8,008	Packstone, grayish brown, mostly mg fragments (mostly crinoids) although some are coarser. Bedding indistinct (upper half) and grades downward to thin and medium horizontal bedding. *Oolites* (<1 mm) are abundant from about 7,995 to 7,997 ft.
8,008–8,135	Not described, consists of 127 ft limestone (packstone/grainstone strata, as above).

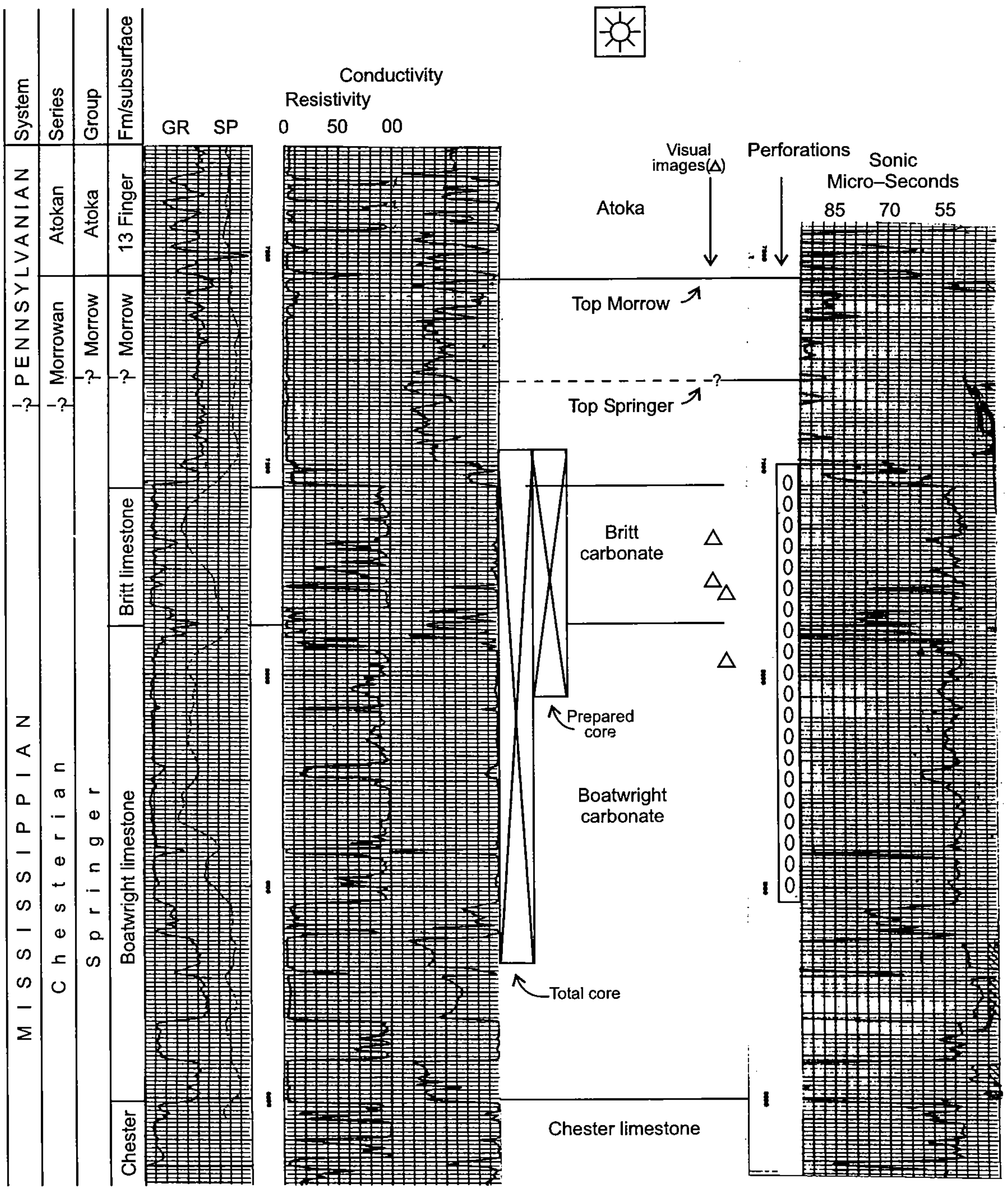
Shell Oil Co. No. 1-19 Coulter

(SW¼NE¼ sec. 19, T. 21 N., R. 17 W.)

Reservoirs cored: Springer Britt and Boatwright carbonates

Depositional environment (Springer): Marine carbonate bank

Core depth: 7,893–8,135 ft
Log depth: 7,893–8,135 ft ± a few feet
KB: 1,779 ft

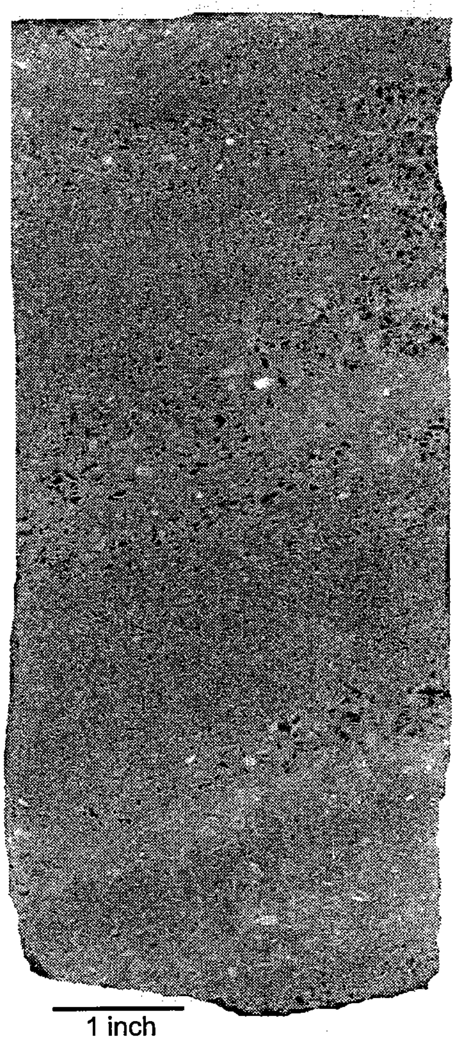


T.D.: 8,250 ft
Completion date: 9/26/64
Perforated: 7,901–8,104 ft
IPF 3,690,000 CFGPD

Shell Oil Co. No. 1-19 Coulter

(SW¼NE¼ sec. 19, T. 21 N., R. 17 W.)

BRITT CARBONATE



Core depth: 7,934.4–7,935 ft
Log depth: about 7,934.4–7,935 ft

Crinoidal/oolitic packstone/grainstone(?): Zones or beds of crinoidal packstone and oolitic packstone alternate every few inches throughout this interval. Porous zones that compose the reservoir are evident by conspicuous vugs/voids that coincide with oolitic facies. Although this is a carbonate rock (limestone), there is distinct layering of fragmental fractions in a manner similar to detritial rocks. The clastic fragments in this case are medium to coarse fractions of crinoids and/or oolites, and they appear to be largely grain-supported.

Core depth: 7,954–7,954.5 ft
Log depth: about 7,955–7,955.5 ft

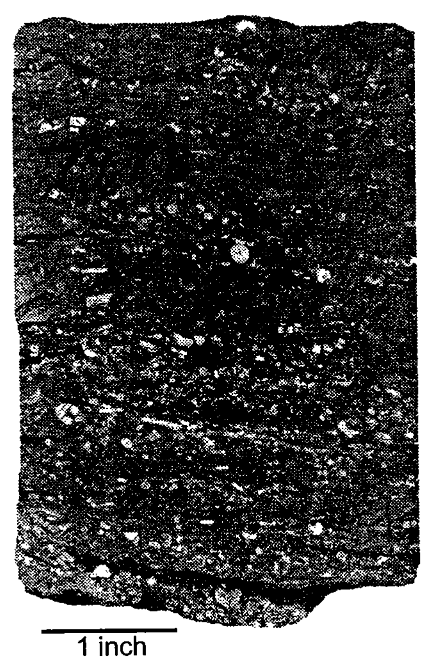
Crinoidal wackestone: A dark gray, clay-rich carbonate interval has abundant crinoid fragments exemplifying *graded bedding.* The crinoid fragments are "rafted" in a clay-rich carbonate matrix, and hence the classification as wackestone. The abundance of clay affects the gamma-ray response in the form of a minor inflection to the right as shown on the accompanying well log. This type of lithology is important only for correlation purposes.

Shell Oil Co. No. 1-19 Coulter

(SW¼NE¼ sec. 19, T. 21 N., R. 17 W.)

Core depth: 7,957.5–7,958.1 ft
Log depth: about 7,957.5–7,958.1 ft

Crinoidal packstone/wackestone: A greenish gray clay-rich matrix partially surrounds crinoid fragments ranging in size from <0.1 to >0.5 in., although most are <0.25 in. Shaly layers define horizontal bedding that is otherwise indistinct in the carbonate strata. These types of strata, in the absence of conspicuous oolites, and the apparently larger clay-matrix fraction, do not form good reservoirs.



Core depth: 7,977.9–7,978.25 ft
Log depth: about 7,980–7,980.3 ft

Crinoidal wackestone/mudstone and interbedded shale: A greenish gray clay-rich matrix surrounds white crinoid fragments <0.1 to ~0.2 in. The interbedded shale laminations are <0.1 in. thick, black, and have wavy bedding surfaces. *This lithology, in addition to strata consisting entirely of black shale, separates the Britt from the Boatwright Springer carbonate units.*

Appendix 5
Springer Field Data Elements

Table A5-1. — Cunningham Sandstone

Field	Single-Zone Completion Avg Gas (MCF)	Single-Zone Completion Avg Oil (BBL)	Well Count	Avg Depth (ft)	Thickness (ft) Avg Perf	Thickness (ft) Min Sat'd	Thickness (ft) Max Sat'd	Porosity (%) Avg Perf'd	Porosity (%) Min Sat'd	Porosity (%) Max Sat'd	Initial Pressure (psi)[1] Min	Initial Pressure (psi)[1] Avg	Initial Pressure (psi)[1] Max
ALEDO	3,621,025	265	2	12,628	12	13	24	6.2	5.9	10.8			
ALEDO SE			1	12,561	11	14	23	3.5	3.5	7.9			
ALEDO WEST			1	12,995	16	30	30	3.3	3.3	3.3			
ANTHON	334,052	142	1	12,735	18	21	82	8.0	3.0	6.2	6,071	6,071	6,071
ANTHON NE			2	12,193	23	45	68	9.0	5.6	9.5			
ANTHON NW			2	11,947	21	40	43	4.0	2.7	4.5			
APACHE EAST			1	16,719	13	31	50	8.0	5.1	7.1			
ARAPAHO	4,114,514	11,585	5	14,877	35	10	114	6.4	2.8	7.0	10,041	10,905	11,768
ARAPAHO NE	319,910	290	4	14,397	18	11	46	8.8	7.0	11.0	3,546	3,816	4,085
ARNETT			1	11,394	11	18	18	8.0	6.0	6.0			
ARNETT AIRPORT NE	126,874	1,089	2	11,094	11	14	22	9.0	6.8	8.0	2,806	2,806	2,806
ARNETT EAST	5,098,925	30,494	1	10,690	16	22	22	8.0	6.4	6.4			
ARNETT SE			4	11,955	20	20	30	9.6	6.1	11.0	2,614	3,814	5,885
BINGER NE	178,004	9,239	5	13,366	11	6	42	9.6	4.0	12.0	3,252	4,816	6,379
BISHOP	196,510	0	2	13,252	9	12	20	7.0	4.0	5.9	5,171	5,171	5,171
BRIDGEPORT	1,439,241	194	23	12,726	13	4	47	7.4	3.8	12.0	980	5,025	7,215
CARLTON LAKE WEST			1	12,398	27	30	38	8.9	8.9	8.9			
CEMENT	1,190,457	12,698	5	14,355	19	15	112	10.4	3.4	12.3	9,308	9,308	9,308
CESTOS SE	1,228,284	125,850	9	9,456	14	10	51	13.1	7.0	15.5	2,745	3,287	4,355
COLONY NW	1,098,836	0	17	16,245	29	6	169	7.3	4.0	10.0	10,833	11,350	11,867
CRANE SE	863,624	2,437	16	11,067	17	4	52	8.0	3.0	11.0	2,973	4,270	5,655
CUSTER CITY EAST			7	12,532	18	3	60	4.8	2.0	9.0			
CUSTER CITY NORTH	420,921	2,052	7	11,638	25	15	80	8.6	4.3	11.4	3,979	3,979	3,979
CUSTER CITY SE			1	12,972	41	41	41	6.0	6.0	6.0			
CUSTER CITY SOUTH	1,405,793	0	2	14,208	35	26	82	8.7	6.0	10.0	4,876	6,820	8,763
EAGLE CITY			2	9,411	5	7	8	5.6	2.0	8.1			
EAGLE CITY SOUTH	2,050,078	24,160	13	10,015	7	2	26	9.9	3.0	15.0	3,066	5,112	7,158
EAGLE CITY WEST	20,565	0	2	9,626	7	11	16	7.6	5.2	6.5			
EAKLY-WEATHERFORD	490,288	4,596	26	15,983	19	2	84	7.9	3.0	11.0	7,405	9,202	11,604
ELK CITY	11,113,801	14,732	6	19,690	57	40	122	6.5	3.0	9.0	7,855	13,495	15,964
ELM GROVE	3,510,070	5,325	41	12,344	13	4	58	7.1	2.0	13.3	2,235	6,157	9,240
FAY EAST	1,316,500	4,000	33	10,739	12	4	30	7.6	2.5	13.2	2,343	5,410	7,852
FONDA SE	0	3,349	4	8,598	11	6	29	10.9	6.5	17.0			
GAGE			2	9,405	6	11	13	7.0	5.0	5.2			
GEARY SW	9,592,582	19,294	1	12,560	12	28	28	7.0	5.5	5.5	9,014	9,014	9,014
GOODWIN SOUTH			3	11,284	21	6	44	5.8	4.8	8.0			
GOODWIN SOUTH			1	11,306	13	34	34	7.1	4.0	4.0			
GRAND WEST	615,360	0	1	12,792	36	6	44	6.5	6.5	7.0			
GREENFIELD NW	2,024,130	71,719	3	10,207	13	4	74	8.3	6.0	11.0	5,600	6,067	6,533
GREENFIELD WEST	147,598	71	2	11,129	7	8	14	8.5	7.0	8.0	3,053	3,053	3,053
HARMON SE			1	11,603	6	7	7	10.5	10.5	10.5			
HUCMAC NORTH			3	9,125	17	5	24	8.2	5.0	10.5			
HUCMAC NW	1,130,079	51,186	1	9,211	7	7	7	11.0	11.0	11.0			
HUCMAC SE			1	9,756	7	26	26	6.5	4.9	4.9			
HUCMAC SOUTH	205,140	54,077	5	9,649	21	14	43	8.2	7.1	9.5			
HUNTLEY WEST	925,895	0	2	18,786	51	13	94	5.1	4.7	5.6	16,020	16,020	16,020
HYDRO			1	13,264	22	24	24	7.4	7.2	7.2			
INDIANAPOLIS			2	14,630	13	14	19	9.0	6.0	10.0			
LEONEL SE			2	9,376	5	4	9	8.5	7.0	10.0			
LOOKEBA	3,758,565	2,992	13	13,894	19	6	40	7.6	5.5	13.0	4,249	6,747	10,114
LOOKEBA EAST	1,299,387	16,629	17	13,043	10	5	43	7.0	4.5	10.4	3,221	5,890	8,629
MACKIE			1	16,525	27	88	88	7.0	4.0	4.0			
MUTUAL SE	769,904	751	2	8,983	24	14	46	13.0	11.7	12.0			
MUTUAL SW			1	9,834	24	24	24	12.2	12.2	12.2			
NOBSCOT			1	10,038	22	24	24	10.0	9.9	9.9			
NOBSCOT NE	4,354	4,254	2	9,977	9	6	34	10.0	8.5	10.2			
NOBSCOT NW	801,323	12,887	45	10,299	16	5	54	8.7	4.1	11.7	2,669	3,629	4,749
OAKWOOD NORTH	246,754	19,174	4	9,629	19	9	43	8.4	6.4	9.0	2,052	2,052	2,052
OAKWOOD SW	111,075	74,559	6	10,001	20	16	66	10.0	5.8	10.8			
OAKWOOD WEST			5	9,881	15	8	65	8.1	5.9	8.0			
PEEK NE	492,465	6,876	5	12,156	11	8	44	7.0	3.0	8.0			
PUTNAM	2,353,943	10,408	100	10,282	18	4	121	9.1	2.0	15.5	1,345	3,720	6,605

Field Data Elements

Observed Spacing (ac)		Calc. Avg. Drainage Area (ac)			Ult. Rec.	Volumetric Original Gas in Place (BCF)				Calculated Undrained Reserves (BCF)			
Avg	Sum	Perf'd	Sat'd	P/Z	(BCF)	Perf'd	7%+ φ	4%+ φ	Sat'd	Perf'd	7%+ φ	4%+ φ	Sat'd
200	800				4.16	0.48	3.11	3.88	3.88	-3.68	-1.05	-0.28	-0.28
440	1,760				0.04	1.45	7.41	13.13	14.58	1.41	7.37	13.09	14.54
640	640				0.02	0.25	0.00	0.19	0.47	0.23	-0.02	0.17	0.45
340	2,720	27	17	18	0.33	7.82	20.99	57.34	64.81	7.48	20.66	57.00	64.48
213	640				0.85	5.58	16.73	23.23	23.42	4.72	15.88	22.38	22.57
480	960				5.76	3.26	0.20	5.13	7.09	-2.51	-5.57	-0.64	1.33
533	1,600				0.33	2.86	28.67	47.14	48.19	2.54	28.35	46.81	47.87
204	2,240	436	275	225	15.91	17.79	14.43	30.82	39.12	1.88	-1.48	14.91	23.20
640	3,200	62	52		3.38	27.51	29.47	39.65	39.65	24.13	26.08	36.27	36.27
640	640				0.06	2.06	1.26	2.04	2.53	2.00	1.20	1.98	2.47
640	1,280	45	29	27	0.31	6.11	7.13	7.13	7.94	5.80	6.82	6.82	7.63
640	640				0.60	4.18	3.65	4.37	4.63	3.58	3.05	3.77	4.03
480	2,400	278	254	260	21.84	34.51	35.41	44.64	44.93	12.67	13.57	22.81	23.10
373	2,240	19	11	107	2.24	16.77	33.25	36.12	36.80	14.53	31.01	33.89	34.57
640	1,280			18	0.20	0.52	0.52	0.52	1.56	0.32	0.32	0.32	1.36
217	6,080	718	154	138	34.29	30.92	28.38	49.61	51.13	-3.37	-5.91	15.32	16.84
640	1,280				0.05	0.00	23.22	24.15	24.15	-0.05	23.17	24.10	24.10
423	8,880	112	96		8.89	25.92	222.52	298.55	309.74	17.03	213.63	289.65	300.84
187	2,800	234	169	198	12.54	11.37	25.08	28.82	31.51	-1.17	12.54	16.28	18.97
455	8,640	29	18	37	34.38	178.00	130.18	285.01	326.66	143.62	95.81	250.64	292.28
216	3,680	233	158	361	15.14	20.56	19.95	25.33	29.23	5.42	4.81	10.19	14.09
498	4,480				1.08	24.53	32.82	53.75	60.64	23.45	31.74	52.67	59.56
218	2,400	383	137	62	7.73	30.36	27.29	45.04	48.01	22.63	19.55	37.31	40.27
640	640				0.02	6.09	1.49	5.31	6.09	6.07	1.46	5.29	6.07
352	1,760	51	51	59	3.45	28.35	40.18	52.50	52.50	24.90	36.74	49.05	49.05
400	800				1.07	1.00	0.45	0.45	1.36	-0.07	-0.62	-0.62	0.29
340	5,440	492	441	423	14.23	19.64	39.74	43.35	43.57	5.41	25.51	29.12	29.34
160	320				0.09	0.56	0.61	0.89	1.07	0.47	0.52	0.80	0.98
408	21,600	74	61	67	12.44	149.44	220.80	341.57	366.18	137.00	208.35	329.12	353.74
503	3,520	205	126	146	67.34	188.54	158.78	263.09	324.57	121.20	91.44	195.75	257.23
215	9,440	678	566	343	130.11	53.31	46.11	65.44	69.67	-76.80	-84.00	-64.67	-60.45
268	9,920	702	637	191	35.26	47.08	52.78	67.93	69.91	11.82	17.52	32.68	34.65
80	320				0.13	0.43	0.42	0.45	0.45	0.30	0.30	0.32	0.32
640	1,280				0.26	1.76	1.04	2.23	2.77	1.51	0.78	1.98	2.52
640	640	1475	805	832	10.03	4.35	3.11	7.58	7.98	-5.68	-6.92	-2.45	-2.05
520	2,080				3.97	9.81	6.07	9.62	10.58	5.85	2.10	5.65	6.61
320	320				0.73	1.37	1.22	1.37	2.01	0.63	0.49	0.63	1.28
640	1,280				1.74	15.63	8.16	21.31	21.31	13.89	6.42	19.57	19.57
224	1,120	129	73	112	4.36	13.77	15.10	30.28	30.92	9.41	10.74	25.92	26.56
640	1,280	39	25	41	0.20	3.81	4.01	5.46	5.46	3.61	3.82	5.26	5.26
640	640				0.10	0.68	0.57	0.80	0.80	0.58	0.47	0.69	0.69
80	480				0.03	1.80	2.26	2.34	2.34	1.78	2.24	2.31	2.31
80	80				1.42	0.04	0.04	0.04	0.04	-1.38	-1.38	-1.38	-1.38
320	320				0.03	0.38	0.33	0.52	1.05	0.35	0.30	0.50	1.02
160	800				1.24	6.58	6.30	8.02	8.05	5.34	5.06	6.77	6.81
640	1,280	15	14	10	1.10	49.17	4.13	44.44	51.63	48.08	3.03	43.34	50.53
160	160				0.00	1.54	0.96	1.63	1.63	1.54	0.96	1.63	1.63
640	1,280				0.76	12.79	9.08	17.20	17.20	12.03	8.33	16.44	16.44
400	800				0.32	2.74	4.74	4.74	4.74	2.42	4.42	4.42	4.42
303	5,760	273	199	286	33.83	48.07	57.28	93.71	94.35	14.24	23.45	59.88	60.52
362	8,320	147	114	231	15.24	35.57	23.29	54.62	55.13	20.33	8.05	39.38	39.89
640	640				0.08	9.34	5.53	14.82	17.39	9.25	5.45	14.73	17.30
320	640				1.54	5.75	5.91	6.31	6.31	4.21	4.37	4.77	4.77
640	640				0.44								
160	160				0.01	0.74	0.75	0.80	0.80	0.73	0.75	0.79	0.79
160	320				0.01	0.71	1.72	1.78	1.78	0.70	1.71	1.78	1.78
251	12,800	206	144	169	29.04	72.18	72.23	95.87	98.74	43.14	43.19	66.83	69.70
200	800	27	27	35	2.69	4.51	4.84	7.08	7.24	1.83	2.15	4.39	4.55
93	560				0.66	4.78	4.98	5.93	6.08	4.12	4.32	5.27	5.42
224	1,120				0.42	1.05	1.30	1.39	1.40	0.63	0.88	0.97	0.98
480	2,880				1.96	12.36	12.86	19.93	23.90	10.40	10.90	17.97	21.94
245	28,720	411	248	155	206.89	245.26	340.83	460.40	471.48	38.37	133.94	253.51	264.60

(continued on p. 114–115)

Table A5-1. — Cunningham Sandstone

Field	Single-Zone Completion Avg Gas (MCF)	Single-Zone Completion Avg Oil (BBL)	Well Count	Avg Depth (ft)	Thickness (ft) Avg Perf	Thickness (ft) Min Sat'd	Thickness (ft) Max Sat'd	Porosity (%) Avg Perf'd	Porosity (%) Min Sat'd	Porosity (%) Max Sat'd	Initial Pressure (psi)[1] Min	Initial Pressure (psi)[1] Avg	Initial Pressure (psi)[1] Max
REYDON			1	15,688	44	108	108	4.0	4.0	4.0			
SEILING NE	1,355,366	18,278	7	8,664	7	5	22	12.1	6.3	15.0	3,791	3,946	4,101
SEILING SW	164,406	1,587	5	9,105	9	4	22	8.4	6.0	12.5			
SHATTUCK			1	10,522	13	13	38	5.5	5.5	7.0			
SICKLES NORTH	30,523	0	6	13,722	15	6	33	7.9	4.9	11.5	2,528	4,224	5,920
SQUAW CREEK	2,822,223	2,928	27	11,414	13	4	76	9.5	5.3	15.0	3,861	6,720	8,888
STRONG CITY DISTRICT			1	16,020	10	10	10	8.0	8.0	8.0			
THOMAS SOUTH	1,005,550	19,885	4	11,895	16	20	35	9.7	6.0	10.0			
VERDEN	2,108,694	24,293	18	16,529	35	8	213	9.8	3.8	16.9	2,014	8,105	10,902
VICI SW			1	10,728	17	22	22	10.0	10.0	10.0			
WATONGA-CHICKASHA	4,421,327	11,027	107	10,814	11	2	80	10.3	1.0	19.0	3,006	6,337	9,199
WATONGA SOUTH	1,187,447	12,880	1	9,888	6	6	6	14.0	14.0	14.0	6,222	6,222	6,222
WEATHERFORD	66,246	0	4	13,778	10	8	40	6.1	3.0	11.5	4,920	4,920	4,920
WEATHERFORD NE	158,741	276	1	12,802	31	44	44	7.0	6.8	6.8	3,788	3,788	3,788
GRAND TOTALS			**666**	**12,066**	**18**	**2**	**213**	**8**	**1.0**	**19.0**	**980**		**16,020**

[1]Initial pressure data prioritized in this order: DST, BHP, SITP, FTP.

BCF Billion cubic feet

Source: Petroleum Information/Dwights LLC, ©2000.
Data current to April 2000.

Field Data Elements *(continued)*

Observed Spacing (ac)		Calc. Avg. Drainage Area (ac)			Ult. Rec.	Volumetric Original Gas in Place (BCF)				Calculated Undrained Reserves (BCF)			
Avg	Sum	Perf'd	Sat'd	P/Z	(BCF)	Perf'd	7%+ ϕ	4%+ ϕ	Sat'd	Perf'd	7%+ ϕ	4%+ ϕ	Sat'd
640	640				0.19	8.67	0.69	9.85	21.28	8.48	0.50	9.67	21.10
350	2,800	369	154	194	7.39	11.35	25.37	25.37	25.87	3.96	17.98	17.98	18.49
80	480				1.85	1.31	1.87	2.11	2.11	-0.54	0.03	0.26	0.26
640	1,280				0.15	2.04	1.20	2.04	2.04	1.89	1.05	1.89	1.89
180	2,880	1	1		0.97	11.21	15.30	22.60	24.10	10.24	14.34	21.64	23.14
568	17,600	332	240	217	74.40	201.84	249.28	270.13	270.94	127.44	174.87	195.73	196.54
640	640				0.06	2.01	2.01	2.01	2.01	1.95	1.95	1.95	1.95
160	640				7.16	3.85	4.93	5.86	6.10	-3.31	-2.23	-1.29	-1.06
341	14,320	97	56	61	31.04	198.13	368.34	563.82	637.12	167.09	337.29	532.78	606.08
640	640				0.10	3.05	3.49	3.95	3.95	2.95	3.39	3.85	3.85
261	30,800	450	301	230	251.85	320.74	465.86	513.35	519.09	68.89	214.01	261.49	267.24
640	640	142	142	129	1.32	5.95	5.95	5.95	5.95	4.64	4.64	4.64	4.64
500	4,000	195	195		0.19	4.99	13.48	25.20	30.00	4.80	13.29	25.01	29.81
160	160	14	10		0.16	1.78	0.59	2.45	2.45	1.62	0.43	2.30	2.30
		260	**171**	**174**	**1,130**	**2,291**	**3,030**	**4,341**	**4,662**	**1,161**	**1,900**	**3,212**	**3,532**

NOTE: A minus (–) preceding production in the "Balance" columns indicates over-production in regard to volumetric reserve calculations. Positive numbers indicate under-production in regard to the particular field AND is an estimate of POTENTIALLY REMAINING UNPRODUCED GAS RESERVES.

Table A5-2. — Britt Sandstone

Field	Single Zone Completion		Well	Avg	Thickness (ft)			Porosity (%)			Initial Pressure (psi)[1]		
	Avg Gas (MCF)	Avg Oil (BBL)	Count	Depth (ft)	Avg Perf	Min Sat'd	Max Sat'd	Avg Perf'd	Min Sat'd	Max Sat'd	Min	Avg	Max
ALEDO	2,669,024	1,147	1	12,554	6	6	6	9.0	9.0	9.0	4,520	4,520	4,520
ALEDO SE	1,877,566	3,676	7	12,547	14	4	58	8.6	5.0	10.3	1,433	4,388	6,801
ANADARKO WEST	57,347	0	1	18,958	3	8	8	8.0	4.0	4.0	3,841	3,841	3,841
ANTHON	2,525,834	3,337	18	12,949	12	6	66	8.3	1.0	15.0	3,885	6,613	9,044
ANTHON NE	3,860,088	377	4	12,281	9	4	18	10.4	1.0	16.0	5,698	5,698	5,698
ANTHON NW	985,111	0	4	12,233	7	6	9	9.3	4.0	12.0	4,821	4,821	4,821
ANTHON SE	3,693,860	4,534	8	13,697	21	6	38	8.0	5.0	13.0	3,502	6,727	9,958
APACHE EAST	30,379,821	665	4	17,499	23	26	60	8.8	3.8	8.9	15,418	15,418	15,418
APACHE NORTH			1	4,194	20	21	21	19.0	19.5	19.5			
ARAPAHO			1	15,094	27	22	35	5.2	4.3	6.0			
BINGER NE	365,294	1,877	6	13,317	12	14	20	7.9	4.0	8.7	3,062	5,324	6,587
BRIDGEPORT			4	12,902	9	5	19	6.1	2.0	8.7			
BROXTON NORTH	5,420,059	0	6	20,665	20	10	107	7.9	4.5	9.8	9,995	14,110	16,453
BROXTON SOUTH	141,439	2,028	3	5,603	27	12	61	11.8	11.8	11.8	735	1,523	2,310
CANTON NW			2	8,551	20	19	20	8.6	8.3	9.0			
CANUTE NORTH	886,847	0	1	20,170	37	64	64	5.0	5.7	5.7	13,217	13,217	13,217
CARNEGIE NORTH	927,167	0	1	22,434	52	60	60	5.0	4.5	4.5	9,879	9,879	9,879
CARPENTER NE	991,573	0	1	12,784	10	10	10	6.7	6.7	6.7	3,702	3,702	3,702
CARTER NORTH	2,085,085	19	3	9,458	68	56	166	13.5	12.3	14.0	4,589	4,880	5,085
CEMENT	2,912,178	7,515	16	14,720	35	5	171	10.7	3.0	18.0	4,492	8,781	11,913
COLONY NW			15	16,511	9	4	68	10.3	4.0	15.0			
CRANE SE	1,217,072	844	8	11,049	21	4	44	6.4	4.0	8.0	3,556	3,556	3,556
CUSTER CITY EAST			3	12,396	5	6	17	6.3	4.0	6.0			
CUSTER CITY NORTH	1,210,318	5,761	5	12,163	10	4	18	6.9	5.0	9.0	5,637	6,370	7,980
CUSTER CITY SOUTH	1,664,858	488	5	14,581	32	10	68	9.0	6.0	10.0	6,200	7,731	9,792
EAGLE CITY			1	9,264	6	6	6	6.5	6.5	6.5			
EAGLE CITY WEST	1,278,693	19,414	1	9,673	5	8	8	8.1	7.5	7.5	6,889	6,889	6,889
EAKLY-WEATHERFORD	6,462,194	3,148	76	15,733	17	4	62	8.2	2.0	12.0	3,556	10,597	13,202
ELM GROVE	61,830	142	8	12,108	9	4	26	3.8	2.0	4.2	3,660	4,003	4,346
FAY EAST	1,466,999	13,924	43	10,741	10	3	42	7.2	2.5	12.0	3,290	5,429	6,974
FLETCHER NE	10,101,944	2,227	2	17,461	23	40	50	8.9	6.7	7.9	12,225	12,225	12,225
FONDA SE			1	8,882	7	7	7	2.6	2.6	2.6			
FORT COBB NW	481,027	0	1	19,610	24	24	24	6.0	6.0	6.0	13,429	13,429	13,429
GREENFIELD NW	1,757,378	53,098	25	10,293	15	4	66	8.6	2.0	12.5	2,758	4,990	7,045
GREENFIELD WEST			1	11,449	9	10	10	8.0	7.5	7.5			
HUNTLEY WEST			2	19,495	26	22	30	6.0	5.0	7.1			
INDIANAPOLIS	199,842	8,738	1	14,890	16	18	20	12.0	7.0	12.0	7,400	7,400	7,400
LAVERTY NW	2,689,803	36,965	3	17,842	22	19	35	9.4	8.0	9.1	5,819	10,258	13,155
LEONEL SE			1	9,214	2	4	4	4.0	4.0	4.0			
LOOKEBA	513,306	0	3	13,926	10	4	22	9.7	5.9	11.0	8,148	8,148	8,148
LOOKEBA EAST	222,410	305	9	12,996	8	5	26	7.8	3.0	11.4	7,008	7,299	7,590
NOBSCOT NW	3,447,261	11,682	8	10,209	9	7	56	9.4	4.6	11.3	1,669	3,996	6,322
OAKWOOD NORTH	30,561	10,588	8	9,362	7	4	20	10.0	6.5	11.8			
OAKWOOD SW			1	9,910	10	16	16	8.0	6.8	6.8			
OAKWOOD WEST			2	9,945	20	26	26	8.6	7.2	9.2			
PUTNAM	1,314,989	18,477	8	10,631	11	5	46	8.4	4.2	11.7	3,828	4,476	5,417
SAYRE EAST			2	13,882	71	46	168	10.5	7.7	10.3			
SICKLES NORTH	2,014,499	799	18	13,934	21	8	56	7.3	5.6	8.1	2,350	5,899	10,627
SQUAW CREEK	1,266,799	715	4	11,414	10	4	24	7.8	6.0	9.0	7,574	7,574	7,574
STRONG CITY DISTRICT			1	16,112	6	22	22	7.0	4.0	4.0			
THOMAS SOUTH	2,586,444	4,123	1	12,052	17	22	50	10.0	4.5	8.8	5,818	5,818	5,818
VERDEN			7	17,087	32	10	117	7.1	3.2	8.5			
WATONGA-CHICKASHA	1,894,824	33,512	140	10,117	12	2	84	10.6	1.0	20.0	1,023	5,311	8,853
WATONGA SOUTH	780,343	9,880	5	9,897	14	14	34	9.9	7.0	10.0	3,970	5,476	6,865
WATONGA WEST	53,339	584	2	9,438	7	10	15	12.5	11.0	12.0			
WEATHERFORD	2,484,975	508	9	13,535	17	6	34	7.5	4.5	9.5	3,436	6,658	8,239
GRAND TOTAL			**522**	**12,814**	**17**	**2**	**171**	**8**	**1**	**20**	**735**		**16,453**

[1]Initial pressure data prioritized in this order: DST, BHP, SITP, FTP.

BCF Billion cubic feet

Source: Petroleum Information/Dwights LLC, ©2000.
Data current to April 2000.

Field Data Elements

Observed Spacing (ac)		Calc. Avg. Drainage Area (ac)			Ult. Rec.	Volumetric Original Gas in Place (BCF)				Calculated Undrained Reserves (BCF)			
Avg	Sum	Perf'd	Sat'd	P/Z	(BCF)	Perf'd	7%+ ϕ	4%+ ϕ	Sat'd	Perf'd	7%+ ϕ	4%+ ϕ	Sat'd
320	320			637	2.67								
320	2,240	197	172	204	12.65	19.79	10.04	19.90	23.28	7.13	-2.62	7.25	10.62
40	40	59	45		0.06	0.04	0.04	0.04	0.05	-0.02	-0.02	-0.02	-0.01
320	6,720	399	342	237	45.10	56.49	59.99	74.32	79.22	11.38	14.89	29.22	34.12
400	1,600	390	390	299	13.26	15.73	15.67	16.43	16.47	2.46	2.41	3.16	3.20
240	960	311	311	151	8.76	3.99	2.72	3.76	4.01	-4.77	-6.04	-5.00	-4.75
260	2,080	233	220	254	29.29	29.00	24.03	29.46	30.14	-0.30	-5.26	0.17	0.85
576	2,880	598	263	226	55.63	77.20	110.96	159.02	167.38	21.58	55.33	103.39	111.75
320	320				0.02	3.51	3.69	3.69	3.79	3.50	3.67	3.67	3.77
240	960				0.35	6.29	4.55	14.02	16.92	5.94	4.20	13.67	16.57
267	1,600	96	81	113	3.69	10.48	9.23	11.15	12.30	6.79	5.54	7.46	8.61
267	1,600				2.15	2.39	2.49	3.70	3.81	0.23	0.34	1.55	1.66
263	1,840	712	156	135	32.10	72.95	95.36	149.36	155.47	40.85	63.26	117.26	123.37
427	1,280				0.51	0.69	0.63	0.69	0.69	0.17	0.12	0.17	0.17
60	120				0.11	0.81	0.81	0.81	0.81	0.70	0.70	0.70	0.70
640	640	31	16	31	0.89	18.40	15.91	29.04	36.22	17.51	15.03	28.16	35.34
640	640	38	36	19	1.34	22.72	3.67	16.60	23.59	21.37	2.33	15.26	22.25
160	160	249	249	354	1.13	0.72	0.49	0.72	0.72	-0.40	-0.64	-0.40	-0.40
640	1,920	111	42	28	17.22	100.91	197.03	205.90	205.90	83.69	179.81	188.68	188.68
359	10,400	66	49	41	42.69	258.96	522.32	641.96	651.77	216.27	479.62	599.27	609.07
480	7,680				22.02	67.86	78.43	102.92	135.20	45.84	56.41	80.90	113.18
220	1,760	101	72	75	7.71	11.10	8.55	12.91	14.43	3.39	0.84	5.20	6.72
533	1,600				0.62	2.68	1.61	3.70	4.49	2.06	0.99	3.08	3.88
256	1,280	385	385	456	7.21	5.58	2.01	5.54	5.58	-1.63	-5.21	-1.67	-1.63
320	1,920	78	57	48	7.01	60.52	45.80	68.49	68.49	53.51	38.79	61.48	61.48
160	160				0.61	0.38	0.15	0.38	0.38	-0.24	-0.46	-0.24	-0.24
640	640	362	245	277	1.32	2.34	2.19	3.46	3.46	1.01	0.87	2.14	2.14
369	32,480	404	293	225	421.29	602.45	684.28	904.34	918.27	181.16	262.99	483.04	496.98
280	2,240	18	12	234	2.28	2.93	2.07	2.49	4.60	0.65	-0.21	0.21	2.32
254	11,440	450	413	351	49.09	35.92	32.15	40.49	45.21	-13.17	-16.94	-8.60	-3.88
640	1,280	217	150	128	19.91	51.59	67.91	81.19	82.62	31.68	48.00	61.29	62.71
160	160				0.00	0.13	0.00	0.06	0.13	0.13	0.00	0.06	0.13
640	640	18	18	28	0.48	16.88	4.92	16.88	16.88	16.40	4.44	16.40	16.40
198	4,960	352	241	232	41.96	47.27	46.97	66.74	67.96	5.31	5.01	24.78	26.00
640	640				0.06	1.81	1.81	1.81	1.89	1.75	1.75	1.75	1.83
640	1,280				0.07	11.98	3.91	11.18	11.98	11.91	3.83	11.11	11.91
640	1,280	10	8	14	0.22	13.50	21.26	23.78	23.78	13.28	21.04	23.56	23.56
427	1,280	98	84	88	9.23	37.75	32.46	42.93	43.61	28.52	23.23	33.70	34.38
640	640				0.00	0.31	0.00	0.62	0.62	0.31	0.00	0.62	0.62
320	1,920	121	80		0.97	4.72	7.43	9.14	9.07	3.75	6.47	8.17	8.10
495	5,440	134	102	62	4.61	16.50	21.05	24.59	25.27	11.88	16.44	19.98	20.66
260	2,080	398	195	347	8.69	10.58	8.78	17.48	18.99	1.89	0.09	8.79	10.30
220	1,760				0.83	3.35	3.36	4.19	4.36	2.52	2.53	3.36	3.53
80	80				0.01	0.19	0.20	0.23	0.26	0.18	0.19	0.22	0.25
240	480				0.01	3.88	4.06	4.79	4.85	3.87	4.05	4.78	4.85
267	3,200	289	231	185	6.35	10.80	10.50	17.75	19.93	4.45	4.15	11.40	13.58
640	1,280				1.44	73.86	81.48	81.48	90.31	72.42	80.05	80.05	88.87
187	3,360	339	246	257	37.43	34.47	25.93	41.63	43.16	-2.96	-11.50	4.20	5.73
384	1,920	412	325	304	4.25	10.85	11.57	16.11	16.11	6.60	7.32	11.86	11.86
640	640				0.07	1.05	0.80	1.05	2.21	0.98	0.73	0.98	2.14
160	320	201	178	175	2.68	2.13	2.93	5.04	5.63	-0.55	0.25	2.36	2.96
400	4,800				6.76	62.01	60.48	107.14	121.62	55.25	53.72	100.38	114.86
333	52,240	265	191	170	192.00	468.41	697.96	740.33	746.54	276.41	505.96	548.33	554.54
160	800	162	111	170	4.22	3.69	5.85	6.81	7.10	-0.53	1.62	2.58	2.87
480	960				0.11	5.21	10.78	10.78	10.78	5.10	10.67	10.67	10.67
284	2,560	241	221	249	17.59	13.09	10.57	13.54	14.16	-4.50	-7.02	-4.05	-3.43
		237		**194**	**1,149**	**2,399**	**3,080**	**3,873**	**4,022**	**1,253**	**1,934**	**2,726**	**2,876**

NOTE: A minus (–) preceding production in the "Balance" columns indicates over-production in regard to volumetric reserve calculations. Positive numbers indicate under-production in regard to the particular field AND is an estimate of POTENTIALLY REMAINING UNPRODUCED GAS RESERVES.

Table A5-3. — Boatwright Sandstone

Field	Single Zone Completion Avg Gas (MCF)	Single Zone Completion Avg Oil (BBL)	Well Count	Avg Depth (ft)	Thickness (ft) Avg Perf	Thickness (ft) Min Sat'd	Thickness (ft) Max Sat'd	Porosity (%) Avg Perf'd	Porosity (%) Min Sat'd	Porosity (%) Max Sat'd	Initial Pressure (psi)[1] Min	Initial Pressure (psi)[1] Avg	Initial Pressure (psi)[1] Max
APACHE EAST	8,258,251	347	7	18,946	25	10	154	8.7	4.3	9.9	15,615	16,490	16,989
APACHE SE	252,210		2	7,729	55	84	111				3,511	3,560	3,609
BINGER NE	1,118,715	579	3	13,579	13	17	36	8.2	7.0	8.0	8,967	8,967	8,967
BINGER SOUTH	5,753,627		2	15,815	21	12	29	11.3	10.5	12.0	4,793	6,917	9,040
BROXTON NORTH			1	21,184	6	6	16	7.0	7.0	7.0			
BROXTON SOUTH	207,572		1	2,630	31	31	31				159	159	159
CEMENT	4,305,410	30,289	17	15,696	30	17	218	10.1	4.8	15.5	4,518	8,948	11,748
COLONY NW	4,189,274		21	16,825	6	6	22	12.8	5.0	18.0	6,097	9,420	12,276
CYRIL NW	1,121,624	11,828	1	16,102	38	49	49	9.0	8.3	8.3	8,757	8,757	8,757
CYRIL WEST	1,678,898	110	2	19,229	25	38	60	9.0	4.6	8.8	14,180	14,180	14,180
EAKLY-WEATHERFORD	2,632,709	1,715	31	16,241	18	2	71	9.1	5.0	16.0	2,462	7,925	12,909
FLETCHER NE			1	18,601	12	44	44	7.8	3.2	3.2			
HUNTLEY EAST	468,179		1	18,522	22	29	29	5.9	5.3	5.3	6,928	6,928	6,928
HUNTLEY WEST			3	19,862	27	10	48	6.0	5.4	6.9			
LOOKEBA	21,320		6	14,085	10	6	26	9.4	7.0	11.8			
LOOKEBA EAST			1	13,660	12	4	14	5.9	5.5	9.0			
NOBSCOT NW			1	10,342	8	19	19	8.5	7.8	7.8			
SICKLES NORTH	2,884,124	405	1	13,857	6	3	6	9.0	7.0	9.0	10,741	10,741	10,741
VERDEN	2,712,011	27,356	52	17,225	54	4	358	8.0	3.0	13.0	1,754	8,719	12,106
WATONGA-CHICKASHA	2,396,531	10,420	42	12,032	14	2	139	8.6	3.2	17.0	3,956	7,516	9,630
GRAND TOTAL			**196**	**15,108**	**22**	**2**	**358**	**8**	**3**	**18**	**159**		**16,989**

[1]Initial pressure data prioritized in this order: DST, BHP, SITP, FTP.

BCF Billion cubic feet

Source: Petroleum Information/Dwights LLC, ©2000.
Data current to April 2000.

Field Data Elements

Observed Spacing (ac) Avg	Sum	Calc. Avg. Drainage Area (ac) Perf'd	Sat'd	P/Z	Ult. Rec. (BCF)	Volumetric Original Gas in Place (BCF) Perf'd	7%+ φ	4%+ φ	Sat'd	Calculated Undrained Reserves (BCF) Perf'd	7%+ φ	4%+ φ	Sat'd
462	4,160	60	60	279	50.24	144.04	265.49	388.17	419.85	93.79	215.25	337.92	369.61
640	1,280			1280	0.50								
427	1,280	40	36	79	2.31	15.15	14.18	26.84	26.84	12.84	11.87	24.53	24.53
240	480	364	310	364	12.68	17.53	15.99	17.53	17.53	4.85	3.31	4.85	4.85
80	160				1.18	0.00	0.18	0.46	0.46	-1.18	-1.01	-0.72	-0.72
640	640				0.94								
392	8,240	30	26	55	61.57	307.22	444.58	568.60	578.50	245.65	383.01	507.02	516.93
488	10,240	272	81	435	45.45	77.30	129.57	136.08	136.08	31.85	84.12	90.63	90.63
640	640	25	32	30	1.15	24.35	24.35	29.06	29.06	23.20	23.20	27.91	27.91
640	2,560	19	14	26	2.11	57.56	70.87	118.49	120.36	55.45	68.75	116.37	118.25
372	17,120	268	215	339	65.32	258.09	300.33	370.72	380.14	192.77	235.01	305.40	314.82
640	640				3.75	9.78	7.99	13.16	14.71	6.02	4.24	9.41	10.95
640	640	51	78	60	0.61	6.46	0.95	6.93	7.65	5.86	0.34	6.32	7.05
640	1,920				0.06	15.94	2.95	15.86	16.39	15.88	2.89	15.80	16.33
274	1,920				2.45	11.08	12.67	16.44	16.44	8.63	10.22	13.99	13.99
480	960				0.10	1.80	1.87	3.27	3.42	1.70	1.77	3.17	3.32
160	160				0.12	0.54	0.96	1.09	1.17	0.42	0.84	0.97	1.05
200	800	617	541	617	3.34	1.73	2.09	2.34	2.34	-1.61	-1.25	-1.00	-1.00
386	24,720	58	44	104	200.56	947.20	1061.65	1614.71	1767.68	746.64	861.09	1414.15	1567.12
272	13,600	331	266	533	51.87	64.81	88.21	104.27	105.74	12.94	36.34	52.40	53.86
		178	**142**	**323**	**506**	**1,961**	**2,445**	**3,434**	**3,644**	**1,456**	**1,940**	**2,929**	**3,139**

NOTE: A minus (–) preceding production in the "Balance" columns indicates over-production in regard to volumetric reserve calculations. Positive numbers indicate under-production in regard to the particular field AND is an estimate of POTENTIALLY REMAINING UNPRODUCED GAS RESERVES.

Table A5-4. — Britt Carbonate

Field	Single Zone Completion Avg Gas (MCF)	Avg Oil (BBL)	Well Count	Avg Depth (ft)	Thickness (ft) Avg Perf	Min Sat'd	Max Sat'd	Porosity (%) Avg Perf'd	Min Sat'd	Max Sat'd	Initial Pressure (psi)[1] Min	Avg	Max
ARNETT EAST			1	10,807	9	62	62	6.5	2.0	2.0			
CEDARDALE NE	174,649	342	7	7,117	10	18	33	7.0	3.0	7.3	1,791	1,901	2,011
CEDARDALE NW	1,422,282	2,555	29	7,493	20	22	84	7.5	2.5	11.3	699	2,585	3,862
CESTOS	326,521	1,491	2	9,003	33	82	88	6.0	2.5	5.0	3,898	3,898	3,898
CESTOS SE	238,925	169,113	4	9,574	47	82	136	6.1	2.5	5.0	1,628	1,628	1,628
CHESTER WEST	4,121,742	8,721	58	7,889	19	12	96	8.2	1.8	18.5	356	2,830	3,725
FONDA SW	98,484	98,314	3	8,727	8	7	16	9.5	5.5	11.0			
FORT SUPPLY NE			3	7,323	9	4	32	10.0	7.0	12.0			
GAGE	16,391	0	5	9,114	20	10	112	5.5	2.5	6.2			
GRAND WEST	19,847	0	1	12,392	13	26	26	3.5	2.0	2.0	2,254	2,254	2,254
HUCMAC NORTH			2	9,096	7	6	11	9.4	7.8	11.0			
MOCANE-LAVERNE	405,185	3,230	27	8,194	38	9	156	6.9	2.0	8.0	1,435	2,067	2,441
MUTUAL	45,068	0	1	8,628	38	50	50	5.0	4.8	4.8			
MUTUAL NORTH	271,975	336	2	8,194	12	26	60	8.9	2.4	5.4	3,383	3,383	3,383
MUTUAL SW			1	10,088	8	20	20	3.0	3.0	3.0			
OAKWOOD NORTH			3	9,357	14	9	20	3.3	3.3	12.0			
OAKWOOD WEST			2	9,897	8	10	37	9.0	6.8	9.9			
PEEK SOUTH	393,797	1,028	1	13,243	37	47	47				6,409	6,409	6,409
PUTNAM			12	9,975	18	8	88	3.7	1.2	4.1			
SEILING NE	1,124,593	5,449	21	8,749	34	11	144	6.1	1.5	8.7	1,427	3,128	4,024
SEILING SW	250,375	3,601	8	9,116	48	31	104	3.8	2.4	4.1	1,696	3,320	4,363
SHARON WEST			2	9,331	17	49	118	3.7	2.0	2.0			
SHATTUCK			1	10,671	26	196	196	3.4	2.0	2.0			
TANGIER	366,987	563	4	8,358	18	6	138	9.0	3.0	7.0	2,973	2,973	2,973
TOUZALIN	557,651	199	2	9,667	7	20	22	8.3	7.0	7.0			
TRIVOLI SW	106,329	36,089	16	8,360	25	12	72	6.5	3.3	12.0			
WOODWARD			4	8,452	44	6	108	2.5	1.7	9.5			
WOODWARD SE	1,381,376	4,394	5	7,911	14	10	74	10.3	3.0	11.7	3,567	3,643	3,718
GRAND TOTAL			**227**	**9,169**	**21**	**4**	**196**	**6**	**1.2**	**18.5**	**356**		**6,409**

[1]Initial pressure data prioritized in this order: DST, BHP, SITP, FTP.

BCF Billion cubic feet

Source: Petroleum Information/Dwights LLC, ©2000.
Data current to April 2000.

Field Data Elements

Observed Spacing (ac)		Calc. Avg. Drainage Area (ac)			Ult. Rec.	Volumetric Original Gas in Place (BCF)				Calculated Undrained Reserves (BCF)			
Avg	Sum	Perf'd	Sat'd	P/Z	(BCF)	Perf'd	7%+ ϕ	4%+ ϕ	Sat'd	Perf'd	7%+ ϕ	4%+ ϕ	Sat'd
640	640				0.54	1.96	1.17	1.81	4.16	1.42	0.64	1.27	3.62
297	2,080	57	34	45	1.31	3.26	2.44	3.99	5.59	1.95	1.12	2.68	4.27
243	7,040	455	196	210	31.01	35.68	31.89	45.85	56.81	4.67	0.88	14.84	25.80
320	640	70	31		0.73	3.21	1.77	3.40	5.62	2.48	1.04	2.67	4.89
360	1,440	2	2		1.04	8.88	3.80	10.57	14.34	7.84	2.76	9.53	13.29
312	18,080	622	354	355	170.00	92.81	110.97	144.52	173.17	-77.19	-59.03	-25.48	3.17
80	240				0.22	0.04	0.13	0.19	0.19	-0.17	-0.09	-0.02	-0.02
480	1,440				2.43	4.20	0.44	0.44	8.57	1.77	-1.99	-1.99	6.14
576	2,880				0.55	3.25	11.87	23.00	30.53	2.69	11.32	22.45	29.97
640	640	15	13		0.02	0.84	0.00	0.75	0.96	0.82	-0.02	0.73	0.94
80	160				0.01	0.29	0.02	0.02	0.29	0.28	0.01	0.01	0.28
533	14,400	127	80	84	8.64	73.17	55.34	100.61	158.19	64.53	46.70	91.97	149.55
640	640				0.05	2.38	0.80	2.13	3.01	2.33	0.76	2.09	2.96
640	1,280	62	42	45	0.27	4.23	3.45	4.40	6.33	3.96	3.18	4.13	6.05
640	640				0.01	0.07	0.00	0.00	0.17	0.05	-0.01	-0.01	0.16
160	480				0.00	0.01	0.88	0.88	0.89	0.00	0.88	0.88	0.88
320	640				0.04	0.49	0.62	1.50	1.50	0.45	0.59	1.46	1.46
320	320				0.40								
280	3,360				6.98	11.76	1.78	13.45	22.54	4.79	-5.20	6.47	15.56
328	6,880	185	77	82	19.28	37.34	16.08	38.45	55.58	18.05	-3.20	19.17	36.30
220	1,760	35	21	29	1.70	9.47	0.52	2.64	14.38	7.76	-1.18	0.94	12.67
320	640				0.07	0.43	0.17	0.41	1.54	0.36	0.10	0.34	1.47
640	640				0.75	2.28	0.00	0.70	10.12	1.53	-0.75	-0.05	9.37
560	2,240	36	10	11	0.37	6.60	15.45	27.85	37.67	6.23	15.08	27.48	37.30
640	1,280				2.09	3.55	9.53	9.53	9.53	1.47	7.45	7.45	7.45
110	1,760				2.21	7.87	3.42	7.49	9.50	5.66	1.21	5.29	7.29
640	2,560				0.07	0.81	1.93	2.20	10.40	0.75	1.87	2.13	10.34
384	1,920	665	85	83	5.89	9.10	18.09	21.79	22.75	3.20	12.20	15.89	16.86
		194	**79**	**105**	**257**	**324**	**293**	**469**	**664**	**68**	**36**	**212**	**408**

NOTE: A minus (–) preceding production in the "Balance" columns indicates over-production in regard to volumetric reserve calculations. Positive numbers indicate under-production in regard to the particular field AND is an estimate of POTENTIALLY REMAINING UNPRODUCED GAS RESERVES.

Table A5-5. — Boatwright Carbonate

Field	Single Zone Completion		Well	Avg	Thickness (ft)			Porosity (%)			Initial Pressure (psi)[1]		
	Avg Gas (MCF)	Avg Oil (BBL)	Count	Depth (ft)	Avg Perf	Min Sat'd	Max Sat'd	Avg Perf'd	Min Sat'd	Max Sat'd	Min	Avg	Max
CEDARDALE NE	1,525,052	1,872	185	6,938	27	6	120	6.6	1.4	13.0	669	2,398	3,660
CEDARDALE NW	63,152	1,799	29	7,469	24	18	119	7.4	3.0	11.0	1,412	2,830	3,302
CHESTER WEST			12	7,947	37	33	128	5.9	2.0	6.5			
FORT SUPPLY NE	182,262	444	5	7,130	31	35	102	6.8	2.5	9.0	1,488	1,631	1,803
KLINE NE			1	7,756	5	20	20	12.5	12.5	12.5			
SEILING NE			1	9,102	4	4	4	5.0	5.0	5.0			
TRIVOLI SW			1	8,390	4	7	7	7.5	7.4	7.4			
WOODWARD			1	8,394	34	68	68	2.2	2.0	2.0			
			235	**7,891**	**21**	**4**	**120**	**7**	**1.4**	**13**	**669**		**3,660**

[1]Initial pressure data prioritized in this order: DST, BHP, SITP, FTP.

BCF Billion cubic feet

Source: Petroleum Information/Dwights LLC, ©2000.
Data current to April 2000.

Field Data Elements

Observed Spacing (ac)		Calc. Avg. Drainage Area (ac)			Ult. Rec.	Volumetric Original Gas in Place (BCF)				Calculated Undrained Reserves (BCF)			
Avg	Sum	Perf'd	Sat'd	P/Z	(BCF)	Perf'd	7%+ φ	4%+ φ	Sat'd	Perf'd	7%+ φ	4%+ φ	Sat'd
254	47,920	410	274	219	213.48	245.48	210.93	327.57	425.43	32.00	-2.55	114.09	211.95
291	8,720	19	10	64	6.49	54.05	18.94	34.60	91.87	47.56	12.45	28.11	85.38
307	7,360				17.41	15.82	16.02	35.73	68.08	-1.59	-1.40	18.31	50.67
384	1,920	45	25	20	1.08	6.98	1.96	3.14	13.14	5.89	0.88	2.05	12.06
640	640				0.00	0.84	3.38	3.38	3.38	0.84	3.38	3.38	3.38
640	640				0.25	0.26	0.00	0.00	0.26	0.01	-0.25	-0.25	0.01
640	640				0.01	0.00	0.00	0.00	0.00	-0.01	-0.01	-0.01	-0.01
640	640				0.00	0.31	0.00	0.10	0.57	0.31	0.00	0.10	0.57
		158	**103**	**101**	**239**	**324**	**251**	**405**	**603**	**85**	**12**	**166**	**364**

NOTE: A minus (–) preceding production in the "Balance" columns indicates over-production in regard to volumetric reserve calculations. Positive numbers indicate under-production in regard to the particular field AND is an estimate of POTENTIALLY REMAINING UNPRODUCED GAS RESERVES.

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