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The Booch Gas Play in Southeastern Oklahoma: Regional and Field-Specific Petroleum Geological Analysis

Dan T. Boyd

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The Booch Gas Play in Southeastern Oklahoma: Regional and Field-Specific Petroleum Geological Analysis

by

Dan T. Boyd

Prepared for a one-day workshop, this volume is part of a continuing series that provides information and technical assistance to Oklahoma's oil and gas operators.

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Front Cover

Representative of many producing Booch gas reservoirs, this outcrop is in a "borrow pit" in the N½NW¼SE¼ sec.1, T. 8 N., R. 24 E., in the Panama 7.5-minute quadrangle. Called the Warner Sandstone at the surface (Knechtel, 1949), this stratigraphic interval is correlative with the middle Booch parasequence 3/3A in this study. Strata here dip about 20° to the north, away from the Backbone Anticline and toward the Bokoshe Syncline.

The outcrop is a single coarsening-upward progradational sequence with black prodelta shales at the base. These shales grade upward into delta-front shales, siltstones, and minor sandstones that are capped by a 15-ft channel sandstone. Features such as lenticular and wavy bedding are evidence that some of the delta-front sediments may have been tidally reworked. The capping sandstone may be a tidal channel, although there is no evidence for erosion of the underlying beds.

This outcrop is one of several that will be included in a guidebook that complements this study of the Booch gas play in southeastern Oklahoma. This guidebook is being prepared by Neil Suneson and Dan Boyd and will be published by the Oklahoma Geological Survey.

Photograph by Dan T. Boyd

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PART I

Regional Overview of the Booch Gas Play

INTRODUCTION

This study is the latest in a series of play-based workshops sponsored by the Oklahoma Geological Survey and the Petroleum Technology Transfer Council designed to aid State oil and gas operators. The Booch Gas Play complements a similar study for Booch oil that was done as part of the Fluvial-Dominated Deltaic (FDD) Oil Reservoir series (Northcutt and others, 1995).

The Booch Gas Play is the first play-based workshop in which the special publication includes digital files. In addition to general oil and gas reference files, the accompanying compact disc (CD) contains shape files for the regional study maps and well data on Excel spreadsheets for the regional and field studies. These datasheets include well names, locations, tops, thicknesses, gross and net sandstone, and Booch production in the field-study areas. Also included are listings of Booch core and core analyses that are maintained in the Oklahoma Petroleum Information Center operated by the Oklahoma Geological Survey. All of the data on which this study is based are provided in digital format so that maps and datasheets can be edited or expanded for any area that might be considered prospective. This study is intended to help speed the evaluation process for those that may be interested in pursuing Booch gas, as well as to provide a valuable resource for those already producing Booch reservoirs.

Booch sandstones have produced oil and natural gas since before Statehood, with cumulative production through April 2004 of ~78 MMBO (million barrels of oil) and 467 BCF (billion cubic feet) of gas from 2,690 active and abandoned wells. About 10% of these wells were/are commingled with production from other formations. The 710 active gas wells remain an important source of production, being responsible for roughly 23 MMCF (million cubic feet) of daily production (IHS Energy, 2004). Using the standard 6 MCF (thousand cubic feet) of natural gas as one barrel of oil equivalent (BOE), and in keeping with much of the rest of the State, gas represents about 70% of both cumulative and current Booch production.

The Booch (pronounced "Boke," the same as "coke") stratigraphic interval is the informal subsurface equivalent used by the oil and gas industry to identify sandstones contained within the lower three-quarters of the McAlester Formation. This formation is part of the lower Krebs Group, which is Middle Pennsylvanian (Desmoinesian) in age (Fig. 1). The term *Booch sandstone* was first used in 1906 to describe the producing reservoir in two wells drilled in Okmulgee County (sec. 20, T. 13 N., R. 14 E.) on the Booch farm in Morris Field (Clark, 1930; Jordan, 1957).

The Booch and its equivalents produce across wide swaths of the eastern part of the State in the structural provinces of the Arkoma Basin and Cherokee Platform (Fig. 2). In addition to 32 scattered wells in which the productive reservoir is identified only as McAlester, Booch production has also been called *Tucker* and *Taneha* in regions mostly north of the study area on the Cherokee Platform (Fig. 3). These sands are the proximal, largely oil-producing fluvial equivalents of Booch sands that thicken and produce gas in the Arkoma Basin. There are no productive reservoirs in the State that are identified by their formal surface names, such as Warner, Lequire, Cameron, Tamaha, or Keota (IHS Energy, 2004).

Stratigraphic terminology is complex, and surface names often bear no relationship to those used in the subsurface. Thousands of wells have penetrated the Booch, and these have distinctive, correlatable log character. Because continuous records of thousands of feet of the stratigraphic section can never be matched in outcrop, and because well logs are the cornerstone of subsurface interpretation in the petroleum industry, the log database is taken as the starting point in this study. In Oklahoma, operators decide reservoir names and formation tops, making the Booch tops published in the State database inconsistent. However, the interval studied here does conform to the industry consensus for the stratigraphic section that is known as the Booch.

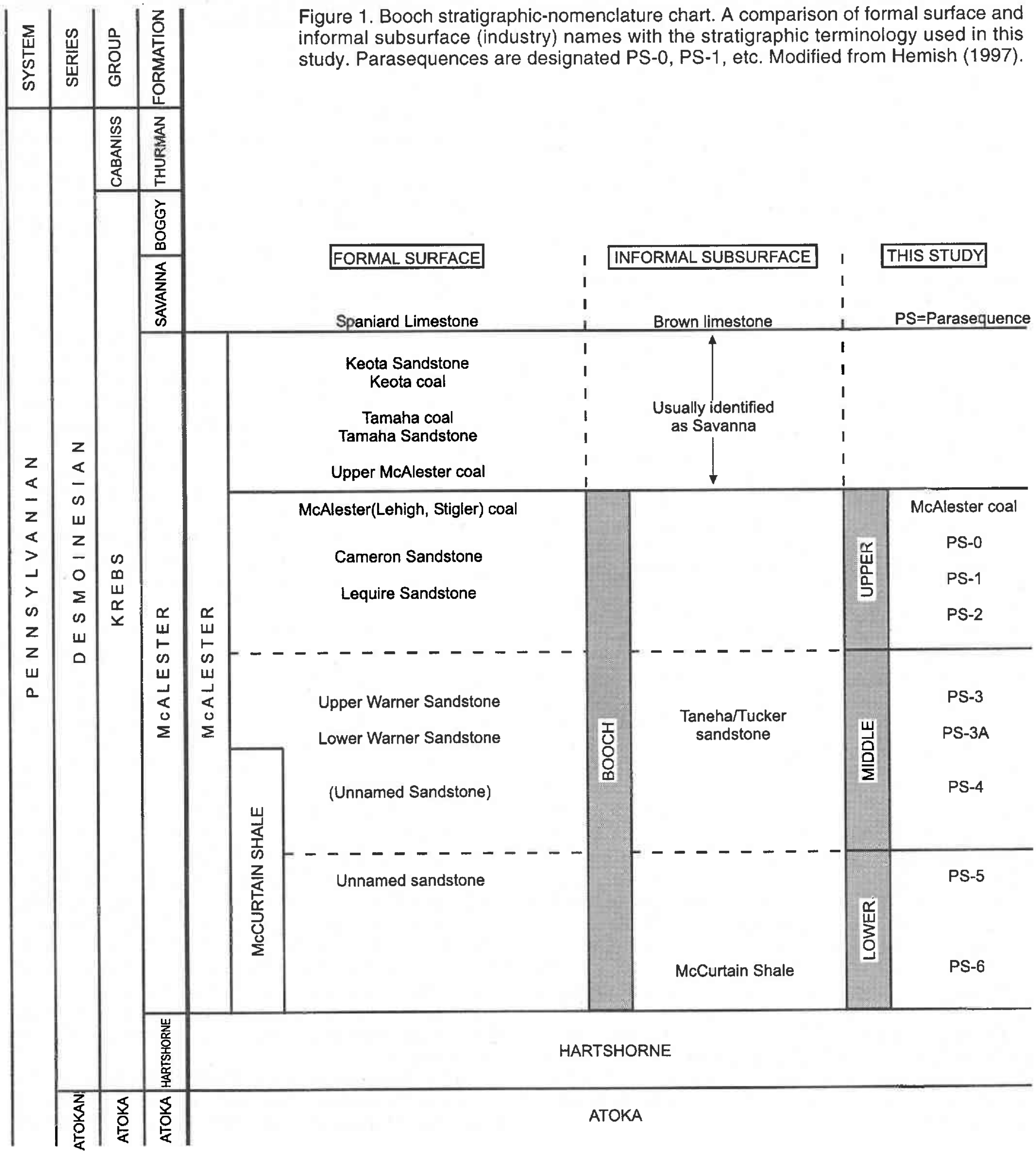
Methodology

The methodology employed here began with retrieval from the IHS Energy database of all of the wells reporting Booch or Booch-equivalent well tops. This was combined with a similar retrieval of Booch and equivalent producers (distinguishing oil and gas wells) to define the broad limits of the play (IHS Energy, 2004). Within this area a series of five regional, stratigraphic, dip cross sections was constructed, with the first beginning on the Kansas border and ending in the deepest part of the basin. To ensure the reliability of correlations, dip sections were linked with four strike cross sections, allowing regional stratigraphic markers to be correlated in loops until they were consistent (Fig. 4). Not surprisingly, the most pervasive markers were found to be the flooding surfaces at the base of marine shales. In the basinal setting these are characterized by a thin, high gamma-ray shale with low resistivity. Although not as regionally consistent, some Booch coals also make excellent local markers (Pls. 1–9, in envelope).

Using this widely spaced grid as a template, an average of four to five wells per township, depending on availability, were correlated to the nearest cross-section log and tabulated on an Excel spreadsheet (included on the CD herein). This amounted to 1,021 wells, including those in the cross sections. Regional log data were gathered from the State collection, which is housed at the Oklahoma Petroleum Information Center (OPIC) in Norman. In the three areas for which field studies were performed, OPIC logs were supplemented with logs from the Oklahoma City Geological Society (OCGS) library. Other gaps in well control, especially in the field study areas, were covered by logs provided by Tilford Pinson Exploration, LLC. About 300 additional wells were correlated in the field studies.

Figure 5 summarizes the location, by section, of the well-log and core data that were used in this analysis, as

Figure 1. Booch stratigraphic-nomenclature chart. A comparison of formal surface and informal subsurface (industry) names with the stratigraphic terminology used in this study. Parasequences are designated PS-0, PS-1, etc. Modified from Hemish (1997).



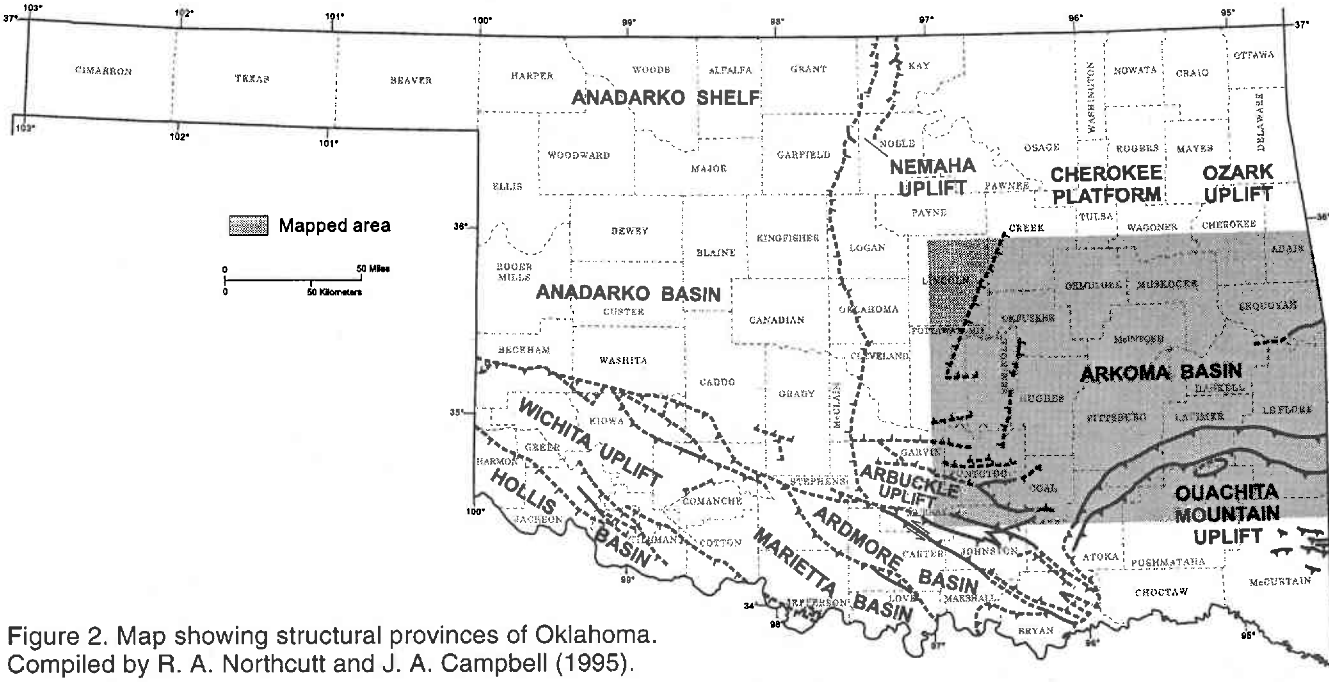


Figure 2. Map showing structural provinces of Oklahoma. Compiled by R. A. Northcutt and J. A. Campbell (1995).

well as the areas that were mapped in field studies. All available logs in the field-study areas were analyzed. Included are the locations of the 43 Booch cores that are stored at the OPIC facility and 200 Booch core analyses that were donated (on microfiche) to the State by Deep Rock Oil Company. Also shown are the locations of outcrops described in a Booch guidebook being prepared by Neil Suneson and Dan Boyd (to be published by the Oklahoma Geological Survey).

A series of 1:250,000-scale maps was constructed, based on the tops and thicknesses tabulated, to place the Booch into a regional context. Regional mapping was done in an area covering 231 townships (>8,300 mi^2). This extends from the shelf, where oil production is dominant, through the limits of Booch preservation on the leading edge of the Choctaw Thrust, to the margins of the Ozark Uplift, to the depositional limits of the Booch along the western edge of the study area. Because control points are separated by an average of 2–4 mi, the regional maps can capture only the most significant features. Smaller sandstone bodies, isopach anomalies, and structures obviously will slip through this net. Detailed mapping is left for the field studies.

Challenges

The tracing of individual depositional cycles was generally not difficult in the southern, more distal (marine) areas of the Booch, where energy was low and distinctive marine shales are well preserved. However, in northern areas on the shelf, especially in the upper Booch, sediments tended to be deposited in nearshore-marine to fluviodeltaic environments of limited areal extent. Here, cycles are thin, and the regional markers are often hard to identify. In these areas, coals, where present, became the markers of choice. In areas of large-scale incisement, stratigraphic markers are also lost, often making it impossible to reliably assign sandstones to a given depositional cycle. To overcome these limitations, some stratigraphic intervals were combined on the regional maps.

The cyclic deposition characteristic of the Booch, for areas distant from cross-sectional control points, sometimes made correlations along the same depositional cycle difficult. This is especially true where the stratigraphic section thins to the north and west. In the regional work, no effort was made to compensate for structural dip to correct apparent thickness to true vertical thickness. This correction would be negligible in all but the steepest dips, and generally for wells closest to Booch outcrops.

For many wells that were drilled to evaluate deeper targets, much of the Booch section was either unlogged or incompletely logged. In addition, owing to the Booch's long history of production, a wide variety of drilling and logging techniques have been used. Especially difficult is the comparison of modern gamma-ray logs—which measure natural gamma radiation and equate this to shaliness—to older spontaneous-potential (SP) logs, which indirectly measure permeability by tracking the electrical potential between formation fluids and drilling mud. The gamma-ray curve is an excellent measure of "cleanness," or the volume of clay present, and is consistent from well to well. The SP curve depends on the salinity difference between the formation water and the mud filtrate and is far more sensitive to mud and hole conditions during the logging process. Where salinities (resistivities) are similar, permeable sandstones are difficult to identify only on the basis of an SP log.

Gross sand in this study is taken to be all sandstone, regardless of permeability, that is at least halfway between the shale baseline and the cleanest sandstone line on a gamma-ray log. Where only an SP log is available,

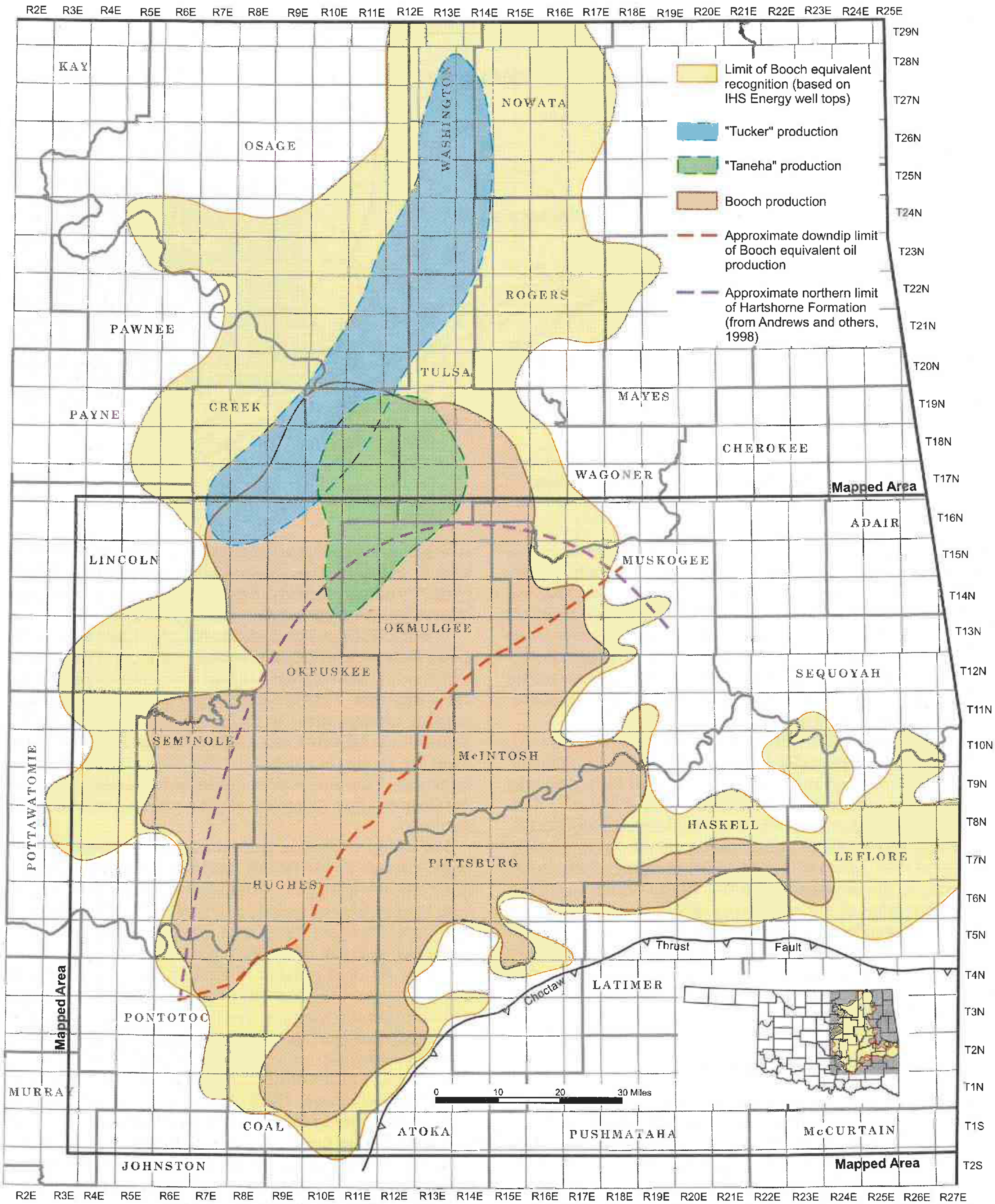


Figure 3. Map showing Booch and equivalent production. Map shows limits of Booch recognition and areas of Booch, Tucker, and Taneha oil and gas production. From IHS Energy (2004).

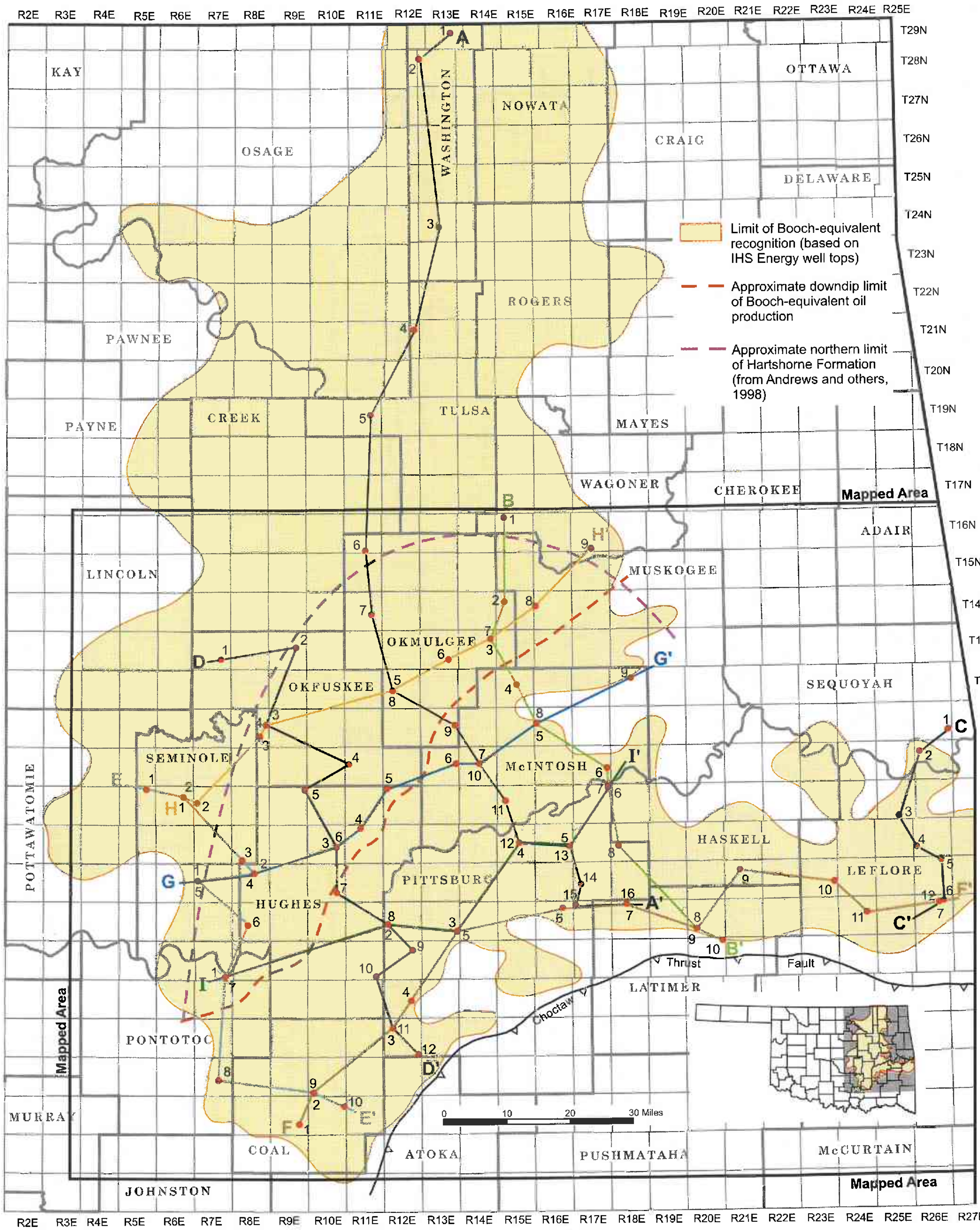


Figure 4. Map showing Booch gas-play outline and lines of regional cross sections. Indicated are limit of Booch recognition, downdip limit of Booch oil, and limit of Hartshorne Formation. Cross-sectional grid shown here is used to identify stratigraphic markers and maintain consistent regional correlations.

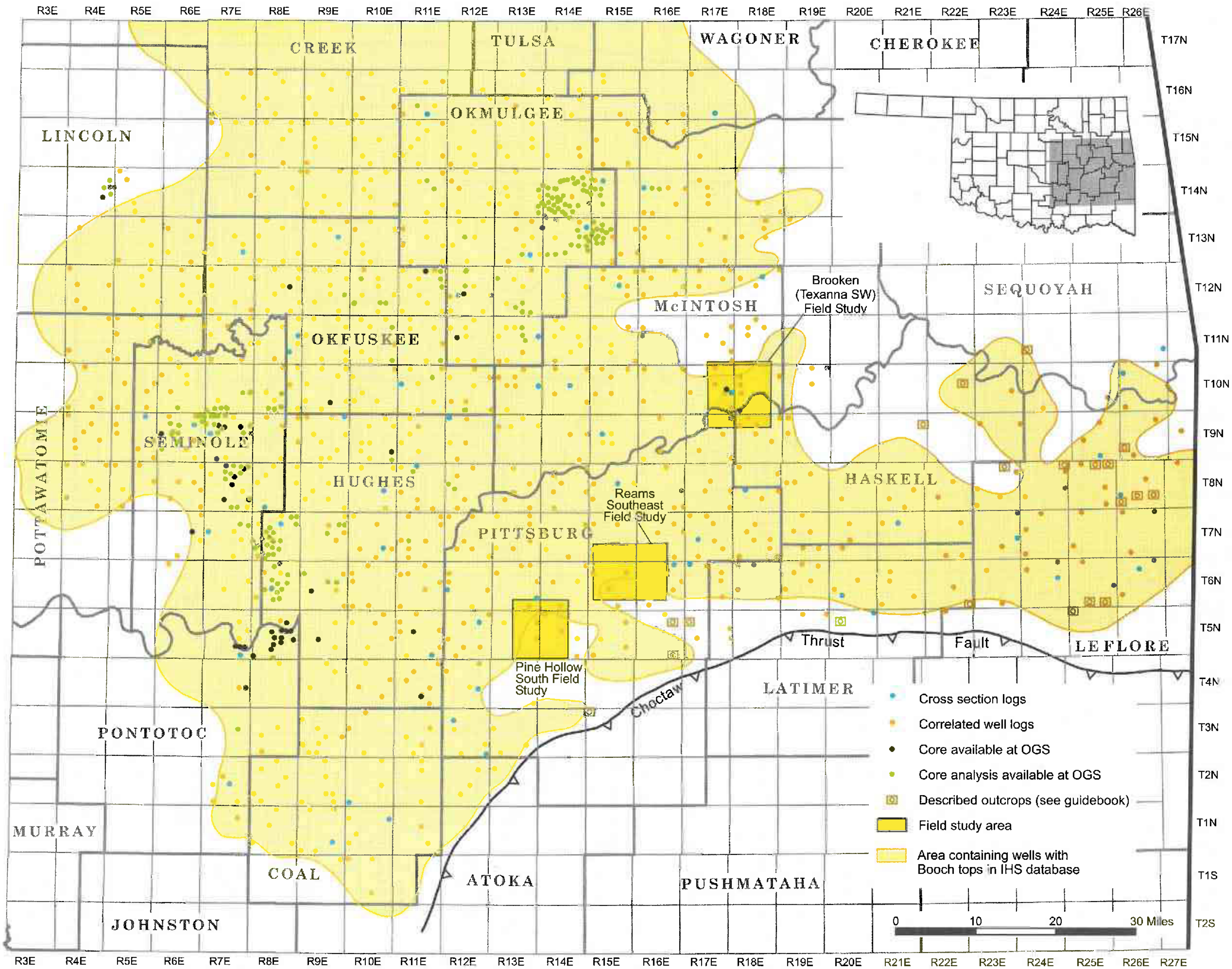


Figure 5. Booch regional-data map, showing outline of Booch recognition and the wells, cores, and core analyses used in the regional section of this study. In field-study areas all data available were utilized in addition to the regional subsurface data shown. Marked outcrops correspond to those described in the Booch guidebook being prepared by Neil Suneson and Dan Boyd, to be published by the Oklahoma Geological Survey.

resistivity separation is used to help normalize the SP curve to gamma-ray logs in other wells. This tends to make some estimates of gross sandstone more qualitative than others. It has also been seen that gas production, albeit marginal, can be established in intervals where little or no gross sandstone is present. See the discussion of "Stratigraphy" in the study of Pine Hollow South Field.

GEOLOGIC HISTORY

Geologic Setting

The Booch gas play is entirely contained within the limits of the Arkoma Basin. The evolution of the Arkoma Basin and the Ouachita orogenic belt reflects the opening and subsequent re-closing of a Paleozoic ocean basin (Houseknecht, 1983). The basin was part of a stable shelf on a passive continental margin from the Cambrian through the Early Mississippian, when shallow-water carbonates and deeper water black shales and cherts were deposited. In middle Mississippian time, the deposition of a thick sequence of turbidites (Stanley Group) began, which, because of the gradual narrowing of the basin owing to plate convergence, had their source to the east. The Arkoma Basin and shelf received sediments (dominantly from the north and northeast) and were tectonically quiescent from Late Mississippian through early Atokan time. In the middle Atokan, continued basinal closure caused flexural bending in the southern part of the basin, resulting in fault-related depressions that were quickly filled with sediment. Middle Atokan sediments came generally from the east, and these completed the filling of the deepest parts of the basin (Johnson and others, 1989).

In Desmoinesian time the basin continued subsiding, but at a rate much reduced from that during the Atokan. Hartshorne sandstone deposition in the Arkoma Basin is largely fluvial in origin, with the stratigraphic section becoming progressively less sandy to the west–southwest (Andrews and others, 1998). The fluviodeltaic and marine sediments of the remainder of the Krebs Group (Booch through Boggy) entered the study area largely from the north. The initial uplift of the Ozark Mountains, which marks the northeastern limit of Booch preservation, occurred during deposition of the Bartlesville sand in early Boggy (late Krebs) time (Visher and others, 1971).

The post-Krebs unconformity marks the end of regional subsidence in the Arkoma Basin and the uplift of the Ouachita fold belt (Sutherland, 1988). This uplift in the southern part of the basin eventually resulted in the removal of all post-Atoka sediments south of the Choctaw Fault, which marks the southern limit of Booch preservation.

The regional Booch isopach map (Fig. 6), in addition to its many small depositional irregularities, highlights two prominent north–south incised-valley systems that begin on the shelf and empty into the Arkoma Basin. The map also shows parts of what may be similarly oriented systems that were removed by later Ozark Uplift erosion. Taking these and the regional orientation of the interval isopach into account, it can be seen that the axis of the basin during Booch time seems to have generally paralleled the Choctaw Thrust, with depositional strike in the west oriented roughly north–south and rotating to an east–west orientation in the direction of Arkansas. It can also be seen that in most areas the gross Booch interval continues to thicken into the fault, indicating that as much as half the Booch sediment that was originally deposited has been removed as a result of uplift of the Ouachita Mountains and subsequent erosion.

The Ouachita and Ozark tectonic events are responsible for bringing the Booch sandstone to the surface along the southern and northeastern limits of the play. Structuring associated with the Arbuckle Uplift also has brought the Booch to the surface in the far southwestern part of the study area. These tectonic episodes occurred well after Booch deposition, and thus had no influence on the location or orientation of potential reservoirs. It is the faults and folds that were formed as a result of Ouachita compression that constitute the main structural overprint seen today in the basin. The resulting structural relief is severe and has created many areas in which Booch sandstones crop out within 2–3 mi of the areas in which they produce (Fig. 7).

The regional structure map (Fig. 8), with its limited subsurface control and 500-ft contour interval, is designed to show only the largest features. Accurately defining all of the major faults that are known to exist would require a level of subsurface control far beyond that used for this study. For this reason, most faults have been omitted from this map, although their presence often can be inferred by outcrop patterns and dip rates. The names of the major folds, many of which bring the Booch to the surface, are shown. The Booch outcrops were defined using hydrological atlases jointly prepared by the Oklahoma Geological Survey and the U.S. Geological Survey. These outcrops generally coincided with the outcrops that were projected on the basis of well control.

Stratigraphy

Nomenclature

Formal stratigraphic terminology is usually based on rocks that can be described and mapped in outcrop. Industry terminology, especially in Oklahoma, is keyed to productive reservoirs and is less concerned with official nomenclature. Here, a local name can be given to a productive reservoir that expands over time to include a wider stratigraphic interval. Eventually something approaching a consensus is reached in which certain stratigraphic markers on well logs are understood to define the limits of a given productive interval. The productive sandstone that was first identified on the Booch farm is correlative with what is called in this study the *middle Booch*, or parasequence (PS) 3A (Fig. 1). This is equivalent to the lower Warner sandstone in formal surface terminology (Jordan, 1957). Over time, other productive sandstones were found above and below the original Booch sand, and these were eventually incorporated into the Booch stratigraphic interval that is known today.

The Booch, as defined by the petroleum industry, is not a direct subsurface equivalent of the McAlester Formation, which is known on the surface. Rather, it repre-

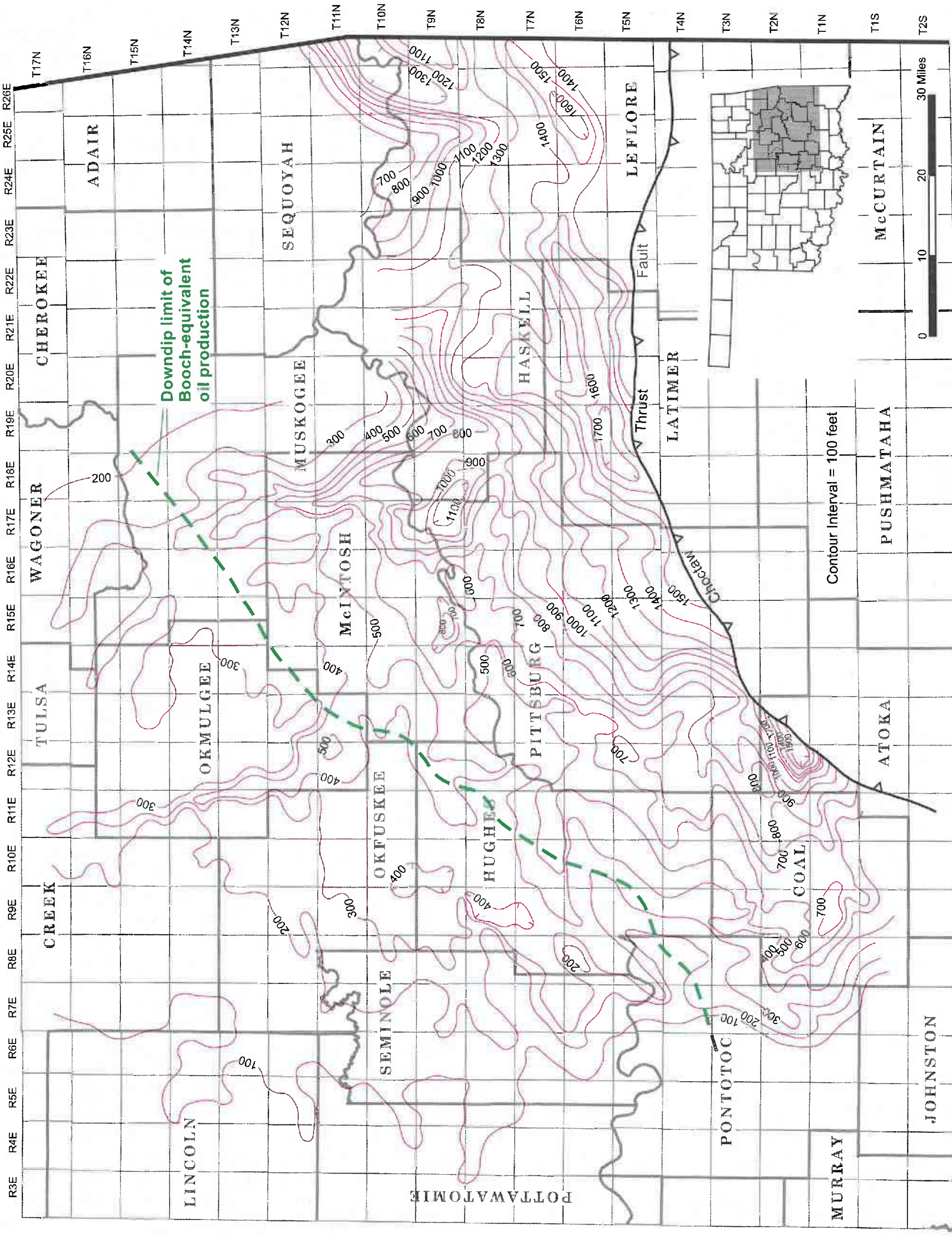


Figure 6. Regional isopach map of the Booch interval. This gross interval corresponds to the stratigraphic section from the top of PS-0 (McAlester coal marker) to the base of PS-6 (top of Hartshorne Formation). Hachures indicate isopach "thicks."

sents roughly the lower three quarters of this formation (Fig. 1). The Brown limestone in the subsurface corresponds to the Spaniard Limestone on the surface, which together mark the top of the McAlester Formation. This interval on the Cherokee Platform is composed of a series of thin limestone beds known variously as Brown; Brown lime; Brown lime Kansas; Brown lime Oklahoma; Brown lime 1, 2, 3; Brown lime upper; and Brown lime lower (IHS Energy, 2004). This zone is not recognized in much of the study area, but where it has been identified it is usually placed 200–500 ft above the top of the Booch interval. The Brown limestone equivalent is usually placed at a stratigraphic position that is roughly equivalent to that seen in Figure 9.

The upper part of the McAlester Formation, between the Brown limestone and the top of the Booch, is usually (incorrectly) identified by operators as the Savanna. This stratigraphic interval, as well as the true Savanna above, are, from an oil and gas perspective, relatively unimportant. There are 117 wells that are listed as having Savanna (or Savanna commingled) gas production, and these have a cumulative production of 17.9 BCF, or roughly 2% of total Booch production (IHS Energy, 2004). This is the maximum volume that can be assigned to the stratigraphic interval that is correlative with the upper McAlester on the surface, and undoubtedly explains why Keota- and Tamaha-age sandstones have not been included in what the industry considers classic Booch.

To correlate surface stratigraphic terminology to that used by the oil and gas industry, outcrop strata and thicknesses have been projected into the subsurface and compared to those measured by well logs. Mining activity that exploited the Hartshorne and McAlester coals, which are excellent stratigraphic markers, served as convenient surface benchmarks in this exercise. Surface to subsurface correlations were aided by synthetic gamma-ray logs constructed through direct measurement of surface outcrops (Neil Suneson and Dan Boyd, Booch sandstone guidebook, in preparation). This work may force some revision of the names that appear on surface geologic maps.

The bulk of the Booch stratigraphic section, because it is composed mostly of shale, is rarely exposed. This means that in general an erosionally resistant sandstone (or siltstone) must be present at the top of a depositional cycle (parasequence) before it will be exposed in outcrop. This is why the McCurtain Shale on the surface is usually defined as the interval between the upper Hartshorne coal and the first McAlester sandstone, which is usually the Warner (Fig. 1). It also explains large thickness variations in the surface-defined McCurtain Shale and why it is always much thicker than the subsurface-defined McCurtain (PS-6). When sandstones appear at the top of either of the intervening two parasequences (PS-5 and PS-4) they are simply called "unnamed" sandstones.

The best stratigraphic marker in the study area is the pervasive Hartshorne sandstone and the coal that usually occurs just above it. The base of the Booch is defined here

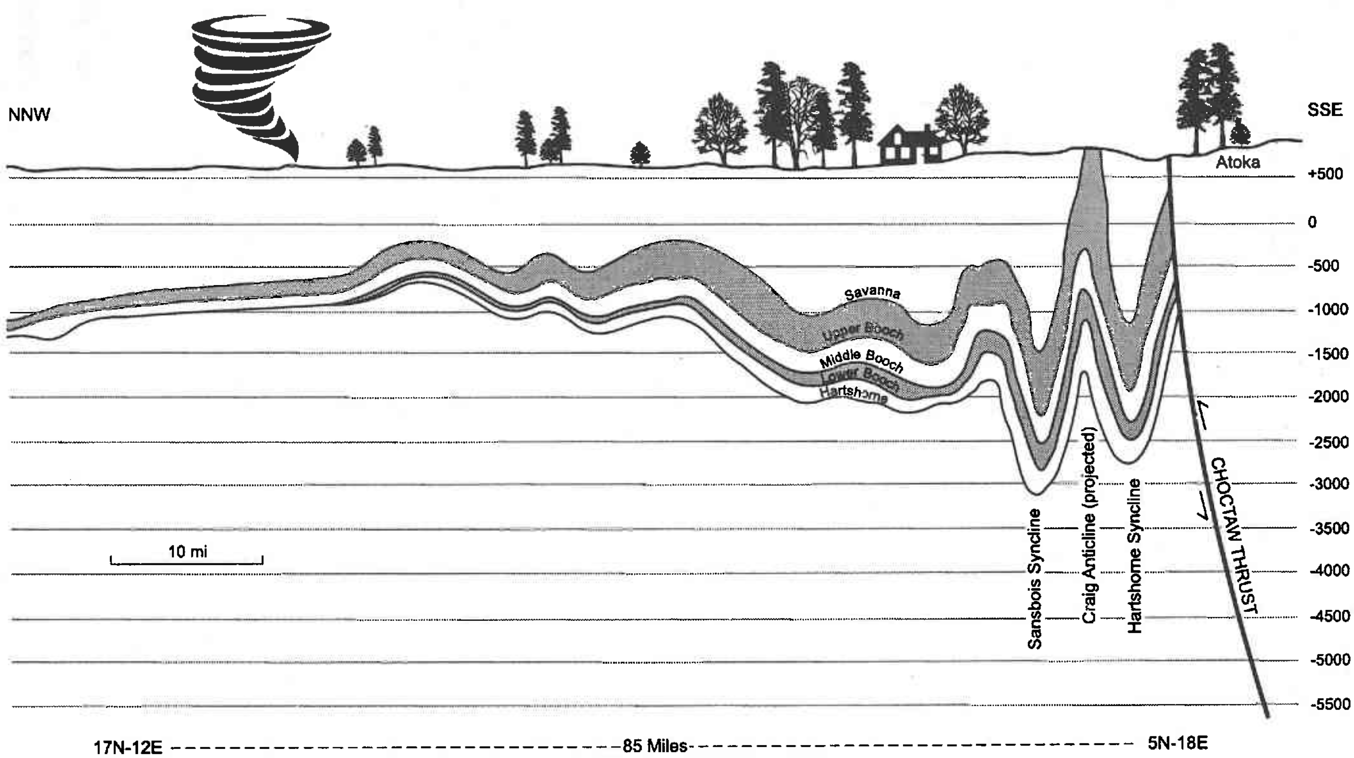


Figure 7. Regional schematic structural cross section. Line of section extends from Choctaw Fault to northern limit of study area, as shown in Figure 8. Companion regional stratigraphic cross section seen in Figure 13.

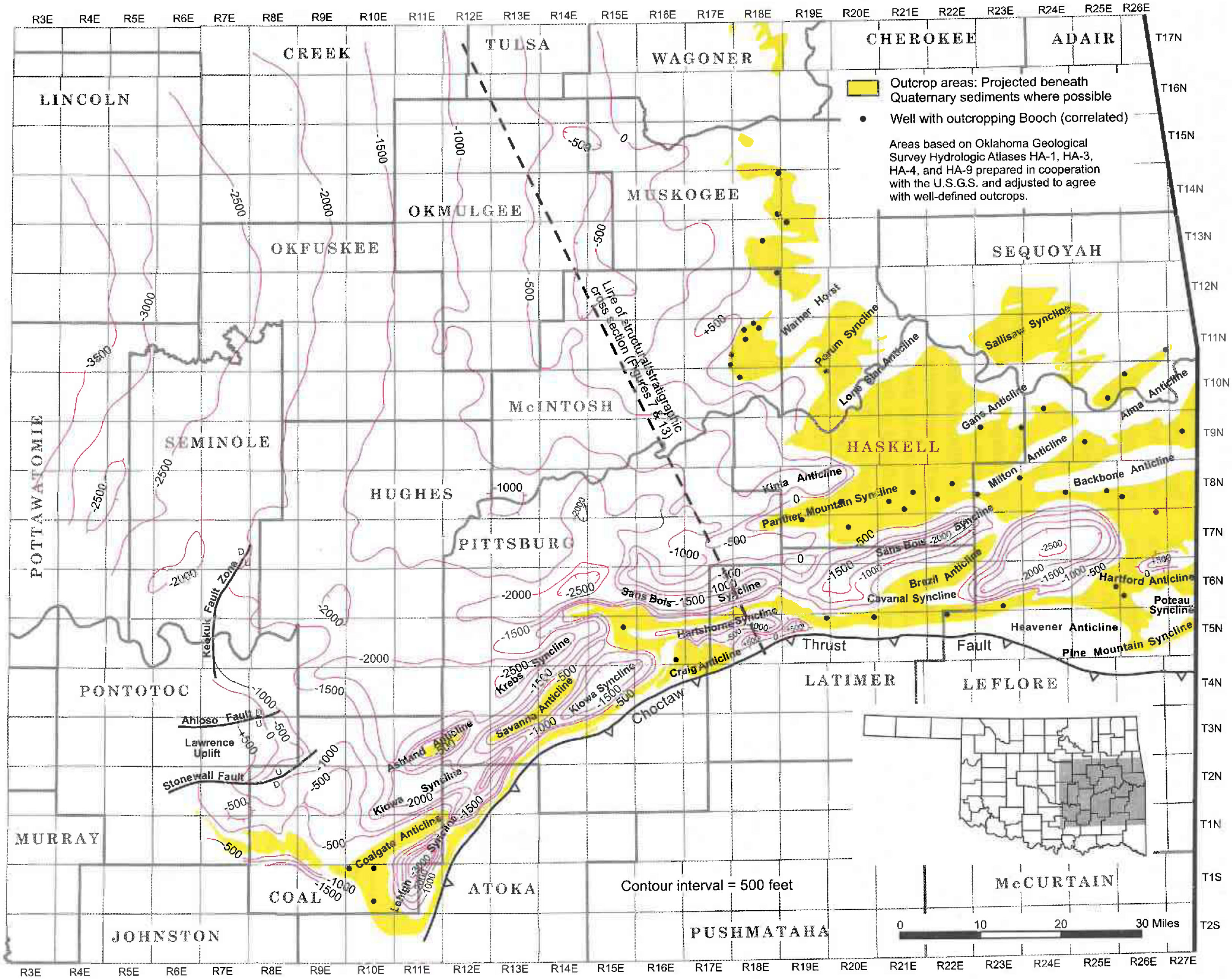


Figure 8. Booch regional structure and outcrop map, showing wells used in regional analysis in which the Booch is known to crop out, and major structural features in the study area. Map also shows the schematic cross-section line in Figures 7 and 13. Depth refers to top of PS-0 (McAlester coal marker). Hachures within closed contours indicate structural lows; those extending outward from closed contours indicate structural highs.

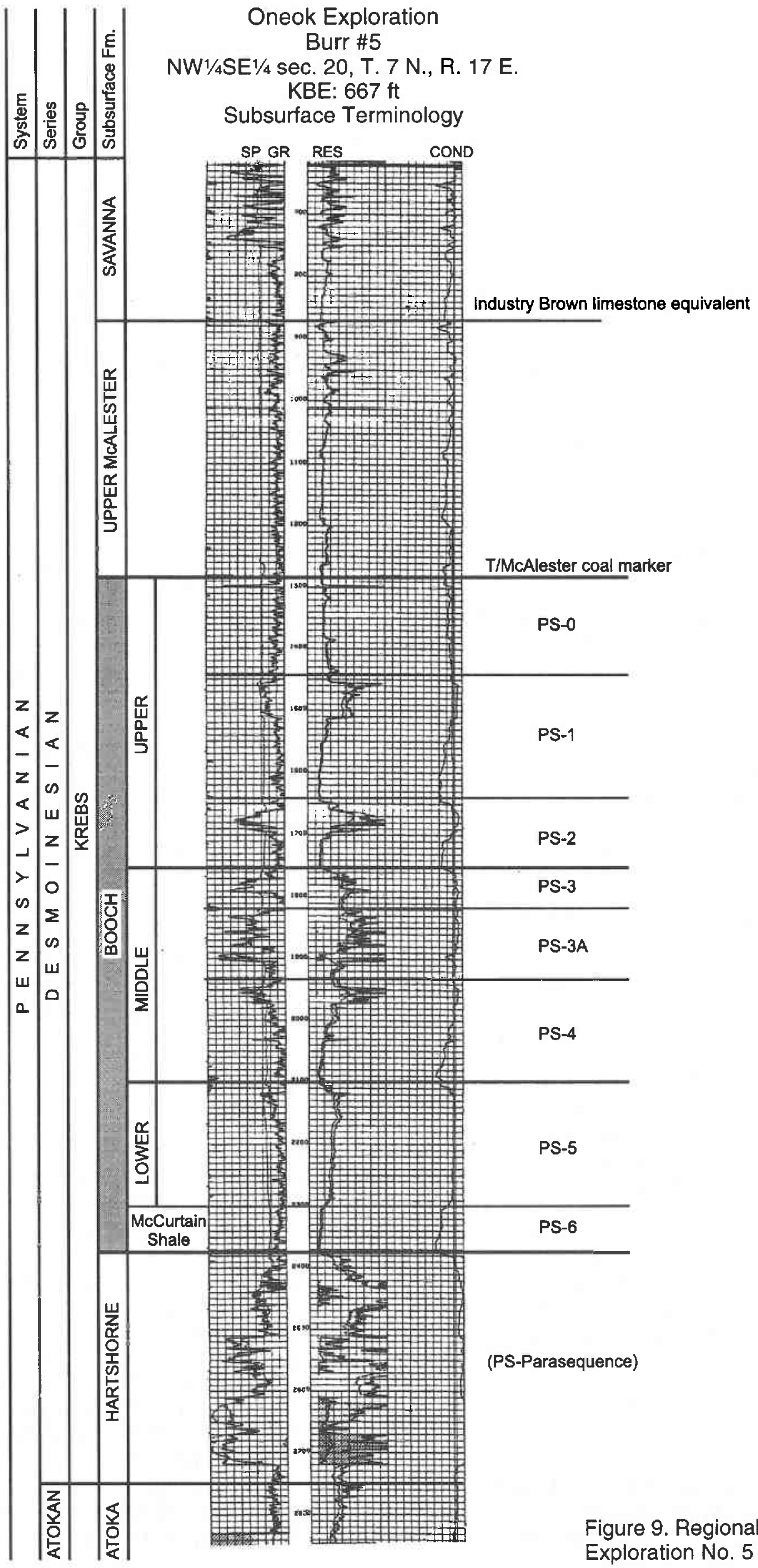


Figure 9. Regional Booch type log. Oneok Exploration No. 5 Burr, Pittsburg County.

as the point at which the relatively high-resistivity sandstones, siltstones, and shales of the Hartshorne give way to the low-resistivity, high-gamma-ray McCurtain Shale (Fig. 9). Like all Booch stratigraphic markers, this surface is most easily seen in the more distal (marine) areas, but its stratigraphic equivalent has been carried throughout the study area, using the regional cross-section grid. In outcrop the basal Booch is seen where the light-brown, fossiliferous, interdistributary shale of the Hartshorne gives way to the black, distal-marine shale of the McCurtain (Suneson, 1998).

The top of the Booch interval, which is a consensus top based on what the industry calls Booch sandstones, occurs at the top of what is usually called the McAlester coal on the surface. This coal, which is also known as the Lehigh or Stigler coal, is present across much of the study area and represents a deltaic facies deposited at the top of the uppermost Booch parasequence (PS-0). This coal, or its stratigraphic equivalent, is defined as the top of the Booch in this study. This does not conform to some previous work (Bennsion, 1979; Northcutt and others, 1995) in which the McAlester and Booch were seen as equivalents, but it does agree with other work (Fields, 1987) in which it was recognized that the Cameron and Lequire Sandstones are correlative in the subsurface with upper Booch sandstones. What is clear is that the Booch, as historically defined by the industry, is below the upper part of the McAlester Formation that occurs between the Spaniard (Brown) limestone and the McAlester coal (Fig. 1).

The numbers applied to the parasequences in this study are not sacred and only reflect the evolution of what were confirmed to be regional stratigraphic markers as work on this study progressed. However, the combining of the eight Booch depositional cycles into lower, middle, and upper intervals *is* stratigraphically significant. These were merged using the period of maximum progradation and sand deposition, here called the middle Booch, to isolate the upper and lower Booch intervals. For simplicity, each major parasequence is assumed to represent the same magnitude of time, with differences in thickness mostly reflecting changes in rates of deposition (Fig. 10).

Taneha and *Tucker* are the old names of stratigraphically equivalent sandstones that produce on the Cherokee Platform (Fig. 3; Pl. 1). They are correlative to middle Booch PS-3/3A sandstones that are called the *Warner* on the surface (Fig. 1). Although these sandstones produce oil and thus are beyond the scope of this study, they are believed to be part of the extensive and widely preserved channel system that brought sediment into the basin during the period of maximum progradation that occurred during middle Booch time. These sandstones are recognized throughout eastern Kansas and southwestern Missouri (Tomes, 1986).

Depositional Setting

General

Lower and Middle Pennsylvanian sediments, of which the Booch is a part, were deposited in an overall transgressive regime, during which smaller magnitude regressional episodes occurred (Fig. 11). Except for the extreme northern and western parts of the study area, the Booch is everywhere underlain by the Hartshorne Formation and overlain by the Savanna Formation (see Fig. 4). The Hartshorne is a sand-rich interval that had its primary source from the east, becoming more marine to the west (Andrews and others, 1998). Booch deposition represents a major shift in source direction, with sediments coming from the north and becoming progressively more marine to the south (Fig. 12). This shift occurred because the fold belt in Arkansas, which was the eastern source of pre-Booch sediments, became quiescent and was presumably standing at or near sea level after Hartshorne time (Sutherland, 1988).

In addition to transport direction, the Booch also differs from the underlying Hartshorne in the proportion of sand present. The Hartshorne is divided into two major depositional cycles, an upper and a lower, each sand-rich and usually capped by a thin but widespread coal. The Booch in this study has been divided into eight depositional cycles, called parasequences, and in most areas these are composed dominantly of shale. Basinward thickening in each Booch interval, as well as in the Hartshorne (Andrews and others, 1998), proceeds fairly uniformly. Although the rate of overall Booch thickening increases roughly 30 mi in front of the Choctaw Fault, at any given time it is difficult to identify any paleoshelf–slope break (Fig. 13).

The term *parasequence* is a sequence-stratigraphic term defined as a relatively conformable succession of genetically related beds that are bounded by marine flooding surfaces or their correlative surfaces (Jackson, 1997). In the Booch, these are cycles of progradation manifested by a shallowing-upward sedimentary cycle that begins with distal-marine shales overlain by progressively more nearshore-marine shales, silts, and sands, some followed by fluviodeltaic sands and shales that are commonly interbedded with coals. Desmoinesian parasequences are responsible for more Oklahoma coal than any other Pennsylvanian stage, and these are correlative with the classic Pennsylvanian cyclothems present in the Appalachian Basin (Visher, 1996).

Cyclicity is present at every level in the sedimentary record, and parasequences correspond to one of the smallest scales of depositional cyclicity. Each represents a single episode of progradation, or seaward movement of the shoreline, with the outbuilding of sediment occurring under relatively static sea-level conditions (Visher, 1996). Because depositional environments migrate landward with time, within such sequences lithologically correlatable sediments become slightly older in the direction of the basin axis. The resulting shallowing-upward succession shows that accommodation space was being filled more rapidly than it was being created, whereas the succeeding flooding surface records a rise in sea level, indicating a rapid increase in accommodation space.

Contacts between adjacent parasequences are generally sharp, with distal-marine shales lying directly on top of more shallow-water or nonmarine facies. Although not identified in the Booch, flooding surfaces can exhibit small-scale erosion of up to a few feet (Holland, 2000).

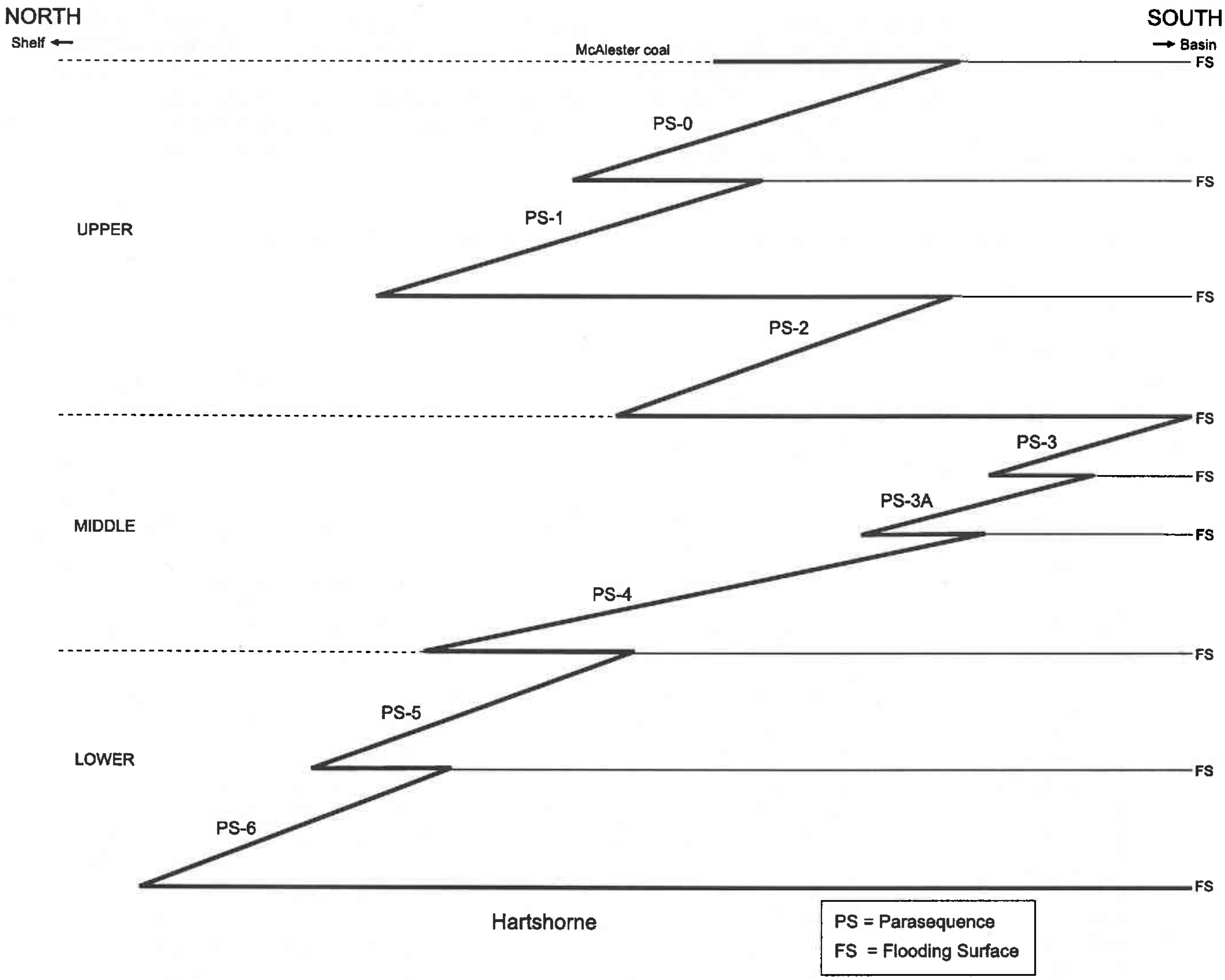


Figure 10. Booch schematic progradational history. Cross section shows Booch parasequences, their bounding flooding surfaces, and the relative average shoreline position for each.

Flooding surfaces are typically marked by a few feet of very high gamma-ray readings, followed by a thicker, low-resistivity marine shale (Pls. 1–9). Because they record a regional event that begins the deposition of a widespread and distinctive black shale, these flooding surfaces make ideal markers with which to subdivide the stratigraphic section. However, describing marine shales as distal marine is not to say "deep marine." Although they may have been deposited in water tens of miles offshore, none of the Booch shales are believed to have been deposited in water more than a few hundred feet deep.

The Booch stratigraphic interval was probably deposited over a period of ~2 m.y., based on its relative thickness in comparison with the rest of the Desmoinesian Series sediments, which were deposited during 7 m.y. (305–312 m.y.b.p.) (Haq, 1987). This gives each of the eight parasequences an average duration of 250,000 years. Such an estimate conforms in magnitude to the general time frame for parasequence deposition described in the literature, where durations of tens to hundreds of thousands of years between flooding surfaces have been measured (Holland, 2000).

Pronounced global climatic changes can cause eustatic (worldwide) changes in sea level that can profoundly impact depositional patterns. However, the cyclicity observed in the Booch is believed to be more local in nature, resulting from a combination of changes in the rate of sediment influx, mild epeirogenic uplift, and subsidence resulting from compaction caused by sediment loading. Published records of eustatic sea-level changes show too few events to account for all of the cycles observed (Shelton, 1996). Some Booch flooding surfaces may be related to smaller scale eustatic rises in sea level, but determining the level of their influence is beyond the scope of this study (Fig. 11).

Changes in relative sea level during Booch deposition in the Arkoma Basin are revealed by a succession of sediments indicative of gradual shallowing (progradation), followed by a sudden deepening (flooding surface), which characterize parasequences (Fig. 10). Where sandstones are present they occur near the top of each cycle and range from single to multistoried channel fills and associated overbank splays to a variety of nearshore-marine sands from tidal channels, mouth bars, and other delta-front sands. In gross aspect the marine sands tend to be oriented perpendicular to the channel trends. In terms of thickness, the incised valleys in which multistory channel-fill sands were deposited are the thickest and regionally most prominent. Although the regional gross-sandstone isopach combines the entire Booch strati-

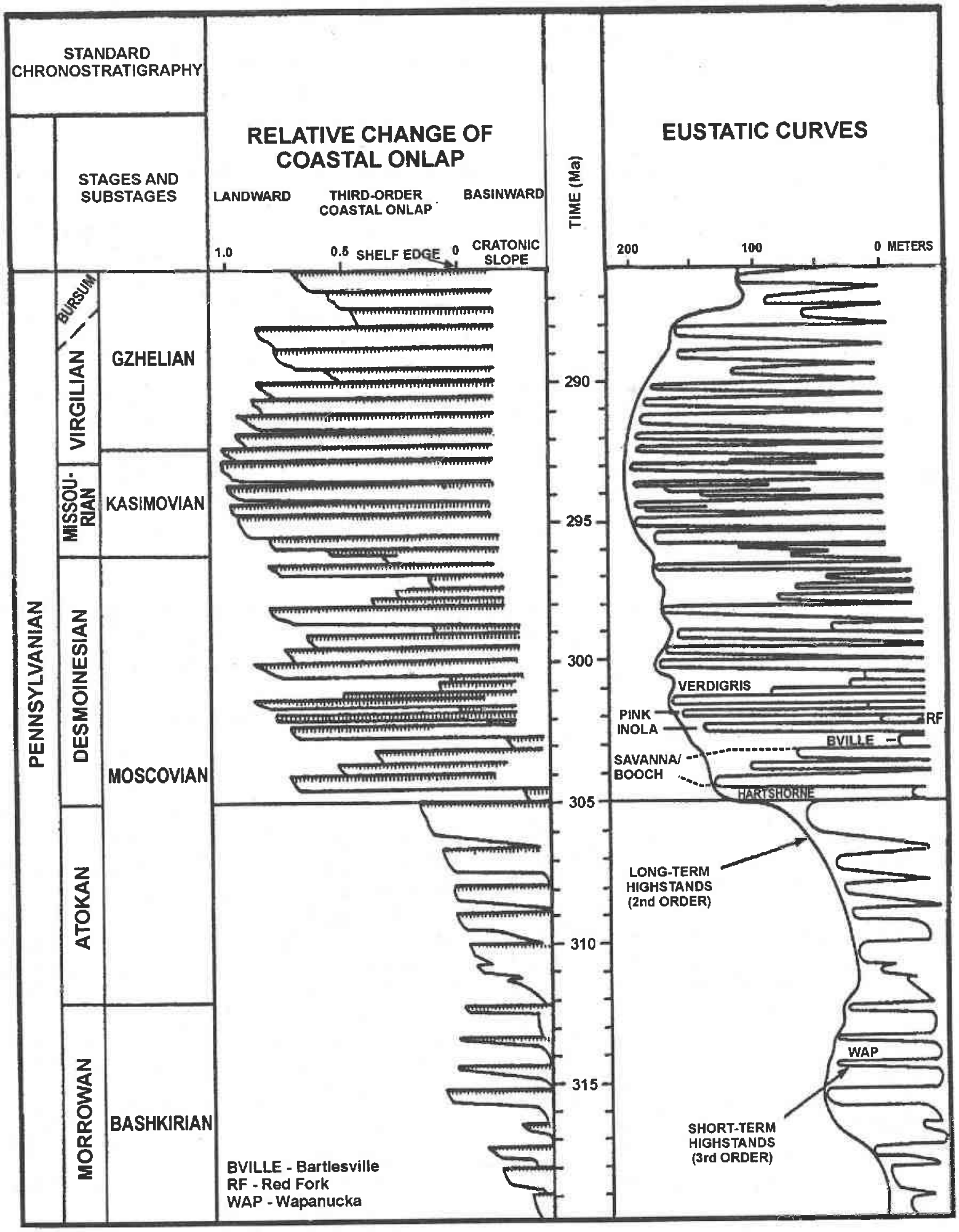


Figure 11. Eustatic sea-level curves. Chart shows major shifts in sea level in the Pennsylvanian, and three eustatic cycles for the period of time in which the Booch and Savanna were deposited. From Ross and Ross (1988).

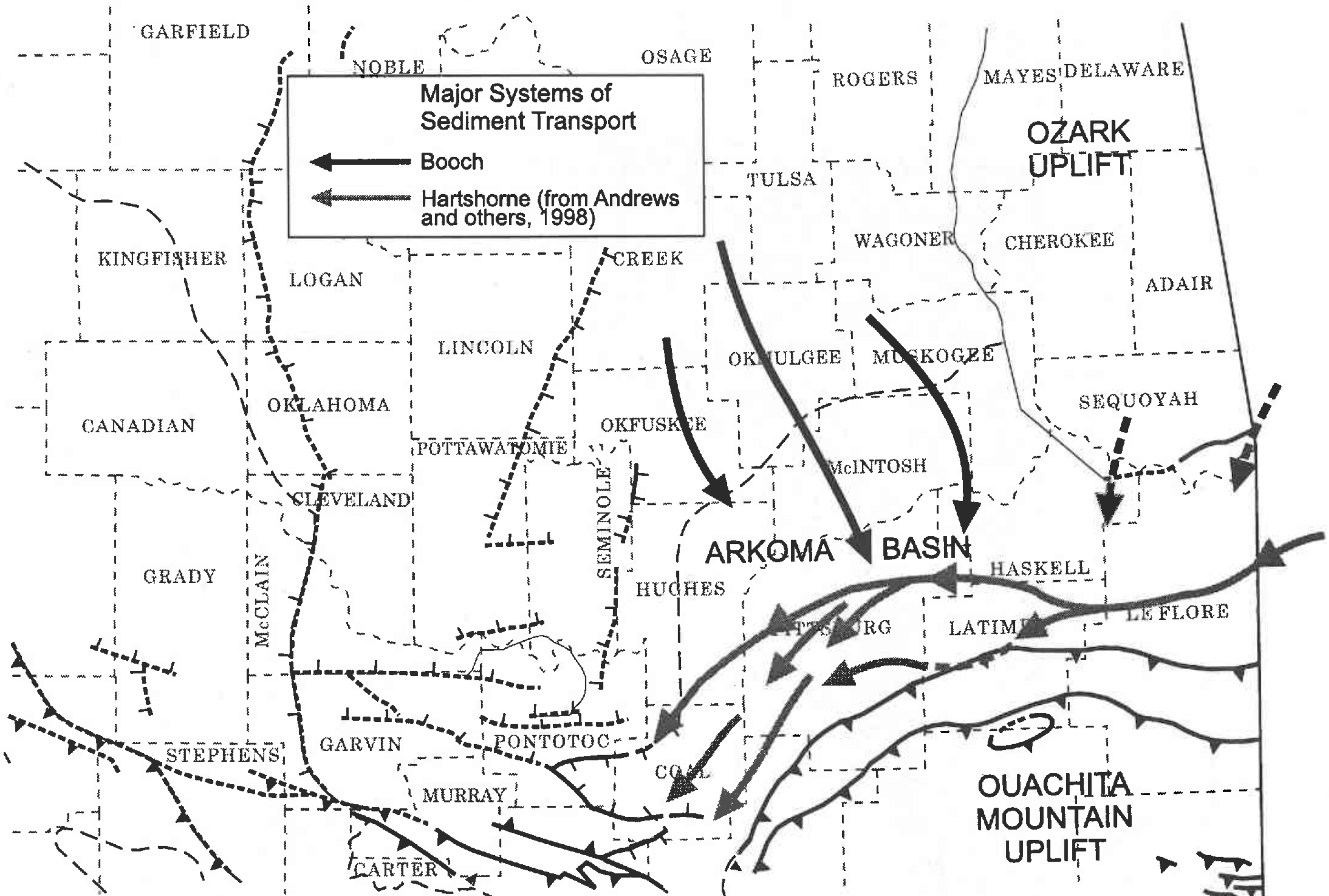


Figure 12. Regional Hartshorne and Booch transport directions. Map shows a 90° shift in transport direction from east to west in the Hartshorne to north to south in the Booch.

graphic section, the orientations of the fluvial and the perpendicular marine-influenced systems that they fed are readily apparent (Fig. 14).

A southern component for the source of sediments, from an area now occupied by the Ouachita Mountains, has been inferred for the entire Desmoinesian sedimentary sequence (Bennsion, 1979). Much of the record of Booch deposition in the Arkoma Basin has been lost behind the Choctaw Thrust. However, no evidence has been found, either in outcrop or in subsurface work carried out for this study, that indicates anything but a northern source of Booch-age sediments. This includes the southernmost part of the study area (T. 1–2 S., R. 11 E.), where, in the Lower Hartshorne, the presence of a chert-pebble conglomerate derived from the Bigfork Chert (Ordovician) indicates the presence of a southern source (Andrews and others, 1998). This is not to say that there was no southern source for the Booch, but simply that direct evidence for it is lacking.

The fluvial systems that brought sediments to the Arkoma Basin at this time had low gradients and a source area that is believed to have originated far to the north, possibly as far away as the Canadian Shield (Tomes, 1986). This is inferred from the generally fine grain size of these sediments, the distance that paleoshorelines moved inland during transgressive (flooding) events, and the lack of any deep-water sands. Where not incised, almost all sandstone occurs at or near the tops of depositional sequences. Their absence among the distal-marine shales below indicates that nowhere did the depositional slope increase to a point at which submarine sloughing and sand movement would have been possible, as in a turbidity flow.

Paleomagnetic studies place Oklahoma near the equator during Desmoinesian time. The presence of abundant coals, including *Calamites* and *Lepidodendron* plant debris, confirms that the climate at this time was tropical (Bissell, 1984). In this tropical locale the Booch was deposited in a generally low-energy, tidally dominated deltaic setting. An excellent modern analog that exhibits all of the deltaic environments identified in the Booch is the Mahakam delta, Indonesia, which, although much larger, is also a tidally dominated system near the equator (Fig. 15). The depositional environments that these have in common include the incised valley updip and the deltaic distributary channels and associated overbank splays. They also exhibit the marine-influenced tidal channels, mouth bars, and delta-front sands, as well as the coal-

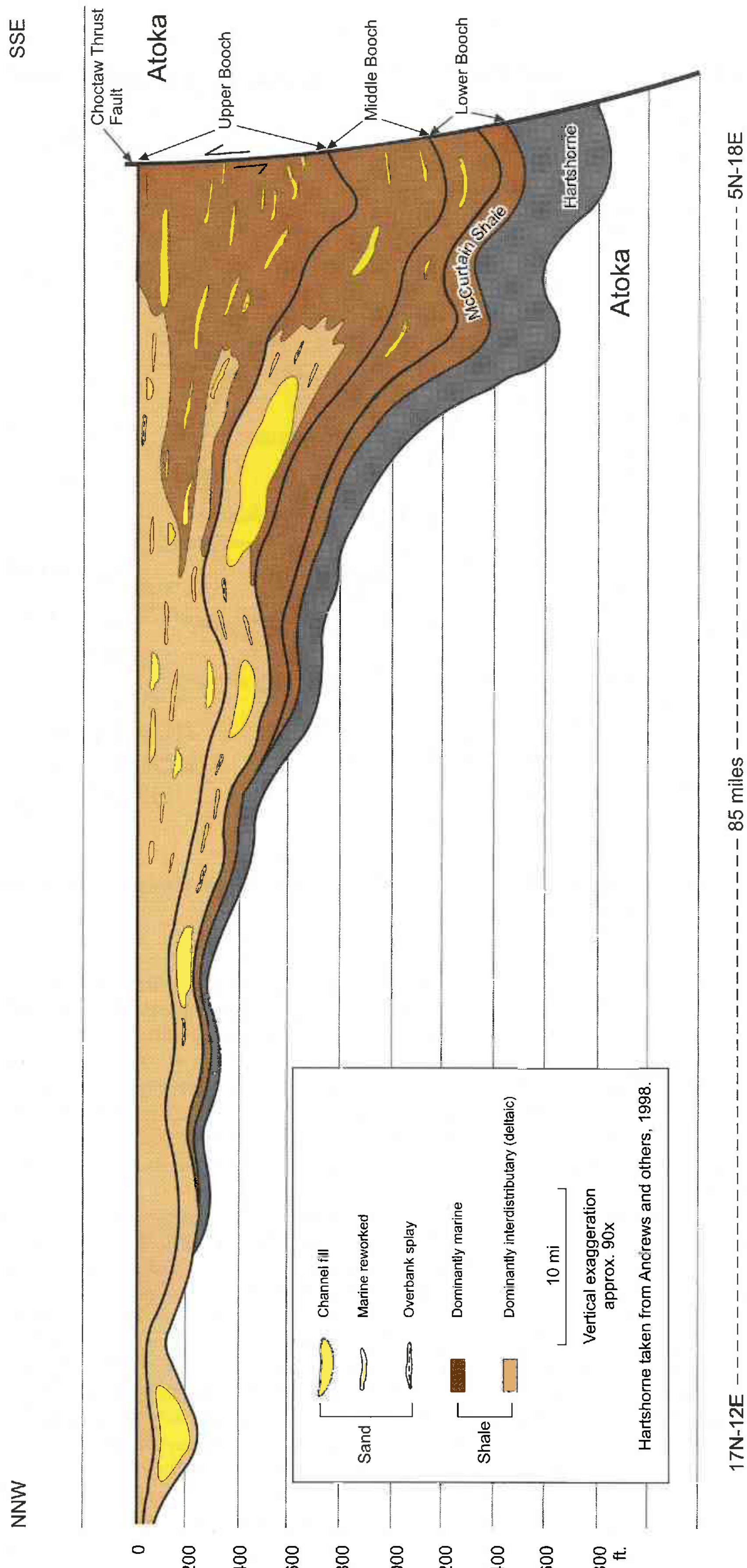


Figure 13. Regional schematic stratigraphic cross section. Section is hung from the top of Booch and extends from the Choctaw Fault to the northern limit of the study area, as shown in Figure 8. Companion regional structural cross section is seen in Figure 7.

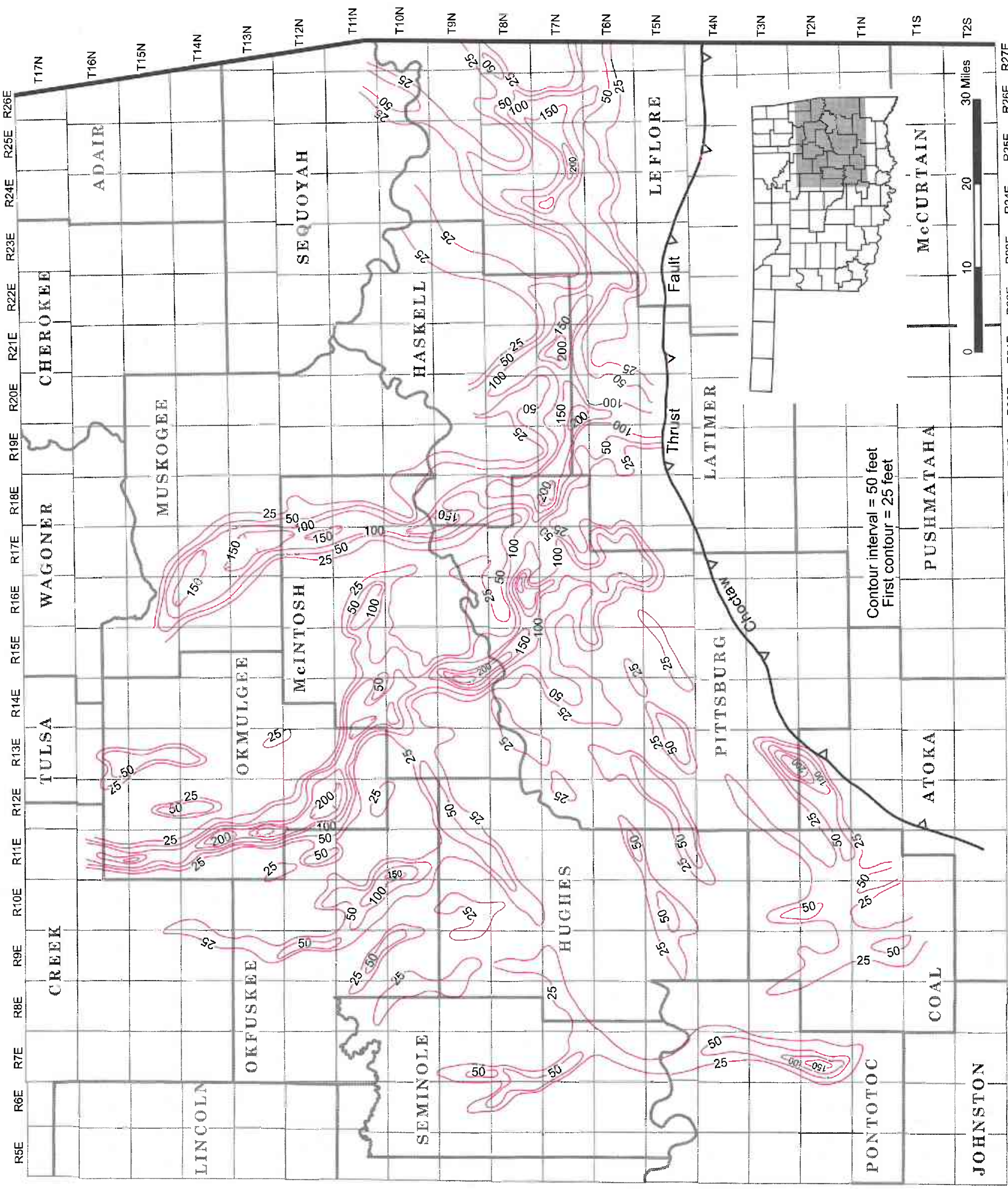


Figure 14. Booch regional gross-sandstone isopach map, showing major sandstone trends reaching a thickness of at least 25 ft, as encountered in the regional data grid. Fluvial systems are oriented generally north to south, and the nearshore-marine sandstones that these fed, west to east.

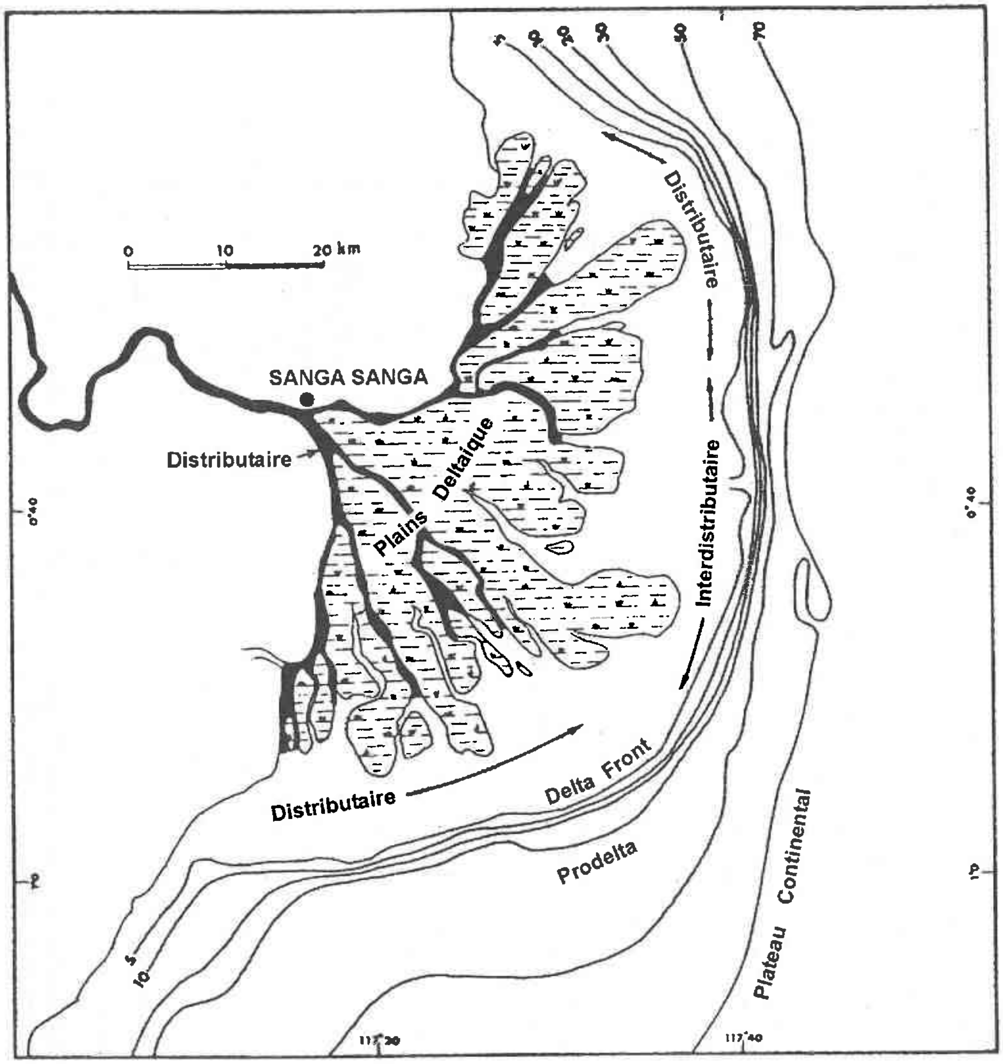


Figure 15. Depositional environments of the Mahakam delta, East Kalimantan, Indonesia. A classic example of a tidally dominated delta system that, although much larger, is analogous to the delta systems seen in the Booch. From Allen and others (1979). Bathymetric contours in meters.

producing swamps present in the delta plain. A critical difference is that none of the preserved Booch deltas had a steep slope beyond the delta front, while seaward of the Mahakam delta, deep-water sands are present beyond the shelf edge (Fig. 16).

Lower Booch

The lowermost Booch parasequence (PS-6) contains no sandstone and was deposited in an exclusively distal-marine environment. Known in the subsurface as the McCurtain Shale, this interval is not identified north of T. 11 N. and tends to be thickest from 2 to 12 mi in front of the Choctaw Fault. Thinning seen in the direction of the Choctaw Fault indicates that the deepest part of the basin at this time was probably in front of the fault (Fig. 17).

Often seen as only a low-resistivity shale lying directly above the Hartshorne (Fig. 9), PS-6 becomes silty at the top in some areas, with an increasing resistivity profile characteristic of parasequence cycles (Pl. 3). In places where resistivity does not increase upward, PS-6 becomes difficult to distinguish from the overlying prodelta shale of PS-5, which could expand the mapped limits of the subsurface-defined McCurtain Shale. Minor thickness variations are probably a result of depressions left on the surface of the Hartshorne that were later filled by this prodelta shale (Fig. 17). In outcrop this interval is a black to dark-gray, fissile shale with phosphatic and sideritic septarian nodules (Bissell, 1984).

The subsurface definition of the McCurtain Shale differs from that used by surface geologists, who identify all of the shale between the Hartshorne and the first Booch sandstone as McCurtain Shale (Fig. 1). The need for subdividing the outcrop-defined McCurtain Shale is supported by field work that describes the shale as becoming coarser grained in the upper part and having a maximum thickness of >500 ft. Its thinning as a result of downcutting by the overlying Warner sandstones (PS-3/3A) has also been noted (Bissell, 1984). Where PS-5 and PS-4 are sand poor they are rarely exposed, and in these areas they are lumped with the McCurtain Shale. However, even where sand is not present, electric logs still show the classic funnel-shaped, progradational log character of de-

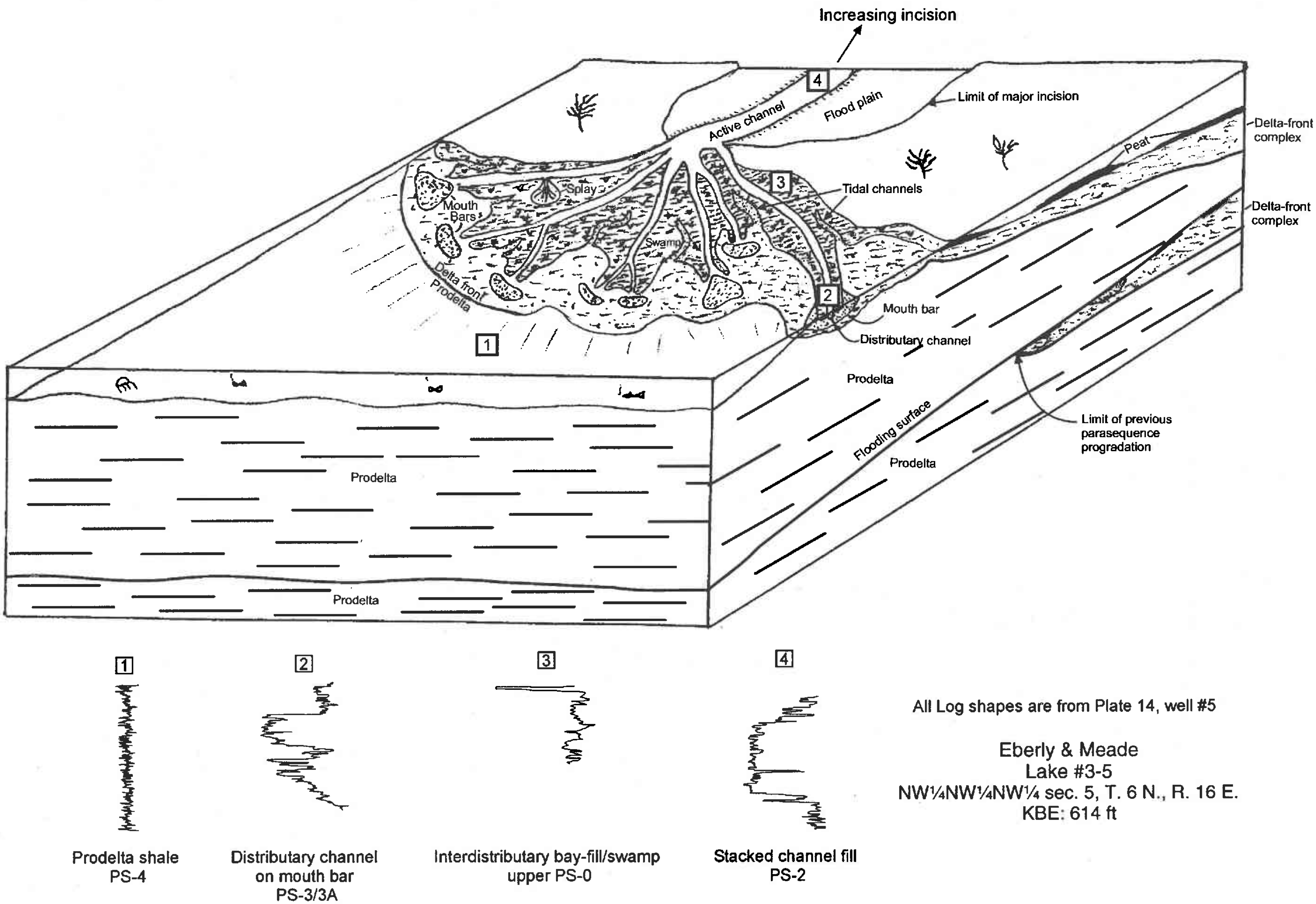


Figure 16. Schematic Booch tidal delta. This diagram shows the major depositional environments encountered in the Booch and their appearance on logs. Modeled after the Mahakam delta, Indonesia.

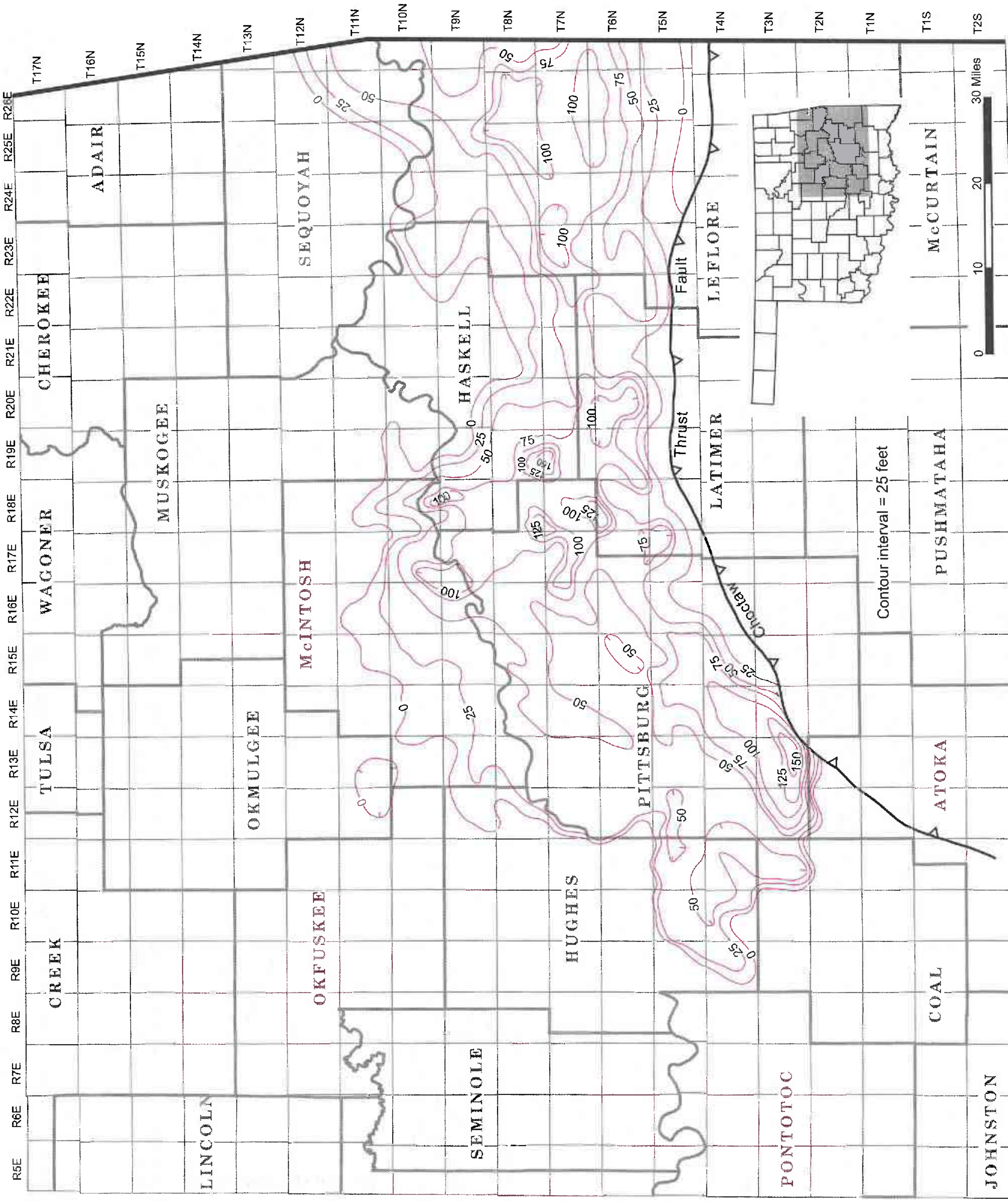


Figure 17. Isopach map of lower Booch (McCurtain Shale; PS-6) interval. This interval contains no sandstone but does show the basinal axis at this time, preserved as a line of isopach "thicks," north of the Choctaw Thrust.

creasing gamma-ray values and increasing resistivity for both of these parasequences.

The remainder of the lower Booch is represented by PS-5. It is 3 to 5 times thicker than the underlying PS-6 and extends north of the mapped area on the Cherokee Platform, but it is still composed dominantly of shale (Fig. 9). Several isopach "thicks" in this parasequence correspond to those seen in the underlying PS-6, which probably indicates that depressions left on the Hartshorne surface were incompletely filled by PS-6. There are also no north–south-trending isopach "thins" indicative of any large-scale downcutting after PS-5 time. The massive incised valleys that were formed mostly during PS-3/3A time in the middle Booch were accommodated almost entirely by the underlying PS-4 interval, and rarely reached deep enough to affect the thickness of PS-5 (Fig. 18).

On a regional basis, PS-5 is notably sand poor. It was deposited during a period of sustained marine transgression that saw only minimal deltaic progradation (Fig. 13). However, some small-scale deltaic complexes were present at this time, one in the vicinity of the Pine Hollow South Field study area in west-central Pittsburg County. Although the PS-5 sandstones in this area were identified on the regional gross-sandstone isopach, there are probably other sandstone-rich areas that are of a scale that makes them difficult to identify on a regional basis. The sandstones that appear on the regional map, based on general orientation, appear to be a mix of fluvial and nearshore-marine deltaic environments. The deltaics appear to predominate on the regional map because they are more pervasive than the narrower channel systems, and thus are easier to identify on the widely spaced, regional dataset (Fig. 19).

Where PS-5 sandstone is present, it is usually <10 ft thick and is oriented parallel to the paleoshoreline, as one would expect of sands reworked in a marginal-marine setting. The thickest PS-5 sandstones occur in the southwestern part of the study area in Coal and northernmost Atoka Counties. Here, there appear to be two north–south-trending channel systems that fed an east–northeast-trending series of tidally reworked sandstones. However, the orientation of the paleoshoreline in this corner of the basin is not clear, and the sandstone-distribution pattern is certainly far more complex than that shown. With limited regional well control, it is possible to connect sandstones with sharp (erosional?) basal contacts that are inferred to represent channel fill, and those with a coarsening-upward log profile that are typical of a delta-front environment, in more than one way. An alternative explanation might source the sands from the Arbuckle Mountains to the west, although this would require detailed work to confirm (Pls. 4–6).

Middle Booch

The middle Booch is composed of three parasequences: PS-4, PS-3A (lower Warner), and PS-3 (upper Warner), and it fundamentally differs from the lower Booch. Although roughly the same thickness within the basin, it is far more pervasive on the shelf, extending across wide areas of the Midcontinent (Tomes, 1986). It is the sandiest Booch interval, which makes it the best exposed in outcrop. Having the most reservoir-quality sandstone, it is also regionally the most productive Booch-age interval, correlative with both the Tucker and Taneha sandstones on the shelf, where it produces mostly oil (Figs. 1, 3).

Like the rest of the Booch, middle Booch sediments were derived exclusively from the north. Warner sandstone (PS-3/3A) outcrops in T. 8 N., R. 24 E., that have documented paleocurrent directions from north to south–southwest and south–southeast, confirm this northern source (Papusch, 1983). Evidence is sparse, but thick, stacked channel-fill sands in the southeastern part of the study area indicate that major uplift of the Ozark Uplift, at least in Oklahoma, had not occurred by middle Booch time (Pl. 3). However, the Ozark Uplift does appear to have been periodically emergent well north of the study area in parts of Missouri, as evidenced by a thick chert conglomerate at the base of the Warner sandstones (Tomes, 1986).

The lower Booch, which is dominated by marine sediments laid down during a generally transgressive period, is followed by PS-4, the first middle Booch parasequence. This begins with the deposition of a prodelta shale that in many places is almost as thick as that seen in PS-5. After what appears to have been an extended period of mostly distal-marine deposition in the study area, the process of regression, which often left only thin delta-front sands capping PS-4, seems to have accelerated, possibly in response to a eustatic fall in sea level (Fig. 10). This increased the rate of downcutting in existing channel systems on the shelf and formed the template for later incision.

The isopach of the middle Booch interval highlights the presence of several incised valleys that run along depositional dip into the basin and at least two, thinner strike-parallel trends (Fig. 20). The large, dip-parallel systems have long been recognized as having a fluvial origin (Busch, 1959). Because incision does not extend into the lower Booch, the major isopach "thicks" are purely compactional and result from the relative resistance to compaction of stacked channel-fill sands.

Reliably assigning separate channel fills in an incised valley to a particular parasequence is difficult. However, in places it appears that the basal sandstones in the middle Booch valley fills are PS-4 in age because they are capped by a shale that appears to be related to the PS-3A flooding surface (Pl. 1). On this basis, incisement is believed to have begun at the end of PS-4 time, with maximum progradation (marine regression) occurring during PS-3/3A deposition. Marine incursions occurred after deposition of PS-4 and PS-3A, but these did not transgress as far north as the other Booch flooding surfaces (Fig. 10). This allowed middle Booch progradation to begin farther into the basin than at any other time, and it created the greatest period of marine regression, valley incisement, deltaic progradation, and sand deposition since the Hartshorne.

The regressions that occurred during PS-3A and PS-3 time deepened and widened existing PS-4 drainages to

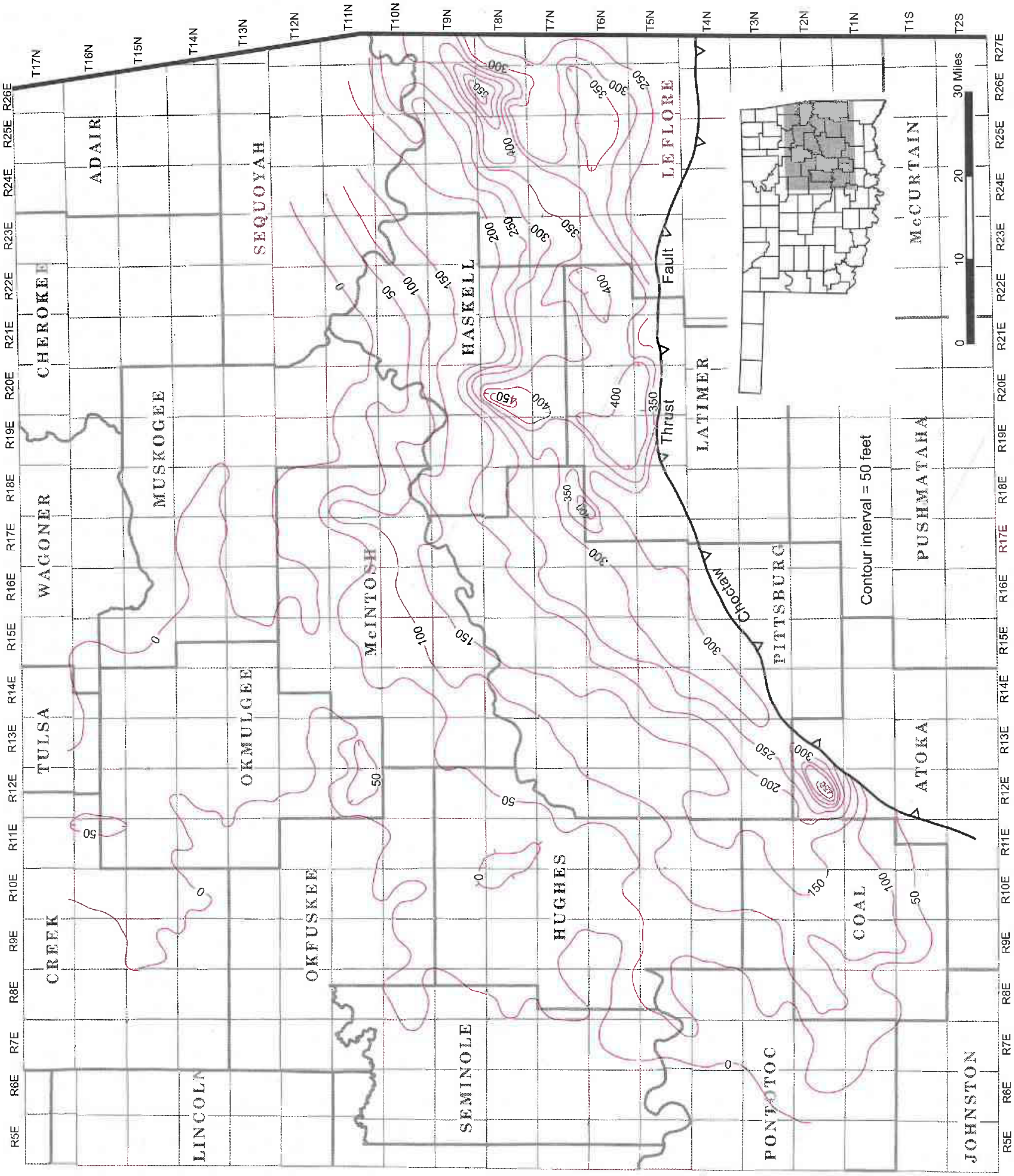


Figure 18. Isopach map of lower Booch (PS-5 + PS-6) interval. No distinct "thins" associated with large-scale downcutting in the middle Booch (PS 3/3A) are present, because this incision was accommodated by the underlying PS-4. Bathymetric lows are seen as isopach "thicks."

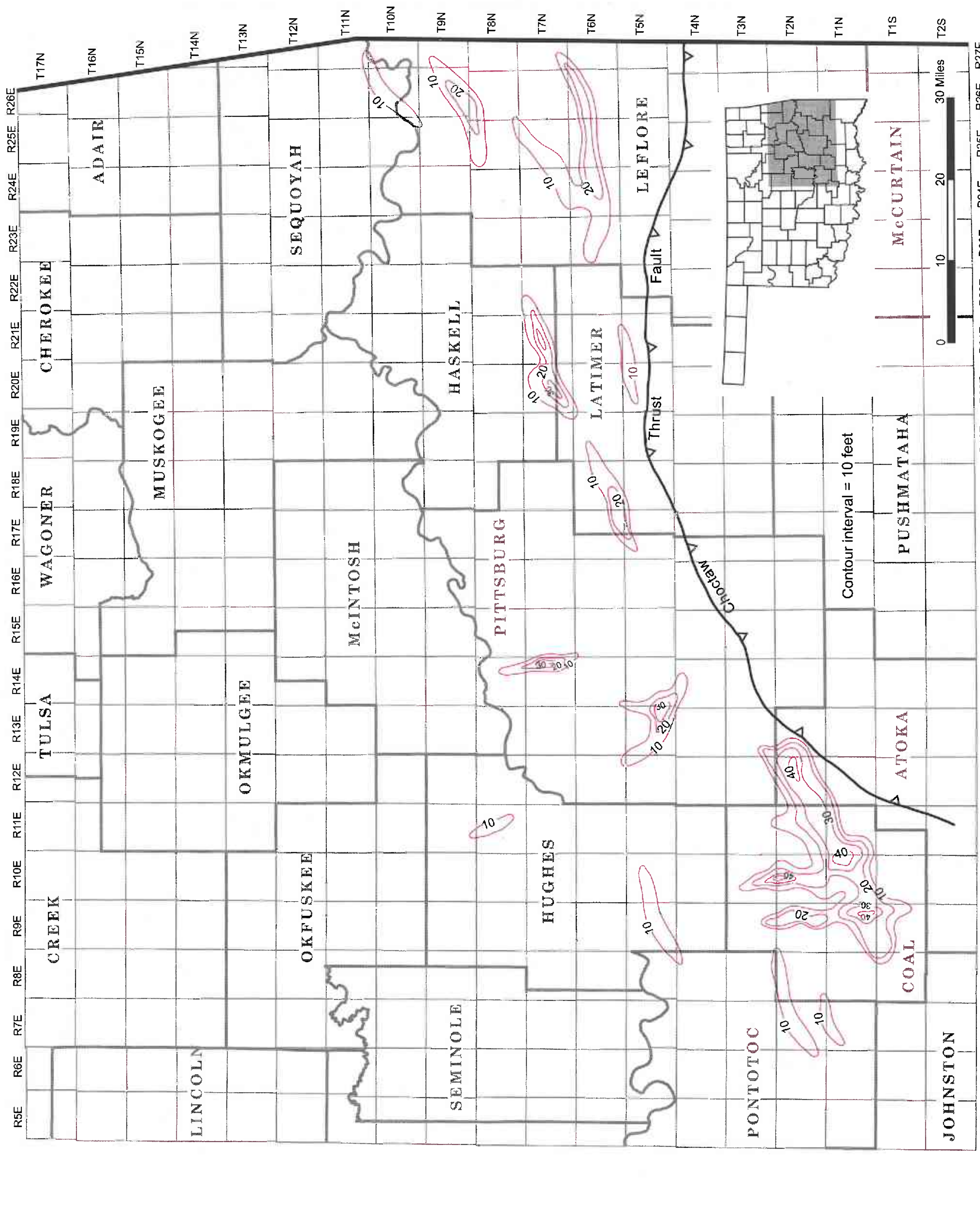


Figure 19. Isopach map of lower Booch (PS-5) gross sandstone. The orientation of most sandstone complexes, parallel to paleo-strike, suggests deposition as marine-reworked sands. The narrowness of these sand bodies makes it likely that others were missed by the regional data grid.

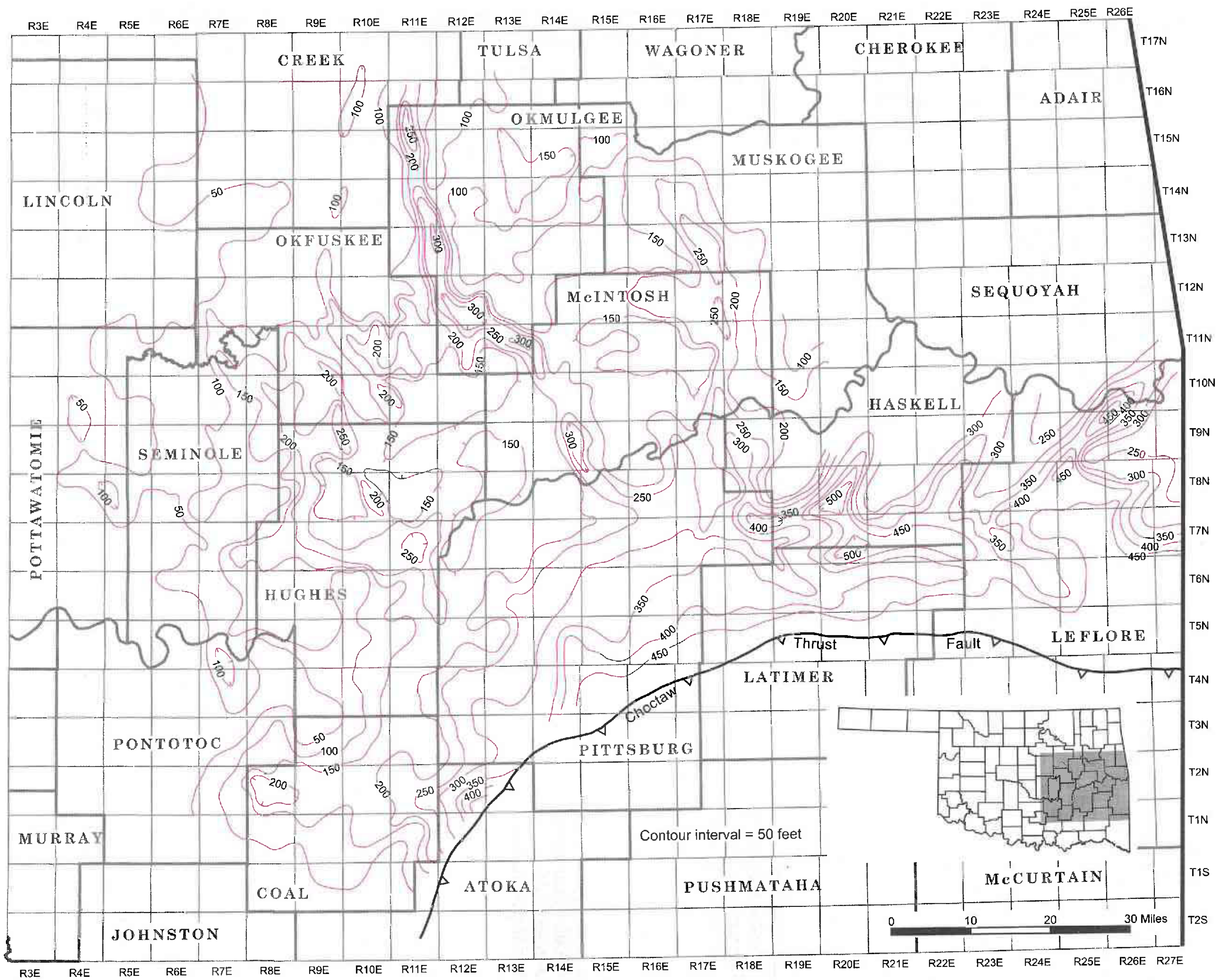


Figure 20. Isopach map of middle Booch (PS-3, PS-3A, PS-4) interval. Although the shape of the basin has remained the same, continued regional thickening into the Choctaw Thrust indicates that the area of thickest middle Booch sediments may have been removed. Major incised valleys seen in Figure 21 are also visible here.

the point that they became incised valleys. The valleys became home to stacked channel-fill sequences that are >250 ft thick in places (Fig. 21). The wells in which at least 20 ft of the middle Booch sandstone is PS-4 in age are highlighted on the regional sandstone map shown in Figure 21. Most of these are channel-fill sands associated with the prominent incised valley in the center of the study area. Other places of possible PS-4 incisement may have been obscured by later PS-3/3A downcutting.

PS-4 sandstones to the south appear to have originated as nearshore-marine sands that were later overridden by PS-3A and PS-3 incisement. For all stratigraphic intervals, conditions tended to become more marine to the south (Pls. 1–9). There may be other areas in which PS-4 sandstone is present, but none where it can be reliably separated from overlying channel fills. In the areas within large incised valleys, middle Booch erosion was accommodated mostly by the underlying PS-4 shale, which in places has been completely removed (Pl. 1).

Less prominent isopach "thicks" of middle Booch gross sandstone are the two strike-parallel trends that run perpendicular to the incised valleys. These are interpreted as amalgamations of sand deposited in various deltaic environments that lay along two paleoshorelines. These deltaic shoreline systems are obviously far more complex than can be regionally mapped, but the sands range in environment from distributary-channel fills and splays to mouth bars, tidal channels, and other delta-front sands (Fig. 22).

The more updip of the two shorelines appears to be mostly PS-3A in age, and all middle Booch sandstone updip of this shoreline appears to be only fluvially related (Pl. 7). In the southwestern part of the study area the north–south-trending sandstone "thick" is believed to be a continuation of this paleoshoreline. The downdip shoreline complex appears to be made up of sandstone from all three middle Booch parasequences, in some cases showing stacked channel-fill sands mixed with thinner deltaics (Pls. 1, 6). In areas where no delta system was present to mark the paleoshoreline, it becomes difficult to trace. The two isolated, strike-parallel sandstone "thicks" just in front of the Choctaw Fault may represent another, more distal shoreline, but far more detailed mapping would be necessary to confirm this (Fig. 21). Occurring at the top of progradational sequences, these sands certainly were not deposited in a deep-water-marine setting (Pls. 2, 4).

Fluvial incision of >100 ft only 10 mi north of the Choctaw Fault, occurring as the gross interval continues to thicken, indicates that yet another series of shoreline sands was likely deposited south of the fault. These probably would reflect the point of maximum regression that is believed to have occurred at the end of PS-3 time. Deep incision of the gently dipping paleodepositional slope indicates that if such a shoreline existed, it must have been well south of the present-day Choctaw Fault. If so, uplift and erosion of the Ouachita Mountains is responsible for its absence. Based on the number and location of apparent shoreline sands preserved during the middle Booch, it appears that the process of deltaic progradation (marine regression) was not smooth or continuous, but occasionally paused long enough to deposit thicker sands in some areas.

Upper Booch

Using surface terminology, *Cameron* and *Lequire* are the names given to the sandstones in the upper Booch (Fig. 1), although a consistent correlation with the sandstones in any of the three upper Booch parasequences does not exist. In this study the upper Booch is defined as the stratigraphic interval comprising parasequences 2, 1, and 0. Although reservoir-quality sandstones are relatively abundant, the upper Booch represents a transition away from the massive incision characteristic of the middle Booch and back to a generally more marine depositional setting.

Upper Booch sediments were deposited on a surface not much different from those at other times during Booch deposition. Paleostrike in the southwestern part of the study area began with a north–south orientation and gradually rotated more east–west, following the general outline of the basin in the direction of Arkansas. On the basis of the interval isopach, which seems to thin in front of the Choctaw Fault, the axis of the basin at this time appears to have been just in front of the fault. As is seen in the rest of the Booch, the shelf north of the basin seems to have originally continued across the Ozark Uplift, indicating that major uplift here began after deposition. As in the middle Booch, the upper Booch also extends well north of the study area, where it can be >150 ft thick (Fig. 23).

The upper Booch is intermediate between the lower and middle intervals in sand content. Although sandstones are locally abundant, the fluvial systems that transported sediment into the basin appear to have been smaller than those for the middle Booch. Their scarcity on the regional map is probably a function of the wide spacing of well control; in the Reams Southeast Field study in north-central Pittsburg County, for which all available well records were analyzed, thick fluvial systems were found to be present. Although the upper Booch is thick north of the study area, there is little sandstone preserved north of T. 10 N. The most widespread sandstones are concentrated within 20 mi of the Choctaw Fault, and similar to the lower Booch, these tend to be strike-parallel nearshore-marine and deltaic sands (Fig. 24).

The maximum flooding surface that began PS-2 and upper Booch deposition was more pronounced than any since the end of lower Booch deposition (Fig. 10). This flooding surface initiated the deposition of a thick prodelta shale that is >100 ft thick within the basin. Overlying this shale is the typical succession of progressively shallower marine sediments that finally end with delta-plain sands, silts, shales, and some coals.

The maximum upper Booch transgression occurred at the beginning of PS-1. This prodelta shale is >300 ft thick, making it overall the thickest seen in the Booch. Its generally more marine nature and lack of major prograding delta systems may explain why the PS-1 sandstones evaluated in the field studies tend to be comparatively thin and of poor reservoir quality. With a wide regional grid

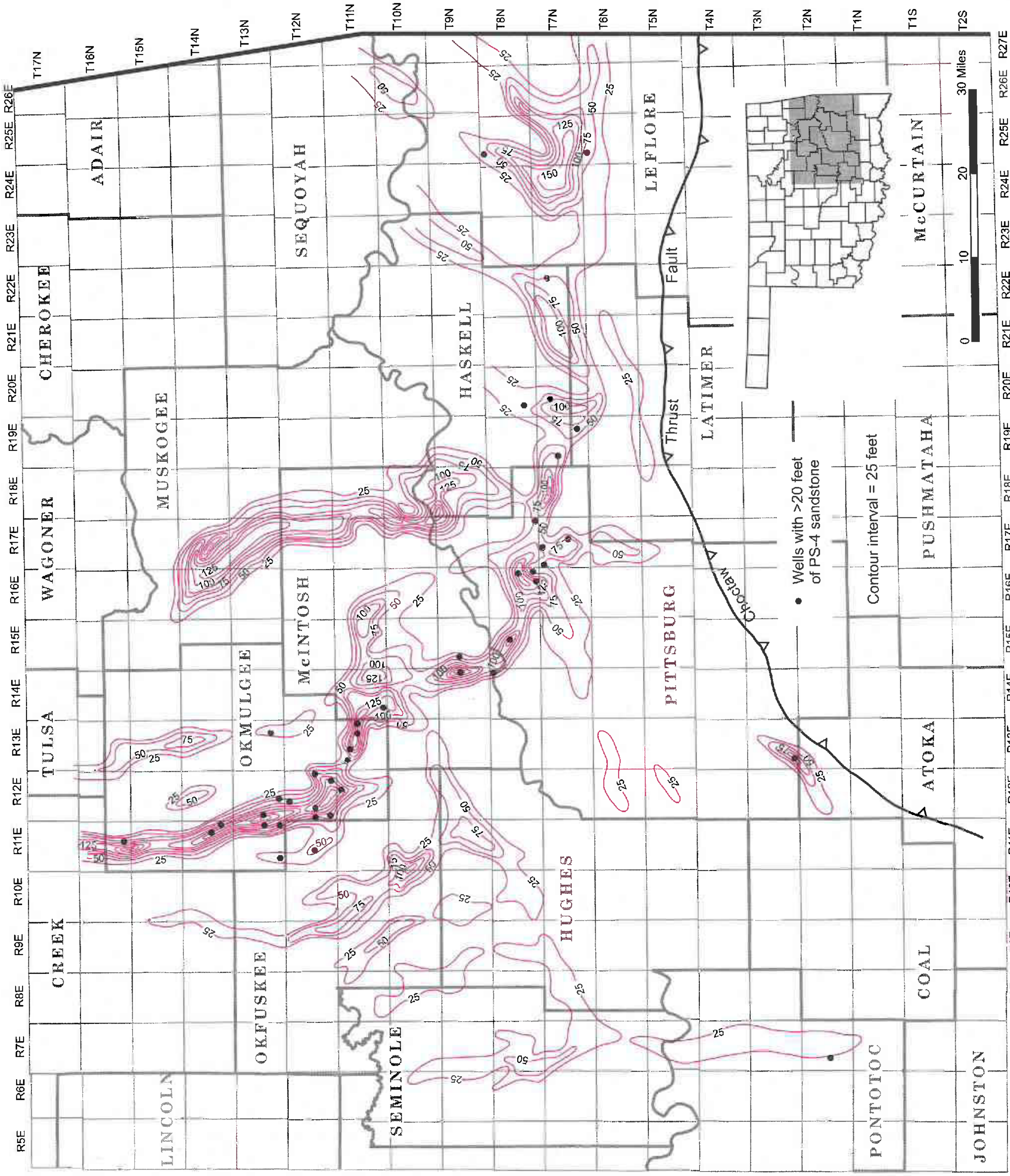


Figure 21. Isopach map of middle Booch (PS-3, PS-3A, PS-4) gross sandstone, showing two prominent incised valleys and several parallel systems. Thinner sand trends running perpendicular to the valleys are indicative of marine influence near paleoshorelines.

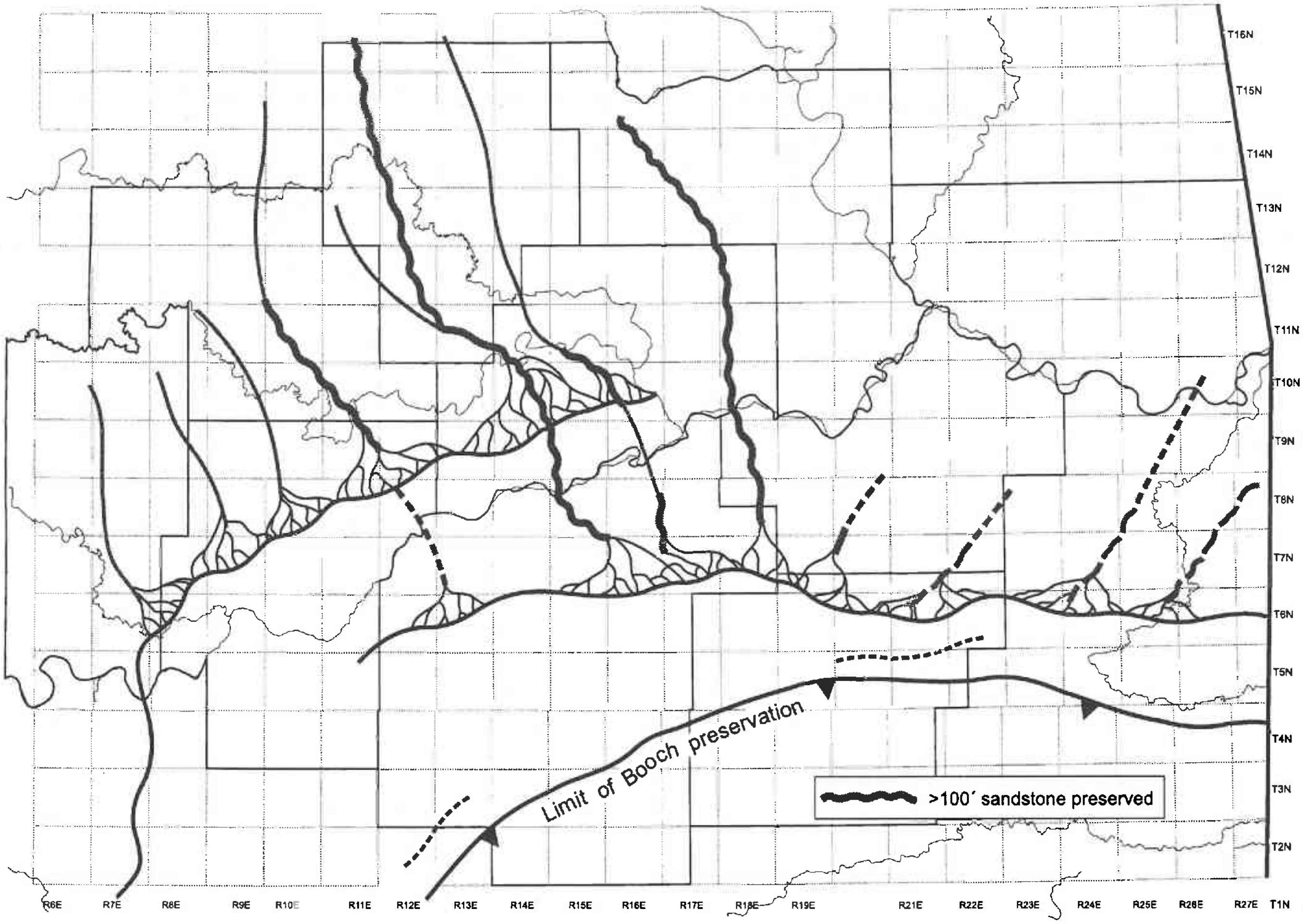


Figure 22. Schematic middle Booch depositional systems. Map shows axis of major fluvial incisement, delta complexes, and inferred paleoshorelines. The presence of sandstones adjacent to the Choctaw Thrust indicates that the basin axis at this time was farther south. Compare to Figure 21.

and only three field studies, it is possible that better sandstones may have developed in areas of the basin that were not evaluated in detail.

The final cycle of Booch deposition occurred in PS-0. This parasequence contains little prodelta shale, but based on the Reams Southeast and Pine Hollow South field studies, distributary-channel and mouth-bar sands are locally abundant. Next to the middle Booch, PS-0 sandstones are probably the most important Booch gas producers.

The McAlester coal marks the end of PS-0 deposition and the top of the Booch stratigraphic interval. This coal is more uniform and widespread than any other found in the Booch. This may indicate that the interdistributary swamps were more pervasive and that the rate of progradation that took place during PS-0 time was slow enough to allow thicker delta-plain coals to accumulate than at any time since deposition of the Hartshorne (Fig. 16).

In the remainder of the McAlester Formation, flooding surfaces become indistinct, sandstones become more discontinuous, and the recognition of transgressive–regressive cycles becomes far more difficult than in the Booch. Lithologies suggest that the upper McAlester Formation, from the McAlester coal through the Brown (Spaniard) limestone, is composed of three parasequences (Bissell, 1984). In addition to generally poorer quality reservoir sandstones, in many areas there are fewer thick prodelta shales that are characteristic of the Booch stratigraphic section. This could have reduced the interval's sourcing and sealing capability, which, combined with fewer reservoir-quality sandstones, may explain why the upper McAlester is so much less productive than the underlying Booch.

PETROLEUM SYSTEM

Source, Migration, and Seal

Middle Pennsylvanian marine shales, several of which are present within the Booch, are among the most important source rocks in Oklahoma. To be classified as a potential hydrocarbon source, a rock must have a minimum of 1% total organic carbon (TOC). The TOC values in Desmoinesian–Atokan marine shales in the Arkoma Basin range from 2% to 18%, making them among the richest in the Midcontinent (Johnson and Cardott, 1992).

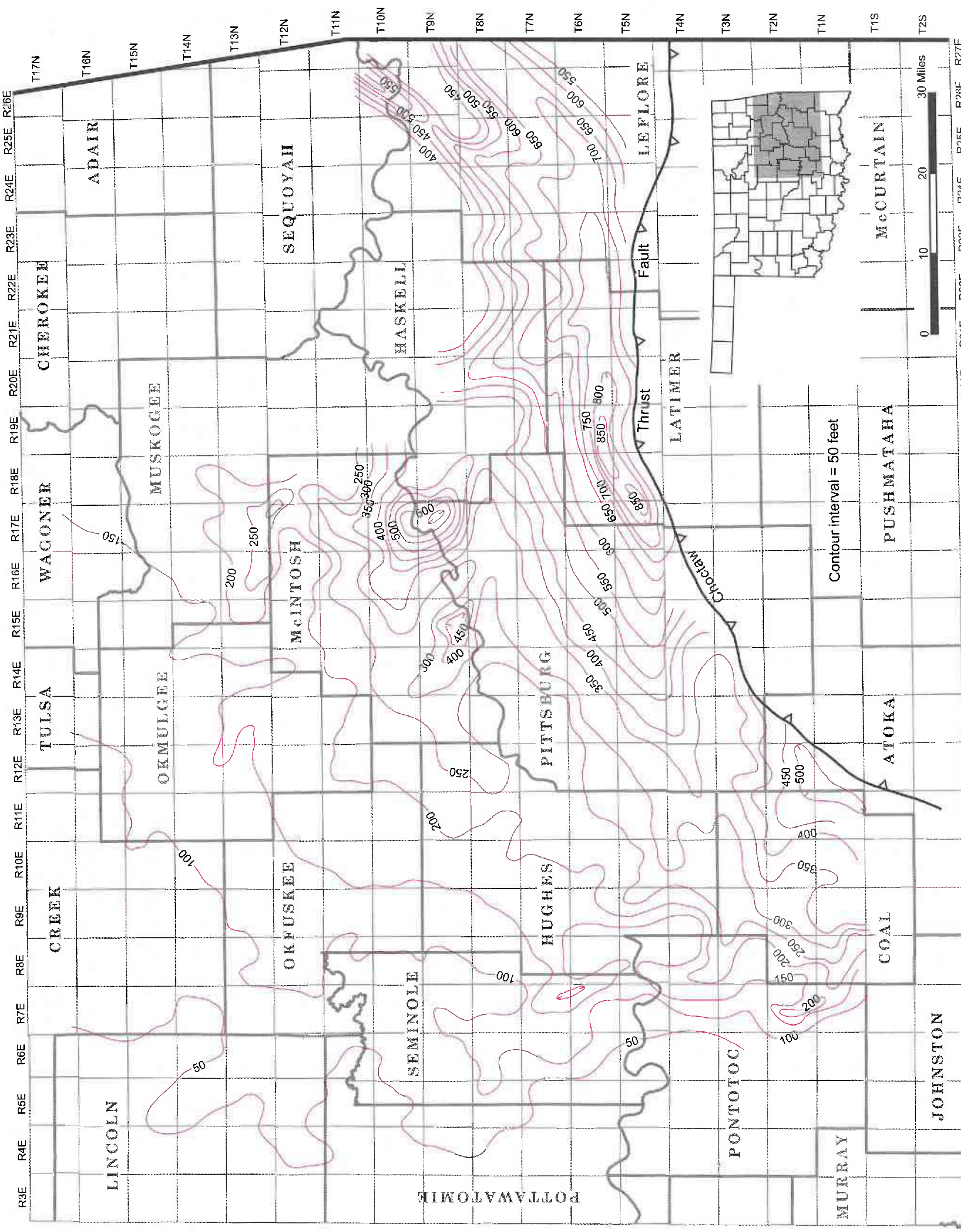


Figure 23. Isopach map of upper Booch (PS-0, PS-1, PS-2) interval, showing the depositional axis just in front of the Choctaw Fault. Distinct regional trends tend to be obscured by the combining of three thick parasequences.

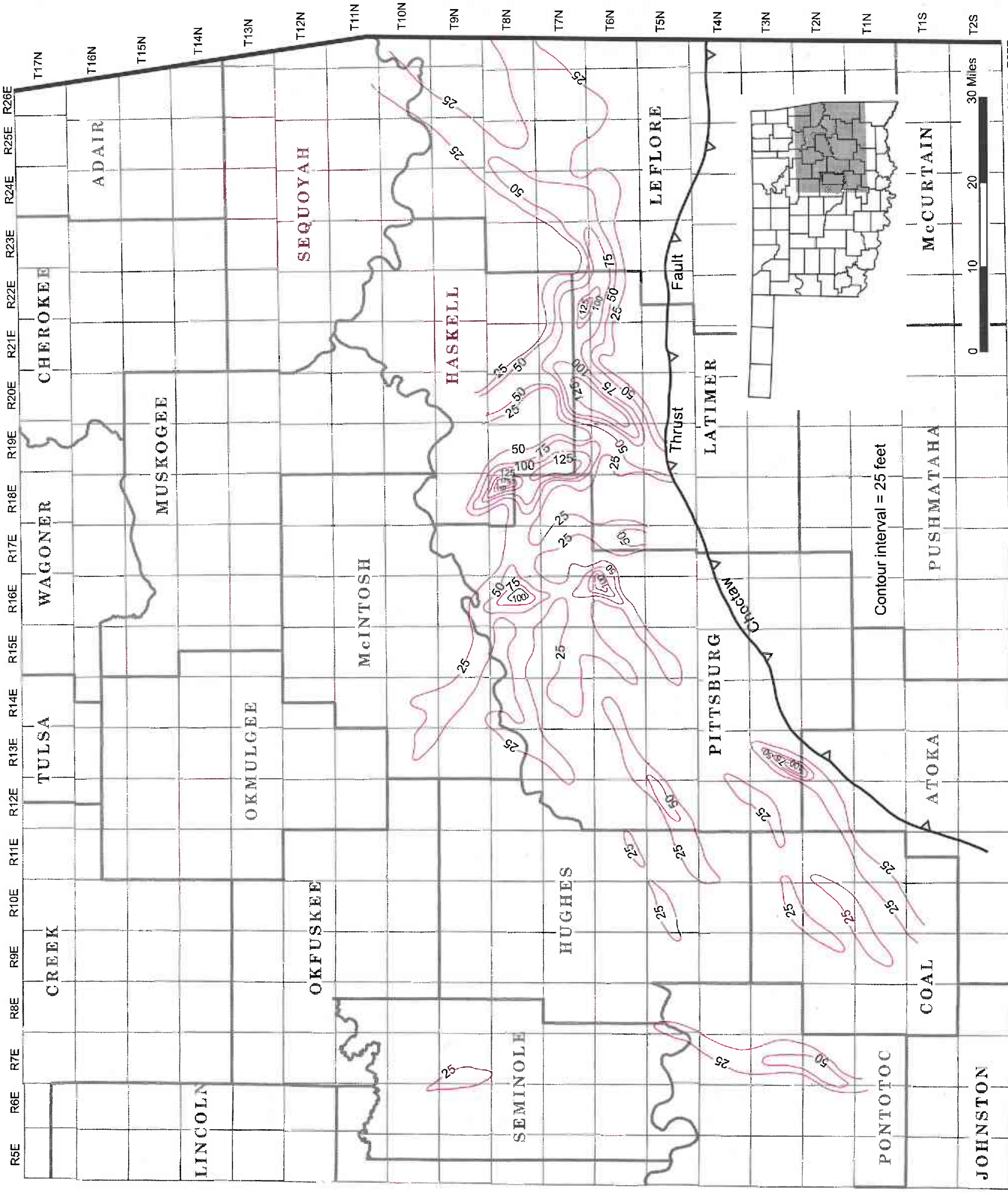


Figure 24. Isopach map of upper Booch (PS-0, PS-1, PS-2) gross sandstone. This interval is intermediate in sandstone content between the sandy middle and shaly lower Booch.

Desmoinesian-age source rocks contain only a small percentage of the mixed amorphous/coaly (Type II) organic matter that is capable of generating wet gas, but they are rich in coaly (Type III) kerogen (Horn and Curtis, 1996; Byrnes and Lawyer, 1999). A preponderance of coaly (gas-prone) kerogen is not unexpected, given the abundance of plant material in the swamps that were invariably present in the delta plain (Fig. 16). These interdistributary swamps are responsible for the numerous coals that are seen in the Booch. This organic debris was not restricted to the delta but was also carried by distributary channels far out to sea, where it was eventually incorporated into and preserved by prodelta shales. Combined with the coals, these black shales are the primary source rocks for the Booch.

In terms of source-rock maturity, even the shallowest rocks in the Arkoma Basin are thermally mature. This is because the tectonic compression and uplift of the Ouachitas removed large volumes of overburden that were formally present. As a result, the maximum burial depth for sediments in the basin could have been several times their current depth. This allows source rocks in the Booch, which are seldom found below 3,000 ft, to be always thermally mature. Estimates of overburden removal have been calculated on the basis of shale bulk densities, interval transit times, and stratigraphic projections of missing section. These estimates indicate that between 5,000 and 15,000 ft of stratigraphic section has been removed from the Oklahoma portion of the Arkoma Basin (Fig. 25) (Byrnes and Lawyer, 1999).

As measured by vitrinite reflectance (R_o), the oil-generation window begins at an R_o of 0.50 and ends at ~1.35. Dry-gas generation begins at an R_o of ~1.00 and continues through a value of at least 3.20 (Fig. 26). The Hartshorne coal is an excellent reference for Booch source-rock maturity, because it lies just below the base of the Booch. Also, because it is one of the thickest and most widespread coals in the State, it has been mined longer and has been analyzed more often than any other Oklahoma coal. The minimum measured vitrinite reflectance for the Hartshorne coal is 0.65 in Coal County, rising to 1.50 at the Arkansas border (Fig. 27). The pattern of increasing maturity to the east is believed to have been caused by heat flow along Atokan syndepositional faults (Houseknecht, 1992).

Because the Hartshorne is slightly deeper, the values shown (Fig. 27) represent the maximum thermal maturities for the overlying Booch shales. However, this shows that the Booch is clearly mature throughout most of the study area and that any hydrocarbons generated should have remained stable (are not overmature). The line that separates the area in which the Booch produces only gas from that where both oil and gas are produced (Fig. 3) has no relationship to the environment in which the reservoir was deposited. In addition, the fact that at least eight cycles of progradation have blanketed the entire study

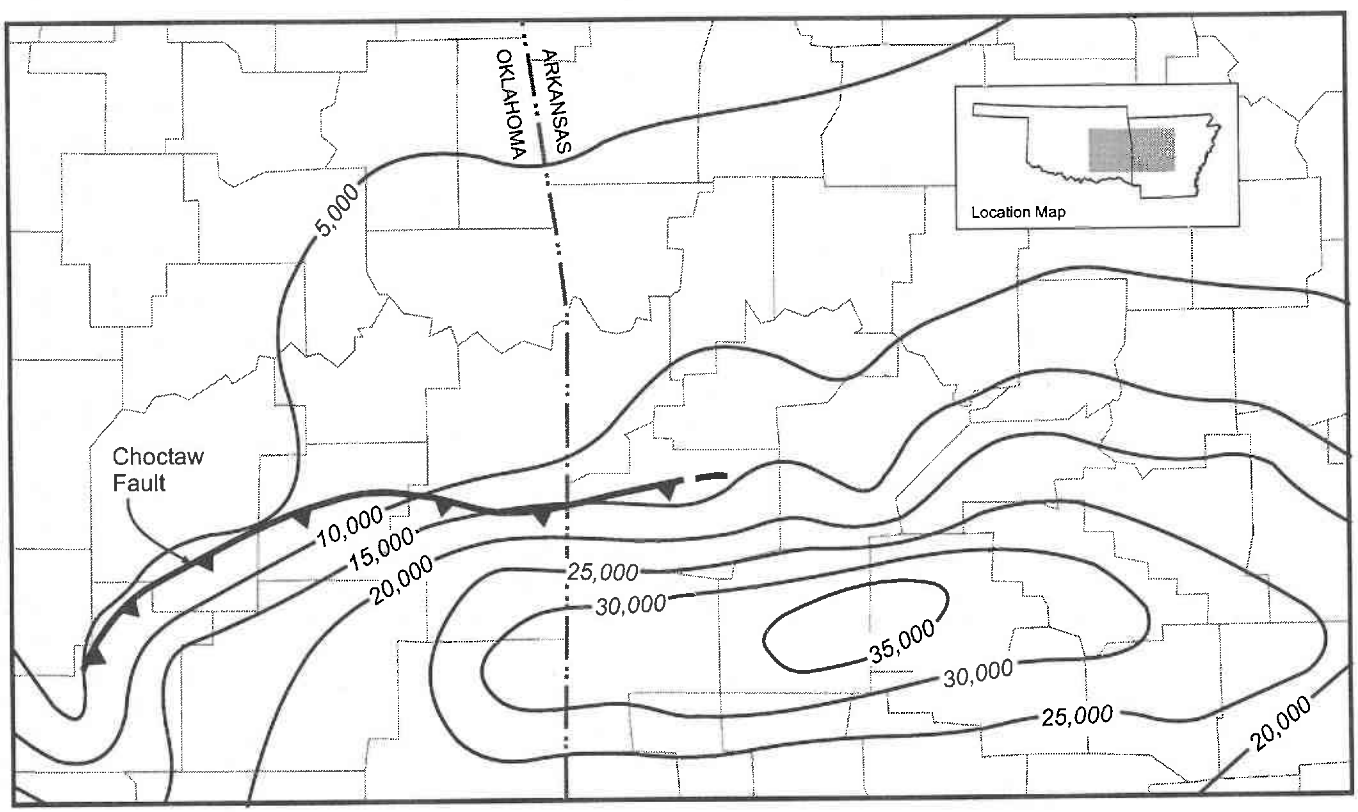


Figure 25. Map of estimated removed overburden (in feet) in the Arkoma Basin. This map helps explain anomalously high maturities for rocks that are near the surface today. Modified from Byrnes and Lawyer (1999).

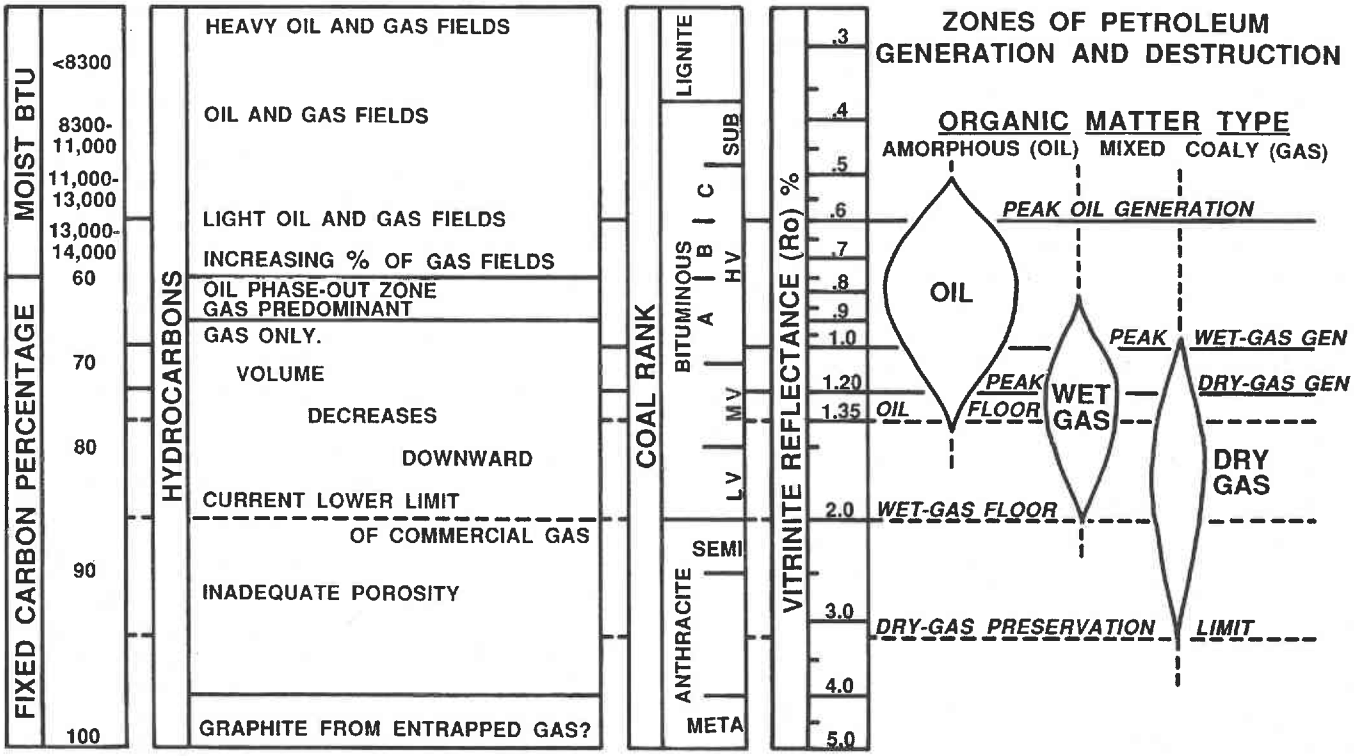


Figure 26. Relationship between thermal maturity and hydrocarbon occurrence. Chart shows zones of hydrocarbon generation and destruction expressed in terms of vitrinite reflectance. From Houseknecht and others (1992).

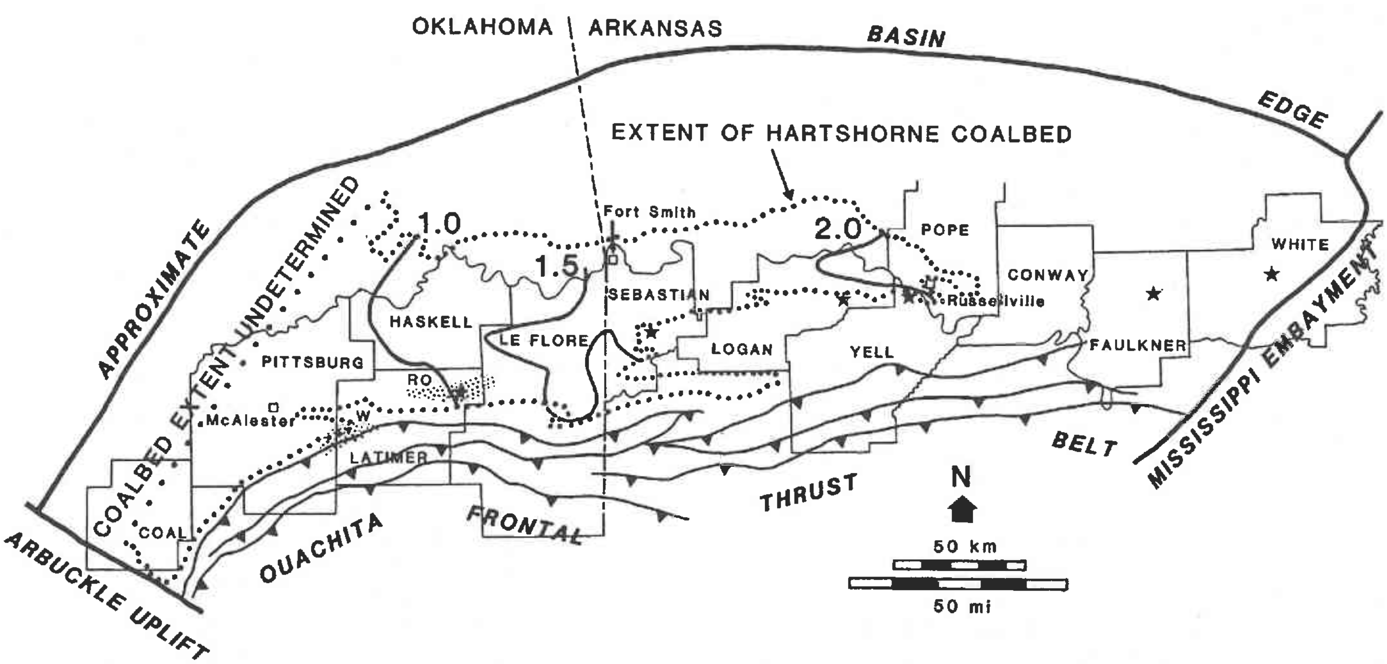


Figure 27. Hartshorne coal thermal maturity in the Arkoma Basin. Map shows maximum maturity for overlying Booch source rocks. Contours indicate percentages of vitrinite reflectance. From Houseknecht and others (1992).

area with the same potential coal and prodelta-shale source rocks implies that there is probably no difference in source-rock composition (Pls. 1–9).

The 100% Booch gas line is roughly parallel to the structural strike of the basin (Fig. 6). This implies a difference in thermal history between areas on either side of the line that could be related to proximity to Ouachita tectonism and/or maximum depth of burial. If so, then any oil that might have been generated south of the 100% gas line has been thermally cracked to gas. The viability of this explanation is hurt by the fact that most of the study area has Hartshorne R_o values of <1.0 (Fig. 27), which is not enough to convert all of the oil to gas (Fig. 26). Because heat flow was apparently insufficient to crack all oil to gas, the 100% gas line may in part be the result of variations in kerogen type and/or source rocks for Booch oil reservoirs.

Because many of the basin's best natural-gas source rocks are stratigraphically adjacent to Booch reservoirs, there is no need to invoke long-distance migration to explain Booch gas production. The Booch is offset by many large-scale reverse faults that gave it access to deeper (Atoka-age) source rocks through direct juxtaposition as well as vertical migration along fault planes. However, many productive Booch sandstones are stratigraphically isolated from these faults and thus had no access to deeper source rocks. This suggests that there must be at least some component of self-sourcing. If this is true, the gas generated in the Booch coals and prodelta shales could use adjacent fluvial sandstones as conduits to help charge any interconnected sands that may be updip.

Most lateral seals in the Booch are stratigraphic, but there are areas in which entrapment relies on fault seal. Both fault and stratigraphic trapping mechanisms are illustrated in the three field studies that follow. Faults often appear to be excellent seals, as evidenced by the ability of some to trap gas columns hundreds of feet thick. However, such seals are not universal; at least one fault in Pine Hollow South Field seems to be leaky. This means that if fault planes were ever avenues for gas migration, their ability to seal must have been episodic. If the underpressure that is observed in the Arkoma Basin is indeed the result of fluid movement along fault planes (Greg Hall, personal communication, 2004), this pressure bleed-off must also have occurred before migration of the gas that is currently trapped.

Reservoir

In the broadest terms, Booch reservoirs can be classified as either dip-parallel channel/valley-fill sands (with their associated overbank deposits) or strike-parallel nearshore-marine mouth-bar/tidal-channel/delta-front sands. Although paleostrike and dip were commonly close to present-day strike and dip, interval isopachs are necessary to confirm the "lay of the land" at the time of deposition. The regional map shown in Figure 28 has limited control and has lumped upper, middle, and lower Booch sandstones. For this reason it cannot begin to show the level of detail that exists in sandstone distribution, especially around paleoshorelines, where a variety of depositional environments exist in close proximity. (See the Reams Southeast and Pine Hollow South field studies.)

Reservoir quality is usually a function of the strength of depositional energy, giving the higher energy channel-fill sands an advantage over the tidally reworked nearshore-marine sands. For both, however, the best reservoir quality is preserved where early hydrocarbon migration retarded the growth of diagenetic cements. This is a common occurrence in oil and gas fields worldwide and is confirmed for the Booch in the reduced porosity observed in many fields below the gas–water contact (Houseknecht, 1992).

Although they contain coarser material, channel sands are more poorly sorted and have more detrital and diagenetic clays that tend to inhibit the growth of silica cement. Marine sands, which often have been reworked twice a day by tides, are better winnowed than channel fills and so have better nucleation sites for silica. This makes it easier for migrating formation waters to precipitate silica and thereby reduce porosity in marine sands (R. D. Andrews, personal communication, 2004). As a result, regardless of the size of the system, channel sands are almost invariably better reservoirs than nonchannel sands.

Almost all Booch sandstones can be classified as sublitharenites (Fig. 29). Their porosity is intergranular and represents more than one stage of precipitation and dissolution of authigenic cements, primarily silica and siderite (Fields, 1987). In spite of commonly being deposited in a nearshore-marine depositional environment, carbonate cement is rare. The thickest sandstones are found in channel fills, which, during periods of rapid incisement, can be stacked into wider and deeper valley fills tens of miles inland. Approaching the shoreline, the depth of incisement decreases until single-story distributary-channel-fill sands associated with the active delta plain are reached.

A donation of core analyses (~8,300) to the Oklahoma Geological Survey from Deep Rock Oil Company included ~200 analyses of Booch reservoirs. (A listing of these is included on the CD.) Although all of these analyses are for areas where the Booch is oil productive and were made for the purpose of waterflood evaluation, depths and environments of deposition are similar to those in the study area (Fig. 5). Because the wells cored are usually at least 40 years old and outside of the study area, they were not reviewed individually but are shown here for comparison purposes only.

The depths of the sandstone reservoirs that were analyzed are shallow, ranging from ~500 to 3,700 ft. The reservoirs show no relationship whatsoever between depth and porosity (Fig. 30), but this is not surprising given the narrow depth range in which the Booch occurs. A much better relationship can be seen between their maximum porosity and permeability (to water). The average values of porosity and permeability show the same relationship, but because a great deal of nonreservoir-quality core was analyzed, only the maximum values are shown (Fig. 31).

About 5% of the cores analyzed had maximum permeabilities above 1 darcy, 30% above 100 millidarcies (md),

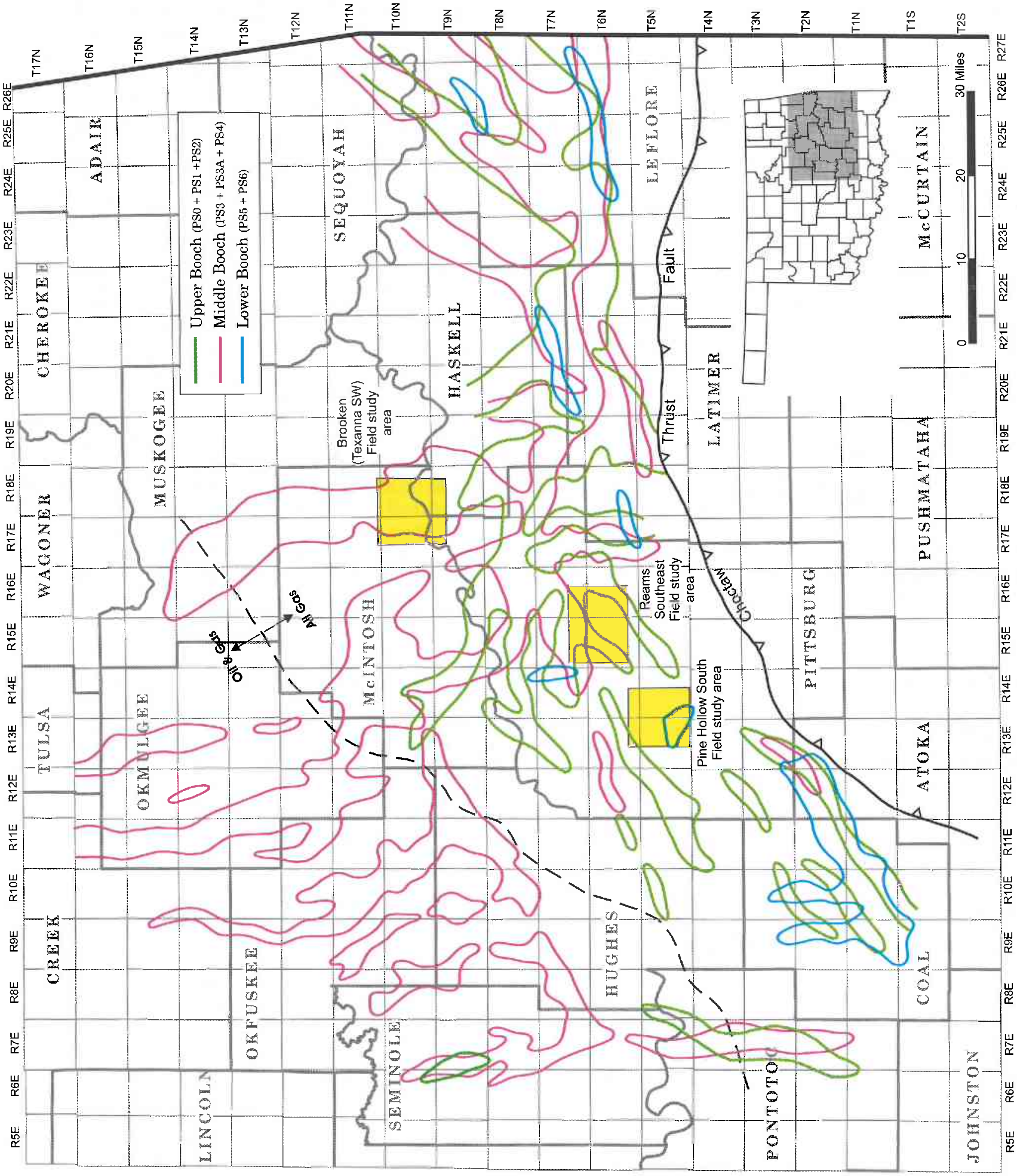


Figure 28. Map of Booch regional gross-sandstone isopach trends. Shown are major sandstone trends (>20 ft thick) for the upper, middle, and lower Booch as identified in the regional data grid.

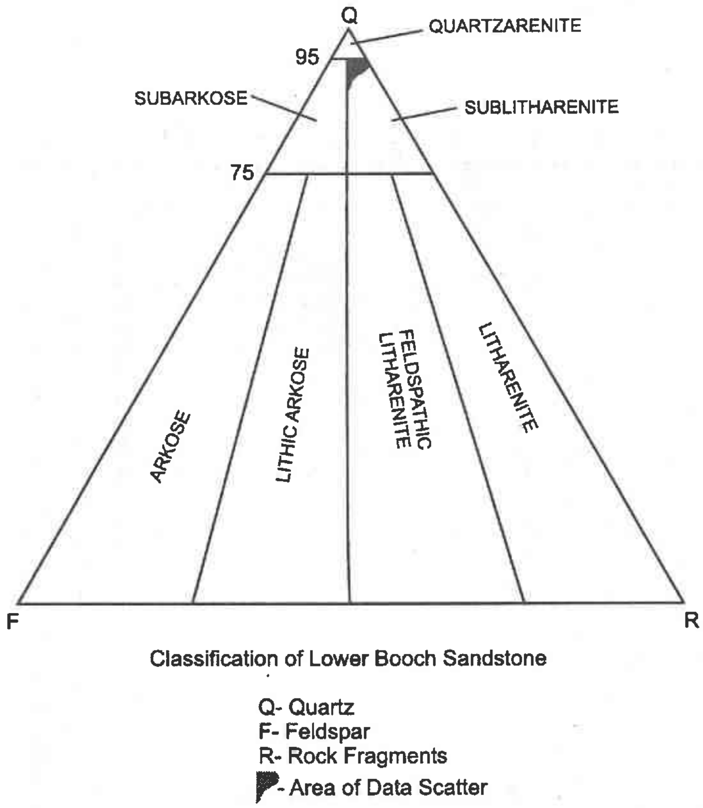


Figure 29. Classification of "lower" Booch sandstone. The quartz-rich sublitharenites analyzed here refer to the middle and lower Booch in this study. From Fields (1987).

and 50% above 50 md. A wide range of permeabilites is possible for a given porosity, but the trend of increasing permeability with porosity is apparent. In terms of permeability to water, at least 15% porosity is generally necessary to break the 10-md threshold. On the other end of the scale, 100+ md permeability is generally restricted to those sandstones with at least 20% porosity. It must be remembered that a rock that will barely permit the flow of water can be capable of producing high rates of natural gas. In most areas with normal or underpressured reservoirs, including the Booch in this study, an 8% porosity cutoff tends to be the industry standard in defining gas pay.

Trap

With rich, mature source rocks adjacent to reservoir-quality sandstones, the only remaining component of the Booch petroleum system is the trap. Because the Booch lacks anything that could be called a blanket sand, gas accumulations in the study area, even on large structures, invariably have a strong stratigraphic component. The faults and folds that were propagated into the Arkoma Basin as a result of Ouachita compression are responsible for much of the gas production in the basin, but these tend to be less critical to entrapment of less pervasive Booch sandstones. Because this compression occurred much later than Booch deposition, structure and stratigraphy are completely independent. This can make a closure that was overrun by one or more prograding

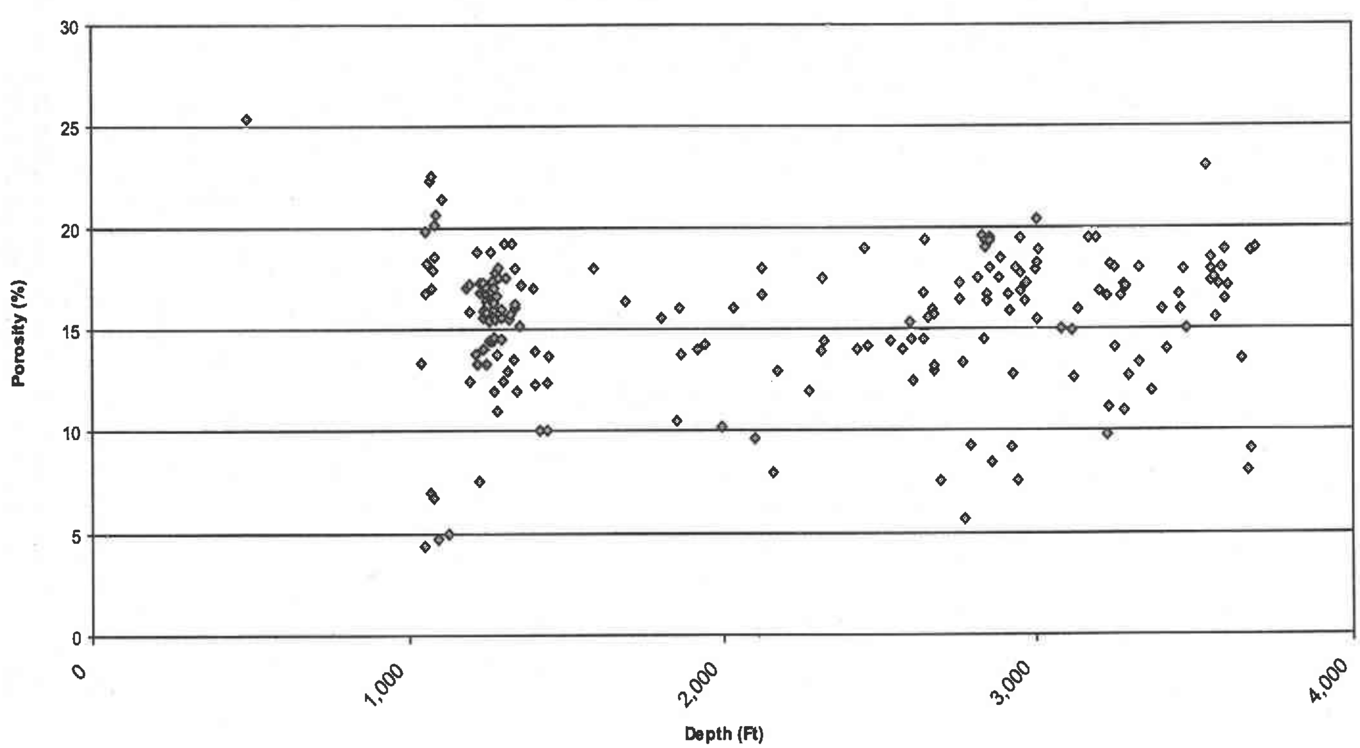


Figure 30. Average core porosity versus depth for Booch reservoirs. Variations in porosity are inferred to reflect differences in environment of deposition rather than compactional effects. Data taken from shallow oil reservoirs. See Figure 5.

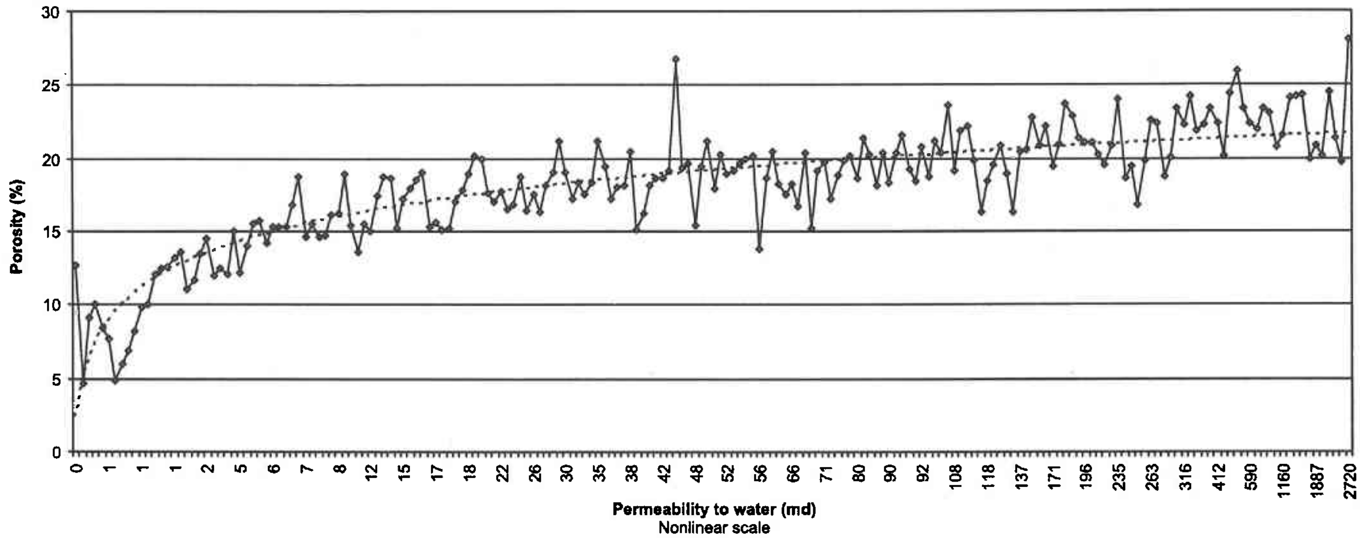


Figure 31. Maximum core porosity versus maximum permeability for Booch reservoirs. The bulk of Booch gas reservoirs are concentrated at the far left side of the graph where porosity is <15% and permeability is <10 md. Data taken from shallow oil reservoirs. See Figure 5.

delta systems a prolific gas producer, whereas a structure of the same size that was bypassed by these systems may be relatively barren.

This is not to minimize the importance of structure, but to show the critical effect of stratigraphy. Booch production in all three of the fields studied relies on a sealing fault or a structural closure, but the difference between excellent, marginal, and no production is the location, orientation, thickness, and quality of the sandstones present. Most Booch production seems to be associated with the large compressional structures present in the Arkoma Basin. However, Booch reservoirs are also capable of providing their own updip seal and forming pure stratigraphic traps away from large faults and folds. These more subtle traps highlight the fact that reservoir orientation relative to structural dip is the most critical aspect of Booch entrapment.

Production from Booch gas fields is invariably driven by pressure depletion. This is not surprising, given the generally discontinuous nature of the reservoir sandstones. For the lesser quality marine sands, permeability commonly is only high enough to allow gas to flow but not water. However, even for higher quality channel-fill sands or stacked channel fills as seen in Brooken (Texanna SW) Field (see field study), water movement still appears to be negligible. This could be a function of a relatively small water volume beneath the gas, but it is more likely related to the high compressibility of gas relative to water. This compressibility in high-quality, high-production-rate reservoirs permits rapid reservoir voidage and pressure reduction, which keeps water movement from ever becoming a problem.

The subsurface pressure gradient in the study area, extending in places from the base of the Atoka to the surface, is well below normal hydrostatic pressure (~0.43 psi/ft) (Greg Hall, personal communication, 2004). The Booch is severely underpressured in the areas studied, with an average gradient of ~0.23 psi/ft. This reduces the formation volume factor (B_g), which equates the number of standard cubic feet (scf) of gas that can occupy a reservoir cubic foot (rcf). This has the effect of reducing both the gas initially in-place and reserves by roughly 50% from what could be produced from a normally pressured reservoir. Low initial reservoir pressures also reduce flow rates and necessitate gas compression earlier in the producing life of a field. The generally dry nature of the produced gas and the lack of water production discussed previously make the need for compression of Booch gas reservoirs in the study area almost universal (Greg Hall, personal communication, 2004).

PART II

Field Studies

Brooken (Texanna SW) Field

INTRODUCTION

Brooken Field, like most fields in Oklahoma, is an amalgam of smaller fields that produce from a variety of reservoirs, which, for accounting purposes, have been combined into a large, irregular field outline. As currently configured, Brooken Field encompasses ~100 mi^2 in four counties and includes the old Featherston NW, Hoyt–Haskell E, Russellville N, Texanna, and Texanna SW Fields (Boyd, 2002). This field study is concerned only with Booch production in Brooken Field, specifically that part north of Lake Eufala that was originally called Texanna SW Field (Fig. 32). The average productive depth for this part of greater Brooken Field is 1,300 ft.

Exploration in the Brooken area began in 1924, with Brooken Field proper discovered in 1929. The discovery

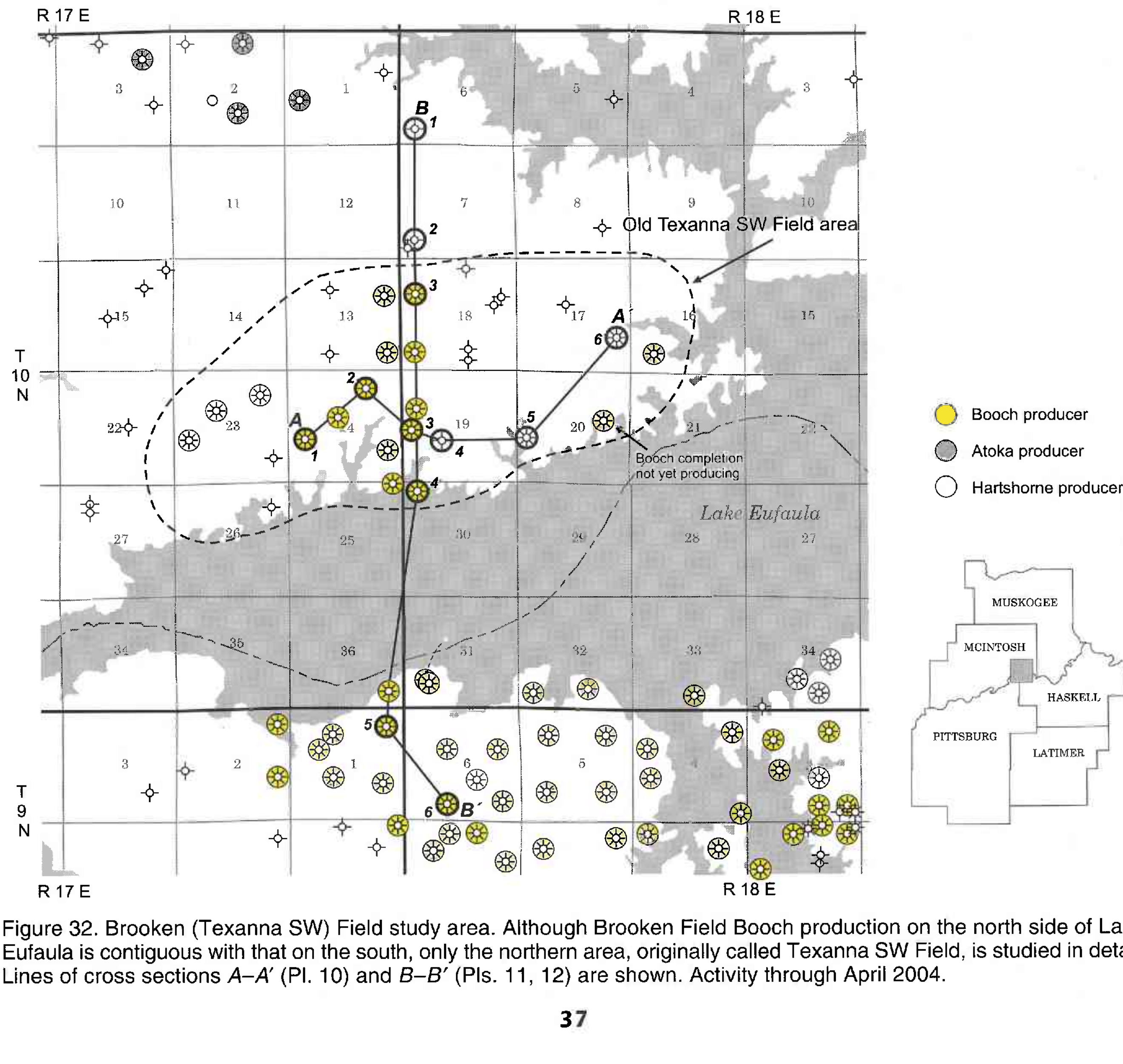


Figure 32. Brooken (Texanna SW) Field study area. Although Brooken Field Booch production on the north side of Lake Eufaula is contiguous with that on the south, only the northern area, originally called Texanna SW Field, is studied in detail. Lines of cross sections *A–A′* (Pl. 10) and *B–B′* (Pls. 11, 12) are shown. Activity through April 2004.

of the largest producing reservoir, the middle Booch sandstone, did not occur until 1980 with the drilling of the Sun Oil No. 1 Fitzer in sec. 4, T. 9 N., R. 18 E. (Bowker and Seale, 1985). Drilled on the downthrown side of the Warner Horst and on the southern shore of an arm of Lake Eufala, this serendipitous Hunton test discovered the largest accumulation of Booch gas ever found.

The "discovery" of stratigraphically equivalent production on the northern side of the lake occurred in September 1981. The Cities Service No. 1 Nixon, drilled in sec. 24, T. 10 N., R. 17 E., confirmed that the reservoir extended beneath the lake. Although given a different field name (Texanna SW) and initially believed to be fault-separated from the discovery to the south, this productive area is now believed to be in direct pressure communication with production south of the lake.

STRATIGRAPHY

The middle Booch pay sandstone in the Brooken Field area was deposited during the period of fluvial incision described in the regional discussion. Brooken Field sits squarely on one of the largest incised valleys that were created during this time (Fig. 28). Such valleys are formed during major periods of regression, when fluvial systems rapidly downcut to keep pace with falling sea level. Incision is much wider and deeper than that seen near or within the delta, although at any given time the active channel occupies only a small part of the total valley. Channel-fill sands tend to concentrate in the middle of the valley, where they erode into underlying sands and create continuous reservoirs that are commonly >150 ft thick. Within the incised valleys some elongate areas oriented parallel to the flow direction occur that are not as deeply incised as those on either side—perhaps marking areas that active channel flow tended to bypass. Along the flanks of the valley, flood-plain shales predominate, although these areas commonly contain isolated channel-fill sands (Fig. 33).

The interval of incisement can be much thicker than the sandstone itself if some of the channel-abandonment facies (clay plug) or flood-plain shales are preserved.

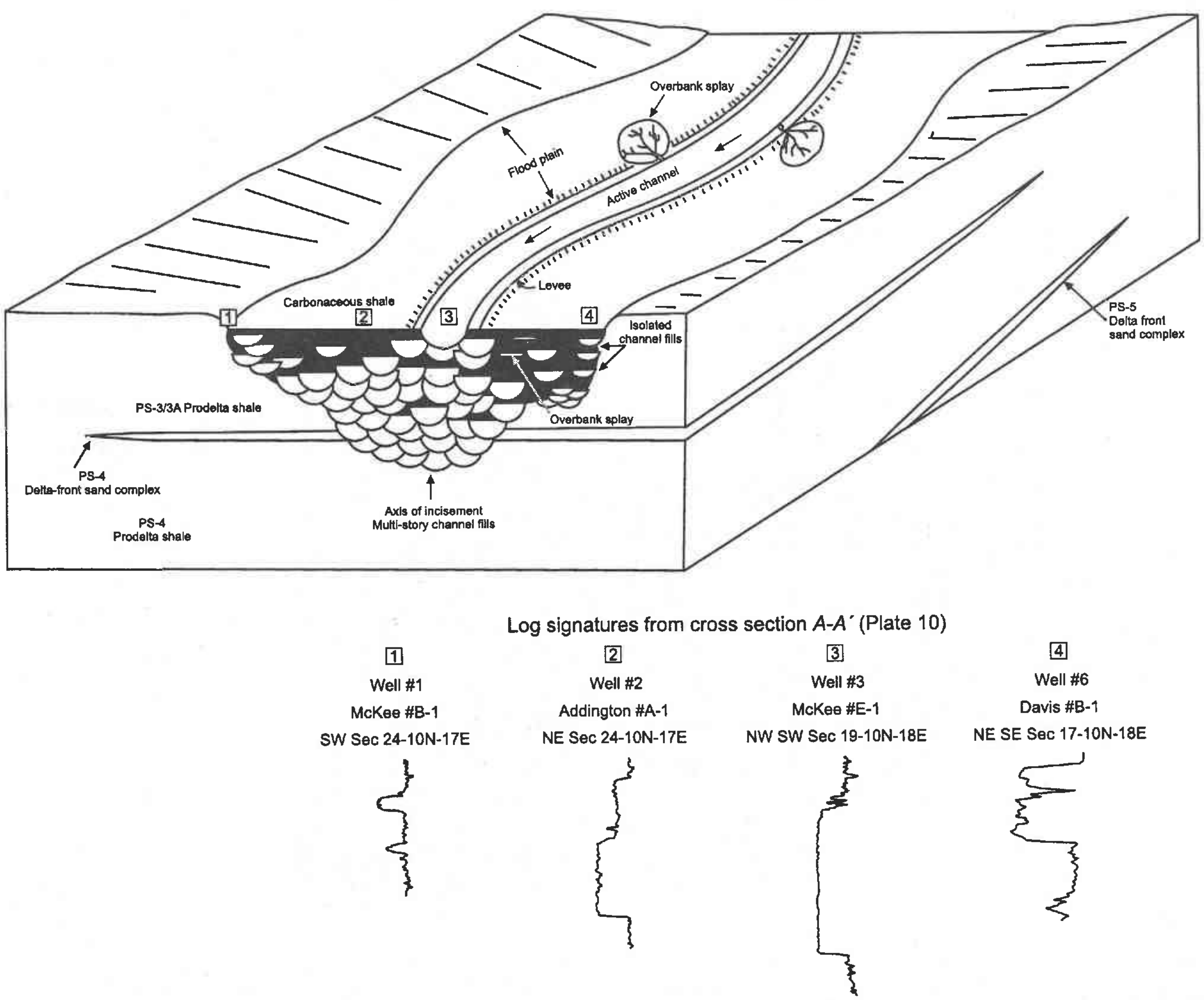


Figure 33. Block diagram of an incised valley. This depiction is based on the Brooken (Texanna SW) Field middle Booch reservoirs. Log signatures from various parts of the incised valley are from cross section *A–A′* (Pl. 10).

Usually present at the top of the incised interval, valley-fill shale can be distinguished from the overlying marine shale by its lower gamma-ray (cleaner) reading and slightly higher resistivity. The clay drape separating single sands also can be preserved, but this is usually no more than 1–2 ft thick (see well 2 in Pl. 10).

Total incisement in the field study area can be >200 ft, with >150 ft of sandstone commonly preserved (Fig. 34). These thick sands do not represent single depositional episodes, but rather multiple channel-fill/abandonment successions. Because each of these sands has an erosional base, the overlying channel sand has usually removed the clay drape that is commonly left behind after channel abandonment. This creates a relatively uniform and clean gamma-ray log. However, because successive sandstones in a single location (wellbore) have usually

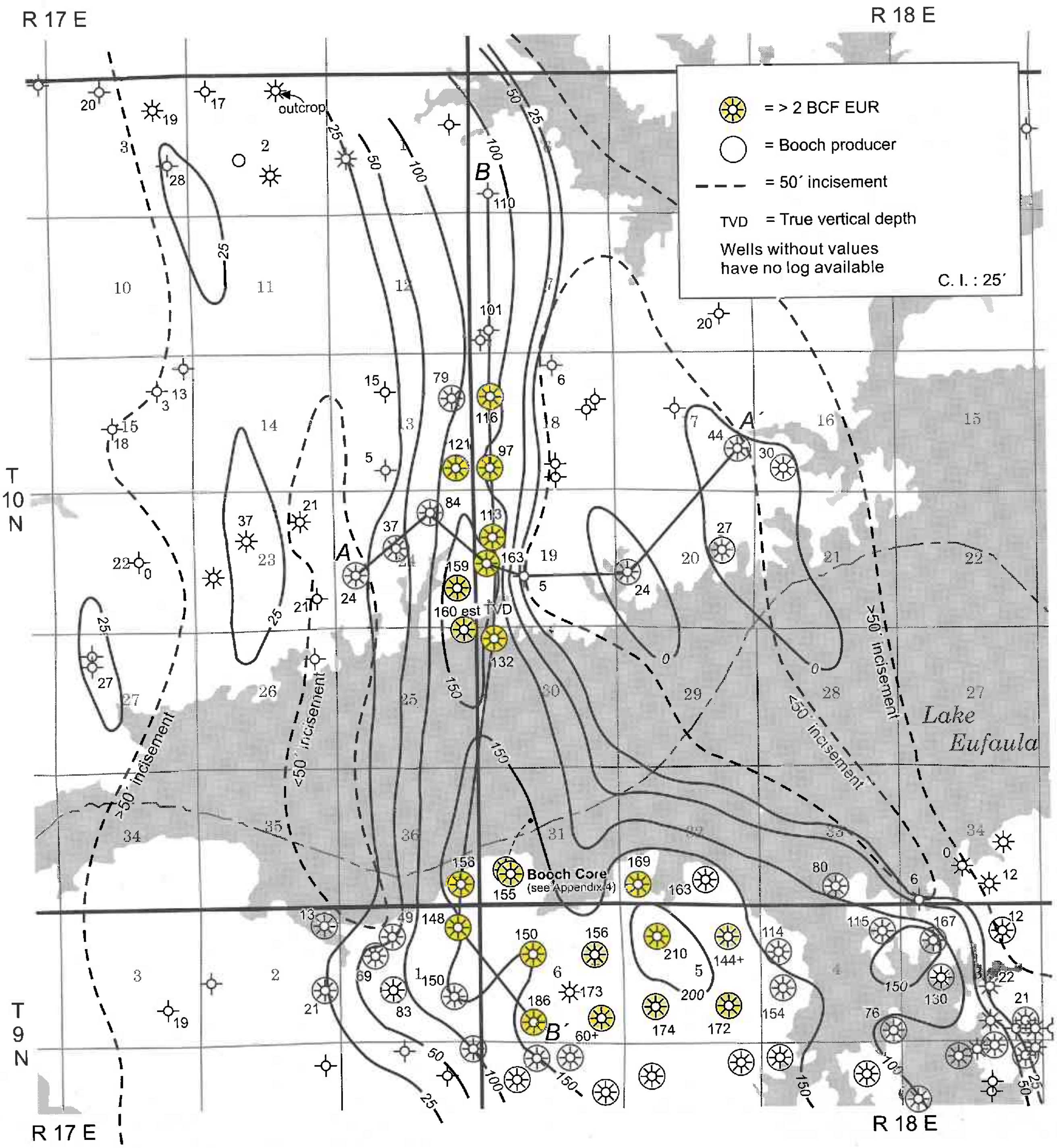


Figure 34. Middle Booch net-sand isopach map and incisement depths (in feet). Dotted lines encompass areas of >50 ft of fluvial incisement. This area is much larger than the sand fairway, which here is defined as having more than 25 ft of net sand and is depicted with solid lines. *EUR*—estimated ultimate recovery.

been deposited under slightly different energy conditions, they are not identical, and individual channel fills often can be distinguished by their density-log response (Fig. 35; Pl. 11). Individual channel fills in these stacked sequences are seldom >30 ft thick.

Not all of the productive middle Booch sandstones are connected to the part located along the axis of incision. The area in which at least 50 ft of middle Booch incisement has taken place in Brooken Field is much larger than the area in which the main reservoir sandstone is present (Fig. 34). Isolated one- and two-story channel-fill sands are productive on both sides of the main field area (Pl. 10). In the area north of the lake these sandstones produce from wells in the following locations: SW¼ sec. 24, T. 10 N., R. 17 E.; SW¼ sec. 20, T. 10 N., R. 18 E.; SE¼ sec. 17, T. 10 N., R. 18 E.; and SW¼ sec. 16, T. 10 N., R. 18 E. (The well in the NE¼ sec. 20, T. 10 N., R. 18 E., is a Booch completion but is not yet producing.) Although reservoir quality in these wells is not as good as that seen in the rest of the field, because they are isolated from the rest of the field, they have not been drained by this production. Their projected drainage area is comparatively small, but the average per-well recovery, from a depth of 1,300 ft, is still a healthy 250 MMCF.

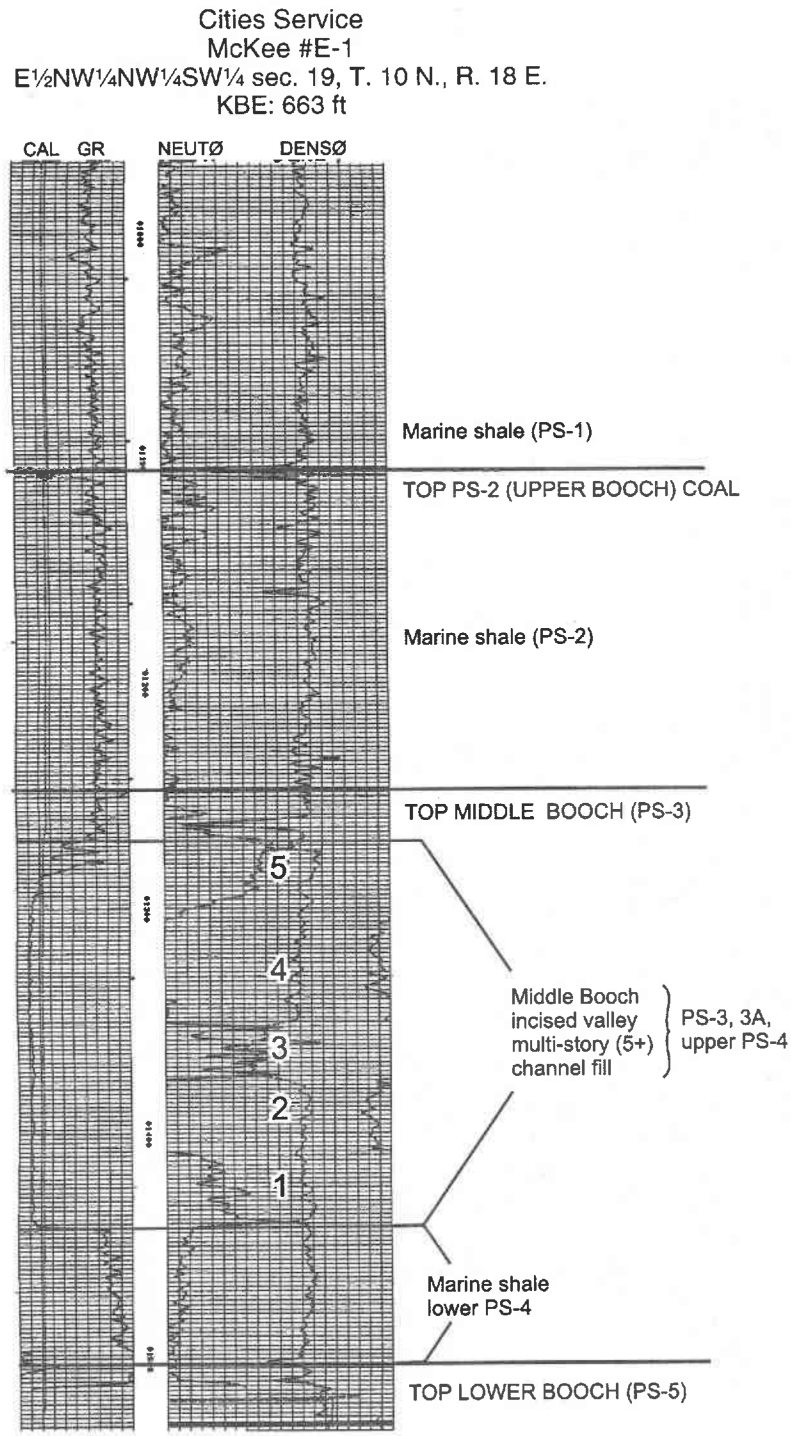


Figure 35. Booch type log for Brooken (Texanna SW) Field. Cities Service No. E-1 McKee, E½NW¼NW¼SW¼ sec. 19, T. 10 N., R. 18 E., Muskogee County (well #3 on Pl. 10).

There are few outcrops of Booch incised-valley sandstones, probably owing to their relative lack of silica cement and resultant friability. In core and cuttings, the middle Booch sandstone in Brooken Field is white to tan, poorly sorted (coarse to fine grained), and angular to subrounded. Like the rest of the Booch, calcium carbonate is practically nonexistent, with quartz acting as the main cementing agent with some siderite. The sandstone has a uniformly sharp basal contact, indicating rapid initial deposition, with fining-upward sequences apparent in many of the individual channel fills. These exhibit planar and trough cross-stratification that commonly contains coal and shale clasts (Bowker and Seale, 1985). The reservoir quality is excellent, with a maximum porosity of ~25% in the center of the valley fill and corresponding permeability ranging up to 1,300 md.

STRUCTURE

Brooken Field is located on the southwestern flank of the Ozark Uplift, south of the south-bounding fault of the Warner Horst (Fig. 8). This fault at the top of the middle Booch has a vertical displacement of 400–500 ft where it crosses the productive sandstone (Fig. 36). This has exposed the erosionally resistant intervals of the upper and middle Booch on the surface of the Warner Horst just north of the field. Apart from the general shallowing trends to the north and east in the direction of the Cherokee Platform and the Ozark Uplift, no prominent structural features (except the fault) exist in this part of Brooken Field.

A lack of well control makes it difficult to reliably connect the areas north and south of the lake, although a mild structural low does appear to exist under the lake. A fault between the northern and southern areas cannot be ruled out, especially in this area of relatively high

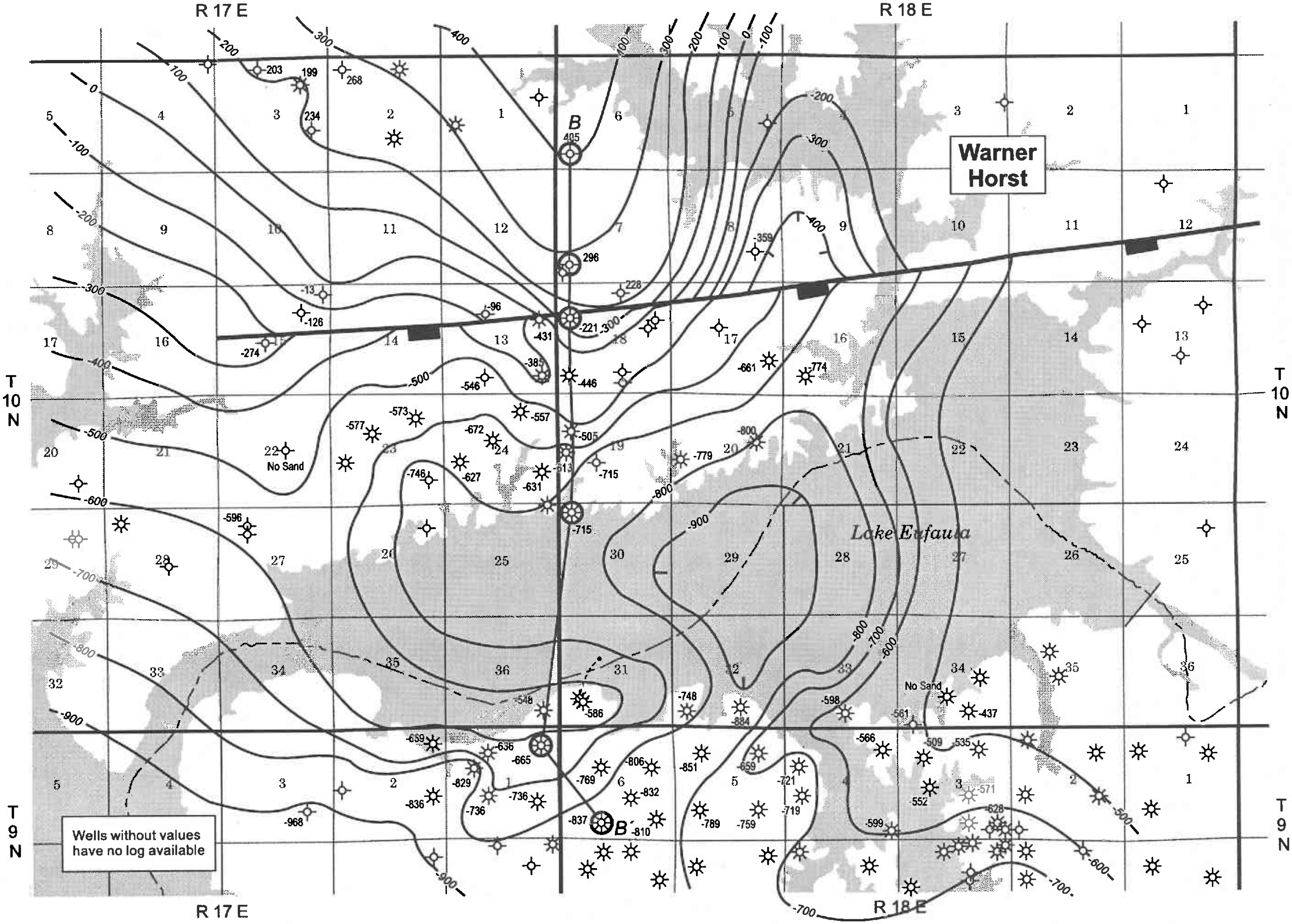


Figure 36. Structure-contour map from the top of the middle Booch sandstone in Brooken (Texanna SW) Field. The lack of well control under the lake makes the interpretation here speculative.

structural relief. However, pressure separation would require a sealing fault with at least 200 ft of throw. Similar structural elevations and pressure histories on both sides of the lake make the presence of such a fault unlikely.

Booch gas is trapped at Brooken as a result of a fault trap created on the southern margin of the Warner Horst (Pl. 12). Displacement on this fault is enough to place the downthrown productive sandstone well below the Booch and Hartshorne sandstones on the upthrown side of the fault. This juxtaposes the productive middle Booch everywhere against upthrown Atoka sediments (Fig. 37). This leaves open the possibility that Atoka shales may have been at least a partial source of Booch reservoir gas.

Given that the field fault has sufficient sealing capacity to hold a gas column >700 ft thick, it is not certain what impact minor sand-on-sand juxtaposition might have had on seal integrity. However, without the fault there would be no trap, and migrating gas would have continued through the sandstones that are present on the Warner Horst and probably leaked to the surface. The trap that was created is elongate, with fault-seal updip and stratigraphic seal on both sides of the productive valley-fill sands. The downdip gas–water contact is 3–4 mi south of the study area at a depth of about –944 ft (Pl. 12).

PRODUCTION AND VOLUMETRICS

For all but one well, the first production from Booch sandstones in Brooken Field began for the area north of the lake in December 1984 (Table 1). Production in the southern area began in late 1982, although the wells closest to the lake did not go on-line until March 1985. Because neither side had a significant head start, it is assumed that the drainage limit for the two sides of the main field reservoir lies roughly in the middle of the lake, i.e., along the southern border of sections 25 and 30. Volumetric estimates of the gas in-place for the Booch in Brooken North (Texanna SW) Field are for the area north of this divide (Fig. 38). The volumetric parameters calculated are shown in Table 2.

The sandstone in most of this field is of such high quality that net and gross thicknesses using an 8% porosity cutoff are essentially the same. A thick gas column with a gas–water contact far to the south means that all net sandstone north of the lake and south of the fault is gas pay. Water saturations were calculated on the basis of a formation-water resistivity that was determined to be 0.065 ohm-m. This value is indicative of water that is fresher than normal seawater and is not unexpected, given the

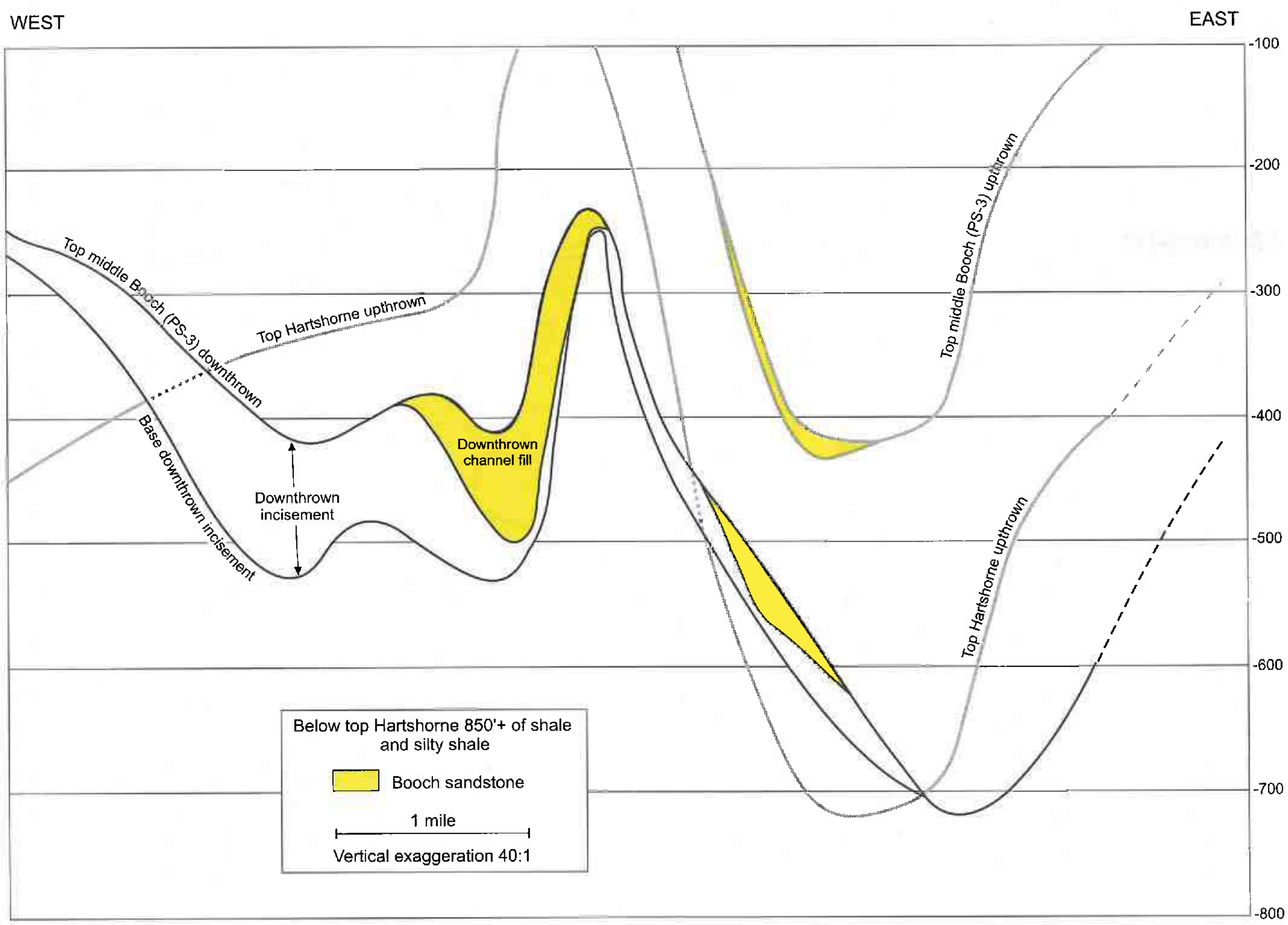


Figure 37. Brooken (Texanna SW) Field fault-plane cross section, showing the stratigraphic juxtaposition along the south-bounding, trapping fault of the Warner Horst. Upthrown tops are in gray; downthrown are in black. Depths are in feet.

TABLE 1. — Booch Gas Production from Brooken North (Texanna SW) Field

Lease name	Well no.	Operator name	Location	Cum. (MCF)	Latest mo. (MCF)	First prod. date
Pinney A	1	GM Properties & Investments Inc.	sec. 13, T10N, R17E C SE¼SE¼	3,178,025	470	1984/12
Grosclos	1	Kerr-McGee Corporation	sec. 13, T10N, R17E SE¼NW¼SE¼NE¼	1,035,746		1984/12
Addington A	1	GM Properties & Investments Inc.	sec. 24, T10N, R17E SE¼NW¼NE¼	1,664,449	251	1984/12
McKee B	1	GM Properties & Investments Inc.	sec. 24, T10N, R17E W½E½NW¼SW¼	186,662	348	1984/12
Nixon A	1	GM Properties & Investments Inc.	sec. 24, T10N, R17E S½S½NE¼SE¼	3,931,078	1,632	1984/12
McKee C	1	GM Properties & Investments Inc.	sec. 24, T10N, R17E SE¼SE¼NW¼	123,162	1,196	1984/12
Army Corps of Eng. A	1	GM Properties & Investments Inc.	sec. 25, T10N, R17E NW¼NE¼NE¼NE¼	3,811,129	1,778	1984/12
Kinney-Gray A	1	GM Properties & Investments Inc.	sec. 18, T10N, R18E S½N½SW¼NW¼	3,674,033	699	1984/12
Brinsfield A	1	GM Properties & Investments Inc.	sec. 18, T10N, R18E C SW¼SW¼	3,437,319	913	1984/12
McKee E	1	GM Properties & Investments Inc.	sec. 19, T10N, R18E E½NW¼NW¼SW¼	4,625,130	2,038	1984/12
McKee D	1	GM Properties & Investments Inc.	sec. 19, T10N, R18E C SW¼NW¼	3,966,978	1,070	1984/12
Army Corps of Eng. B	1	GM Properties & Investments Inc.	sec. 30, T10N, R18E C NW¼NW¼	4,121,345	1,262	1984/12
Total for main Brooken North		12 wells avg. 2.9 BCF and 35 MCFPD/well, 9/03 **EUR: ~34,500 MMCF**		33,755,056	11,657	
Isolated Brooken North Channels						
Haskett A	1	GM Properties & Investments Inc.	sec. 16, T10N, R18E NE¼SW¼SW¼	392,020	1,245	1984/12
Davis B	1	GM Properties & Investments Inc.	sec. 17, T10N, R18E S½NE¼SE¼	322,869	1,152	1984/12
		EUR: ~850 MMCF		714,889	2,397	
Rebecca	2	Drake Exploration Incorporated EUR: ~90 MMCF	sec. 20, T10N, R18E NW¼NW¼SW¼	50,845	660	1998/04
Total for remainder of Brooken Booch **Brooken (proper) — south of the lake**		54 wells @ 1.36 BCF/well, 33 MCFPD/well, 9/03 **EUR: ~76,000 MMCF**		73,500,000	38,500	

NOTE: Data from IHS Energy (through September 2003). EUR — estimated ultimate recovery.

fluvial environment in which these sands were deposited.

A source of uncertainty in all Booch volumetric calculations concerns the pressure gradient and the formation volume factor (B_g) that results. A normal hydrostatic gradient is ~0.43 psi/ft, but using the reported Brooken bottom-hole pressures, gradients as low as 0.17 psi/ft are calculated. This reduces the B_g and the initial gas in-place to a volume significantly below what has already been produced.

Almost all of the reported bottom-hole pressures in the State are not measured but are calculated on the basis of shut-in tubing pressures (Greg Hall, personal communication, 2004). As a result, any fluid (water or condensate) that may accumulate at the bottom of the tubing will reduce both the calculated bottom-hole pressure and the pressure gradient. Circular reasoning notwithstanding, if the initial bottom-hole pressure in this part of Brooken Field is assumed to be ~300 psi (a 0.23 psi/ft gra-

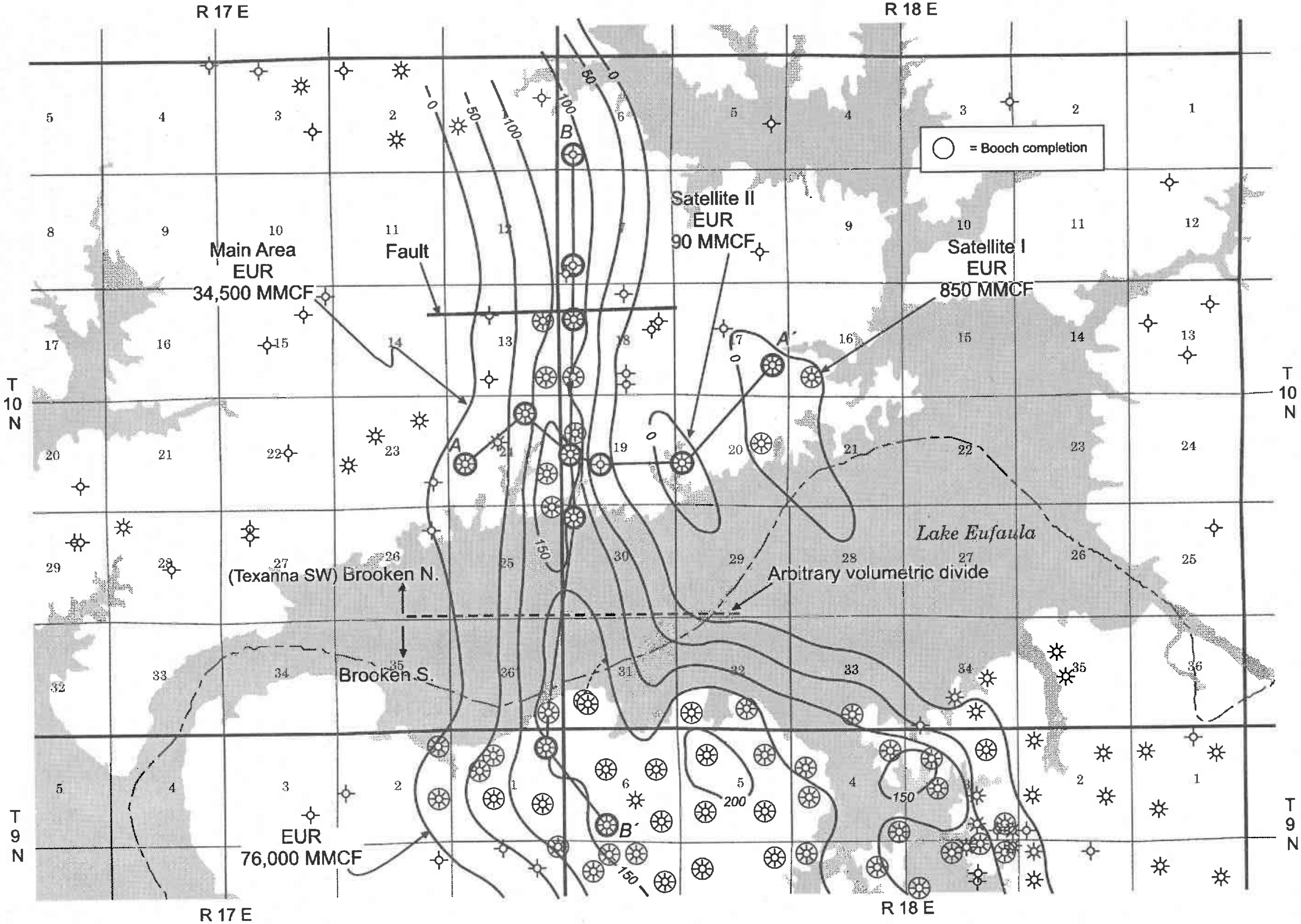


Figure 38. Brooken (Texanna SW) Field volumetrics map. The productive area for this part of the field has been defined as extending from the trapping fault to the north, to an east–west line placed in the middle of the lake, equidistant between producing wells north and south. The two smaller areas to the east are not in communication with the central channel system. *EUR*—estimated ultimate recovery.

TABLE 2. — Brooken North (Texanna SW) Field Booch Volumetric Parameters

Net sand	Avg. net sd	Area (ac.)	Avg. por.	Avg. Sg[a]	Pore vol. (ac. ft.)
Main area:					
0–50 ft	15 ft	1,223	10%	70%	1,284
50–100 ft	75 ft	667	18%	80%	7,204
100–150 ft	125 ft	670	21%	85%	14,949
>150 ft	160 ft	287	24%	90%	9,919
				Total	33,356
Satellite I area:	37 ft	480	10%	70%	1,243
Satellite II area:	18 ft	229	8%	60%	198

[a]Gas saturation.

TABLE 3. — Brooken North (Texanna SW) Field Booch Gas Volumes in BCF

Interval	Gas IIP	Cum. prod.	EUR	Proj. R.F.
Main area:	40.684	33.76	34.50	85%
Satellite I:	1.516	0.72	0.850	56%
Satellite II:	0.241	0.05	0.090	37%

IIP — initially in-place. EUR — estimated ultimate recovery. Proj. R.F. — projected recovery factor.

dient), which is the maximum pressure recorded, the resulting B_g of 28 scf/rcf allows reasonable recovery factors to be calculated. Table 3 summarizes the gas-in-place volumes calculated and the production (in BCF) for the Booch in Brooken (Texanna SW) Field.

Excluding isolated satellite accumulations, the Booch in all of Brooken Field is projected to produce ~110 BCF, of which 107 BCF has already been produced. Remaining recoveries are calculated simplistically by maintaining the latest month's production rate for 5 years. The projected 85% recovery factor for the northern part of the field studied, although high, is not unexpected, owing to the excellent reservoir quality and the ability of operators, through compression, to reduce bottom-hole pressures to below 30 psi. Although now producing only 35 MCFPD per well, the 12 wells north of the lake that are mapped as producing from the main channel sequence have an average ultimate recovery of nearly 2.9 BCF (Table 1). Note: Owing to its proximity to the main valley fill, the Cities Service No. B-1 McKee (SW¼ sec. 24, T. 10 N., R. 17 E.) is included in the volumes calculated for the main channel sequence, although it is not believed to be in communication (see Pl. 10).

Volumetrics for the isolated channel sands within the area of incision (Satellites I and II) can be only crude approximations (Fig. 38). Because they are defined by one or two wells, their thickness, areal extent, and overall reservoir quality can be only rough approximations. The reservoir volumes that were calculated project recovery factors that decrease, as expected, with reservoir quality. However, one would need a better knowledge of the reservoir limits and the well-drainage radius before considering infill drilling to improve recovery.

LESSONS LEARNED

There are certainly no Booch gas accumulations left that are the size of Brooken Field. This field is unique, with stacked channel-fill sands up to 200 ft thick that were deposited in an incised valley up to 10 mi wide. However, Brooken has helped to define a closely related Booch gas play that is still far from fully explored. This is one that targets the channel-fill sands within the incised valley that are isolated from the main depositional axis. These sandstones form pure stratigraphic traps, and being fully encased in interdistributary shales they are immune to depletion from nearby production (Fig. 33).

The Brooken incised valley is only one of several that have been mapped (Fig. 28). For most of these the area that has been incised is much wider than that occupied by the main sandstone depositional axis. This leaves broad areas in which channel sands, charged with gas and/or oil, can exist at virgin pressure. Although these reservoirs have historically been found by accident, it should be possible to identify undrilled sandstones through the use of shallow-investigation (high-frequency) seismic data. This exploratory method could be pursued using a widely spaced (~0.5-mi) two-dimensional (2-D) grid in prospective valley-fill areas, or a vertical seismic profile (VSP) where a well is believed to have clipped the edge of one of these sandstones.

Although per-well recoveries are relatively modest (100–400 MMCF), this play is especially viable for the Booch because isolated channel sands in these incised valleys are usually relatively thick, and the depths are shallow. This reduces well costs and economic recovery volumes, and also improves the likelihood that seismic techniques will be able to distinguish sandstone from shale. Once seismic-evaluation techniques are refined through drilling, the risk associated with finding these isolated sandstones should markedly decrease.

Reams Southeast Field

INTRODUCTION

Reams Southeast Field is composed of the old Reams, Canadian S, McAlester NE, and Rheams Fields, and encompasses ~14 mi^2 in central Pittsburg County (Boyd, 2002) (Fig. 39). The field was discovered in 1915 by the Choctaw Natural Gas No. 1 Z.M. Short well, a Hartshorne producer drilled in the SE¼ sec. 1, T. 6 N., R. 15 E. The lack of a gas market postponed significant Hartshorne development until the mid-1970s, which led to the discovery and development of the shallower Booch reservoirs. The three primary Booch reservoirs have average productive depths that range from 1,300 to 1,500 ft. Production from the Booch was first established in 1975 by the Great Basin Petroleum Company No. 2A D. Silvia well, drilled in the SW¼ sec. 11, T. 6 N., R. 15 E. (IHS Energy, 2004).

Reams Southeast Field now contains 22 Hartshorne producers (+3 commingled), 9 Booch producers (+2 commingled), 3 Atoka (Spiro) producers (+2 commingled), and a single Savanna producer (Fig. 39). Dry holes within the field area either lack reservoir in any of the productive intervals or were drilled before a viable market existed for natural gas. The filling of Lake Eufala has led to the drilling of multiple wells from identical, or nearly identical, surface locations on the shoreline in which some are vertical and others have been directionally drilled under the lake. This practice, combined with operators entering old wells to complete new zones or to recomplete depleted zones, has led to multiple production volumes being entered for wells with identical locations (same well, different operator; same surface location and operator, different bottom-hole location, etc.). This situation, combined with inconsistent reservoir identification by some operators, has made unraveling the drilling/completion/production history of Reams Southeast Field especially difficult. Booch production was confirmed with perforation depths, and where wells were reentered, sidetracked, or recompleted, production was assigned on the basis of the well's surface location (IHS Energy, 2004).

STRATIGRAPHY

Reams Southeast Field, like Brooken Field, has been developed near and along the shores of Lake Eufala. However, it is far more complex stratigraphically, producing from a variety of sandstones that reside in three separate parasequences in the upper and middle Booch. The maps constructed combine all of the sandstones that are present within a given parasequence. Individual sandstone trends and environmental interpretations could be refined if each of the correlatable sandstones present in each parasequence were mapped separately. Although 48 mi^2 was mapped, including a large area around the field, many intriguing things seem to have happened just beyond the mapped area. It is a geologic axiom that in any complex area, confidence in the interpretation can always be improved by expanding the area as well as subdividing (where possible) the reservoirs that are mapped.

Reams Southeast Field is still being drilled, and in early 2004 when this study was done, there were a number of wells for which logs are not yet available. For those wells with logs, a full suite is seldom available, which sometimes forces qualitative estimates of gross and net sandstone. Where a gamma-ray log is not available, gross sandstone is estimated on the basis of SP and resistivity values. Net sandstone must have a porosity >8%, but where porosity logs are not available (which is common), net-sandstone calculations are based on SP and/or microlog/resistivity-log separation.

In some cases an interval that falls below the gamma-ray cutoff for gross sandstone exhibits >8% porosity (sometimes with neutron/density crossover). In a marine environment this can be caused by a thin-bed effect in which shale laminations in a generally sandy interval create an average gamma-ray reading that falls below the gross-sandstone cutoff. In a channel-fill setting the same effect can be caused by the presence of shale rip-up clasts, which are commonly seen in outcrops and cores of Booch channel-fill sands (Fig. 40). To avoid the problem of having some wells with more net sandstone than gross, or having producers with no net sandstone, intervals with >8% porosity and significant neutron/density crossover are counted as both net and gross sandstone.

In the Reams Southeast Field area the lower and lower middle Booch intervals, represented by PS-4 through PS-6, contain virtually no sandstone. This is the result of a depositionally distal location through this time interval and not having the good fortune of being overridden by any of the few delta complexes that did prograde this far into the basin. In PS-3/3A time, sea level was generally lower, allowing the higher energy fluviodeltaic and nearshore-marine environments to predominate and a variety of reservoir-quality sandstones to be deposited. These environments include channel fills (some stacked to 100 ft) with associated overbank splay sands, as well as a variety of tidal-channel, mouth-bar, and other delta-front sands. This is why Booch production in Reams Southeast Field is only from PS-3/3A and stratigraphically higher parasequences (Pls. 13, 14).

In order of deposition, the first interval of economic interest is the middle Booch PS-3/3A package. This sequence is composed mostly of nearshore-marine sediments that rest on a 500-ft interval of PS-4 through PS-6 prodelta shales. In some places the PS-3 and 3A parasequences seem to represent two distinct progradational events and are easy to separate. Here, the overlying PS-3 appears to be a continuation of the progressively shallower deposition seen in PS-3A, usually containing more sand and in some places a distributary channel at the top (Fig. 41).

The cleaner sandstones at the top of PS-3 are seldom >20 ft thick and exhibit no large-scale incision. They form the bulk of the net sandstone present in the PS-3/3A interval, are responsible for all of its production, and are oriented in a generally east–southeasterly direction (Fig. 42). The identification of these sandstones as distributary channels is supported by their log shape, their location at

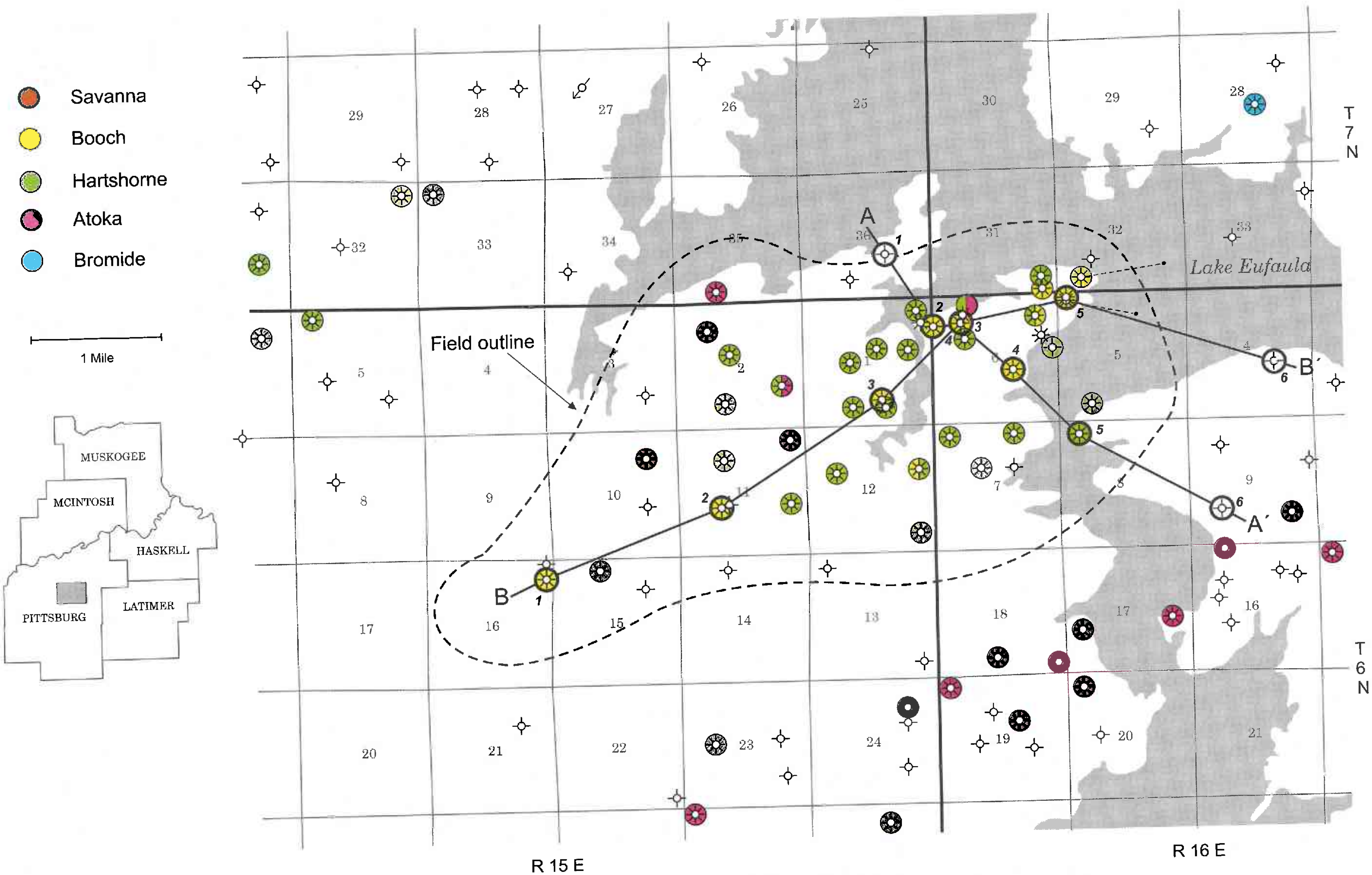


Figure 39. Map of Reams Southeast Field study area and production. Lines of cross sections *A–A′* (Pl. 13) and *B–B′* (Pl. 14) are shown. Activity through April 2004.

the top of a delta-front sequence, and a perpendicular orientation to a paleostrike that trends generally west-southwest (Fig. 43). Although there is no well confirmation, the distributary-channel system that crossed the field during PS-3/3A time is mapped as continuing through the field and taking a more eastward turn under the lake. It is possible that existing well control may mark the point of maximum progradation for this particular delta system and that only a mouth-bar complex lies east of sec. 5, T. 6 N., R. 16 E. This alternative interpretation may be supported by the abrupt termination of the southern arm of the distributary system in the SE¼ sec. 6, T. 6 N., R. 16 E. (Pl. 13). In either case, volumetric calculations are unaffected.

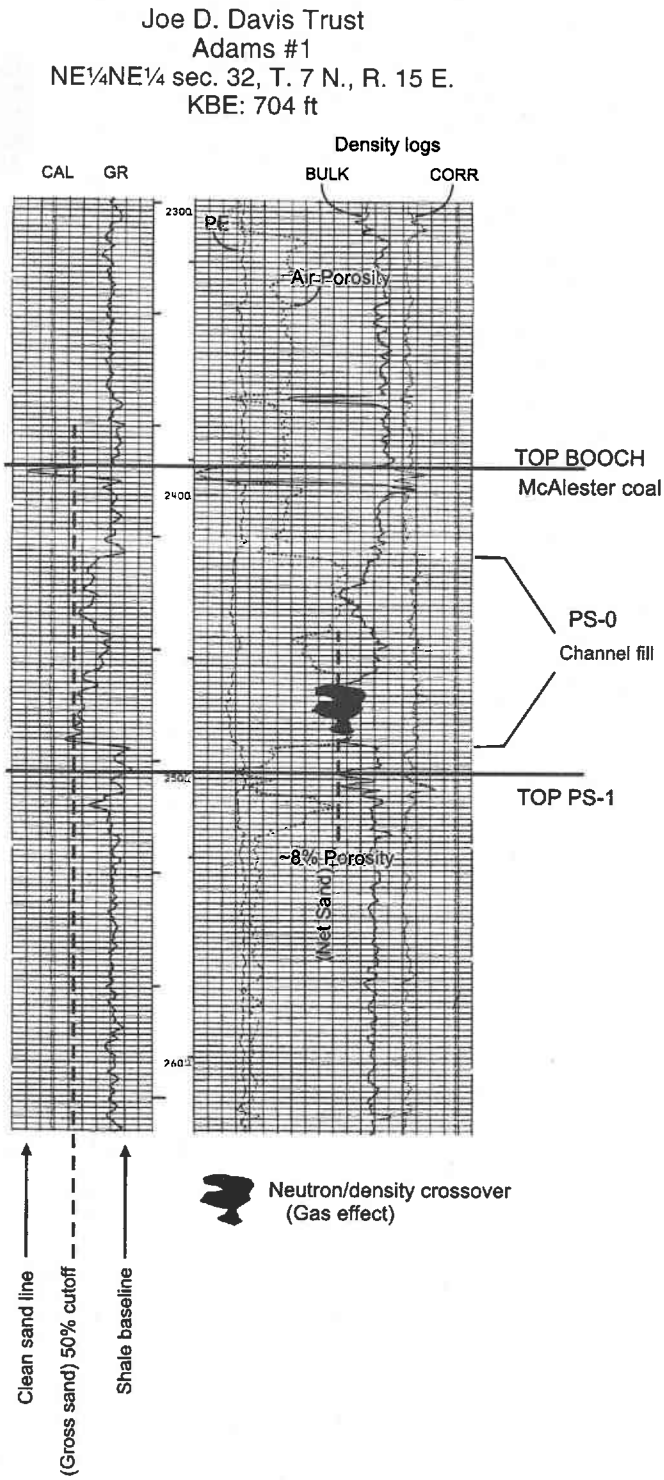


Figure 40. Reams Southeast Field example well log. This log highlights the problem in using a strict net-sandstone gamma-ray cutoff by showing an example of probable gas pay in an interval that is technically too shaly to be of reservoir quality.

The mouth-bar/delta-front sand complexes are thinner, run roughly perpendicular to the channel trends, and make poorer quality reservoirs. Two of these trends are mapped that extend miles west of the main channel system. This apparent transport distance may reflect a component of longshore drift, stacked storm deposits that were pushed from a previous mouth-bar complex westward, or the presence of another distributary channel from the same delta located just west of the mapped area (Fig. 16).

The succeeding parasequence (PS-2) begins with deposition of a thick marine shale that was followed by a progradational event that, except in the easternmost part of the field, is notably sandstone poor. Widespread deltaic/nearshore sedimentation after the initial marine transgression is supported by the presence of a coal that is usually preserved at the top of this parasequence (Fig. 41). Of economic significance is the presence of a thick sequence of stacked channel fills that have incised through much of the underlying sediments at the northeastern margin of the field (Fig. 44). Although not as deep or as wide as those seen in Brooken Field, these sandstones are more properly called a valley-fill sequence because incision can exceed 100 ft and contain up to 85 ft of net sandstone in three to four individual channel fills (Pls. 13, 14).

Parasequence PS-2 was followed by a pronounced marine transgression that saw deposition of the thick, monotonous sequence of mostly distal-marine (prodelta) shales that were deposited during PS-1 time. This parasequence can be up to 200 ft thick, but contains no reservoir-quality sandstone (Fig. 41). Based on gamma-ray profiles, some silt-sized material is present at the very top, but usually the top of the parasequence can be recognized only by the subtle increase in resistivity on logs just beneath the flooding surface that initiated PS-0 deposition (Pls. 13, 14).

The prodelta shale that began PS-0 deposition is deeply incised in the northeastern part of Reams Southeast Field, confirming a major regression that resulted in the deposition of stacked channel-fill sands parallel to those seen in parasequences 3/3A and 2 (Pls. 13, 14). Like PS-2, the maximum incision in PS-0 is >100 ft, at some places penetrating to the top of PS-1. The magnitude of incision and the stacking of channel-fill sands within again makes the term *valley fill* appropriate for these fluvial systems (Fig. 45).

A clearly incised, but much narrower PS-0 channel-fill system appears to feed into the main east–southeast-trending system, meeting in the N½ sec. 6, T. 6 N., R. 16 E. (Pl. 14, well 4). Based on the upper Booch interval isopach

(Fig. 43), which shows a prominent, but apparently only local "thick" (paleo-low) in this channel's location, it is postulated that this secondary system flowed east–northeast. Because it approaches the main channel system at almost a right angle, a possible explanation is that the narrower channel may be the easternmost arm of another delta complex west of the study area. Whether these two systems intersected is difficult to say, especially with no logs available for several key wells in secs. 1, 2, and 11. However, a direct connection of the PS-0 productive wells in secs. 16 and 11, T. 6 N., R. 15 E., to production under the lake is unlikely. This is because the productive well in sec. 16 is structurally ~500 ft low to a clearly wet well in sec. 33, T. 7 N., R. 16 E. Thus, regardless of environmental interpretation, the PS-0 production in secs. 16 and 11 is not constrained by any structural closure and thus is purely stratigraphic in nature (Fig. 45).

The primary (east-southeast-trending) fluvial sands in all three productive parasequences are parallel, but slightly offset from those beneath. Similar paleotopography explains the general trends, but their offset is a common pattern that results because the postdepositional compaction of sands is less than that of shales. This creates topographic ridges along previous channel systems that tend to force succeeding channels into the adjoining topographic lows (Fig. 46). This fact can be used as an aid in determining the likely location of channel-fill sands where well control is limited.

In the Booch reservoirs studied, logged porosity was always greater in the channel-fill sandstones (12–15% average porosity) than those that were deposited in a nearshore-marine environment (9–12% average porosity). Permeability, based on flow rates, confirms the superiority of channel-fill over tidally reworked sandstones. As described previously, this difference is related to the rapid, higher energy deposition of the channel sands relative to the shallow-marine sands. Coarser, but more poorly sorted, channel sands contain more suspended clays that tend to inhibit the growth of silica cement. Better winnowed (cleaner) marine sands have better nucleation sites for silica, making it easier to precipitate (R. D. Andrews, personal communication, 2004).

It must be stressed that the environmental interpretations described are provisional. The area mapped would need to be significantly increased, and correlatable sandstones mapped separately, to confirm the web of channel-fill and associated delta-front sands that have been mapped. Clearly, even analyses using a combination of interval isopachs, sandstone maps, and log signatures do not necessarily yield unambiguous environmental interpretations.

STRUCTURE

The structure at Reams Southeast Field is controlled by a large, east–northeast-trending, high-angle reverse fault (Fig. 47). This has created a steep, three-way upthrown fault closure whose crest is in the N½ sec. 6, T. 6 N., R. 16 E. The north–south compression that formed this structure generated 11° dips (up to 1,000 ft/mi) on the southern flank of the structure, with lesser 3° dips (~300 ft/mi) on the western and eastern flanks. Although there may be a four-way (domal) closure at

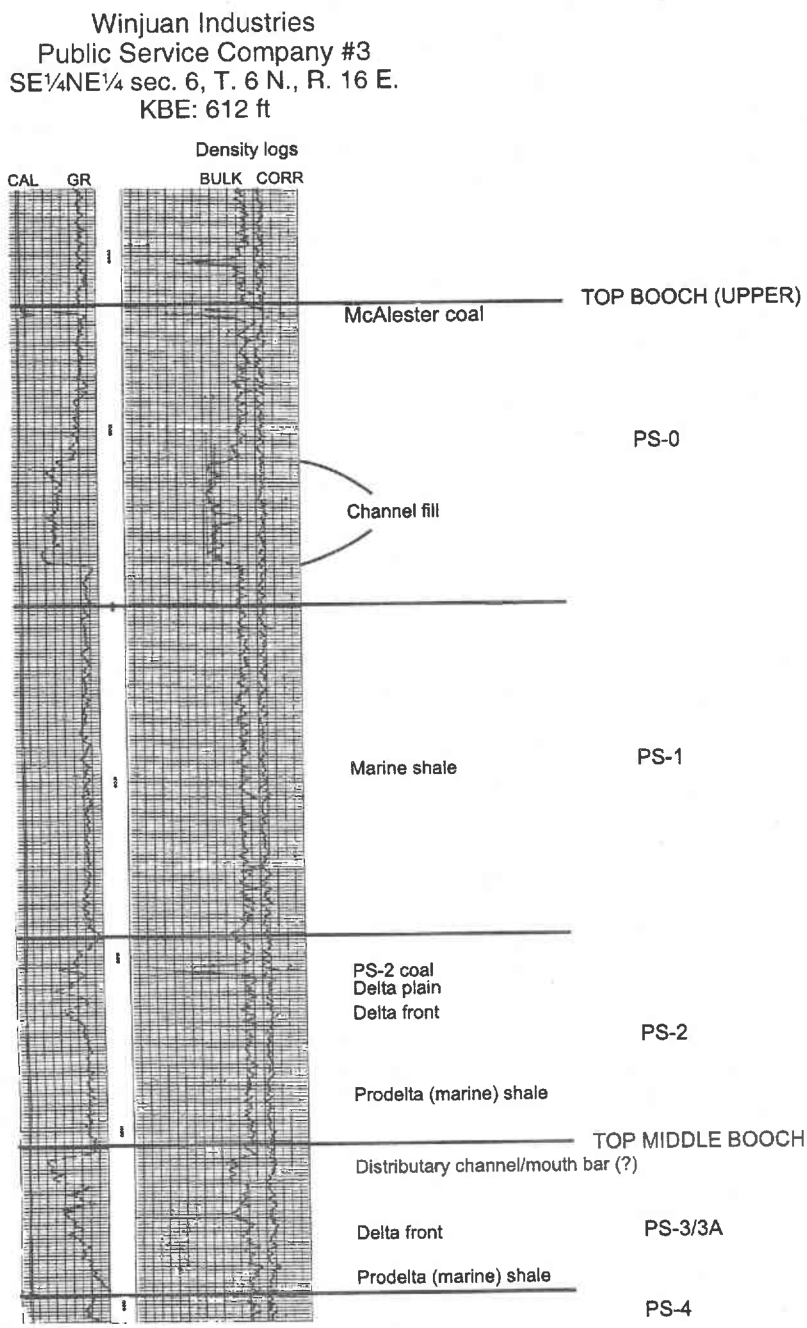


Figure 41. Booch type log for Reams Southeast Field. Winjuan Industries No. 3 Public Service Company, SE¼NE¼ sec. 6, T. 6 N., R. 16 E., Pittsburg County.

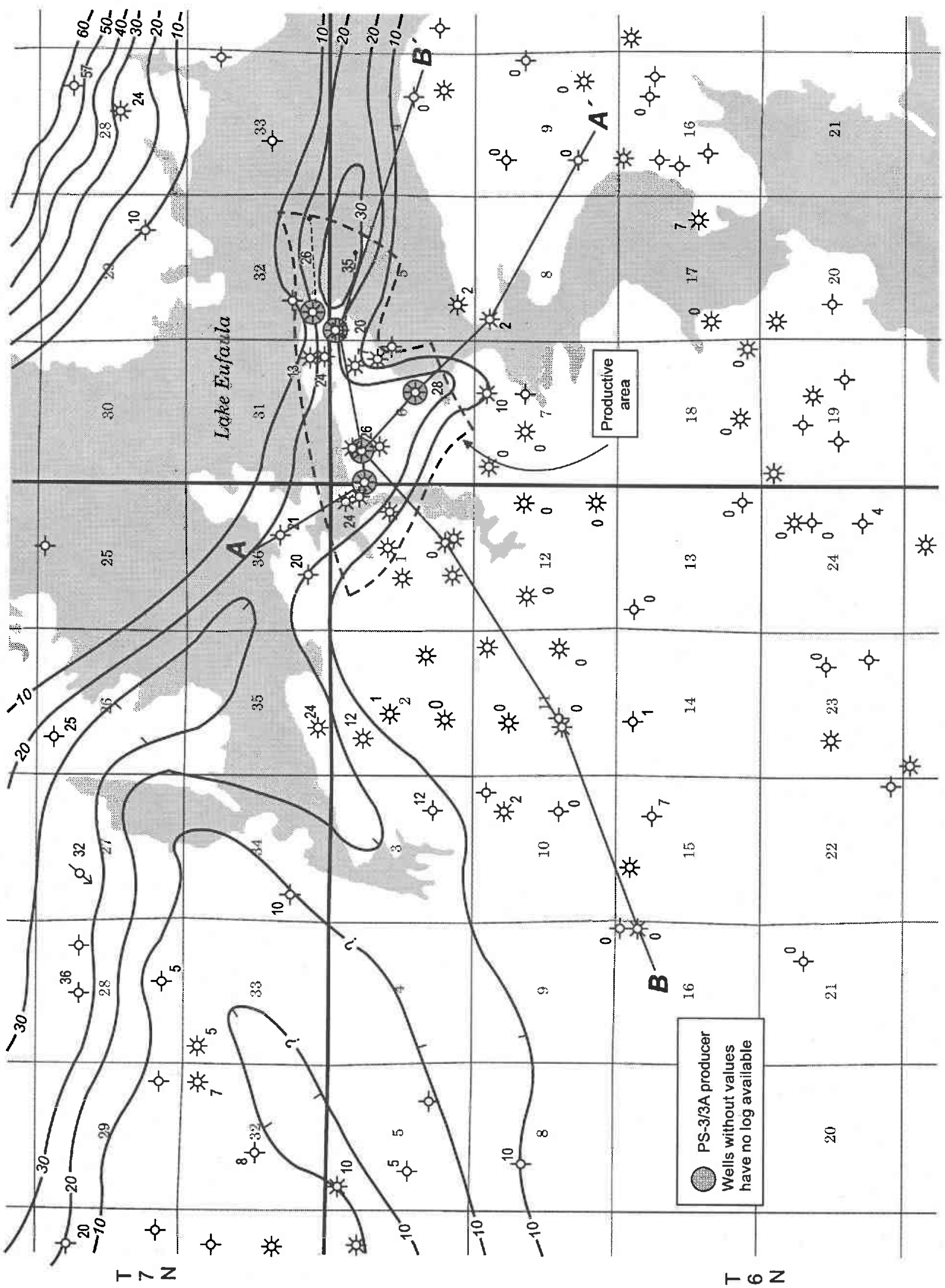


Figure 42. PS-3/3A net-sand isopach map and productive area for Reams Southeast Field. This map shows an east–southeast-oriented distributary-channel system along the northern margin of the field. The two thin, perpendicular sandstone trends to the west are interpreted as mouth-bar complexes overridden by later deltaic progradation. Contour interval, 10 ft.

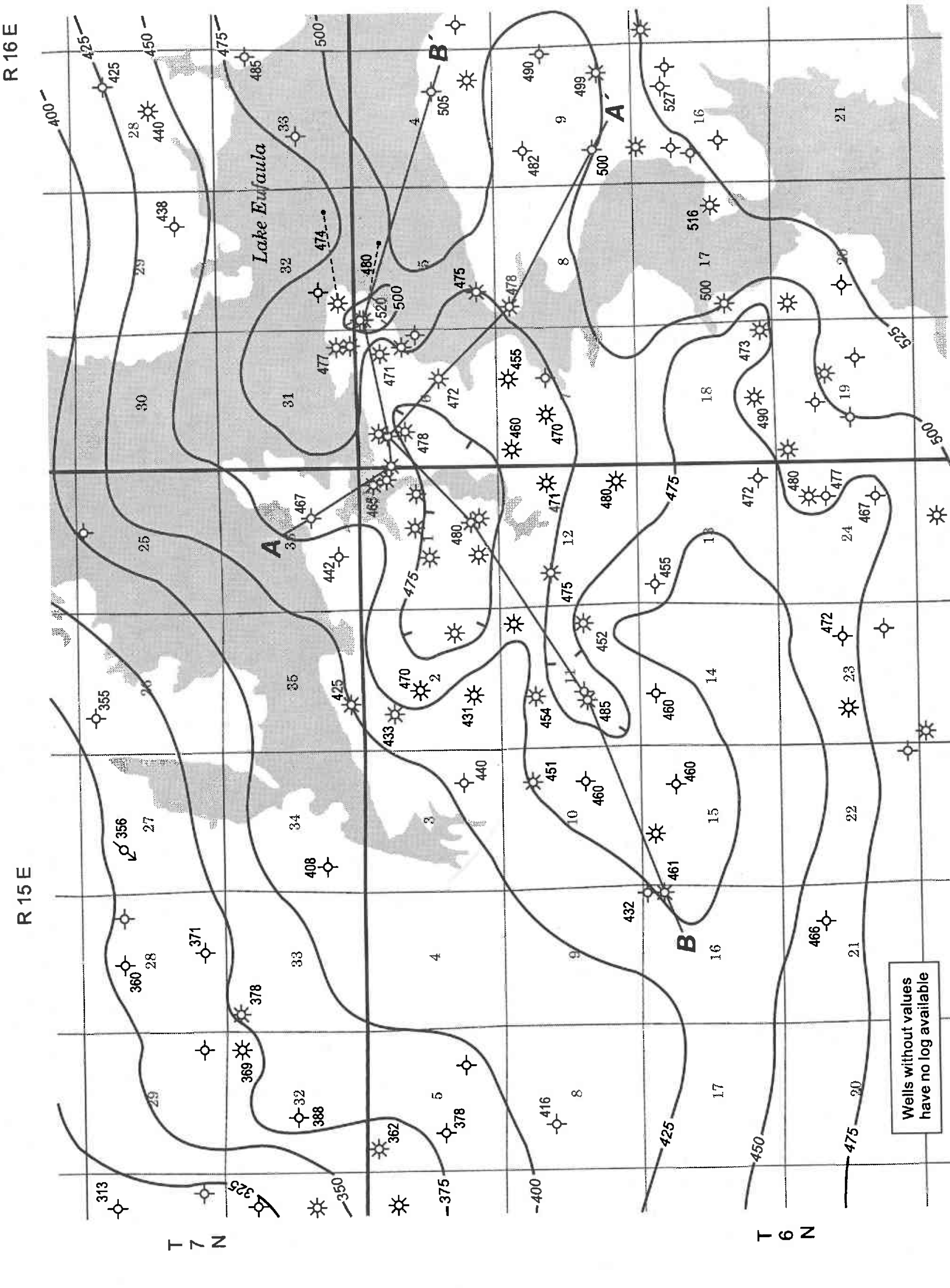


Figure 43. Upper Booch interval isopach map for Reams Southeast Field. Such maps can be useful in determining paleotopography (bathymetry) to corroborate distributary-channel orientations. Note how map complexity increases as well density increases. Contour interval, 25 ft.

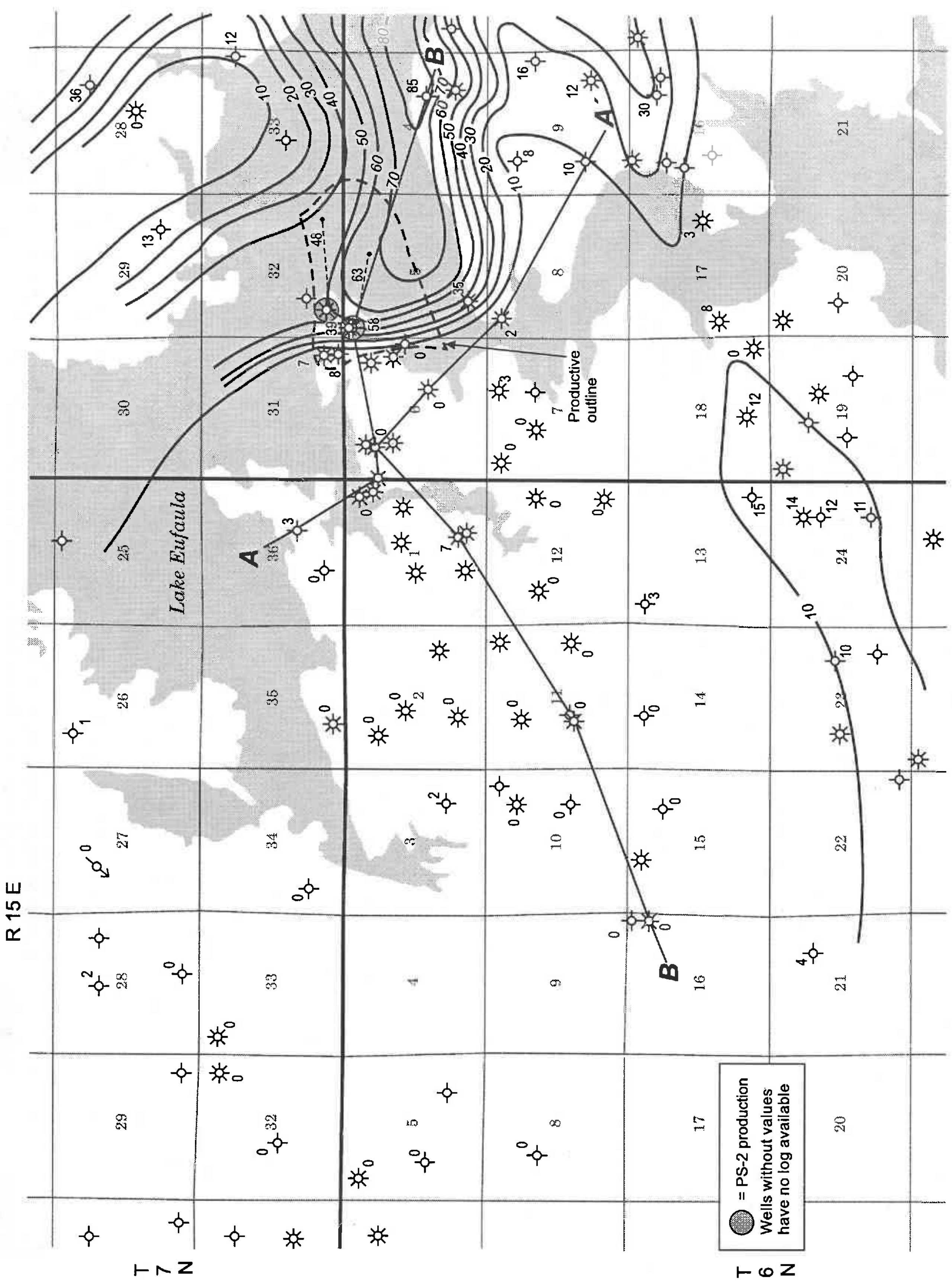


Figure 44. PS-2 net-sand (>8% porosity) isopach map for Reams Southeast Field, showing a thick sequence of stacked channel fills at the northeastern margin of the field. The thinner sandstones oriented perpendicular to the channel fills are believed to be marine-reworked shoreface and/or mouth-bar sands marking a paleoshoreline. Contour interval, 10 ft.

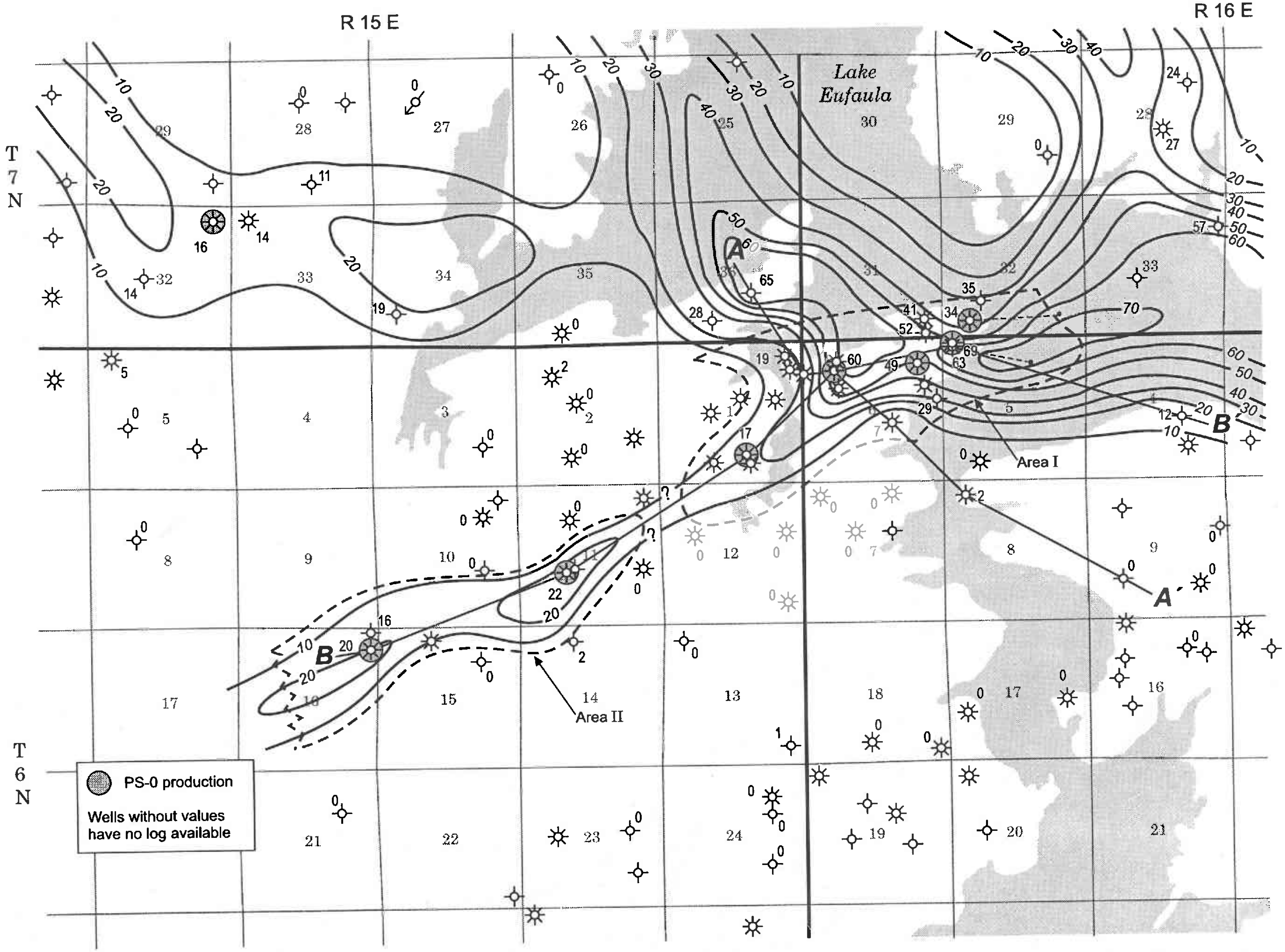


Figure 45. PS-0 net-sand isopach map and productive areas in Reams Southeast Field, showing an incised, narrow, east–northeast-trending distributary channel intersecting a much thicker east–southeast-trending system along the northeastern edge of the field. These two systems are not believed to be connected, because Area II gas production extends structurally much lower than that in Area I. Contour interval, 10 ft.

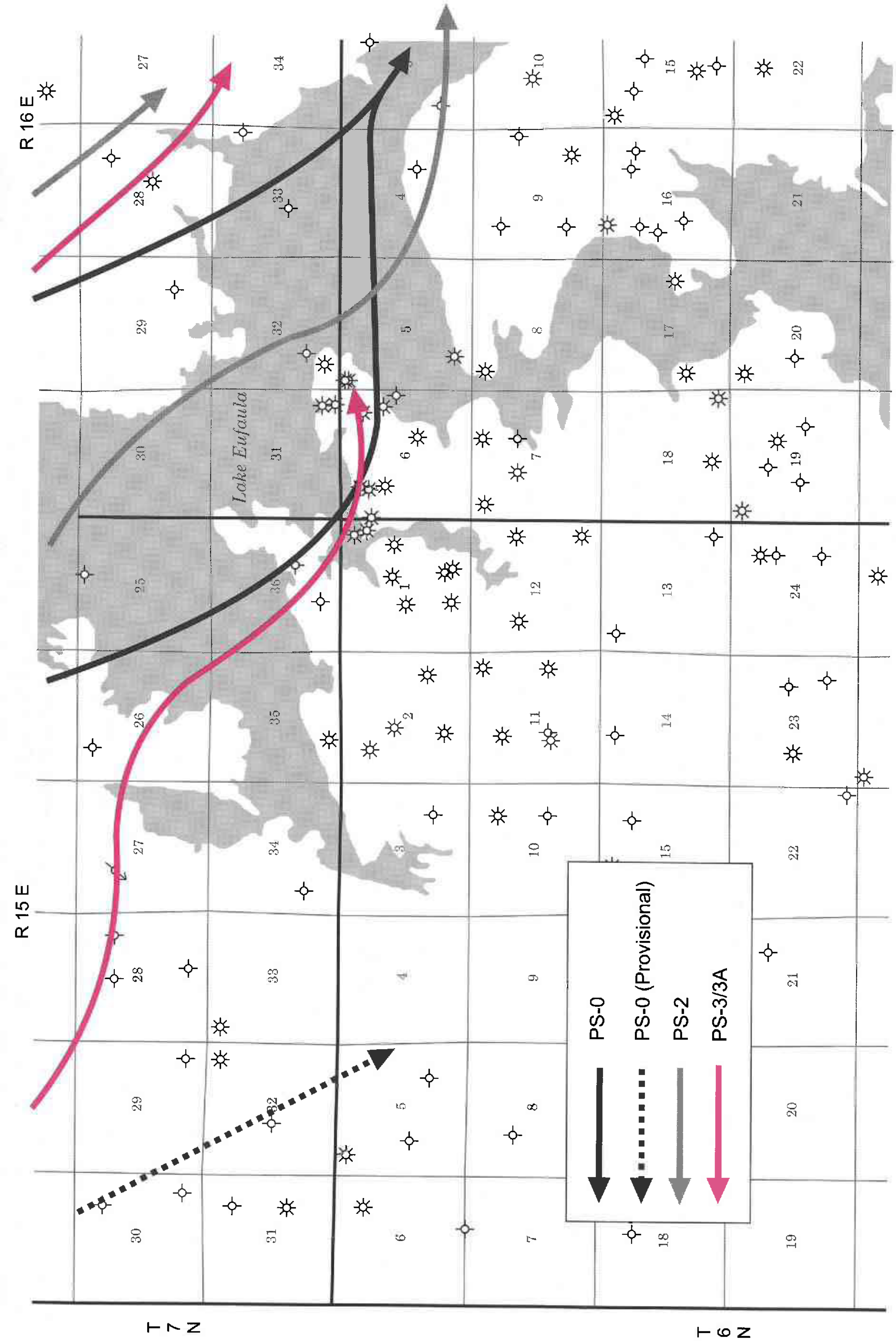


Figure 46. Channel-orientation map for Reams Southeast Field, showing the orientation and offset of the major upper and middle Booch channel systems.

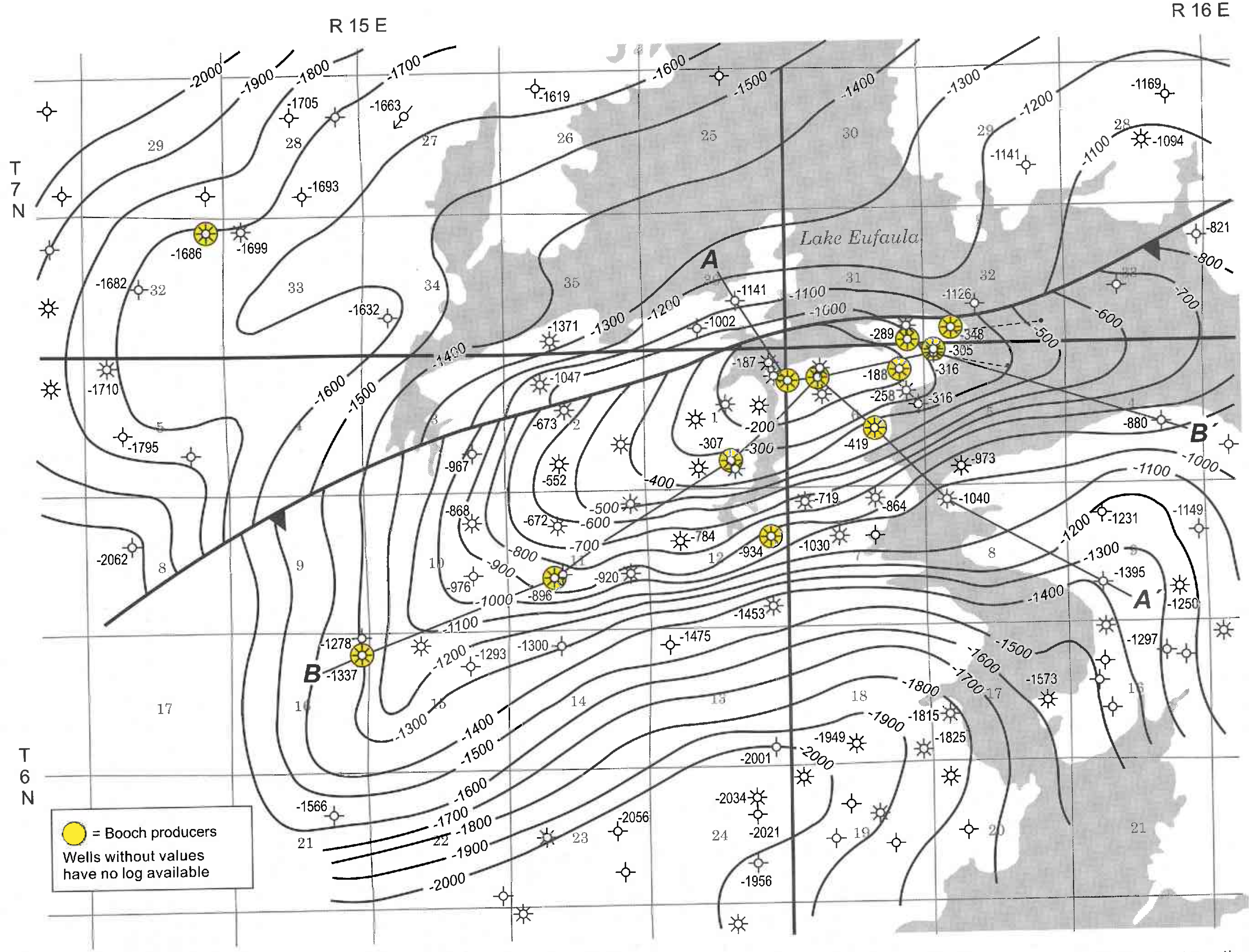


Figure 47. Structure-contour map from the top of the Booch sequence in Reams Southeast Field. The structure in the field is controlled by a large, east–northeast-trending, high-angle reverse fault that has created a steep, three-way upthrown fault closure. Contour interval, 100 ft.

the very top, most of the closure mapped requires a sealing fault. The vertical displacement of the fault at the crest of the structure is ~900 ft, which decreases markedly on both sides of the mapped area. Contours may continue to close into the fault to the northeast, but even if they do not, total vertical closure on the upthrown side of the fault is probably not less than 800 ft.

The present-day Reams Southeast Field structure developed long after Booch deposition and thus had no influence on the location or quality of the reservoir sandstones. None of the channel sands in PS-3/3A, PS-2, and the main channel in PS-0 are in an optimal configuration for trapping gas. The best orientation for a structure to trap fluvial sands is one at right angles to channel flow. Because the sandstones intersect the structure off the crest and at a low angle, the volume of reservoir sandstone under closure is greatly reduced.

If the fault is entirely sealing, the spillpoint for the field is at least 3 mi east of the structural crest. On the basis of the gas/water levels observed, this suggests that Booch reservoirs in Reams Southeast Field are significantly underfilled, which must be either a result of insufficient hydrocarbon sourcing or a leaky fault. Regardless of the cause, it appears that the less than ideal orientation of the structure relative to the productive channel-fill sandstones probably did not greatly reduce the gas volume that was eventually trapped.

PRODUCTION AND VOLUMETRICS

Reams Southeast Field has produced roughly 35 BCF, and about three-quarters of this has come from the Hartshorne. Thirteen wells have been completed in the Booch, upthrown to the fault, in the study area. The production map shows only eleven, because the two wells in the NW¼ sec. 5, T. 6 N., R. 16 E., and the NW¼ sec. 6, T. 6 N., R. 16 E., each represent two separate wells with the same surface location (Fig. 39).

Cumulative Booch production in the mapped area is 4.3 BCF, with an estimated ultimate recovery of 4.8 BCF. Production from two Booch wells was commingled with that of the Hartshorne (NW¼ sec. 6, T. 6 N., R. 16 E.), and in both of these wells thick and permeable PS-0 and PS-3 sandstones led to assigning equal production to the Booch and Hartshorne. The first Booch producer began in September 1975, with five additional wells starting in April 1976. Excepting two wells that have not yet gone on-line, all of the remaining wells began producing between 1993 and 2000. It must be remembered that these volumes are based on existing wells only. Future drilling will increase EURs and probably productive areas (Table 4).

Volumetric estimates were made of the initial gas in-place in the three productive Booch parasequences. It must be stressed, however, that in such a stratigraphically complex area these estimates are of limited value. Sandstone quality, thickness, and areal extent can vary abruptly. So for those reservoirs with a limited number of well penetrations, estimates of areal extent and average reservoir quality are crude. In areas where reservoir quality is relatively poor, the drainage area may not extend much beyond the radius of the fracture treatment. In such cases, infill drilling could dramatically improve recovery factors. Also, because permeability can vary in rocks with the same porosity, an 8% porosity cutoff for gas pay is not absolute. So the size and quality of the fracture treatment can have a large impact on the relative contribution of lower porosity reservoirs, as well as the area drained within the higher porosity zones.

Unlike Brooken Field, where the gas–water transition zone was at most a few feet thick, water saturations in the lower quality reservoirs of Reams Southeast Field increase more gradually from 15–20% on the structural crest to >60% hundreds of feet downdip. For volumetric purposes, the rather arbitrary but commonly used cutoff for gas pay has been made at a water saturation (S_w) of 40% (i.e., a 60% gas saturation). The productive area is calculated on the basis of an overlay of the net-sandstone map on the structural-contour map that is projected to be at the 40% S_w level. For example, in PS-0 the well in sec. 32, T. 7 N., R. 16 E., has an S_w of 30%, and that in the NE¼ sec. 33, an S_w of 60%. This places the water contact below the crestal well, one-third of the vertical distance to the downdip well (Figs. 42, 44, 45). The formation-water resistivity used here is 0.040 ohm-m. Booch reservoir volumes calculated for Reams Southeast Field are shown in Table 5.

Published calculated bottom-hole pressures for Booch reservoirs in Reams Southeast Field yield pressure gradients from 0.08 to 0.22 psi/ft. (See discussion in the Brooken [Texanna SW] Field study.) Using the highest gradient (0.22 psi/ft) measured, the pressure for an average reservoir depth of 1,400 ft becomes 308 psi. This yields a formation volume factor of 22 scf/rcf. Table 6 summarizes the gas in-place volumes calculated and the production (in BCF) for the Booch in the Reams Southeast Field study area.

These results highlight one of the perennial sources of uncertainty in volumetric calculations, and that is assigning production in wells in which more than one zone is producing. Allocating equal production to every zone open in a well is simple, but clearly it can lead to erroneous conclusions. For example, the high recovery factor calculated for PS-3, while possible, is unlikely. Much more probable is that some of the production that has been assigned to this sandstone has actually been produced from other Booch zones or from the Hartshorne. In five of the seven wells in which it produces, PS-3 is commingled with at least one other interval. If PS-3 has indeed been credited with too much production, then its recovery factor will go down as the other zones go up.

Another volumetric challenge is in accurately mapping reservoirs for which there are few penetrations. Area II of reservoir PS-0 is a good example, where a 3-mi-long sandstone complex is defined by three wells. Here the area and reservoir volume could easily be cut in half, thereby increasing the recovery factor for two wells (one of which has yet to go on production) from 24% to 48%.

LESSONS LEARNED

Booch production in Reams Southeast Field is structurally simple but stratigraphically complex. Environmental interpretation is the key to predicting the location of potentially productive sandstones, and it is the finding

TABLE 4. — Reams Southeast Field (Study Area) Booch Production

Operator name	Lease name	Well no.	Location	Status	Gas cum. (MMCF)	Booch cum. prod. (MMCF)			EUR[a] (MMCF)				PS no.[b]	Production (MCF)		
						PS-0	PS-2	PS-3	All Booch	PS-0	PS-2	PS-3		YTD	Latest month	First prod. date
XAE Corp.	USA	1	sec. 1, T6N, R15E SE¼NE¼NE¼	ACT	138			138	200			200	3	1,267	1,267	1997/09
Spartan Resources	Lake Eufaula	1	sec. 1, T6N, R15E NW¼SW¼SE¼	ACT	89	89			150	150			0	640	**640**	1995/09
Quench Oil & Gas Inc.	Silva	2A	sec. 11, T6N, R15E NE¼SW¼NE¼SW¼	ACT	74	74			75	75			0	40	**40**	1975/09
XPLOR	Cole	1	sec. 16, T6N, R15E NE¼NE¼	INA	0	0			75	75			0	0	**0**	
Meade Energy Corp.	Lake	1	sec. 5, T6N, R16E NW¼NW¼NW¼	ACT	1,079	540		540	1,150	575		575	0, 3	2,110	**1,021**	1976/04
Meade Energy Corp.	Lake	3	sec. 5, T6N, R16E NW¼NW¼NW¼	ACT	57		29	29	150		75	75	2, 3	14,035	**1,171**	2000/05
Meade Energy Corp.	Helms	1	sec. 6, T6N, R16E N½S½N½NW¼	ACT	1,378	345		345	800	400		400	0, 3/(H)[c]	4,457	**2,017**	1976/04
Meade Energy Corp.	Helms 1-6	1	sec. 6, T6N, R16E N½S½N½NW¼	INA	1,329	333		333	665	333		333	0, 3 /(H)[c]			1976/04
Eberly & Meade Inc.	Lalman	1	sec. 6, T6N, R16E C NW¼SE¼	INA	72			72	72			72	3			1976/04
Quench Oil & Gas Inc.	P S C	4	sec. 6, T6N, R16E SW¼NE¼NE¼	ACT	328	328			475	475			0	3,814	**1,901**	1993/05
Eberly & Meade Inc.	Lake	1	sec. 32, T7N, R16E SE¼SW¼SW¼	INA	1,060	353	353	353	1,060	353	353	353	0, 2, 3			1976/04
Totals					**5,604**	**2,062**	**382**	**1,810**	**4,872**	**2,436**	**428**	**2,008**		**26,363**	**8,057**	

Booch cum. total: **4,254**
Booch EUR total: **4,872**

NOTE: Data from IHS Energy (through February 2004).
[a]Estimated ultimate recovery (EUR) calculated using latest month's production × 12 × 5 years.
[b]Parasequence completed.
[c]H — Hartshorne. Hartshorne commingled assigns 50% to Booch zone.

TABLE 5. — Reams Southeast Field Booch Volumetric Parameters

Interval	Avg. net sd	Area (ac.)	Avg. por.	Avg. Sg[a]	Pore vol. (ac. ft.)
PS-0:					
Area I	34 ft	1,207	12%	80%	3,940
Area II	11 ft	839	10%	70%	646
PS-2:	40 ft	260	12%	80%	998
PS-3:	24 ft	1,326	12%	80%	3,055

[a]Gas saturation.

TABLE 6. — Reams Southeast Field Booch Gas Volumes in BCF

Interval	Gas IIP	Cum. prod.	EUR	Proj. R.F.
PS-0:				
Area I	3.776	1.988	2.286	61%
Area II	0.619	0.074	0.150	24%
PS-2:	0.957	0.382	0.428	45%
PS-3:	2.928	1.810	2.008	69%
Total	8.280	4.254	4.872	*Avg.* 59%

IIP — initially in-place. EUR — estimated ultimate recovery.
Proj. R.F. — projected recovery factor.

of porous and permeable (channel-fill) sandstones that is the key to identifying the best Booch production. Any structural configuration, including monoclinal dip, can trap Booch reservoirs. The crucial variable is the orientation of the sandstone.

Log shapes, the identification of incision on cross sections, sandstone isopachs, and interval isopachs are all necessary for the prediction of depositional environment. However, even with this input, interpretations are often difficult. An important tool in determining whether a sandstone will generally be oriented parallel to strike (mouth bar or shoreline sands) or dip (fluvial sand) is the interval isopach. Taken between two reliable stratigraphic markers, such a map shows the general paleotopography/bathymetry at the time of deposition. This can help determine an approximate channel orientation with limited well control.

Postdepositional compaction and dewatering create sandstone "thicks" that later become manifested as topographic highs. This tends to force subsequent channels into the adjoining topographic lows, offsetting them from previous channels. This fact, combined with the locations of mouth-bar sands, can be used to help predict the presence and location of unpenetrated distributary-channel fills.

Channel-fill sands are almost universally better reservoirs than marine reservoirs. Although they are better sorted and winnowed than channel sands, marine sandstones tend to attract more diagenetic silica cement, which makes them poorer reservoirs. Environmental interpretation based on log profiles can be misleading, but stratigraphic cross sections can identify where incision has taken place, and visible downcutting invariably means channel fill.

Mapping stacked sandstones that may have been deposited in different environments and with different orientations tends to mask trends. Although the Booch in this study has been subdivided eight times, at the local level individual parasequences commonly can be broken into thinner units, each representing a single bar-forming or channel-filling episode. Because each of these episodes is capable of depositing 10–20 ft (or more) of reservoir-quality sandstone that can economically support the drilling of a well, such detailed mapping is a necessity. In the same vein, as large an area as possible should be mapped around an area of interest, and every available well log used to confirm sandstone trends and environmental interpretation. This helps to better define trends and environmental interpretations and increases the likelihood of seeing the all-important wells classified as "near misses."

Volumetrics in most areas of the Booch are more art than science, which makes their predictive value problematic. Most wells produce from multiple zones, and there is no reliable way to allocate production to those that are open. This makes the precise calculation of recovery factors difficult. Another variable that is difficult to gauge is the sandstone's areal extent. Sand bodies are commonly narrow, and their thickness, as both channel-fill and marine sands, varies abruptly in a direction perpendicular to the overall trend. So even in areas that have four wells per section (160-acre spacing), the average distance between wells (~2,000 ft) can be more than enough to completely miss a potentially productive channel or delta-front sand. For those reservoirs that have been penetrated only once or twice, estimates of average reservoir quality are educated guesses at best.

There are no sharp divides between reservoir- and nonreservoir-quality rock. The cutoffs used here are the general industry standards of 8% porosity and 40% water saturation. However, it must be understood that these are only approximations and that gas pay and non-pay can occur above and below these cutoffs. This is especially true in reservoirs that are universally given fracture stimulations to enhance production. In many areas a calculation of a well's drainage radius is a better clue to its ultimate recovery than rigorous volumetric calculations. If a well can drain 160 acres in a Booch gas reservoir that is 17 ft thick, has 10% porosity, 25% water saturation, and a Reams Southeast Field formation volume factor of 22 scf/rcf, it will access 200 MMCF of gas, and, with a 50% recovery factor, produce 100 MMCF. Although not exceptional, this recovery is still economic for reservoirs that are only 1,400 ft deep.

Pine Hollow South Field

INTRODUCTION

Pine Hollow South Field lies southeast of Reams Southeast Field in west-central Pittsburg County. Greater Pine Hollow South Field comprises the old Arpelar SE, McAlester W, Stuart, Stuart NE, and Stuart SE Fields and encompasses roughly 76 mi^2 in parts of seven townships. Productive Booch sandstones vary widely in depth, with the two primary reservoirs averaging 1,500 and 2,200 ft deep. The area of the field that is studied here is much smaller and is west of the city of McAlester, mostly in T. 5 N., R. 13–14 E. (Fig. 48).

The earliest phase of exploration in the study area lasted from 1931 through 1949. During this period, several wells were drilled investigating the productive potential of the large closure upthrown to the northeast-trending Penitentiary Fault. In spite of penetrating a variety of potentially gas-productive sandstones, the lack of a nearby market caused all of these early wells to be plugged. Hartshorne and lesser Atoka production were the first to be established, and these reservoirs were found downthrown to the fault in the early 1960s. The first upthrown production was established in the Hartshorne by the Apache No. 1 Watson Unit, which was completed in 1966 in the SW¼SW¼ sec. 18, T. 5 N., R. 14 E. (IHS Energy, 2004).

The Booch discovery for the area of Pine Hollow South Field that is studied here was made by the American Land and Trading No. 1 Watson. This well was completed with production commingled from the Booch and Hartshorne in 1981, adjacent to the original Hartshorne discovery in sec. 18, T. 5 N., R. 14 E. Field development continues to be active, with 13 wells in the immediate area being recently staked, drilling, or waiting to be completed. At the time of the study in early 2004, there were 15 upthrown Booch producers in the field area, with 12 of these completed since the year 2000 (IHS Energy, 2004).

No logs are available for the three wells in the study area that are listed as Savanna completions. On the basis of nearby control, these wells were perforated 200–300 ft above the McAlester coal, which defines the top of the Booch. These low-initial-potential (10–63 MCFPD) "Savanna" completions are stratigraphically below the true Savanna as defined in official surface terminology. The productive zones are correlative with the upper McAlester Keota and Tamaha sandstone intervals (Fig. 1).

STRATIGRAPHY

The Booch interval in Pine Hollow South Field is stratigraphically similar to that in Reams Southeast Field. It occupies the same position along depositional strike, and for most parasequence cycles tends to be relatively distal and dominated by prodelta marine shales. However, unlike Reams Southeast Field, Pine Hollow South Field did not have a history of being overrun by major delta systems at the end of Booch progradational episodes. As a result, this field tends to lack the higher quality fluvial/valley-fill sandstones that are characteristic of Booch production in Reams Southeast Field and tends to have thinner, poorer quality marine reservoirs (Fig. 49).

For almost all of the wells completed in the study area, some log data were available, but because full suites were often unavailable, qualitative estimates of gross and net sandstone thicknesses were sometimes required. This involved combining and comparing a variety of other logs if direct indicators of gross/net sandstone or porosity were lacking. (See the discussion of Reams Southeast Field.)

In the study area a variety of Booch sandstones residing in four separate parasequences produce, from lower Booch PS-5 through upper Booch PS-0 (Fig. 50). The isopachs presented for Pine Hollow South Field combine all of the sandstones in a given parasequence. However, the environmental interpretation could be refined if the individual sandstones present in each parasequence were mapped separately. An area of 36 mi^2 was mapped, which includes 2–3 mi around the Booch producers studied. Nevertheless, given the especially narrow, thin nature of the producing Booch sandstone bodies in the area, an even larger mapped area could greatly increase confidence in the sandstone limits and environmental interpretation.

Booch deposition began with PS-6. Although PS-6 shows the upward-increasing resistivity that is characteristic of progradational sequences, this basal parasequence never coarsened to sand size before the flooding event that initiated deposition of the next parasequence. This indicates that even at the point of maximum progradation for PS-6, the environment of deposition was always distal marine (Pls. 15, 16).

Deposition of the succeeding parasequence PS-5 began with a marine prodelta shale that, with time, became much shallower. PS-5 eventually saw the deposition of what is interpreted to be a delta-front complex that in places includes mouth bars and/or distributary-channel sands (Fig. 51). This sequence in many areas concluded with the deposition of a thin (1–2-ft) delta-plain coal just before the next flooding event, which is marked by a shale with high gamma-ray values at the base of PS-4 (Fig. 49).

PS-5 is a key Booch producer in the study area, and seven wells have been completed in this sequence thus far (Fig. 50). Sandstone trends for the interval tend to be circuitous, and several apparently discontinuous sands also seem to be present. Based on a comparison of the sandstone isopach to interval isopachs and log shapes, it appears that a single, thin, southeast-flowing distributary-channel system was present during PS-5 time in the study area. This environmental interpretation is based mainly on the sandstone orientation (parallel to paleodip), as there is no evidence of obvious downcutting that might be associated with a distributary channel. This channel system is believed to have given rise to two strike-parallel delta-front sand complexes, the thicker of which developed in the center of the mapped area. Although the upper Booch interval isopach is used here to show paleotopography, it is similar to the middle and lower Booch interval isopachs (Fig. 52).

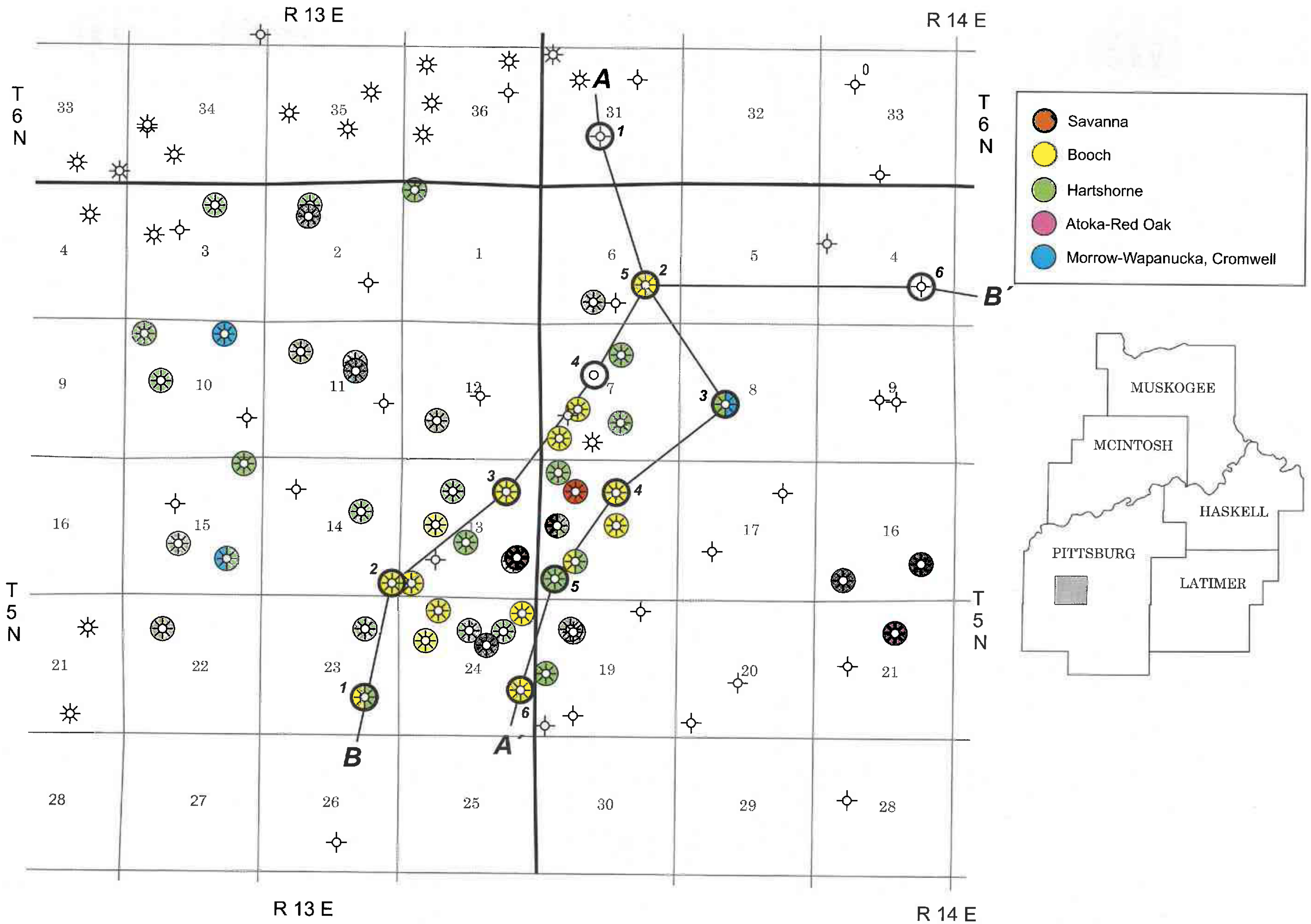
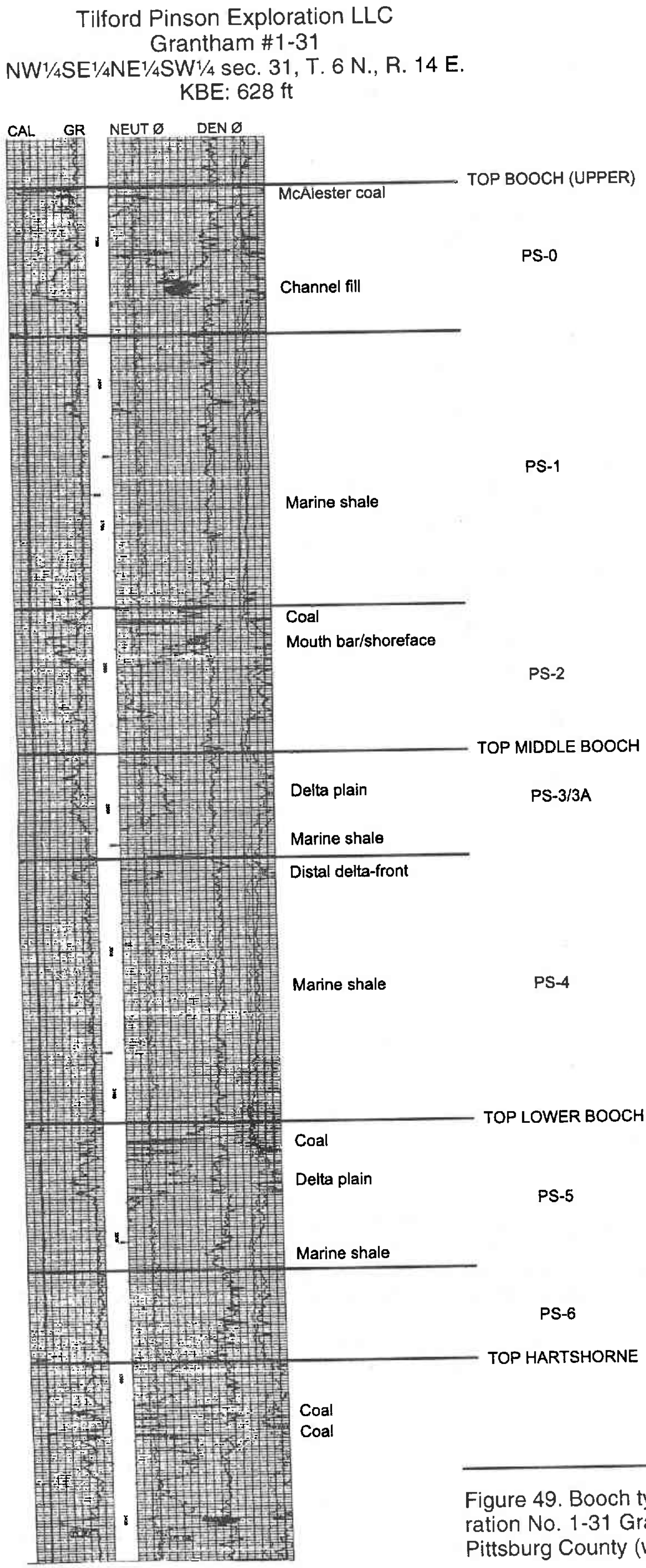


Figure 48. Pine Hollow South Field study area and production map. Lines of cross section *A–A′* (Pl. 15) and *B–B′* (Pl. 16) are shown. Activity through April 2004.



The PS-6 and PS-5 intervals that make up the lower Booch were followed by deposition of the thick prodelta shale in PS-4. This parasequence ends with thin fine-grained sands and silts that nowhere in the study area are of reservoir quality (Fig. 49). The lack of coarser grained sediments in the study area for PS-4 indicates that any deltaic complexes that may have prograded seaward at that time bypassed this area. This circumstance recurred with the deposition of PS-3/3A, an interval that regionally deposited more reservoir-quality sandstone than any other. Although the PS-3/3A prodelta shale here is far thinner than that seen in PS-4, the universally thin marine sands that were deposited at this time also never developed reservoir-quality porosity and permeability (Pls. 15, 16).

The upper Booch sequence began with deposition of PS-2. This interval is, in many respects, a recap of PS-3/3A, with a relatively thin prodelta shale followed by the progradation of a minor (sand-poor) delta complex. This is evidenced by a series of thin delta-front sands and one to two narrow distributary channels that cross the study area (Fig. 53). The sands deposited are thin and usually lack a pronounced trend, perhaps indicating more than one period of marine reworking. The Sandra No. 1 Willy well, in the SE¼ sec. 6, T. 5 N., R. 14 E. (see Pls. 15, 16), has been completed in, though is not yet producing from, one of the thin distributary channels. This is the only PS-2 completion in the study area, but because this well is within the area of fault drag adjacent to the Penitentiary Fault, it may be unique. See later discussion under "Structure."

The next parasequence to be deposited (PS-1) is also sand poor but does serve as a reservoir in two wells in which production is commingled (Fig. 50). It is of poor reservoir quality and has a low net-to-gross ratio, which caused it to be mapped as gross rather than net sandstone. It appears, on the basis of its orientation and gamma-ray shape, to be a delta-front sand complex deposited some distance from an unseen distributary-channel system (Fig. 54). Like PS-2, its relative contribution to local Booch production is minimal.

The final Booch parasequence deposited was PS-0, and like PS-5 it is a major contributor, producing in 7 of the 15 wells in the study area (Fig. 50). During this depositional cycle, two southeast-trending distributary-channel systems appear to have overridden a series of shoreface/mouth-bar complexes that were deposited along the structural axis of the field (Fig. 55). The PS-0 sandstones along the western part of this paleoshoreline are the ones that produce, and so have been penetrated by more wells. This additional subsurface control has also made their shape more amorphous than the PS-0

Figure 49. Booch type log for Pine Hollow South Field. Tilford Pinson Exploration No. 1-31 Grantham, NW¼SE¼NE¼SW¼ sec. 31, T. 6 N., R. 14 E., Pittsburg County (well 1 on Pl. 15, cross section *A–A′*).

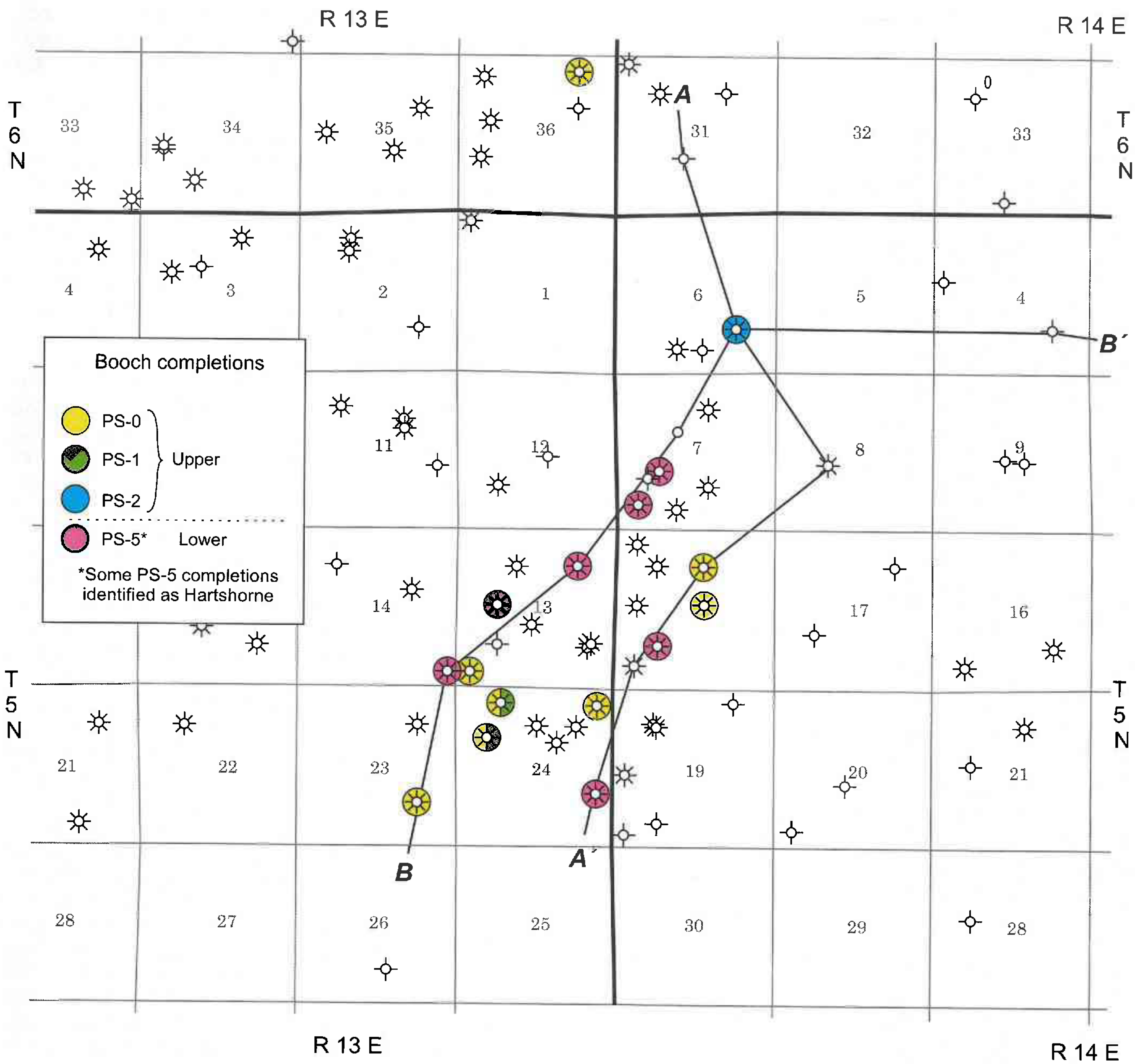


Figure 50. Booch production map for Pine Hollow South Field, color coded by productive parasequence.

channel-bar system to the northeast. These sandstones, being more poorly controlled, are mapped more smoothly, but are undoubtedly as complex as those to the west. Although the northeastern sandstones are structurally higher than those that produce, they also are clearly wet. This is why the two systems are not shown connected.

STRUCTURE

From a structural perspective, the mapped areas of Pine Hollow South and Reams Southeast Fields are similar. The structure at Pine Hollow South is controlled by a large, northeast-trending, high-angle reverse fault called the Penitentiary Fault. This fault has generated at least 1,500 ft of mostly three-way fault closure (Fig. 56).

The steepness of the Penitentiary Fault is demonstrated by the apparent fault drag seen in the Sandra No. 1 Willy well in sec. 6, T. 5 N., R. 14 E. This is structurally the highest well that has been drilled, and it maps as being almost on top of the fault trace. Based on comparisons to nearby wells, the apparent thickening of the Booch in this well increases from ~70% in PS-2 and PS-3 to 125% at the top of PS-5. This indicates that the dip has increased from ~53° to 64° and shows that the drag angle abruptly increased as the borehole approaches the fault. It is difficult to predict the maximum angle that will be reached against the fault, but it seems likely that the well was close to intersecting the fault when it reached total depth. The structural dip on the southeastern flank of the field is ~17° to the southeast. This means that going laterally from the

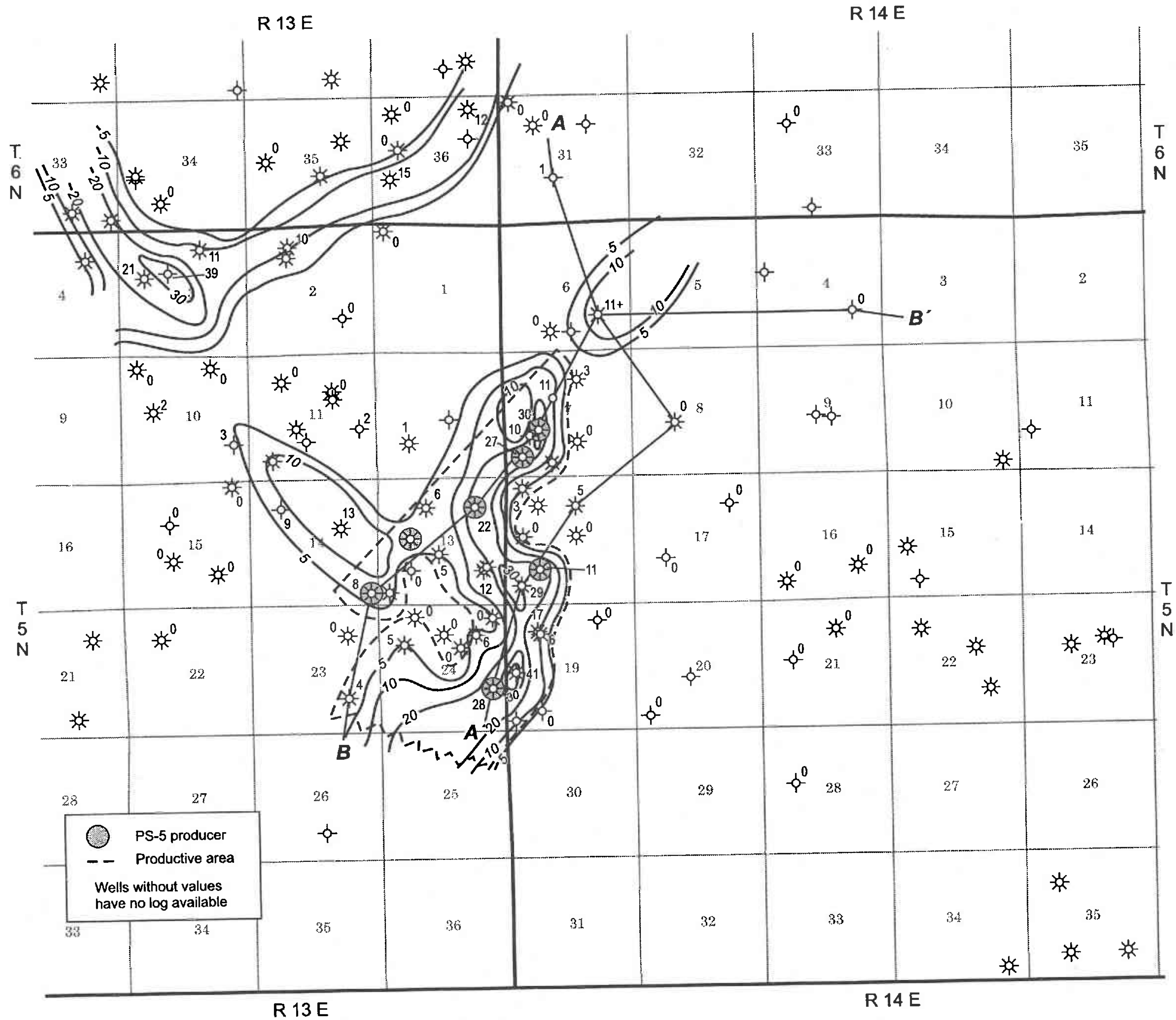


Figure 51. PS-5 net-sand isopach map for Pine Hollow South Field. This relatively sandstone-poor interval is inferred to represent the distal margins of a delta system with its associated distributary-channel and mouth-bar sands. Variable contour interval.

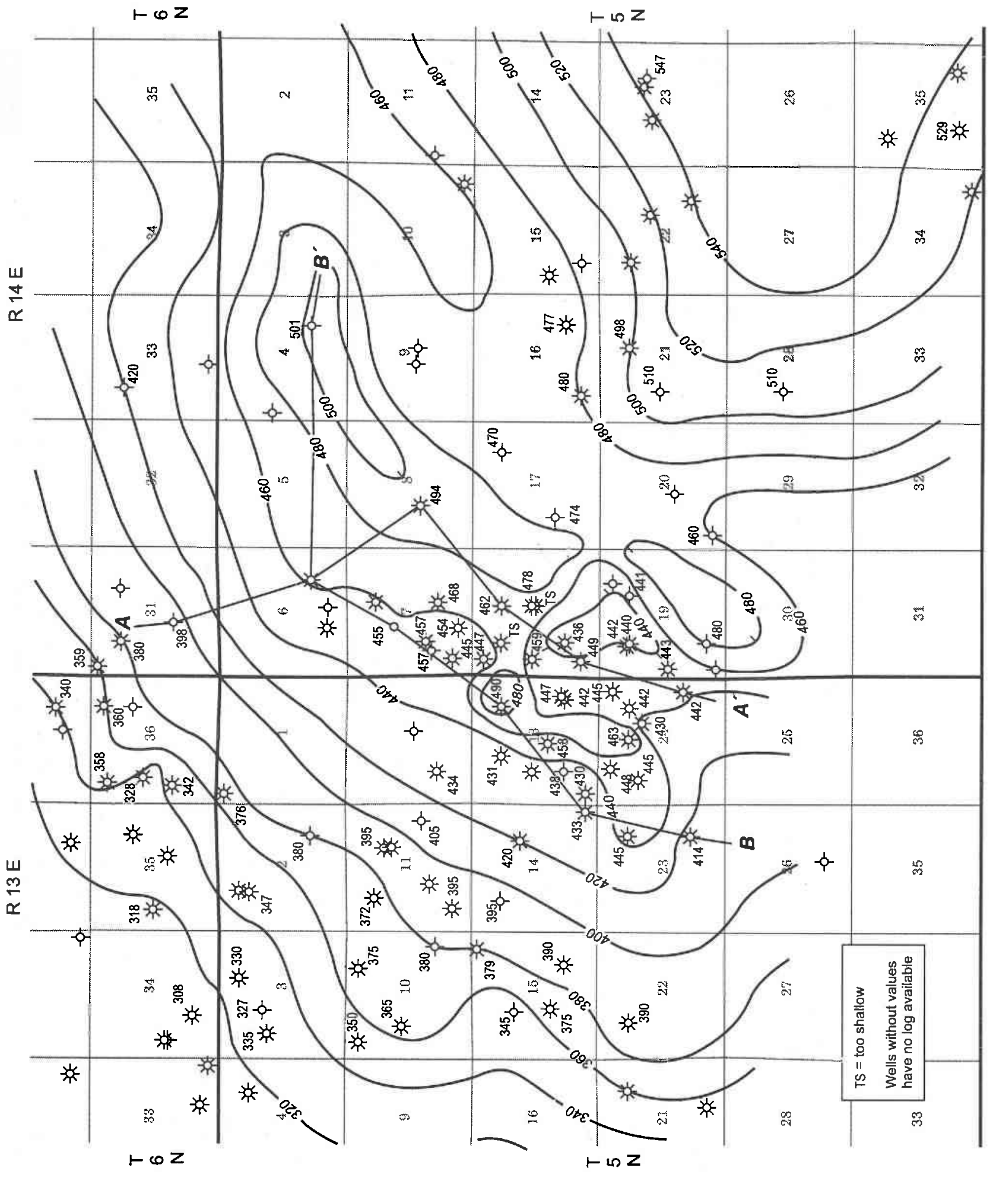


Figure 52. Upper Booch interval isopach map for Pine Hollow South Field. This map is used to help define the paleotopography/bathymetry. Regional paleodip is to the southeast and is similar to that shown in isopachs of the middle and lower Booch intervals. Contour interval, 20 ft.

fault over a distance of probably no more than a few hundred feet, the beds rotate >80° and in the process reverse their dip direction (Fig. 57).

The northwestward dip into the fault implied by the Sandra No. 1 Willy well, combined with regional southeastward dip, makes possible the presence of a narrow four-way dip closure very close to the fault. This opens the possibility that the PS-2 gas reservoir in this well may be structurally trapped on a fault-drag-generated rollover. If this is true, production for this well should decline rapidly, owing to the small size that such a closure could occupy. If the reservoir is fault-sealed, much more gas could be trapped. Time will tell.

The structure in the study area arose long after Booch deposition, so it is not surprising that it is not ideally oriented to trap hydrocarbons in the sandstones that were deposited. The relatively modest production from this 1,500-ft closure is due mainly to the lack of higher quality

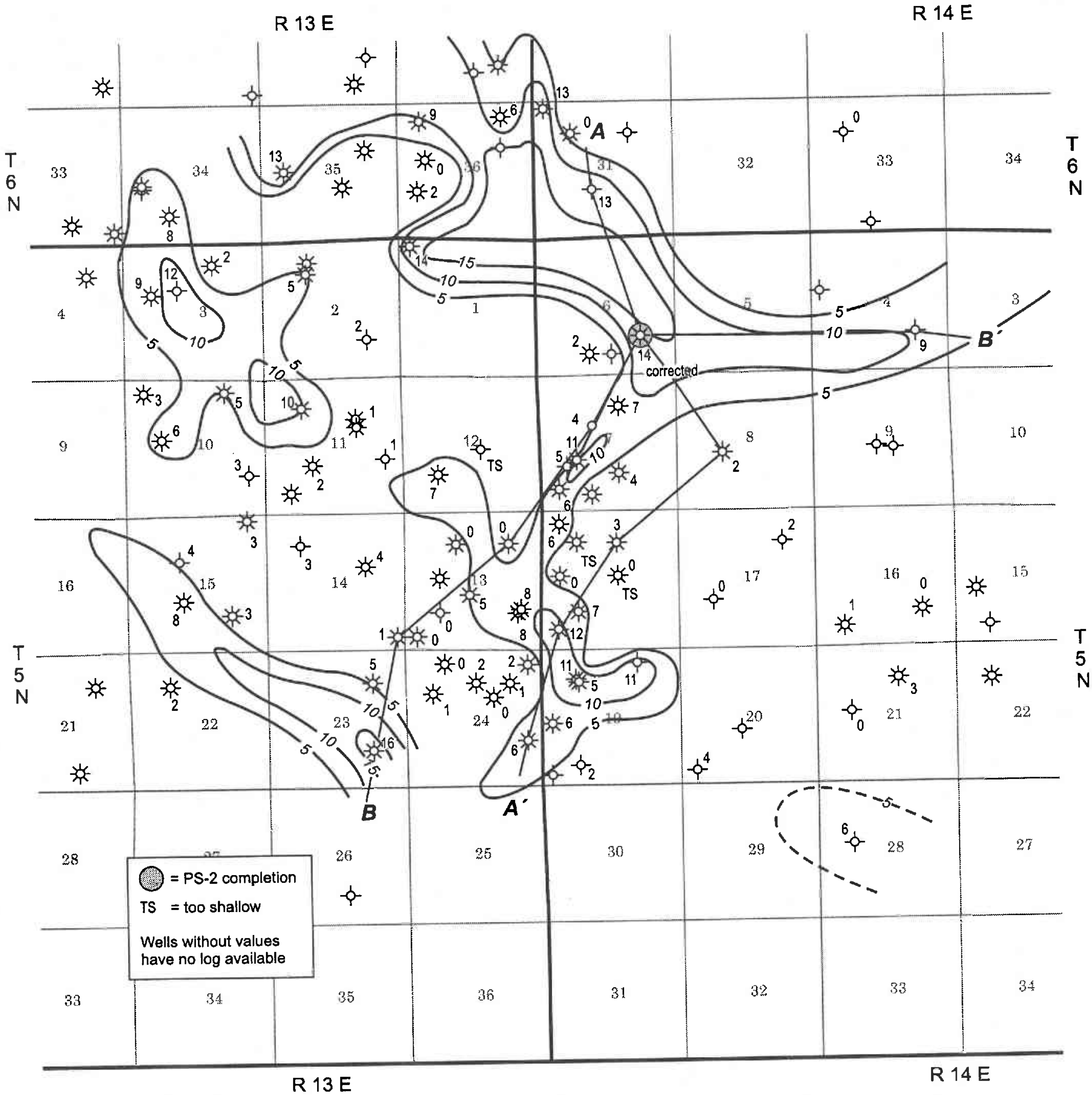


Figure 53. PS-2 net-sand isopach map for Pine Hollow South Field. This map shows the progradation of a minor (sand-poor) deltaic complex across the study area, evidenced by a series of thin delta-front sands and narrow distributary channels. The lack of a pronounced trend may indicate more than one period of marine reworking. Contour interval, 5 ft.

channel-fill sands and the consequent reliance on lesser quality delta-front/shoreface reservoirs.

Another issue is the apparent inability of the fault to seal on the north side of the field, as evidenced by the PS-0 channel-fill and related delta-front sands that are structurally high to production in the south, but are wet. This may be the result of sand-on-sand juxtaposition where the channel crosses the fault. It could also indicate that gas leaked up the fault plane itself, possibly as a result of the change in orientation of the fault trace moving from north to south. Neither option is easy to confirm. The vertical displacement where the PS-0 channel crosses the fault is ~1,200 ft, placing any possible leak point above the interval that is logged in most wells.

Regardless of how it occurs, a lack of fault seal is believed to be the primary reason that the northern half of the Pine Hollow South structure is essentially barren of production. However, the sealing ability of the fault seems to improve to the southwest. Here, sandstones from the main Booch producing parasequences, PS-5 and PS-0, are cut by the fault, and thus must rely on some element of fault seal in order to trap.

PRODUCTION AND VOLUMETRICS

Fifteen wells have been completed in the Booch in the Pine Hollow South Field study area. Four of these are recent completions and have yet to begin producing, and 9

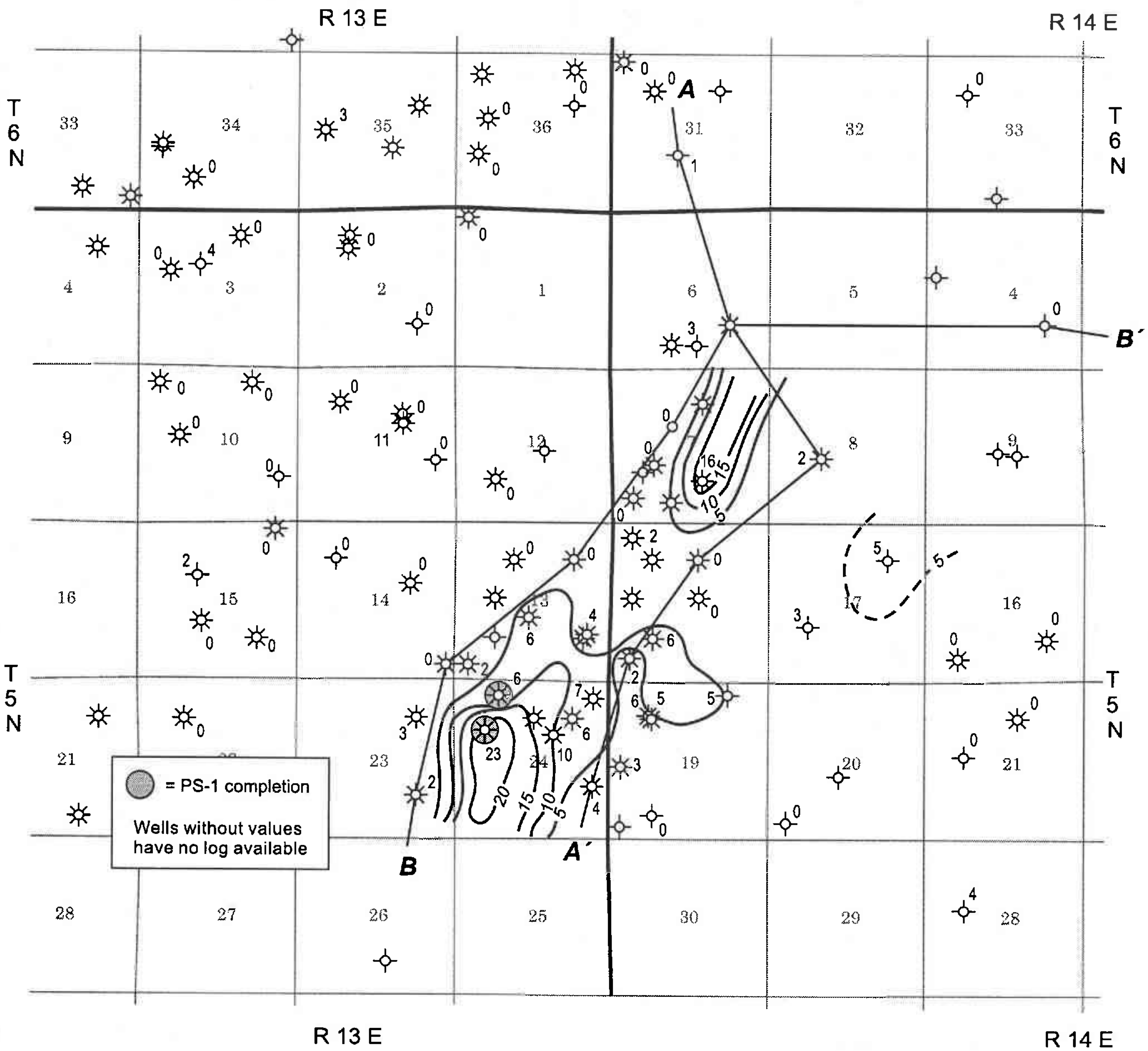


Figure 54. PS-1 gross-sand isopach map for Pine Hollow South Field. This sandstone's poor reservoir quality and low net-to-gross ratio caused it to be mapped as gross rather than net sandstone. On the basis of its orientation and gamma-ray shape, it is inferred to have been deposited as a detached mouth-bar complex, located some distance in front of an unpenetrated distributary channel. Contour interval, 5 ft.

of the remaining 11 have <2 years' production history (Table 7). Two wells have commingled production with the Hartshorne, and, on the basis of the relatively lower quality of the Booch reservoirs, two-thirds of this production has been assigned to the Hartshorne.

The Booch in the study area is estimated to have produced about 600 MMCF and have an estimated ultimate recovery of 1,375 MMCF. (This does not include future production from the four nonproducing wells or any others that may eventually be drilled.) Ultimate recoveries are calculated by maintaining the latest month's production for 5 years and adding this to the cumulative production. The young age of most of the wells increases the level of uncertainty regarding ultimate-recovery projections.

Volumetric estimates have been made of the initial gas in-place for only the two primary Booch parasequences, PS-0 and PS-5. PS-1 production is commingled with that

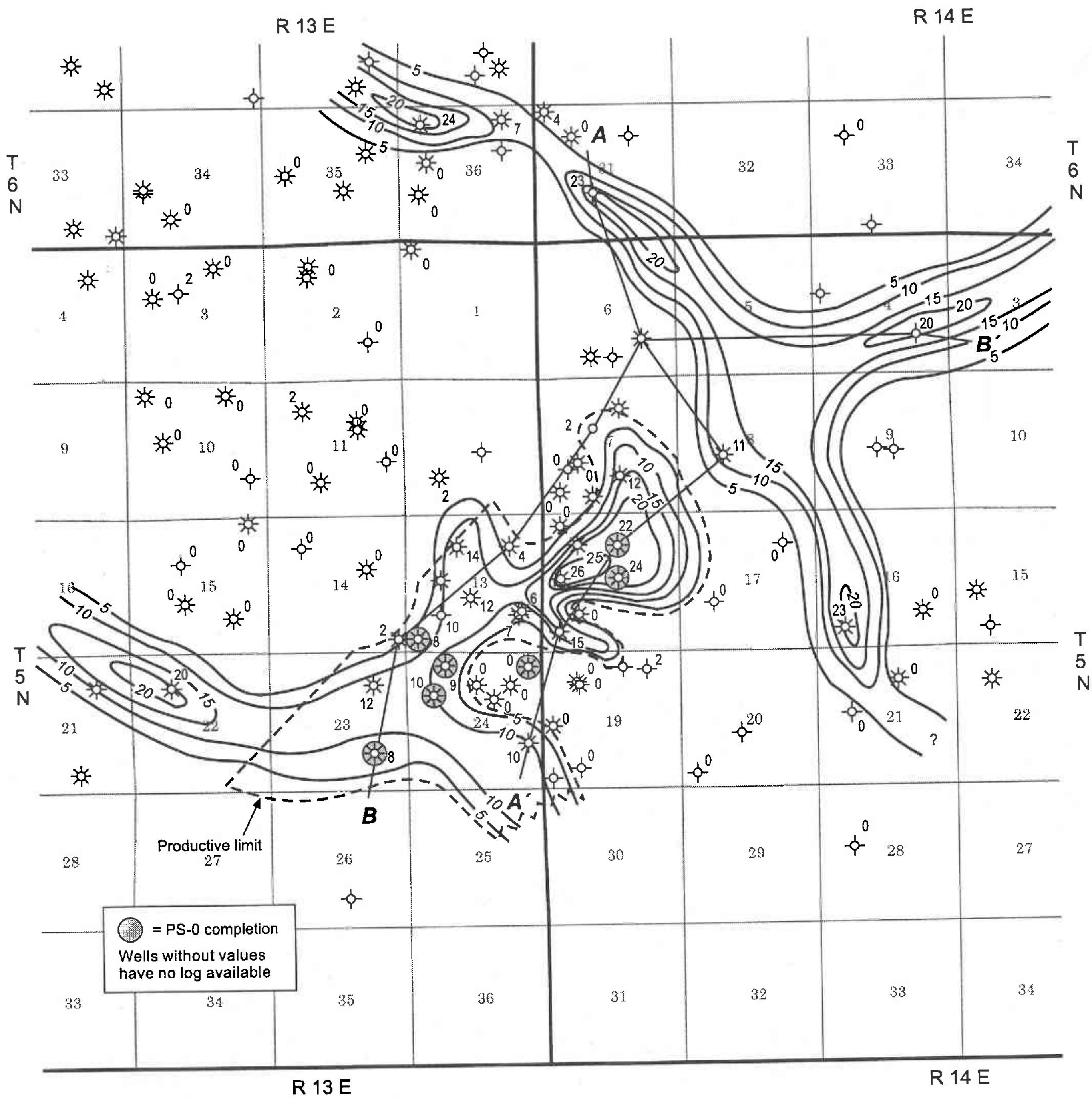


Figure 55. PS-0 net-sand isopach map for Pine Hollow South Field, showing two southeast-trending distributary-channel systems that appear to have overridden a series of shoreface or mouth-bar sands that were deposited parallel to the structural axis of the field. Contour interval, 5 ft.

of PS-0 in two wells and is believed to be relatively minor. Production from these wells is combined with that from PS-0. The single PS-2 completion next to the fault has yet to produce. However, uncertainty as to its productive limits, which are defined only by this well (and are likely small), forces so many assumptions that the value of volumetrics here becomes negligible.

PS-0 gas volumes were calculated for the southern channel–delta-front system that lies on the upthrown side of the fault. The gas–water contact is placed at −1,500 ft, halfway between the lowest producer in sec. 23 and the highest wet well in sec. 22. Although these wells are technically fault separated, offset has decreased to almost nothing at the projected gas–water contact. (The formation-water resistivity used here is 0.037 ohm-m.)

PS-5 volumes include all net sandstone on the upthrown side of the fault, excluding that seen in the structurally high, but wet, well in sec. 6. The southern limit of

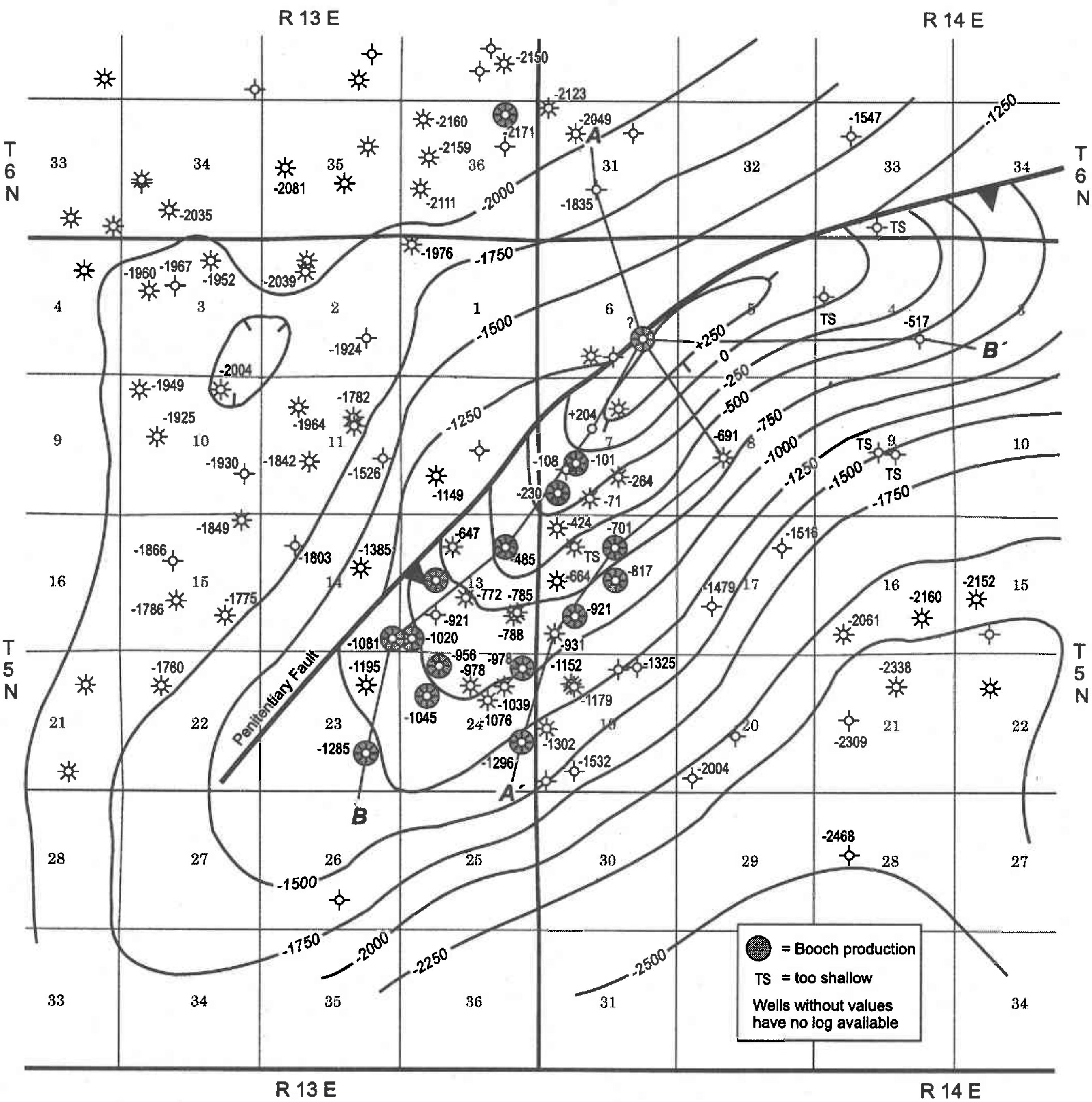


Figure 56. Structure-contour map depicting the top of the Booch sequence for Pine Hollow South Field. The large structural closure upthrown to the Penitentiary Fault helps trap most Booch production in the field. The lack of production on the north side of the structure is inferred to be due to the loss of seal as the fault turns to the east. Contour interval, 250 ft.

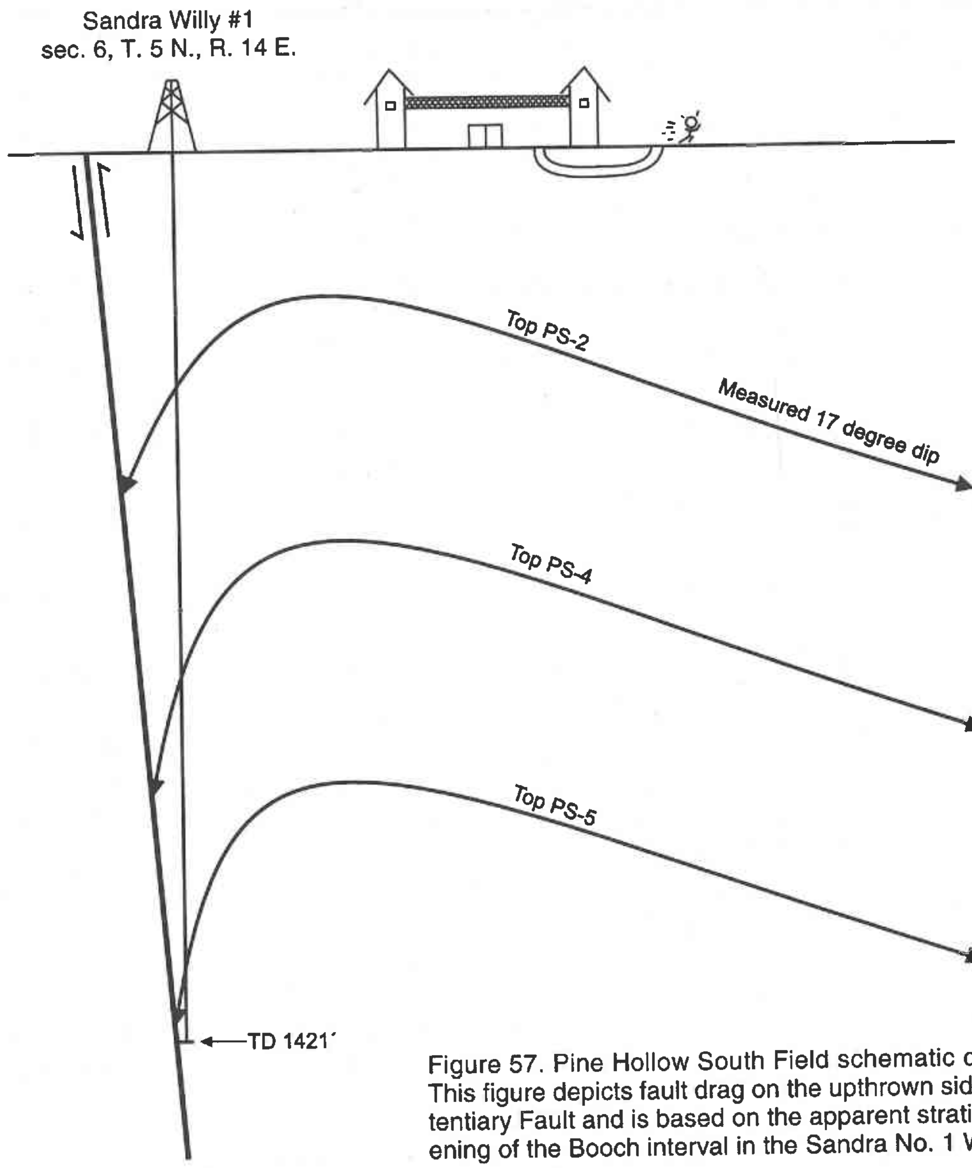


Figure 57. Pine Hollow South Field schematic cross section. This figure depicts fault drag on the upthrown side of the Penitentiary Fault and is based on the apparent stratigraphic thickening of the Booch interval in the Sandra No. 1 Willy well.

gas pay in PS-5 is somewhat nebulous, as no logs are available for the well in sec. 26, T. 5 N., R. 13 E. For volumetric purposes, the limit of production is placed at the southern edge of secs. 23 and 24, at the last structural contour that closes into the fault. This matches the geographic gas–water contact that has been estimated for PS-0 (Pl. 16; Fig. 55). Booch reservoir volumes calculated for the study are shown in Table 8.

As discussed previously, in stratigraphically complex areas, volumetric estimates are of limited value. This is especially true for the Booch in Pine Hollow South Field. The field is in the midst of development, and most productive wells have only 1–3 years of history. Commingling production with other zones is common, both within and outside of the Booch, which makes the allocation of production difficult.

Both of the productive intervals evaluated, PS-0 and PS-5, could be further subdivided to refine both the environmental interpretation as well as volumetric calculations. Sandstone quality, thickness, and areal extent vary abruptly, reducing confidence in estimates of average reservoir quality. In an area undergoing active development, new wells can dramatically change the mapped volumes. New wells can also improve recovery factors, especially where the drainage area may be limited. Gas-pay cutoffs are not absolute, and the size and quality of fracture treatments can also have a large effect on recovery factors and the relative contribution that poorer quality reservoir may make. This could especially be a factor in the productive sandstones in PS-1 and PS-2.

The maximum pressure gradient from published bottom-hole pressures in Pine Hollow South Field is 0.18 psi/ft (IHS Energy, 2004). Based on this, a formation volume factor of 17 scf/rcf was used for PS-0, and 22 scf/rcf was used for the deeper PS-5. These conform to formation volume factors used in other fields in the area (Greg Hall, personal communication, 2004). Table 9 summarizes the gas-in-place volumes calculated and the pro-

TABLE 7. — Pine Hollow South Field (Study Area) Booch Production

Operator name	Lease name	Well no.	Location	Status	Gas cum. (MCF)	EUR[a] (MMCF)			Production (MCF)			
						All Booch	PS-0	PS-5	PS no.[b]	YTD	Latest month	First prod. date
Tag Team Resources LLC	Frank	1	sec. 13, T5N, R13E SW¼SW¼SW¼	ACT	5,229	50	50		0	189	**189**	2002/02
Tag Team Resources LLC	Sandra	1	sec. 13, T5N, R13E C NE¼	ACT	130,848	225		225	5	1,569	**1,569**	2000/04
Marbet LLC	Marbet LLC	31	sec. 14, T5N, R13E SE¼SE¼SE¼	ACT	71,342	275		275	5	9,512	**3,135**	2002/05
Marbet LLC	Marbet LLC	25	sec. 23, T5N, R13E C SE¼	ACT	54,576	50	50		0, (H)[c]	2,345	**1,114**	2001/07
Tag Team Resources LLC	Nell Mary	6	sec. 24, T5N, R13E NE¼SW¼NW¼	ACT	349	50	50		0, 1	349	**349**	2003/12
Tag Team Resources LLC	Nell Mary	2	sec. 24, T5N, R13E C NE¼NE¼	ACT	29,335	125	125		0	1,439	**1,439**	2002/11
Tag Team Resources LLC	Nell Mary	1	sec. 24, T5N, R13E NW¼NE¼NW¼	ACT	27,557	150	150		0, 1	1,843	**1,843**	2002/11
Tag Team Resources LLC	Nell Mary	3	sec. 24, T5N, R13E S½NE¼SE¼	ACT	7,962	75		75	5	941	**941**	2003/01
Tag Team Resources LLC	Watkins Blake	1	sec. 7, T5N, R14E S½N½SW¼	ACT	59,377	100		100	5	364	**364**	1991/01
Tag Team Resources LLC	Geneva	4	sec. 18, T5N, R14E SW¼SW¼NE¼	ACT	7,731	25	25		0	247	**247**	2002/03
Tag Team Resources LLC	Watson	1	sec. 18, T5N, R14E C SW¼	ACT	645,357	250		250	5, (H)[c]	13,498	**1,152**	1981/08
Totals					**1,039,663**	**1,375**	**450**	**925**		**32,296**	**12,342**	

NOTE: Data from IHS Energy (through February 2004). EUR — estimated ultimate recovery.
[a]EUR calculated using latest month's production × 12 × 5 years. Many recent wells are not yet on production, making EURs provisional.
[b]Parasequence completed.
[c]H — Hartshorne. Hartshorne commingled assigns 33% to Booch zone.

duction (in MMCF) from the Booch in the Pine Hollow South Field study area.

The identical recovery factor for both of the major Booch producers is probably coincidental. The short production history for most wells makes ultimate-recovery estimates difficult. Recovery from the two PS-5 wells that are not yet on production, plus any future drilling, will probably push the PS-5 recovery factor much higher. If the PS-1 contribution to PS-0 production is removed, its recovery factor would decrease, but one PS-0 well is not yet on production. This, plus any future drilling, will tend to push the PS-0 recovery factor higher.

LESSONS LEARNED

Many of the lessons that were learned here are repetitions of those gleaned from the Reams Southeast Field study. Like that of Reams Southeast Field, Booch production in Pine Hollow South Field is structurally simple but stratigraphically complex. Environmental interpretation is the key to predicting the location of potentially productive sandstones, and finding porous and permeable sandstones is the key to identifying productive Booch reservoirs. Any structural configuration, including monoclinal dip, can trap Booch hydrocarbons. The crucial variable is the orientation of reservoir-quality sandstones relative to structural dip.

Booch production in this part of Pine Hollow South Field comes from the steeply dipping southwestern flank of a large, upthrown fault closure. Although the fault provides the lateral seal, the critical updip trapping component is stratigraphic. Fault seal is not universal, as faults have been documented in this study as being sealing, non-sealing, and both. The Penitentiary Fault in the study

TABLE 8. — Pine Hollow South Field Booch Volumetric Parameters

Interval	Avg. net sd	Area (ac.)	Avg. por.	Avg. Sg[a]	Pore vol. (ac. ft.)
PS-0:	10 ft	2,528	9%	75%	1,706
PS-5:	17 ft	1,952	10%	80%	2,655

[a]Gas saturation.

TABLE 9. — Pine Hollow South Field Booch Gas Volumes in BCF

Interval	Gas IIP	Cum. prod.	EUR	Proj. R.F.
PS-0:	1,264	88	450	36%
PS-5:	2,544	485	925	36%
Total	3,808	573	1,375	*Avg.* 36%

IIP — initially in-place. EUR — estimated ultimate recovery.
Proj. R.F. — projected recovery factor.

area seems to be an example of both.

Because structures in the Arkoma Basin were formed in a compressional environment, faults such as the Penitentiary are believed to be very high-angle reverse faults. If the results of the Sandra No. 1 Willy well are typical, then the strata adjacent to these faults behaved plastically during deformation. This has allowed these beds to go from >60° of dip into the fault in the drag area to 10–20° of dip away from the fault in a distance of, at most, a few hundred feet. This opens up the possibility of some four-way dip closure adjacent to the fault. Unfortunately, any such closure would almost certainly be very small.

Log shapes, incisions identified on cross sections, sandstone isopachs, and interval isopachs are all necessary to predict depositional environments, but even with all of this input interpretations are still often difficult. An important tool in determining whether a sandstone will generally be oriented along strike (mouth-bar–delta-front sand) or along dip (fluvial sand) is the gross-interval isopach. Constructed by using two reliable stratigraphic markers, such a map shows the paleotopography/bathymetry at the time of deposition. Environmental interpretations based on log profiles can be misleading, but stratigraphic cross sections can identify where incision has taken place, and visible downcutting invariably means channel fill.

Mapping stacked sandstones that may have been deposited in different environments and with different orientations tends to mask trends. Although the Booch in this study has been subdivided into eight intervals, at the local level individual parasequences can often be broken into thinner units, each representing a single bar-forming or channel-filling episode.

Volumetrics in most areas of the Booch are more art than science, which gives them limited predictive value. Most wells produce from multiple zones, so there is no reliable way to allocate production. Another variable that is difficult to gauge is a sandstone's areal extent. In the relatively small delta systems that prograded across this study area, sandstone bodies are usually narrow, and their thickness varies abruptly. Of note is the fact that as well control increases, individual net-sandstone maps become more complex. This clearly indicates that reservoir geometries are almost always far more intricate than mapped.

Booch reservoirs in Pine Hollow South Field are of relatively poor quality, because this area was bypassed by the major deltas prograding across the basin at this time. This has resulted in the low average recovery factors that have been calculated. However, in the high-gas-price environment in which we now find ourselves, the production volume necessary to make a well an economic success is much lower. This will permit (or force, depending on your point of view) the drilling of more wells to develop and drain these reservoirs. More wells mean more control points and increase the likelihood of finding other reservoirs that, in a wider well-spacing environment, might go undetected.

Summary and Conclusions

The Booch, as defined by the Oklahoma oil and gas industry, is equivalent to the lower three-quarters of the McAlester Formation—from the McAlester coal to the top of the Hartshorne. Booch deposition represents a shift from a mostly fluvial/deltaic Hartshorne with an easterly source to a more marine Booch sequence with a northerly source. Any part of the Booch that may have had a source from the south has since been removed as a result of uplift and erosion behind the Choctaw Thrust.

The Booch interval has been subdivided into eight correlatable, progradational depositional cycles called parasequences. Each of these sequences began with a flooding surface that initiated deposition of marine shale. As progradation continued, delta-front sediments (nearshore marine) gave way to those of the delta plain (distributary channels, splays, tidal channels, and coals). During periods of rapidly falling sea level, delta systems moved basinward, and fluvial incision became more pronounced. The deposition of stacked channel-fill sands in the resulting incised valleys occurred well inland of the paleoshoreline. The period of maximum regression was followed by the next flooding event, which resulted in the deposition of organic-rich marine shale capable of sourcing hydrocarbons, some of which may become trapped in the underlying sandstone.

The depositional slope during Booch time was gentle, such that changes in mean sea level of a few feet could move the paleoshoreline tens of miles. The delta systems responsible for the sediments that were brought into the Arkoma Basin at this time were tidally dominated. From a regional standpoint, the reservoirs that these systems created are either generally strike-parallel nearshore-marine-reworked sands or dip-parallel fluvial sands.

The lower Booch (PS-6 and PS-5) is a generally sandstone-poor interval that in most places did not experience the progradation of major delta systems. It is dominated by thin delta-front sands that were deposited at the end of a marine transgressive period that was characterized by prodelta shales.

The middle Booch (PS-4, PS-3A, PS-3), which is by far the sandiest Booch interval, represents a marked deltaic progradation caused by a prolonged marine regression. It is characterized by high-quality, incised-valley (stacked channel-fill) sands that are correlative with the ubiquitous Warner sandstones on the surface.

The upper Booch (PS-2, PS-1, PS-0), an interval that saw large-scale transgressions in which thick prodelta shales were deposited, also underwent the progradation of major delta systems. These systems deposited reservoirs ranging from nearshore-marine through distributary-channel-fill and incised-valley sands. The sandstones in this interval are correlative with what are called the Lequire and Cameron Sandstones, as defined in outcrop.

The thickness and TOC values for Booch marine shales make them excellent source rocks. Gas-prone kerogen in the shales and the abundant coals combine to make the basinal Booch strongly gas prone. Although in places reservoirs have access to Atoka-age source rocks via cross-fault migration, problems with episodic fault transmissibility and numerous reservoirs with no cross-fault access make it likely that the source for most of the Booch hydrocarbons was the Booch itself. Booch oil reservoirs on the shelf are dominantly fluvial and are probably indicative of either a source other than the Booch, or a change in the local source-rock kerogen type.

Although faults and structural closures are important, the trapping element most critical to Booch gas accumulation is stratigraphic. Faults do not universally seal, and even the largest structural closures require the presence of a prograding delta system to create the reservoirs necessary to trap significant gas. Even for sandstones located on large structures, both lateral and updip seals commonly are still stratigraphic. Thus reservoir volume, quality, and orientation relative to structural dip are the key factors that determine the volume of gas trapped.

Fluvial sands make better reservoirs than marine sands owing partly to their coarser grain size but mostly because they are more poorly sorted. Channel-fill sands are deposited rapidly and contain more clay-size material, making it more difficult for silica (the primary cementing agent) to precipitate. Booch marine sands are clean and well sorted, having been winnowed twice daily from tidal action. This makes them excellent sites for the precipitation of secondary silica cement. The best reservoirs were deposited as incised-valley channel fills, followed in quality by distributary-channel fills, tidal channels, mouth bars, overbank splays, and lower energy nearshore-marine sands.

Volumetrics are of limited predictive value for the Booch. This is due to the widespread commingling of production and a complex stratigraphy and reservoir geometry that make estimates of areal extent, reservoir quality, and thickness difficult. Gas produced from the Booch is driven by pressure depletion. It is also significantly underpressured, which reduces the initial reservoir pressure, production rate, and gas in-place. These factors also force the need for compression early in the life of most Booch producers.

On the other side of the ledger, complex stratigraphy and the lack of a need for structural closure has left many opportunities for continued exploitation of Booch gas. Abundant well control means that stratigraphic risk can be managed, making wide areas prospective. The formation is shallow, cheap to drill, and requires only modest recovery in a high-gas-price environment to be economic. In addition, for most prospective areas the more prolific Hartshorne lies just beneath the Booch, making it an attractive secondary objective to reduce risk.

This study draws conclusions based on a widely spaced regional data grid and three field studies chosen to highlight production from various parts of the Booch stratigraphic interval. In a play of this size and complexity a great deal must be left unaddressed. This work is meant to be only a starting point for those interested in pursuing Booch natural gas and has been designed as such. Digital files have been included with this study to help operators jump-start such an effort. For those who are already familiar with the Booch, I hope this study offers some new perspectives on this venerable producing formation. The conclusions outlined are not presented as dogma, but simply another contribution to the petroleum industry's general pool of knowledge.

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Appendixes

Appendix 1

Various Size Grade Scales in Common Use

(from Blatt and others, 1980, table 3-3)

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 (Kies)		—3 in.—
Pebbles				
				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			Coarse sand	Medium sand
		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(feet) (volume)
BCF	billion cubic feet (of gas)
B_g	gas formation volume factor (scf/rcf)
BHP	bottom-hole pressure
BOE	barrels of oil equivalent
BOPD	barrels of oil per day
BWPD	barrels of water per day
CAL	caliper (well log)
CILD	conductivity (well log)
ck	choke (production opening)
com.	commingled (production)
cond., COND	conductivity (well log)
cum.	cumulative (production)
den., DEN	density (well log)
DST	drillstem test
EUR	estimated ultimate recovery
frac.	fracture (well treatment)
gal	gallon(s)
GasIIP	gas initially in-place
GLE	ground-level elevation
GR	gamma ray (well log)
GWC	gas–water contact
ILD	induction (well log)
ind., Ind.	induction (well log)
IPF	initial production rate flowing
KBE	kelly-bushing elevation
lb	pound(s)
ls	limestone
MCF	thousand cubic feet (of gas)
md	millidarcies, or 0.001 darcy
MD	measured depth
MMBO	million barrels of oil
MMCF	million cubic feet (of gas)
MMCFGPD	million cubic feet of gas per day
m.y.	million years
m.y.b.p.	million years before present
neut., NEUT	neutron (well log)
OA	overall (perforated interval depth)
ohm-m	ohm meters
perf.	perforate(d)
por., POR	porosity
prod.	production
PS	parasequence
PSI, psi	pounds per square inch
rcf	reservoir cubic feet
res., RES	resistivity (well log)
RF	recovery factor
R_o	vitrinite reflectance
R_t	deep, or true, resistivity (well log)
R_{xo}	resistivity of flushed zone (well log)
scf	standard cubic feet
sd	sand
S_g	gas saturation
SP	spontaneous potential (well log)
ss	sandstone
S_w	water saturation
TD	total depth
TOC	total organic carbon
TSTM	too small to measure
TVD	true vertical depth

Appendix 3

Glossary of Terms

(as used in this volume)

Definitions modified from Jackson (1997).

authigenic—Formed or generated in place.

channel fill—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.

clay drapes—Layers of clay and silt deposited on lateral accretionary surfaces of point bars during periods of decreased river discharge.

commingled production—The mixing of hydrocarbon production from two or more reservoirs through a single meter, making it impossible to ascertain individual contributions.

cyclothem—Term proposed by Weller (*in* Wanless and Weller, 1932) for a series of beds deposited during a single sedimentary cycle of the type that prevailed during the Pennsylvanian Period.

darcy—The standard unit of permeability, equivalent to the passage of one cubic centimeter of fluid of one centipoise viscosity flowing in one second under a pressure differential of one atmosphere through a cubic centimeter of a porous medium.

delta—The low, nearly flat, alluvial tract of land at or near the mouth of a river, commonly forming a triangular or fan-shaped plain of considerable area, crossed by many distributaries of the main river, perhaps extending beyond the general trend of the coast, and resulting from the accumulation of sediment supplied by the river in such quantities that it is not removed by tides, waves, and currents. See also: *delta plain, delta front, prodelta, lower delta plain,* and *upper delta plain.*

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 may or may not be steep.

delta plain—The level or nearly level surface composing the landward part of a large delta; strictly, an alluvial plain characterized by repeated channel bifurcation and divergence, multiple distributary channels, and interdistributary flood basins.

density log—A well-log curve of induced radioactivity, showing the bulk density of rocks and their contained fluids.

detrital—In clastic sedimentary rocks, refers to loose rock and mineral material that is worn off or removed by mechanical means.

dewatering—The expulsion, during diagenesis (mostly through compaction), of water from sediments.

diagenetic—Describing 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.

distal—Farthest from the point of origin. In a sedimentological sense, far from the source area. Antonym: proximal.

distributary channel—(a) A divergent stream flowing away from the main stream and not returning to it, as in a delta or on an alluvial plain. (b) One of the channels of a braided stream; a channel carrying the water of a stream distributary.

epeirogenic—Pertaining to vertical basement movement affecting large areas of the continent, in contrast to more localized mountain-building events.

eustatic—Pertaining to worldwide changes of sea level that affect all oceans.

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.

flooding surface—A surface separating younger from older strata across which there is evidence for an abrupt increase in water depth.

fluvial—Of or pertaining to a river; produced by the action of a stream or river.

formation volume factor—The factor applied to convert: (a) a barrel of gas-free oil in a stock tank at the surface into an equivalent amount of oil in the reservoir, or (b) a cubic foot of gas at reservoir pressure to a cubic foot at atmospheric pressure.

friability—Ability of a rock or mineral to be easily broken or reduced to powder, as in a poorly cemented sandstone.

gamma-ray log—Radioactivity log measuring the occurrence of natural gamma rays emitted from rocks in a cased or uncased borehole. Used to distinguish clay-rich shales (high gamma ray) from other sedimentary rocks.

hydrostatic pressure—A condition in which formation pressure at a given depth in the subsurface is balanced by a column of water of equal height. Also called normal pressure, it distinguishes between "over" or "under" pressure.

incised valleys—Entrenched fluvial systems that extend their channels basinward and erode into underlying strata as a result of a reduction in sea level. In the Booch these are usually miles wide and erode into underlying sediment as much as 250 ft.

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

kerogen—Organic matter insoluble in organic solvents.

longshore drift—The movement of sediment along a shoreline caused by waves approaching the coast at an angle.

lower delta plain—Depositional environment within a *delta* that extends from the subaqueous *delta front* to the landward limit of marine (tidal) influence.

microlog—Trade name for a well log consisting of two microresistivity curves. Their response is dominated by the presence of mud cake, whose separation indicates permeable zones.

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

mouth bar—Nearshore marine bar formed directly in front of the point at which a distributary channel feeds into the sea.

neutron–density crossover—The crossing of neutron and density log curves that is usually an indication of the presence of natural gas. Caused by porosity readings that are too low in the neutron log because the concentration of hydrogen in gas is less than that in water.

neutron log—A radioactivity log that measures the intensity of radiation produced when the formation near the wellbore is bombarded by neutrons. Intensity is related to hydrogen concentration, so it cannot distinguish oil from water, but is sensitive to the presence of gas.

overbank splay—See *splay*.

paleo—A combining form denoting great age or ancient conditions.

parasequence—A relatively conformable succession of genetically related beds bounded by flooding surfaces or their correlative surfaces.

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.

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.

proximal—Nearest to the point of origin. In a sedimentological sense, close to the source area. Antonym: distal.

regression—The retreat or contraction of the sea from land areas, and the consequent evidence of such withdrawal. Antonym: transgression.

reserves (gas)—The gas that can be economically produced, given environmental, legal, and technologic constraints.

reservoir cubic foot—In reference to natural gas, a cubic foot at reservoir pressure.

reservoir (gas)—Rock capable of flowing economic volumes of gas, herein described as having at least 8% porosity.

resistivity log—Well log consisting of one or more resistivity curves that measure a formation's resistance to the flow of electricity. These logs can be configured to various depths of investigation from the wellbore to measure the invasion of mud filtrate and so provide a qualitative measure of permeability.

rip-up clasts—Mud clasts, usually of flat shape, that have been "ripped up" by currents from a semiconsolidated mud deposit and transported to a new depositional site.

splay—A small alluvial fan or other outspread deposit formed where an overloaded stream breaks through a levee (artificial or natural) and deposits its material on the flood plain or delta plain.

spontaneous-potential log—Electric-log curve that measures the flow of electricity resulting from differences in salinity between formation water and mud filtrate. Can be used as a qualitative measure of permeability.

standard cubic foot—In reference to natural gas, a cubic foot at atmospheric pressure.

stylolite—A surface or contact marked by an irregular and interlocking penetration of the two sides. The seam is characterized by a concentration of insoluble constituents of the rock, such as clay, carbon, or iron oxides.

sublitharenite—A sandstone that is intermediate in composition between litharenite (a sandstone composed of rock fragments) and a pure quartz sandstone.

syndepositional—Occurring at the same time as deposition.

tectonic—The forces involved or the resulting structural features that have been generated by earth movement.

tidal channel—Channel created by tidal currents that extends from offshore to a tidal marsh or tidal flat.

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

turbidites—Sediment deposited as a result of a submarine flow of sediment in suspension that is denser than the surrounding water (turbidity current). Initiated by updip instabilities in the shelf and slope, they are usually diagnostic of deposition in a deep-water environment.

upper delta plain—Depositional environment in a *delta* that extends from the down-flow edge of the flood plain to the effective limit of tidal inundation of the *lower delta plain*. The upper delta plain essentially is that portion of a delta unaffected by marine processes.

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

vertical seismic profile—Measurement of the response of a geophone, placed at various depths in a wellbore, to a seismic source on the surface.

vitrinite reflectance—A measure of reflectivity of the coal maceral group vitrinite in the determination of the maximum temperature experienced by the sediments in which it is found. Used to grade source-rock maturity for which higher reflectance indicates increased maturity.

Appendix 4

Core Descriptions, Well Logs, and Selected Photographs for the Following Wells:

1. **Cities Service Company**
   Mason "A" #1
   SW¼SW¼ sec. 31, T. 10 N., R. 18 E.
   Middle Booch stacked channel-fill sequence in incised valley.
   Core depth: 1,342–1,511 ft. Corrected log depth: 1,345–1,514 ft.

2. **Cities Service Company**
   McKee "B" #1
   NW¼SW¼ sec. 24, T. 10 N., R. 17 E.
   Two (PS-3/PS-3A) middle Booch parasequences, both containing distributary-channel-mouth bars.
   Core depth: 1,240–1,362 ft. Corrected log depth: 1,243–1,365 ft.

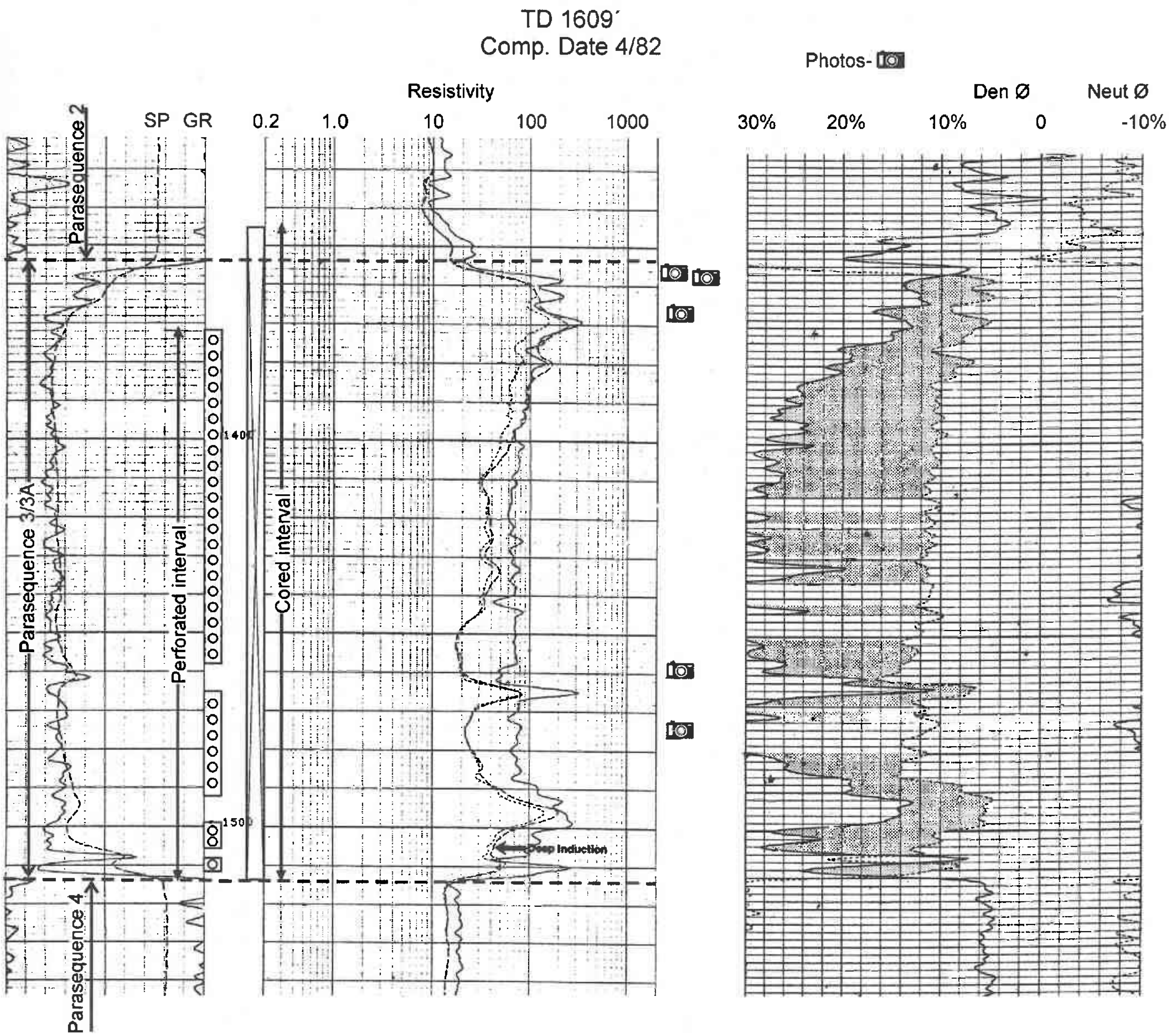
Cities Service Company
Mason "A" #1

SW¼SW¼ sec. 31, T. 10 N., R. 18 E.
Cored from 1,345 to 1,514 ft
Perforated: 1,372–1,458, 1,465–1,492, 1,499–1,506, 1,508–1,512 ft
IPF (natural): 2,060 MCFPD
Cumulative production: 1,378,044 MCF (April 2004)
(All depths are log corrected)

Depth (ft)	Description
1,354.5–1,355.0 (1,345.0–1,355.0)	PRODELTA SHALE (parasequence 2) Shale, black, fissile, and carbonaceous. This 0.5 ft, represented by loose shards, is indicative of entire interval from top of core (1,345.0 ft) to the top of the underlying sandstone (1,355.0 ft). Remaining 9.5 ft apparently discarded.
1,355.0–1,383.5	INCISED-VALLEY CHANNEL FILL (parasequence 3/3A) Sandstone, light-gray, very fine grained, quartz-rich, usually unbedded but containing intervals with high-angle cross-bedding. Contains abundant carbonaceous stylolites, thin intervals with numerous shale rip-up clasts, and several 0.25–1.5-in. reddish-brown siderite-stained zones in which the sandstone becomes mixed with clay and is denser and more micaceous. The upper 2 in. of the sandstone is horizontally laminated with dark-gray shale and contains small shale rip-up clasts. This upper contact marks the PS-2 flooding surface.
1,383.5–1,454.0	Sandstone, light-brown to light-gray, quartz-rich, mostly medium grained and well rounded, but with fine-grained intervals. Dominated by high-angle cross-bedding marked by siderite-stained laminations, although unbedded in places. Excellent intergranular porosity visible. Shale rip-up clasts are rare.
1,454.0–1,474.0	Sandstone, light- to dark-gray, quartz-rich, mostly fine grained, with some medium grained, mostly unbedded, with abundant thin, discontinuous carbonaceous streaks and scattered thin zones containing small (<0.5-in.) mud and shale rip-up clasts.
1,474.0–1,506.5	Sandstone, light-gray, fine- to medium-grained, well-rounded, quartz-rich, some unbedded but mostly characterized by high-angle cross-bedding. Abundant carbonaceous stylolites throughout, and locally abundant reddish-brown mud and dark-gray shale rip-up clasts (1–2 in.); 10 ft of sand missing from this interval is indicated to be identical.
1,506.5–1,507.5	CHANNEL-FILL CLAY PLUG Shale, black to dark-gray to reddish-gray, becoming redder with depth. Horizontal laminations and ripple bedding occur with light-gray, very fine grained sandstone and siltstone, which, in the upper 0.2 ft contains reddish-brown mud clasts in a black-shale matrix. Shale grades into the sandstone above but has a sharp, angular basal contact with the underlying sandstone.
1,507.5–1,512.5	INCISED-VALLEY CHANNEL FILL (INITIAL INCISION) Sandstone, dark-gray, fine- to very fine grained, quartz-rich, with low-angle cross-bedding. Abundant carbonaceous inclusions and siderite-stained laminations. Sharp (knife-edge) upper and basal contacts with no rip-up clasts present.
1,512.5–1,514.0	PRODELTA SHALE (parasequence 4) Shale, black, fissile, and carbonaceous. Preserved as rubble zone beneath sandstone above.

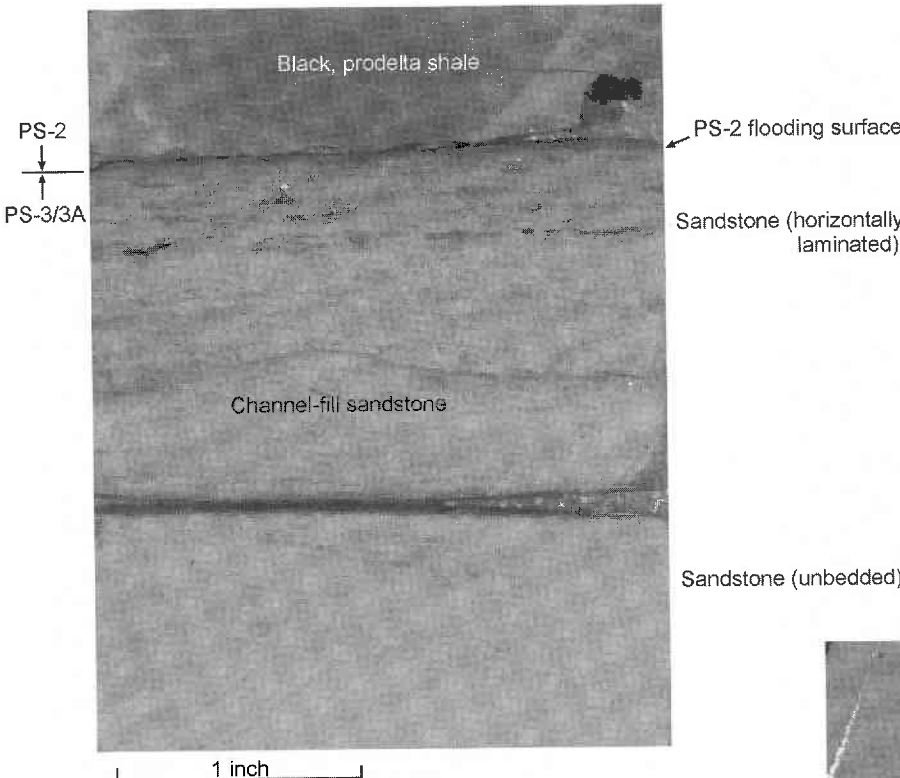
Cities Service Company
Mason "A" #1

(SW¼SW¼ sec. 31, T. 10 N., R. 18 E.)



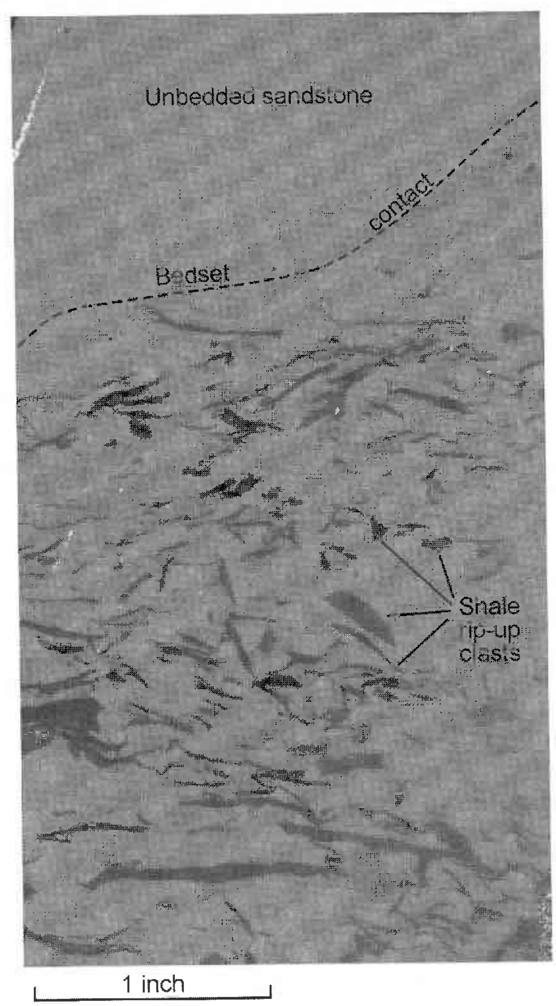
Cities Service Company
Mason "A" #1

(SW¼SW¼ sec. 31, T. 10 N., R. 18 E.)



Mason 1,355 ft:

Upper contact of PS-3/3A incised-valley channel fill shows black prodelta shale overlying fine-grained sandstone horizontally laminated with dark-gray shale and small shale rip-up clasts that grade downward into poorly bedded sandstone. The top of this sandstone marks the PS-2 flooding surface.

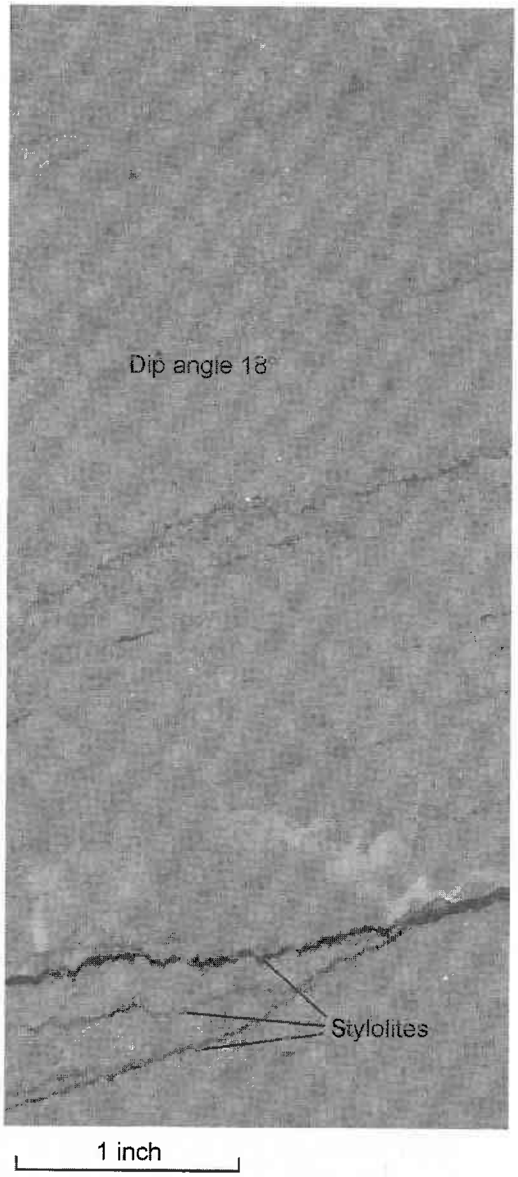


Mason 1,356 ft:

Unbedded sandstone with abundant shale rip-up clasts that are chaotically oriented indicates high-energy, rapid deposition characteristic of channel-fill environments. These clasts were probably eroded from older prodelta shales into which incisement occurred. Excepting clasts near the bottom, most likely originated when the active channel was near the valley margin and lateral incisement of the valley was taking place. Contact with the unbedded sandstone above is irregular.

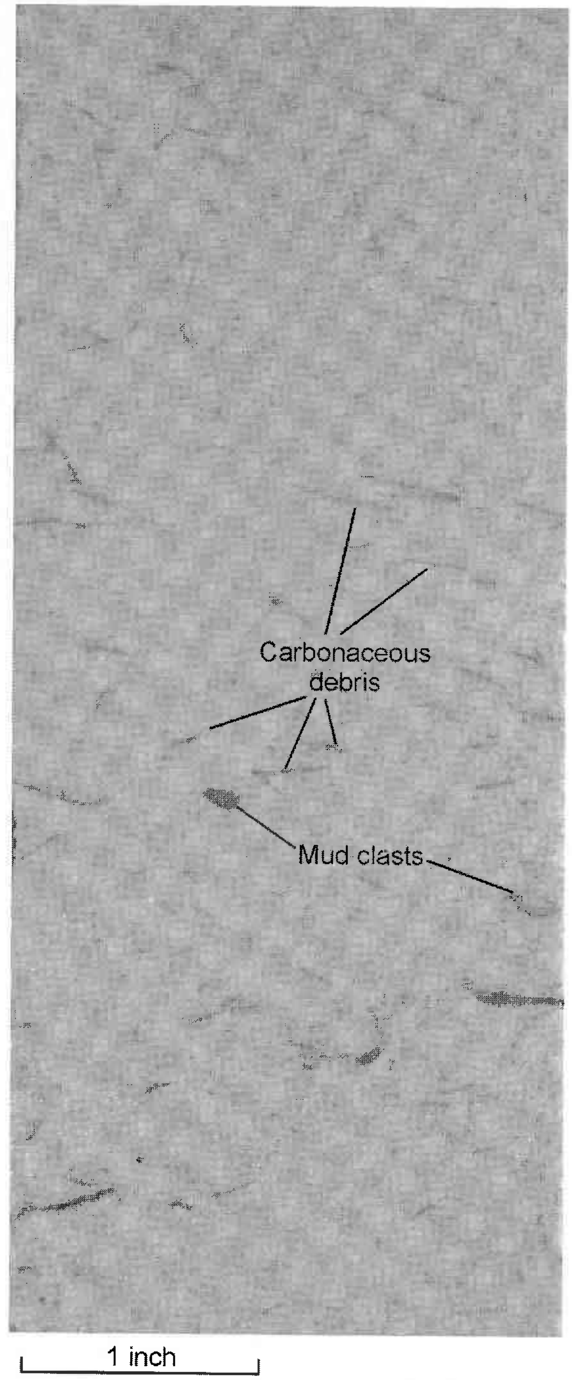
Cities Service Company
Mason "A" #1

(SW¼SW¼ sec. 31, T. 10 N., R. 18 E.)



Mason 1,367 ft:

Medium- and high-angle cross-bedded sandstone is common in the high-energy deposition seen in channel-fill sequences. This interval contains carbonaceous stylolites, formed during the dewatering phase of diagenesis. These are on the surface of several bedding planes that dip as much as 18°.

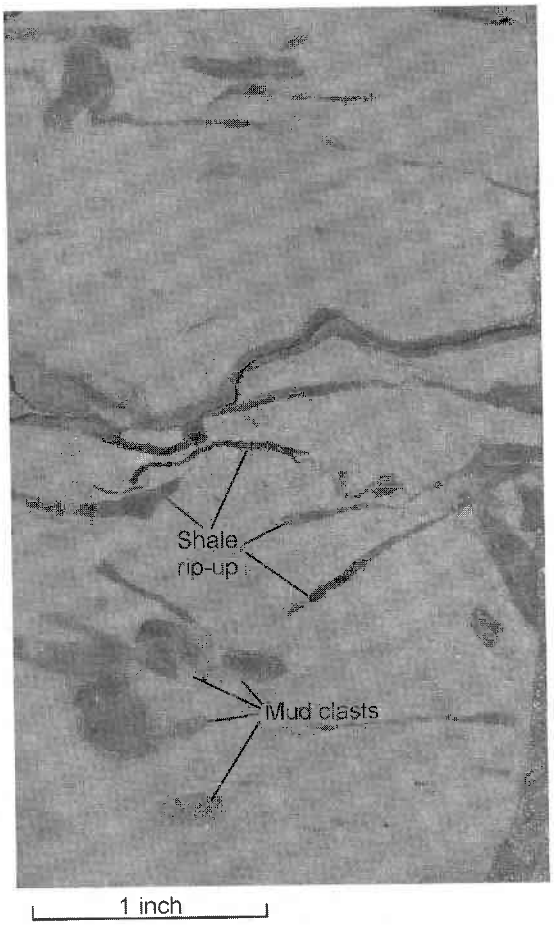


Mason 1,457 ft:

Medium-grained sandstone containing randomly oriented carbonaceous debris and mud clasts is characteristic of rapid fluvial deposition. This carbonaceous debris is likely composed of coalified plant material (leaves and twigs) that was incorporated into the sandy bed load of the fluvial system. The mud clasts are stained with reddish-brown siderite (iron carbonate).

Cities Service Company
Mason "A" #1

(SW¼SW¼ sec. 31, T. 10 N., R. 18 E.)



Mason 1,477 ft:

Medium-grained sandstone containing elongate, angular shale rip-up and rounded mud clasts points to at least two sources for the coarse debris contained within this fluvial deposit. The mud clasts contain small amounts of siderite and are rounded. This indicates little or no compaction owing to burial, and an original source from a levee or other facies associated with cut-and-fill channel environments. The shale rip-up clasts are black, carbonaceous, and partially lithified. These originate from older, compacted sediments that were deposited in a reducing environment. The black prodelta marine shales into which the bulk of incisement has taken place are the likely source of these clasts.

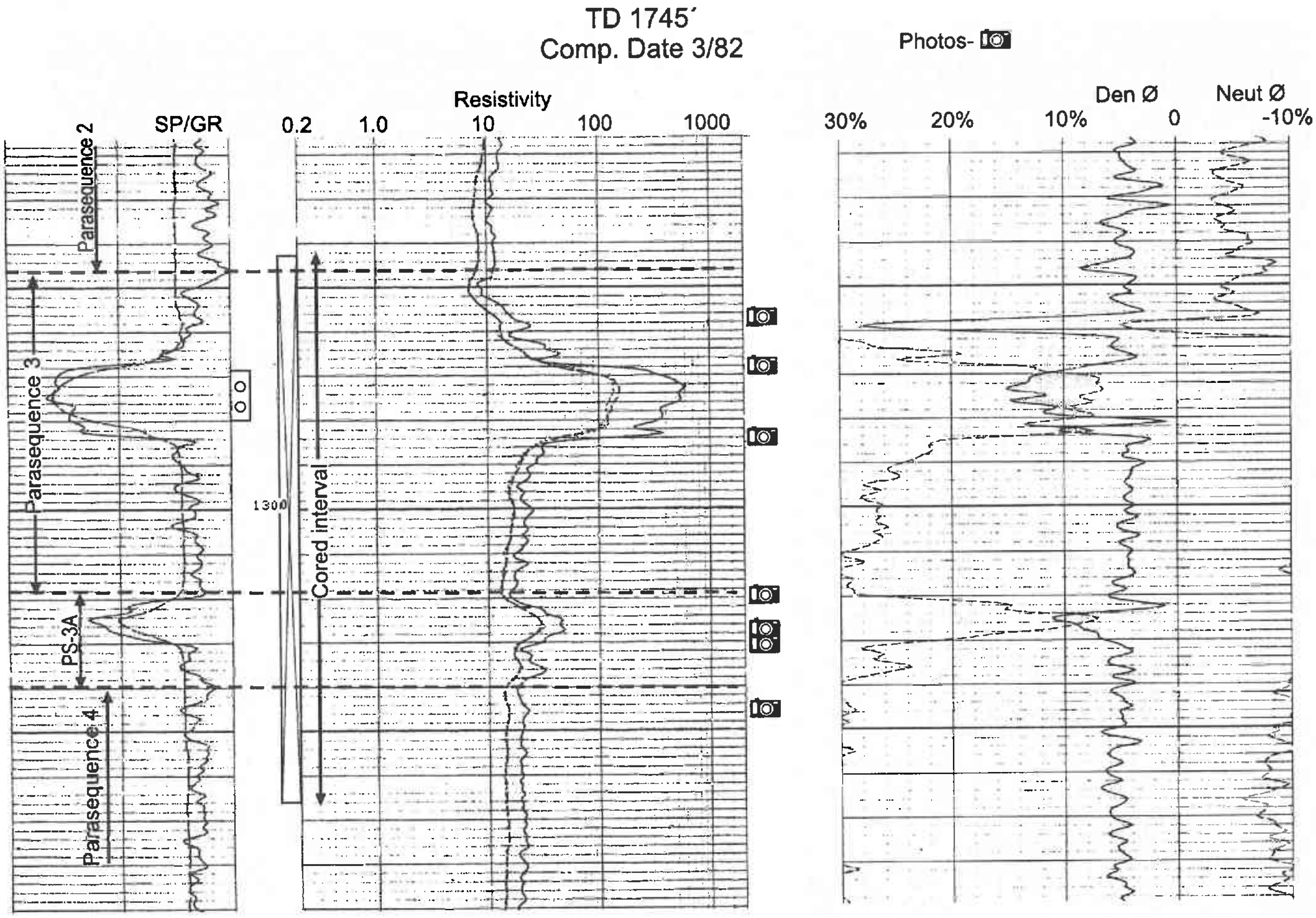
Cities Service Company
McKee "B" #1

NW¼SW¼ sec. 24, T. 10 N., R. 17 E.
Cored from 1,243 to 1,365 ft
Perforated: 1,269–1,280 ft
IPF (acid frac: 1,000 gal acid, 30,000 lb sand): 1,250 MCFPD
Cumulative production: 189,053 MCF (April 2004)
(All depths are log corrected)

Depth (ft)	Description
1,243.0–1,246.0	PRODELTA SHALE (parasequence 2) Shale, black, very fissile and carbonaceous. Preserved as rubble zone of core chips subdivided by depth cards.
1,246.0–1,261.0	INTERDISTRIBUTARY BAY FILL (parasequence 3) Shale, light- to dark-gray, with reddish-brown (siderite-stained) laminations. Pyritized inclusions and thin (≤0.5-in.) coal streaks are locally abundant.
1,261.0–1,264.8	Shale, light- to dark-gray, interlaminated with light-gray, very fine grained sandstone and siltstone, commonly siderite stained. Some horizontal laminations exhibit flame structures from postdepositional dewatering. Sand percentage increases downward. No burrowing noted.
1,264.8–1,283.2	DISTRIBUTARY-CHANNEL-MOUTH BAR Sandstone, light- to dark- to reddish-gray, fine to very fine grained, usually unbedded, but some high-angle (~20°) cross-bedding also present. Contacts with the shale above and especially below are gradual, with cleanest sandstone present in upper part of interval. Lack of an abrupt upper contact indicates gradual bar abandonment or an incomplete facies succession. Abundant carbonaceous stylolites are present throughout with locally abundant dark- to brownish-gray shale rip-up clasts. Several thin (1–4-in.) zones composed of dark-brown to brownish-gray very fine grained sandstone to siltstone mixed with clay, siderite, and carbonaceous debris. These usually have abrupt stylolitic (sawtooth) contacts with the sandstone above and below.
1,283.2–1,320.2	BAR TRANSITION FACIES Shale, dark-gray, interlaminated with light-gray, very fine grained sandstone and siltstone, becoming shalier downward. Sandstone in the upper part is cross-laminated, in places bi-directional, but becomes more horizontally laminated toward the bottom of the interval. Zones in lower half contain numerous fine-grained sandstone-filled horizontal burrows.
1,320.2–1,329.0	DISTRIBUTARY-CHANNEL-MOUTH BAR (parasequence 3A) Sandstone, light-gray, very fine grained, unbedded, becoming shalier downward. Abrupt erosional upper contact marks flooding surface at top of parasequence with 0.5–1.0-in. shaly sandstone lag deposit between unbedded sandstone and shale above. Abundant horizontal and vertical burrows present throughout, with horizontal burrows predominating in the lower part. Interval contains little clean sandstone and grades into the underlying shale below. This interval represents a lower energy (nonreservoir) mouth-bar facies than seen in parasequence 3.
1,329.0–1,341.0	BAR TRANSITION FACIES Shale, dark-gray, horizontally laminated, with light-gray, very fine grained sandstone and siltstone filling the horizontal burrows that are present throughout. Sand percentage (burrowing) decreases downward, becoming nearly all shale near the base. Shale becomes progressively darker downward.
1,341.0–1,360.0	BAR TRANSITION FACIES (parasequence 4) Shale, dark-gray, horizontally laminated, with light-gray, very fine grained sandstone and siltstone filling horizontal burrows that are present throughout. Sand percentage (burrowing) decreases downward and becomes nearly all shale near the base. Shale becomes progressively darker downward, grading into black shale below. Although not capped by a distributary-mouth-bar sandstone, this sequence is identical to that above.
1,360.0–1,365.0	PRODELTA SHALE Shale, black, very fissile and carbonaceous. Upper contact gradual with overlying interval, placed at point where burrows and siltstone laminations disappear.

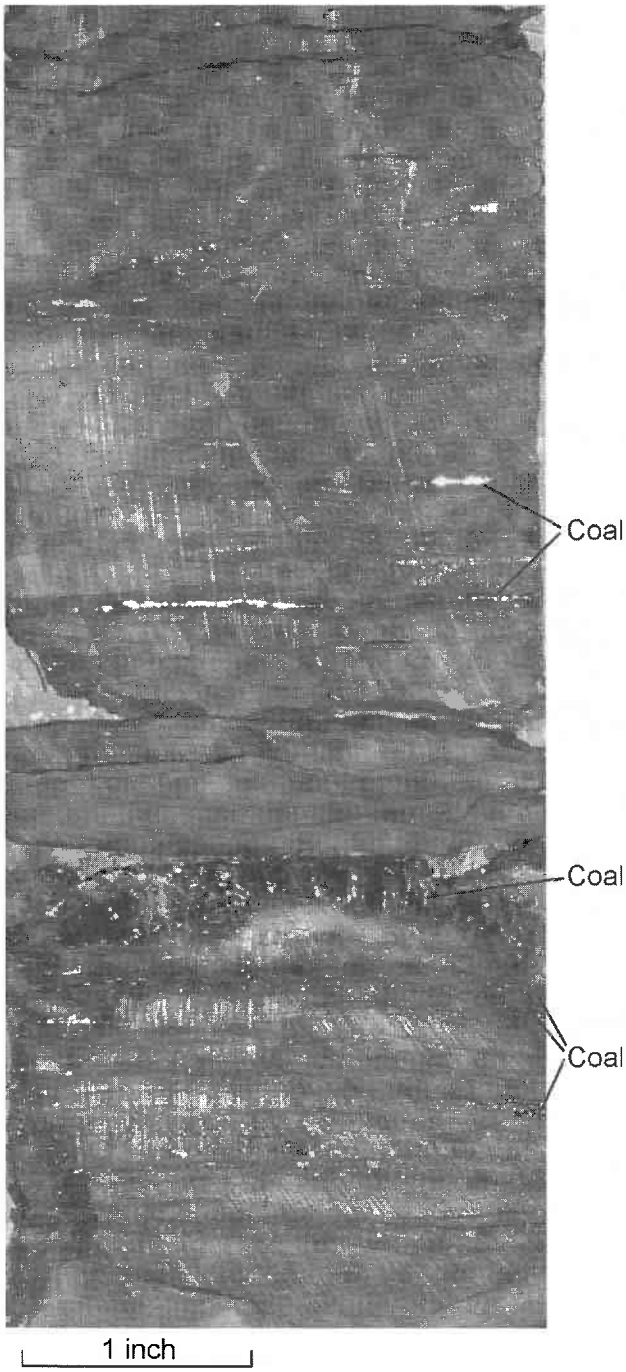
Cities Service Company
McKee "B" #1

(NW¼SW¼ sec. 24, T. 10 N., R. 17 E.)



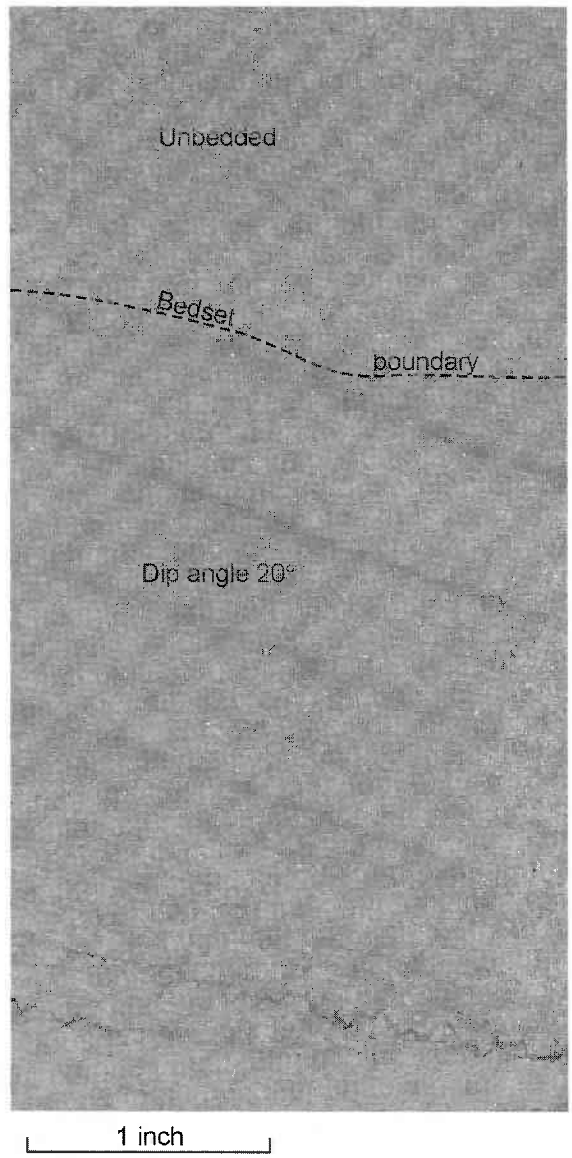
Cities Service Company
McKee "B" #1

(NW¼SW¼ sec. 24, T. 10 N., R. 17 E.)



McKee 1,257 ft:

Black carbonaceous, coaly shale devoid of any coarser grained constituents was likely deposited in a reducing, terrestrial (swamp) setting that might be found in an interdistributary bay-fill environment. Its position near the top of a progradational depositional sequence above a channel-mouth-bar complex confirms a deltaic depositional setting.

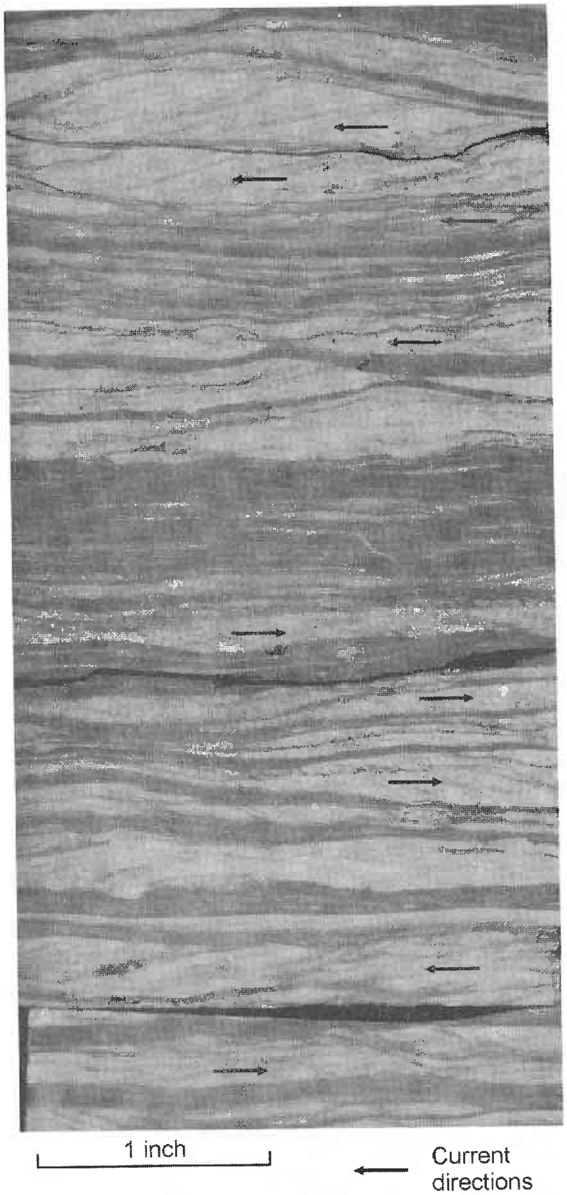


McKee 1,268 ft:

Clean, unbedded sandstone overlying high-angle cross-bedded sandstone can be indicative either of a distributary-channel fill or an upper-mouth-bar environment. The lack of an abrupt upper contact indicates that this is part of a mouth-bar sandstone. Bedding is highlighted by siderite staining and organics.

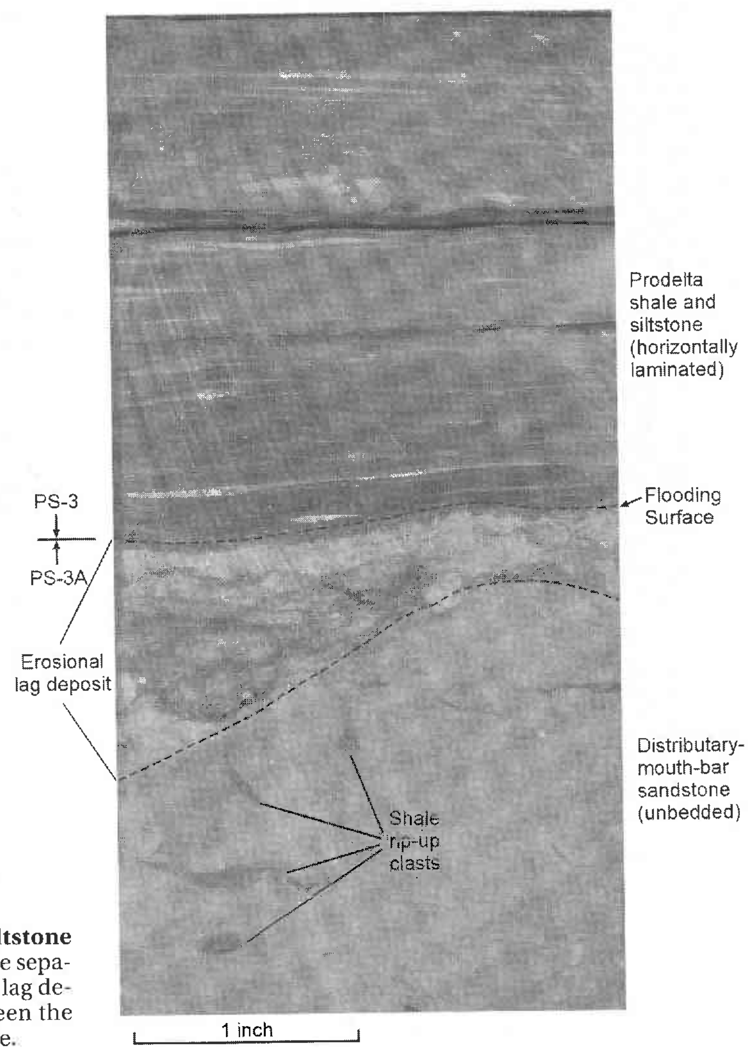
Cities Service Company
McKee "B" #1

(NW¼SW¼ sec. 24, T. 10 N., R. 17 E.)



McKee 1,284 ft:

Bi-directional cross-bedding is commonly indicative of intertidal marine deposition. Here, sand-rich, ripple-bedded zones are filled in and interbedded with generally more shale-rich, horizontally laminated intervals. These may mark periods of less tidal energy, perhaps in slightly deeper water, with correspondingly less sand deposition.

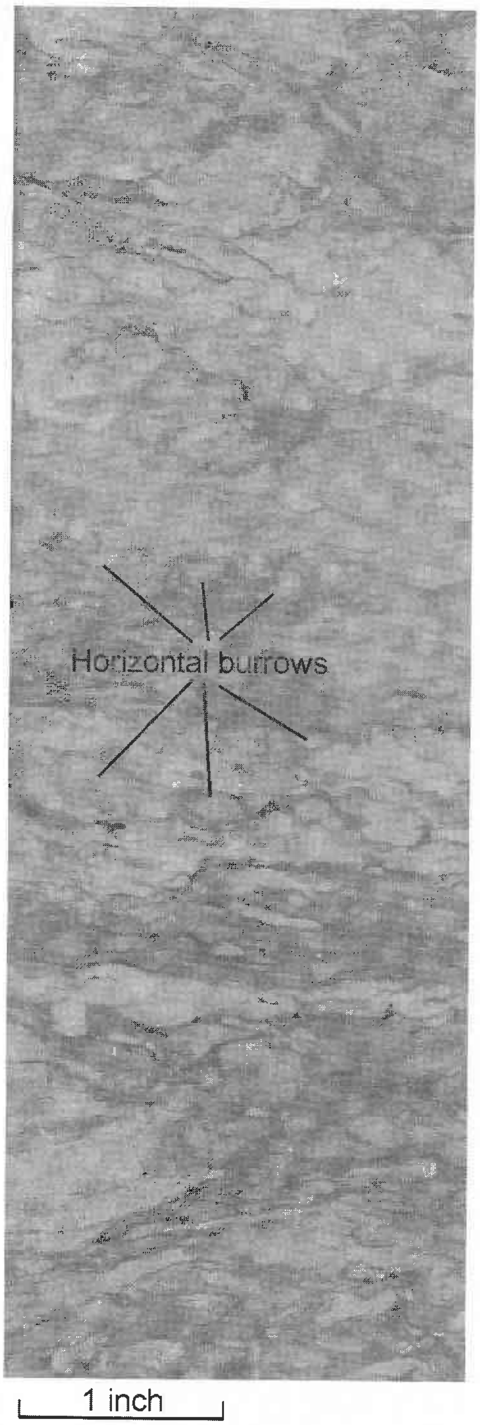


McKee 1,319 ft:

Horizontally laminated black shale and light-gray siltstone overlying unbedded sandstone mark the flooding surface separating parasequences 3 and 3A. An unbedded erosional lag deposit composed of shaly sandstone is preserved between the prodelta shale and the distributary-mouth-bar sandstone.

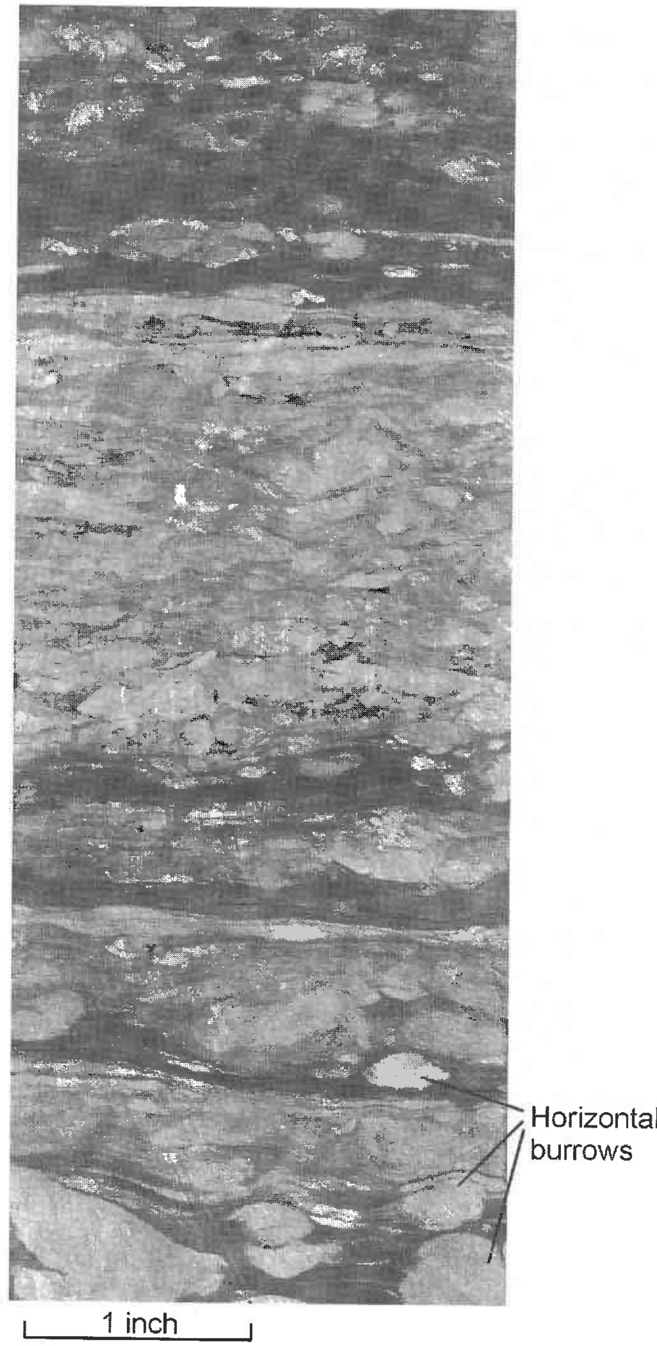
Cities Service Company
McKee "B" #1

(NW¼SW¼ sec. 24, T. 10 N., R. 17 E.)



McKee 1,327 ft:

Very fine grained sandstone massively bioturbated by horizontal burrows indicates deposition in a low-energy, shallow- marine, lower-distributary-mouth-bar to transition-zone environment.

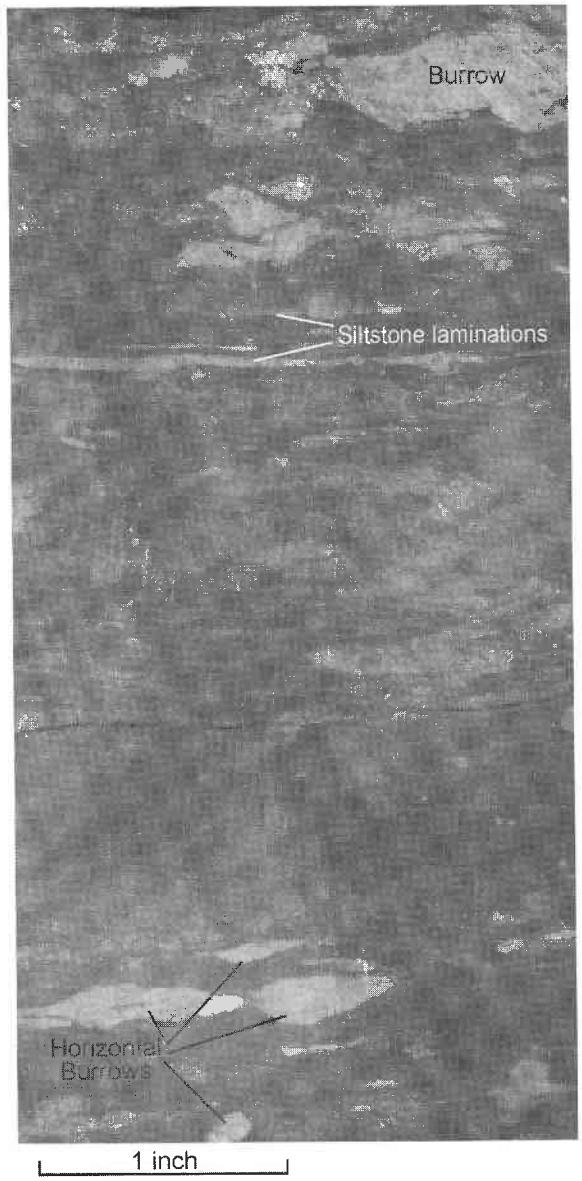


McKee 1,330 ft:

Horizontal burrows filled with fine-grained sandstone alternating with black shale that is horizontally laminated with fine-grained sandstone and siltstone indicate a more distal, lower energy depositional environment than that seen above. The bulk of the sand preserved here is contained within the burrows, making it discontinuous and of poor reservoir quality.

Cities Service Company
McKee "B" #1

(NW¼SW¼ sec. 24, T. 10 N., R. 17 E.)



McKee 1,345 ft:

Black shale containing scattered siltstone laminations and widely spaced horizontal burrows indicates a still deeper water and lower energy depositional environment than that above. This interval is placed near the top of parasequence 4, which in this location has no mouth-bar sediments preserved.