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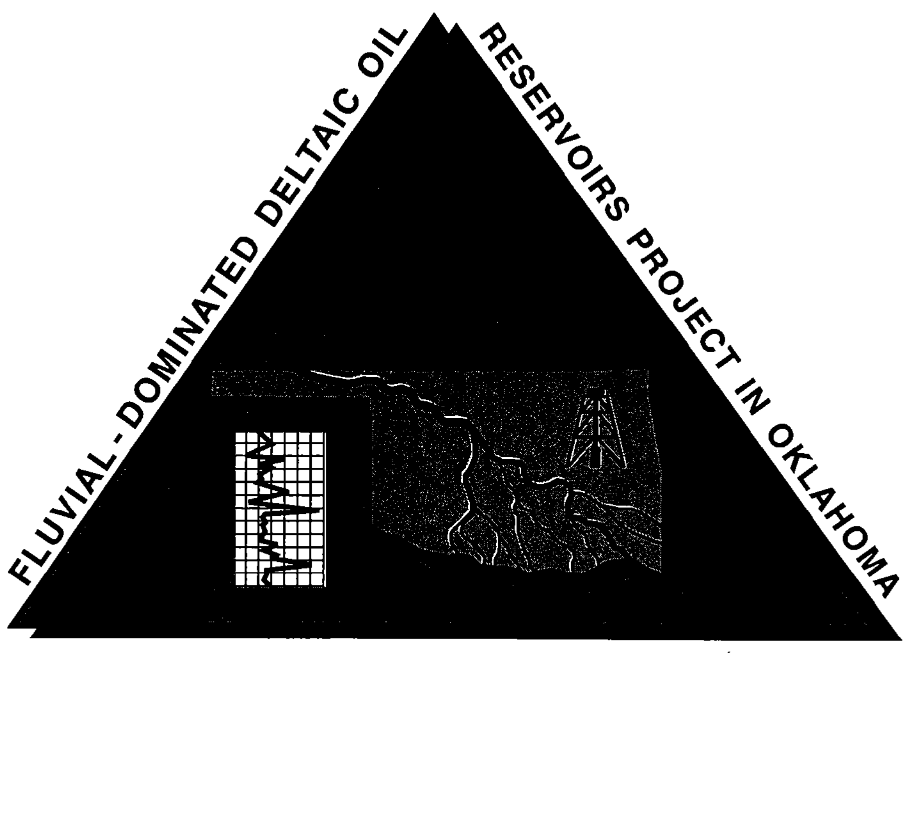
Fluvial-Dominated Deltaic (FDD) Oil Reservoirs in Oklahoma: The Morrow Play



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Charles J. Mankin, *Director*

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Fluvial-Dominated Deltaic (FDD) Oil Reservoirs in Oklahoma: The Morrow Play

PART I.—**Fluvial-Dominated Deltaic (FDD) Oil Reservoirs in Oklahoma**
by
Richard D. Andrews
with contributions from Jock A. Campbell and Robert A. Northcutt

PART II.—**The Morrow Play**
by
Richard D. Andrews

PART III.—**Reservoir Simulation of the Upper Morrow Reservoirs (upper and lower Purdy), Rice NE Field, Texas County, Oklahoma**
by
R. M. Knapp and Zahid Bhatti

This volume is one in a series published as part of the Fluvial-Dominated Deltaic (FDD) Reservoirs project, jointly funded by the Bartlesville Project Office of the U.S. Department of Energy and by the State of Oklahoma.

The University of Oklahoma
Norman, Oklahoma

1995

SPECIAL PUBLICATION SERIES

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Fluvial-Dominated Deltaic (FDD) Oil Reservoirs in Oklahoma

Richard D. Andrews
Geo Information Systems

with contributions from

Jock A. Campbell *and* **Robert A. Northcutt**
Oklahoma Geological Survey
Consulting Geologist, Oklahoma City

INTRODUCTION TO THE FDD PROJECT

This volume is one in a series addressing fluvial-dominated deltaic (FDD) light-oil reservoirs in Oklahoma, published as part of the Fluvial-Dominated Deltaic (FDD) Reservoir project conducted by the Oklahoma Geological Survey (OGS), with participation from the University of Oklahoma Geo Information Systems and OU's School of Petroleum and Geological Engineering (all located in the Sarkeys Energy Center). Primary funding for project, which began in 1993, is provided through a grant from the Department of Energy's Bartlesville Project Office under the Class I reservoir program, and by matching State funds.

The objectives of the Fluvial-Dominated Deltaic (FDD) Reservoir project are to identify all FDD light-oil reservoirs in the State of Oklahoma; to group the reservoirs into plays with similar depositional and diagenetic histories; to collect, organize, and analyze all available data on the reservoirs; to conduct characterization and simulation studies on selected reservoirs in each play; and to implement an information- and technology-transfer program to help the operators of FDD reservoirs learn how to increase oil recovery and sustain the life expectancy of existing wells.

The FDD project was designed to assist operators in Oklahoma by providing them with practical ways to improve production from existing leases and/or to reduce operating costs. Currently available technologies can improve recovery in FDD reservoirs if there is sufficient information about a reservoir to determine the most appropriate course of action for the operator. The needed reservoir-level information is available through the FDD project, and staff will advise interested operators about the implementation of appropriate improved-recovery technologies.

Light-oil production from FDD Class I oil reservoirs is a major component of Oklahoma's total crude oil production. Nearly 1,000 FDD Oklahoma reservoirs provide an estimated 15% of the State's total oil production. Most FDD reservoir production in Oklahoma is by small companies and independent operators who commonly do not have ready access to the information and technology required to maximize exploitation of these reservoirs. Thus, production from Class I oil reservoirs in Oklahoma is at high risk because individual well production commonly is low (1–3 barrels per day) and operating costs are high. Declines in crude oil prices or increases in operating costs can cause an increase in well-abandonment rates. Successful implementation of appropriate improved-recovery technologies could sustain production from these reservoirs well into, and perhaps throughout much of, the 21st century. Without positive intervention, most of the production from Oklahoma FDD oil reservoirs will be abandoned early in the next century.

The technology-transfer program has several parts. Elements include play publications and workshops to release play analyses that identify improved recovery opportunities in each of the plays. In addition, there are sources of publicly accessible information on FDD reservoirs, including the OGS Resources Facility, a computer laboratory.

The computer laboratory contains all the data files for the plays, as well as other oil and gas data files for the State, and the necessary software to analyze the information. Technical support staff are available to assist interested operators in the evaluation of their producing properties, and professional geological and engineering outreach staff are available to assist operators in determining appropriate improved-recovery technologies for those properties. The lab is equipped with PCs, plotters, laser printers, CD-ROM readers, and scanning and digitizing equipment. Geology-related mapping software, such as GeoGraphix, ARC/INFO, ArcView, Surfer, Atlas MapMaker for Windows and Radian CPS/PC, is available for public use. Access to data is through menu-driven screen applications that can be used by computer novices as well as experienced users.

The OGS Resources Facility opened June 1, 1995. In the future, it will be possible to access the facility from other locations through remote modems and, eventually, the Internet.

Technology-transfer events began with the first workshop and publication, addressing the Morrow play, on June 1, 1995. Other plays in this series include the Booch play, the Layton & Osage-Layton play, the Prue & Skinner play, the Cleveland and Peru plays, the Red Fork play, the Bartlesville play, and the Tonkawa play.

FDD-DETERMINING CRITERIA

For purposes of this project, fluvial-dominated deltaic (FDD) reservoirs were interpreted to consist of sandstones that were deposited in a deltaic or strictly fluvial environment.

Depositional environments of sandstone bodies in the Midcontinent region were identified using specific criteria which differentiate between fluvial-dominated deltaic (FDD) and marine deposits. These criteria were interpreted from information gathered from well logs and from the literature and include:

1. Electric log signatures (gamma ray, density-neutron, and resistivity are the most dependable).
2. Geometry of the sand body (from isopach mapping).
3. Texture (grain size and sorting).
4. Fossils and trace fossils.
5. Authigenic minerals (formed in-place after deposition). *Glauconite* is considered a marine indicator although its presence can indicate postdepositional reworking by marine processes (then it is allogenic). *Siderite* is considered evidence of subaerial deposition, of fresh-water origin.
6. Sedimentary structures (bedding types, bioturbation, soft-sediment deformation).
7. Thickness.
8. Contacts (sharp or gradational).
9. Rock type and lithologic relationships (vertical and lateral).
10. Paleocurrents.

DEPOSITIONAL SETTING OF FLUVIAL-DOMINATED DELTAIC RESERVOIRS

The depositional setting of a fluvial-dominated deltaic reservoir system is located at the boundary between a continental landmass and the marine environment where the products of a drainage basin are deposited. The character and distribution of the depositional products depend upon the size and relief of the drainage basin, the composition and distribution of the source rocks, the climate of the region, and the behavior of the marine environment. Brief discussions of the significant features of such a depositional setting are presented here to help readers better understand the properties of the individual fluvial-dominated deltaic reservoirs identified in this project.

For more detailed background information, readers are referred to Brown (1979), Coleman and Prior (1982), Galloway and Hobday (1983), and Swanson (1993).

COASTAL FLOOD-PLAIN SYSTEMS

In the context of fluvial-dominated deltaic reservoir systems, a subaerial coastal plain is considered a depositional environment that extends inland from a marine shoreline or landward from a delta plain. A coastal plain can overlie preexisting strata of any origin or age and may include a variety of fluvial depositional settings, such as flood plains (Fig. 1), incised valley-fill systems, and lowlands containing swamps or marshes. These settings may be controlled structurally or they may be topographic depressions caused by subsidence or erosion. In the case of incised valley-fill systems, the transition from fluvial to marine deposits may be abrupt, and there may be little or no delta formation. On the other hand, there may be a gradational transition in the coastal plain from fluvial to deltaic deposits, and it may be difficult to distinguish between coastal-plain (or flood-plain) deposits and those of an upper delta plain (Fig. 1) except by their geographic relationship to the shoreline. Nevertheless, a coastal flood plain is considered distinct from an upper delta plain, and subaerial deposition in an identified coastal flood-plain environment is considered to occur inland from a delta or marine shoreline.

The most common reservoirs in coastal flood-plain environments occur in channel deposits. Several types of such deposits are identified in the Pennsylvanian of the Midcontinent region; they include point bars, braided river deposits, anastomosing river deposits, and longitudinal and transverse river bars. Point bars

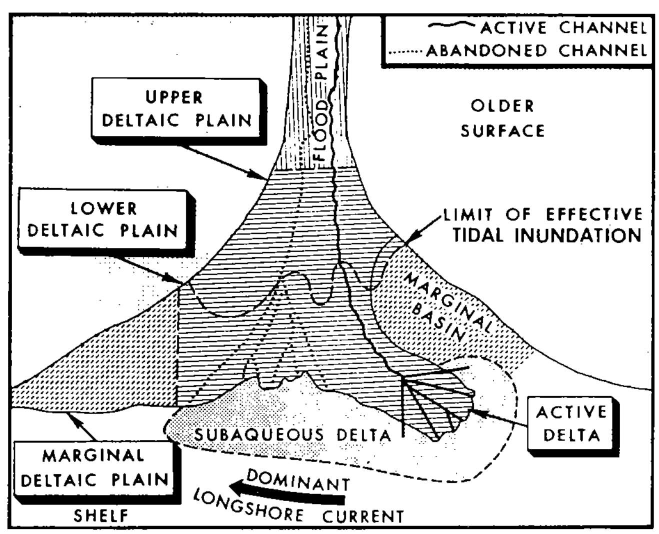
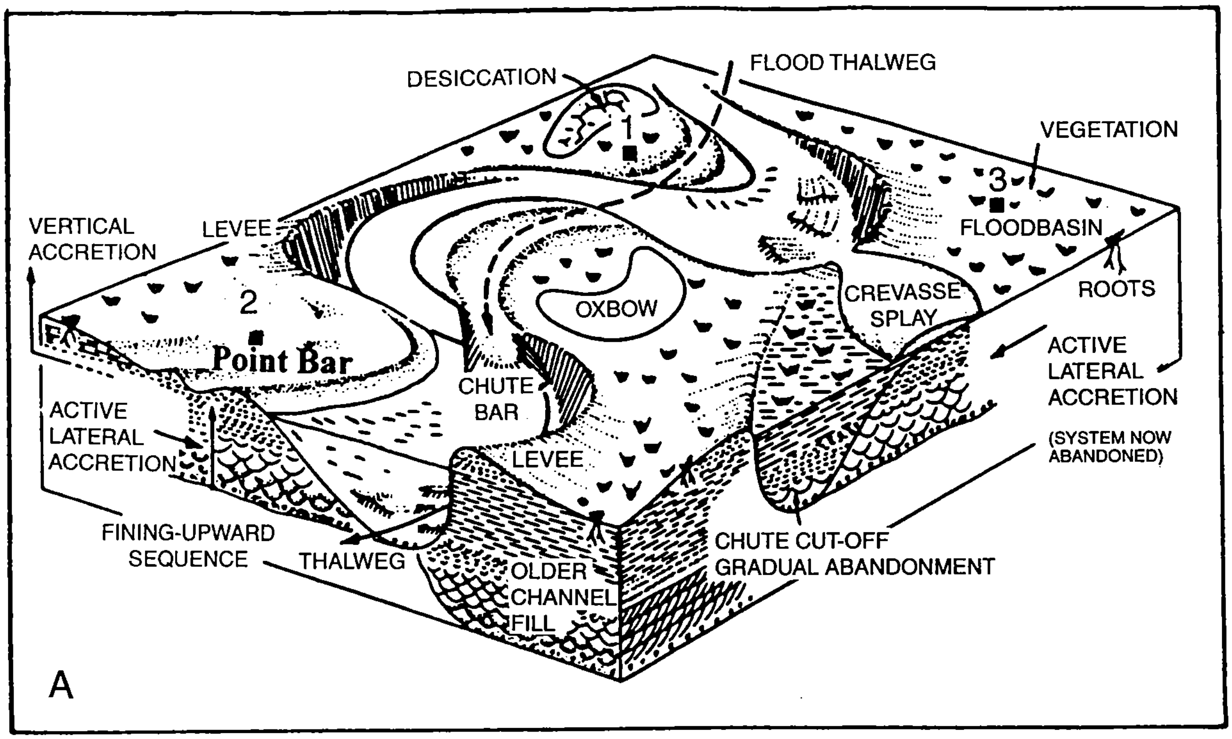


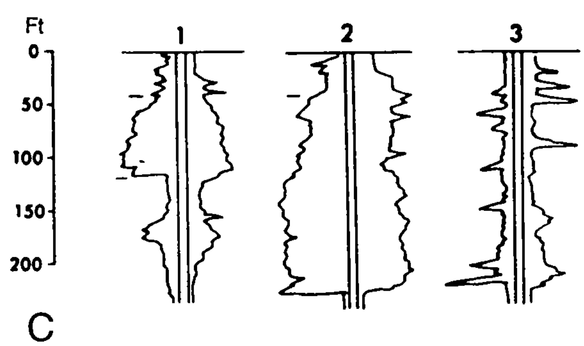
Figure 1. Components of a delta system. From Coleman and Prior (1982).

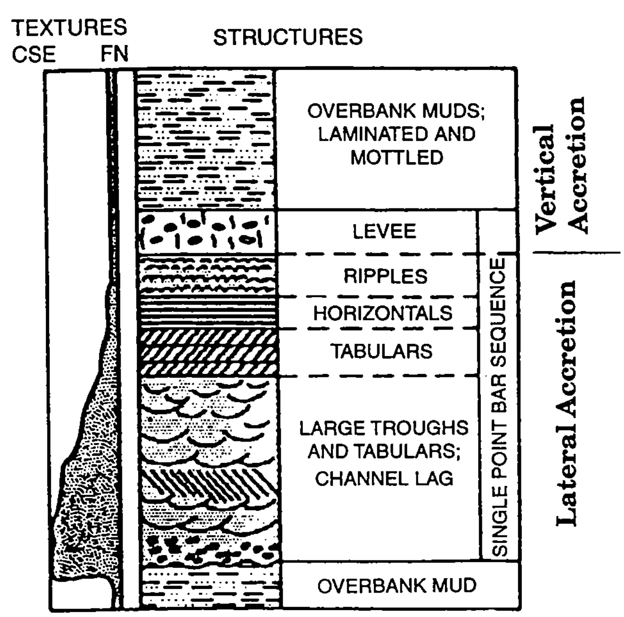
are the most common components of fluvial systems in Oklahoma.

Fluvial Point Bars

Point bars are fluvial accumulations of sand, silt, and mud that are deposited on the down-flow, inside bank of a meander bend, commonly referred to as the depositional bank (Fig. 2A). They are formed by common depositional processes and are not unique to any single depositional environment. Point bars occur in all coastal flood-plain systems as well as in upper delta plains. Point bars also are found in nondeltaic, semimarine environments such as estuarine channels where tidal forces, rather than riverine processes, are the principal sources of energy. Individual point bars may be much more than 100 ft thick and can extend







B

Figure 2. (A) Schematic model of a meandering river system. Erosion of the outside bend of a meander loop leads to lateral accretion of a point bar down-flow on the inside bank of the meander bed. Modified from Walker (1984). (B) Textural and facies characteristics of typical point-bar deposits. Modified from Brown (1979). (C) Idealized electric log responses related to point-bar deposits in (A). From Coleman and Prior (1982).

laterally for more than a mile. Stacked assemblages commonly are hundreds of feet thick. In the Pennsylvanian of the Midcontinent, point bars commonly are 20–50+ ft thick and occur laterally within meander belts that are <2 mi wide. Important attributes of point-bar deposits are included in a summary of fluvial-deltaic sandstone characteristics (Fig. 3).

In the sense of depositional processes, point bars are unique because they form by lateral accretion rather than direct vertical aggradation of the sand body. This depositional style promotes the lateral growth of a sand body over considerable distances without complete inundation. Lateral accretion also accounts for inconsistent deposition of sand which in turn causes compartmentalization of potential reservoirs. This compartmentalization promotes hydrocarbon entrapment but also is an impediment to hydrocarbon recovery and stimulation, and to reservoir characterization. Figure 4 illustrates the depositional environment of point bars and related flood-plain deposits in a tidally influenced, valley-fill river system. This type of depositional model is applicable to many Pennsylvanian sandstones in Oklahoma that were deposited during transgressive events. Descriptions and depositional-environment interpretations are given in Figure 5.

Point bars can make excellent reservoirs but their heterogeneity is a significant problem in reservoir management. In a vertical profile, such as in outcrop, core, or well logs, a typical point bar has a finer grain size upward or blocky textural profile (Fig. 2B). In the lower point bar, coarser fractions commonly are medium to coarse grained, in places are conglomeratic, and commonly contain pebble-size rip-up clasts. Successively higher sediments include fine- to medium-grained sand, silt, and clay. Overall, point bars have individual graded-bed sets that become thinner and finer grained vertically. Shale commonly is interbedded with sandstone in the middle and upper part of a point bar and these bed sets are inclined at a distinct angle that is unrelated to true dip. These shale interbeds, referred to as clay drapes, are effective visual illustrations of the lateral accretionary nature of point-bar deposits. They also are effective in isolating individual sand layers even within a single point bar. Clay drapes originate during periods of decreasing river discharge in mixed-load fluvial systems. Clay drapes seldom are mentioned or implied in most core studies, yet, they can be interpreted from serrated log signatures such as in Figure 2C. They also are visible in outcrops of practically any fluvial meandering system. Sedimentary structures commonly found in lower point-bar sequences consist of massive to graded bedding, high angle tabular and trough cross-bedding, and rip-up clasts. Common sedimentary features found in the upper part of a point bar include root traces, carbonaceous debris, and sandstone with horizontal and ripple laminations.

Because of the above-mentioned heterogeneities in point bars, the potential for hydrocarbon entrapment in a meandering system is very good. However, recovery of oil and/or gas from these types of deposits commonly is restricted to those portions of a point bar that have a reasonable degree of vertical and lateral continuity. Although many authors avoid this issue for fear of being overly pessimistic, in reality, recovery is concentrated in only certain portions of point bars. If a water-saturated zone is present, the best portion of the reservoir (lower point-bar facies) may occur below the oil/water contact. Hydrocarbons then may be concentrated within the central and upper portions of the point bar which commonly are finer grained and more likely to have the greatest amount of reservoir heterogeneity. If the upper part of a point bar is absent due to erosion or nondeposition, hydrocarbons then may be trapped lower within the point-bar interval. This situation is considerably more favorable for oil recovery because sandstone within the lower part of a point bar is generally coarser grained, occurs in thicker beds, and normally has better effective porosity. Consequently, recoverable reserve calculations can be vastly incorrect when they are based on the assumption that the entire sand body represents the true reservoir thickness. Corresponding recoveries from primary production methods commonly are only about 10–20% of the calculated recoverable reserve, and yield is mostly in the range of 50–150 BO/acre-ft, which is typical for many Pennsylvanian sandstones in Oklahoma. Secondary recovery methods, such as water flooding, normally will double the primary recovery, but reservoir response is highly dependent upon proper field engineering and reservoir characterization.

Point bars sometimes are referred to as shoestring or ribbon sands because of their tendency to occur in a sinuous, meandering pattern. An awareness of this characteristic pattern is important to understanding the spatial relationships within, and the physical parameters of, fluvial systems and associated sand deposits. Swanson (1976) and Coleman and Prior (1982) show that the average meander amplitude of an active meandering stream is about half the width of its enclosing meander belt. But as a meander system aggrades vertically above its own flood plain, the hydraulic difference creates instability and leads to avulsion, a lateral shift of the fluvial system to other portions of the flood plain. Obviously, in such a system, lateral and vertical relationships of sandstone beds are complicated.

DELTA SYSTEMS

In this study, a delta is defined as an accumulation of river-derived sediment that is deposited as an extension to the coast (Fig. 1). In a relatively stable tectonic setting and in a moderately subsiding shelf, sediments commonly consist of sand and finer grained clastics, which are deposited in interdistributary bays and in front of the delta. In such settings, however, marine forces such as waves and tidal currents commonly redistribute the sediments and produce different delta

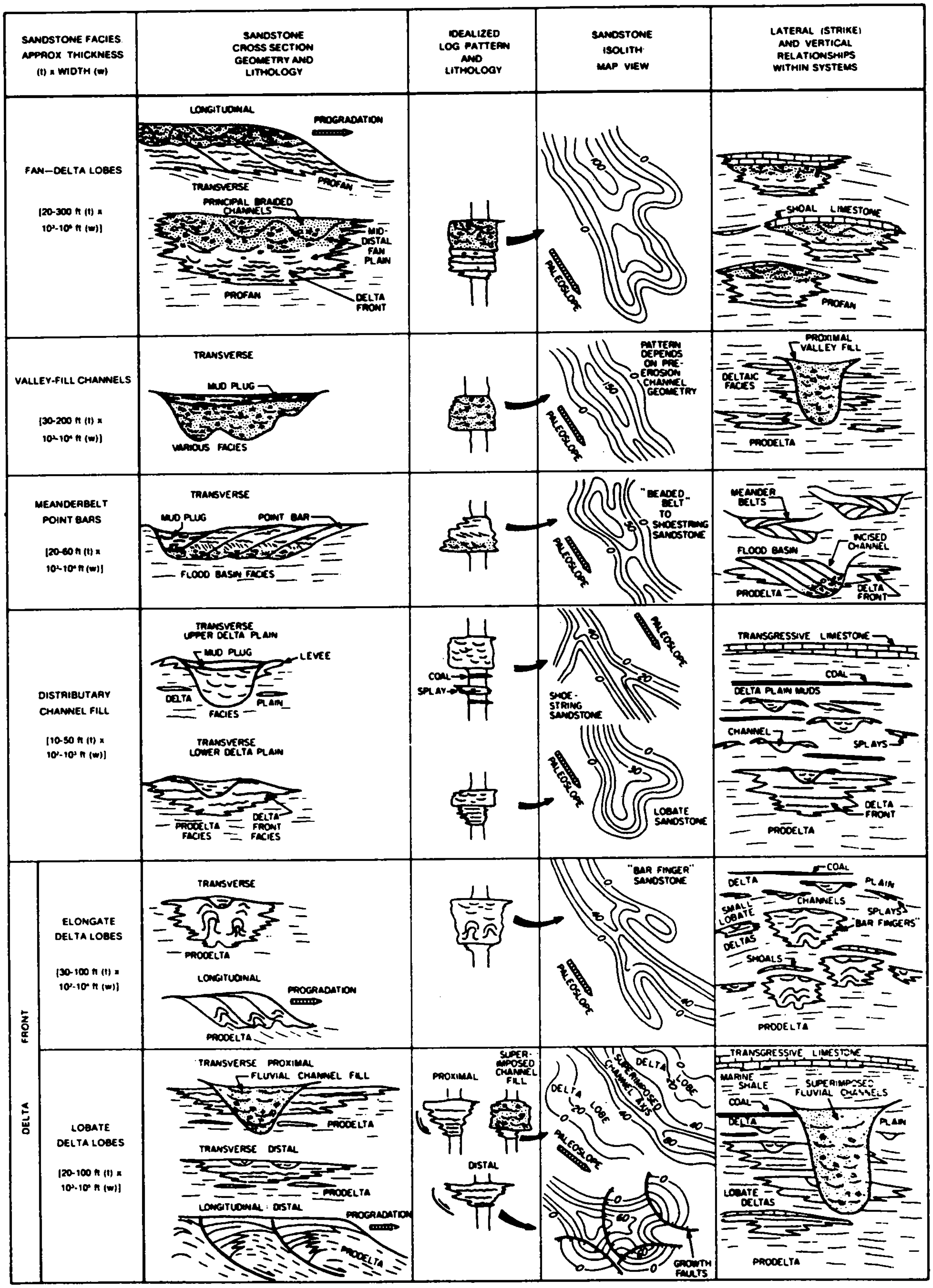


Figure 3. Summary of the characteristics of Midcontinent fluvial and deltaic sandstone bodies. From Brown (1979).

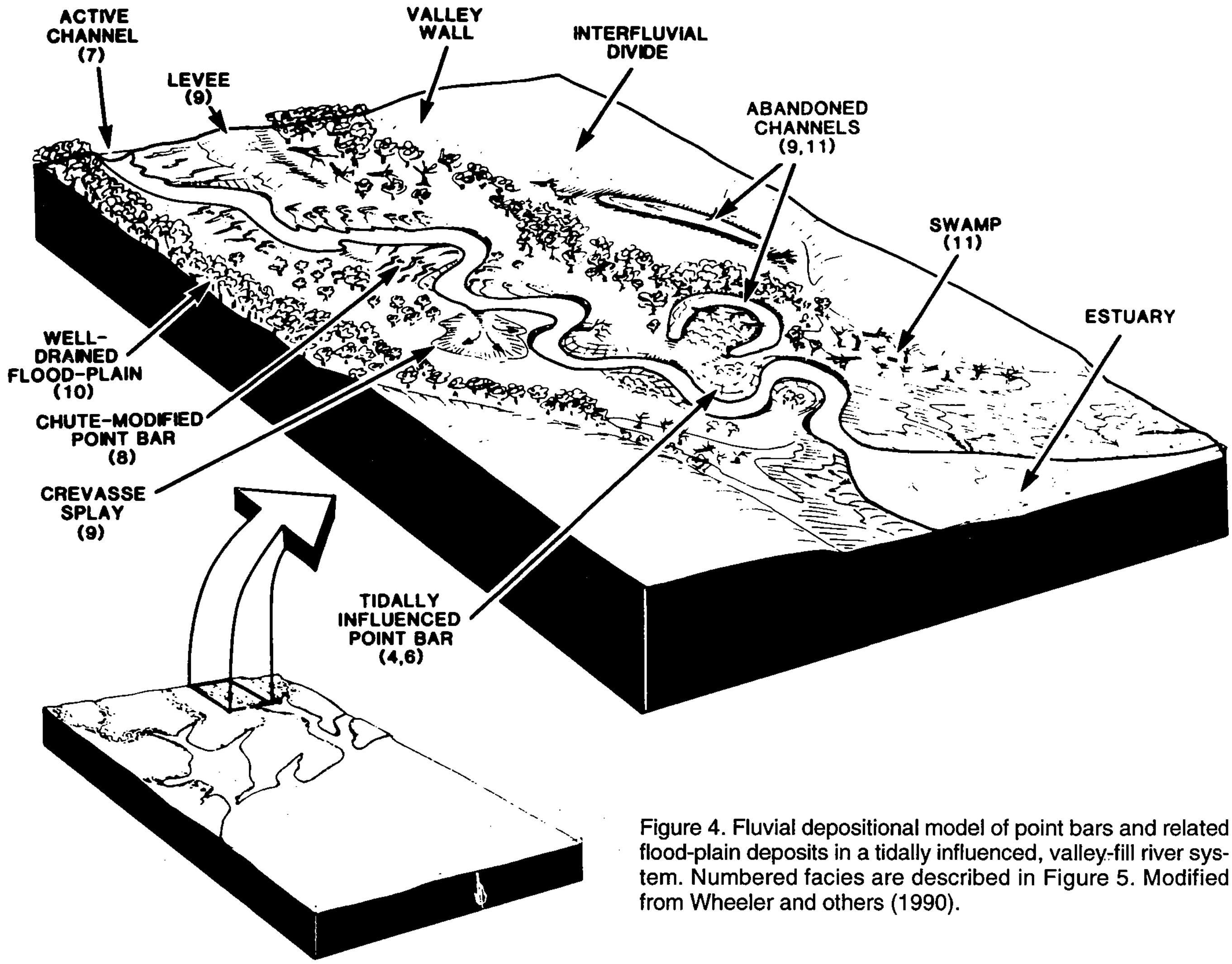


Figure 4. Fluvial depositional model of point bars and related flood-plain deposits in a tidally influenced, valley-fill river system. Numbered facies are described in Figure 5. Modified from Wheeler and others (1990).

morphologies. Figure 6 illustrates the classification of delta systems, which is based on the relative intensity of fluvial versus marine processes. The main emphasis in this project is on reservoir-quality sandstones that are components of fluvial-dominated delta systems.

The basic components of a prograding delta system are shown in Figure 1 and include the upper delta plain, lower delta plain, and subaqueous delta or delta front. In an idealized vertical depositional sequence, fluvial point bars and distributary channels of the delta plain overlie delta front sands and prodelta shale. This relationship is illustrated in Figure 7, which also shows typical log patterns, lithology, and facies descriptions of the various depositional phases of a typical progradational sequence. Progradation refers to a depositional system that is built seaward (offlap). Sedimentary facies in a progradation typically show an upward shallowing depositional origin. Progradation is similar in meaning to regression, which refers to a general retreat of the sea from land areas so that shallower water environments occur in areas formerly occupied by deeper water. This is in contrast to transgression (onlap), which occurs when the position of the sea moves landward and brings deeper water depositional environments to areas formerly occupied by shallower water or by land.

Upper Delta Plain

As shown in Figure 1, the upper delta plain extends from the down-flow edge of the coastal flood plain to the limit of effective tidal inundation of the lower delta plain. The upper delta plain essentially is the portion of a delta that is unaffected by marine processes. Recognizable depositional environments in the upper delta plain include meandering rivers, distributary channels, lacustrine delta-fill, extensive swamps and marshes, and fresh-water lakes. Some of these environments are recognized in normal well log interpretations. For example, meandering rivers have the classic bell-shaped electric log curves of fluvial point bars, and distributary channels tend to have more blocky log profiles. Coal and interbedded shale deposits, evidence of swamps and marshes, also can be interpreted from well logs. Although not diagnostic by

#	FACIES DESCRIPTION	INTERPRETATION
1	**DARK-GRAY, THINLY LAMINATED SHALE:** Slightly calcareous or dolomitic; thinly planar- to wavy-laminated, fissile or platy; includes starved ripple-laminations; rare Planolites, Zoophycus, and Thalassinoides; occurs in both the lower and upper Morrow; ranges from 1 to 57ft (0.3 to 17.4m) in thickness.	**OFFSHORE MARINE:** Inner to Outer Shelf
2	**SHALY CARBONATE:** Gray to dark-gray calcareous wackestone to packstone; generally wavy-laminated but may be burrow-mottled or cross-bedded; skeletal material generally re-oriented and moderately abraded; includes crinoid, brachiopod, bryozoan, mollusc and pelecypod fragments; 0.5 to 10ft (0.2 to 3.1m) thick in the upper Morrow, up to 18ft (5.5m) thick in the lower Morrow.	**SHALLOW MARINE:** Open Shelf or Transgressive Lag
3	**SKELETAL WACKESTONE TO GRAINSTONE:** Gray to tan, limestone or dolomite; planar- to wavy-laminated or cross-bedded; may appear massive or nodular due to weathering or burrowing; includes crinoids, brachiopods, bryozoans, corals, molluscs, gastropods, echinoderms, peloids and intraclasts; occurs only in the lower Morrow; 0.5 to 46ft (0.2 to 14m).	**RESTRICTED TO OPEN MARINE PLATFORM:** Shoals and Bioherms
4	**INTERLAMINATED TO BIOTURBATED SANDSTONE AND SHALE:** Includes interbedded and homogenized lithologies; light-gray, very fine- to fine-grained sandstone and gray to dark-gray shale and mudstone; planar-, wavy- and ripple-laminated; convoluted bedding common; glauconitic; moderately burrowed to bioturbated; Thalassinoides, Planolites, Skolithos, Asterosoma, Chondrites and Rosellia(?); occurs in both the lower and upper Morrow; 1 to 28ft (0.3 to 8.5m) thick.	**NEARSHORE MARINE OR ESTUARINE:** Shoreface or Delta Front; Tidal Flat or Tidal Channel
5	**CROSS-BEDDED, FOSSILIFEROUS SANDSTONE:** Light-gray, fine- to coarse-grained quartz arenite to sublitharenite; trough or tabular cross-bedded in 3 to 18in (7.6 to 45.7cm) thick sets; up to 50% skeletal debris; crinoid, brachiopod, bryozoan and coral fragments; glauconitic; occurs only in the lower Morrow; units up to 25ft (7.6m) thick.	**UPPER SHOREFACE OR TIDAL CHANNEL**
6	**CROSS-BEDDED SANDSTONE WITH SHALE DRAPES:** Gray to tan, fine- to coarse-grained quartz arenite or shaly sandstone; trough or tabular cross-bedded with incipient stylolites, shale drapes and interlaminations between foreset laminae; foresets are often tangential with the lower bounding surfaces and grade laterally into ripple laminations, some oriented counter to the cross-bedding; cross-bed set thickness is 3 to 12in (7.6 to 30.5cm); sparsely burrowed, Planolites; glauconite and carbonaceous debris; occurs primarily in the upper Morrow; up to 28ft (8.5m) thick.	**FLUVIAL OR ESTUARINE:** Upper Point-Bar or Flood-Plain; Tidally Influenced Fluvial Channel
7	**CONGLOMERATE TO CONGLOMERATIC SANDSTONE:** Gray to light-brown; granules and pebbles of mudstone and composite quartz; matrix is fine- to very coarse-grained, poorly sorted, quartz arenite or sublitharenite to subarkose; massive appearing, planar-bedded or cross-bedded; carbonaceous debris; glauconite and phosphate scarce; occurs only in the upper Morrow; up to 21ft (6.4m) thick.	**FLUVIAL CHANNEL:** Braided Stream, Channel-Bottom Lag or Lower Point-Bar
8	**COARSE-GRAINED, CROSS-BEDDED SANDSTONE:** Medium- to very coarse-grained quartz arenite or subarkose to sublitharenite; trough or tabular cross-bedded in sets ranging from 3in (7.6cm) to over 2ft (0.6m) thick; in many cases foreset laminae alternate between coarser and finer grain-size fractions; convoluted bedding is common; carbonaceous debris, including coaly fragments, macerated organic material ("coffee grounds"), leaf and log impressions is prevalent; Planolites burrows are rare; occurs in the upper Morrow; units up to 29ft (8.8m) thick.	**FLUVIAL CHANNEL:** Chute-Modified Point-Bar
9	**RIPPLE-LAMINATED SANDSTONE:** Very fine- to fine-grained quartz arenite; symmetrical or asymmetrical ripples; glauconite and carbonaceous debris are common; trace fossils include Planolites and Skolithos; occurs with many other facies throughout the Morrow; ranges up to 30ft (9.2m) thick.	**FLUVIAL OR MARINE SHOREFACE:** Upper Point-Bar, Splay, Levee or Abandoned Channel-Fill; Middle Shoreface
10	**GRAY-GREEN MUDSTONE:** May have brick-red iron oxide speckles; generally blocky and weathered in appearance; very crumbly; moderate to abundant amounts of carbonaceous debris; compaction slickensides and root-mottling common; calcareous nodules occur in the lower Morrow and beds are 0.5 to 2ft (0.2 to 0.6m) thick; up to 30ft (9.2m) thick in the upper Morrow.	**FLUVIAL FLOOD-PLAIN OR EXPOSURE SURFACE:** Well-Drained Flood-Plain; Alteration Zone or Soil
11	**DARK-GRAY CARBONACEOUS MUDSTONE:** Generally planar-laminated; abundant carbonaceous debris including leaf and stick impressions; pyrite, root traces and slickensides common; occurs only in the upper Morrow; units range up to 30ft (9.2m) in thickness.	**FLUVIAL FLOOD-PLAIN:** Swamp or Abandoned Channel-Fill
12	**COAL:** Massive or laminated; commonly pyritic; occurs only in the upper Morrow; generally 1 to 6in (2.5 to 15.2cm) thick, but ranges up to 2ft. (0.6m).	**SWAMP**

Figure 5. Fluvial facies descriptions and depositional environment interpretations for numbered facies shown in Figure 4. This information was used originally by Wheeler and others (1990) to describe the Morrow in southeastern Colorado and southwestern Kansas, but it is also useful in clastic facies interpretations of many other Pennsylvanian meandering river systems in Oklahoma.

themselves, point bars, coal, and migratory distributary channels are primary elements that characterize the upper delta plain. By combining information about those elements with other data, such as from cores or sequential stratigraphic analysis (Fig. 7), a more accurate depositional interpretation can be made. Such a combination of data can lead to a better understanding of sandstone distribution trends and reservoir characteristics in any depositional environment.

The principal reservoirs found within the upper delta plain are fluvial point bars and distributary channel sands. Point bars have been discussed in the section on coastal plain deposits. Distributary channels are more characteristic of the lower delta plain and are discussed in the following section.

Lower Delta Plain

In the rock record, each component of a delta has characteristics that are determined largely by vertical

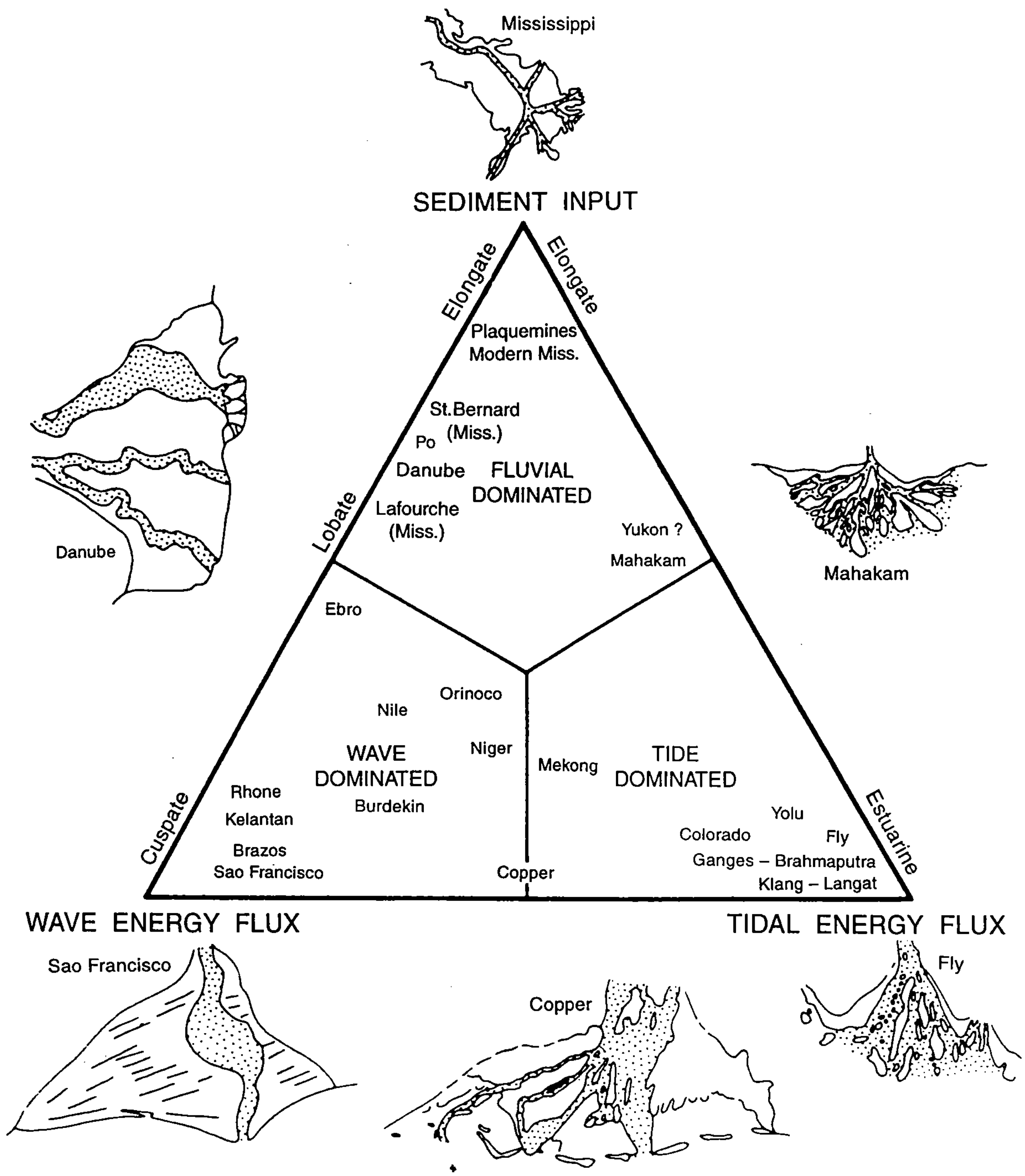


Figure 6. Morphologic and stratigraphic classification of delta systems based on relative intensity of fluvial and marine processes. From Galloway and Hobday (1983).

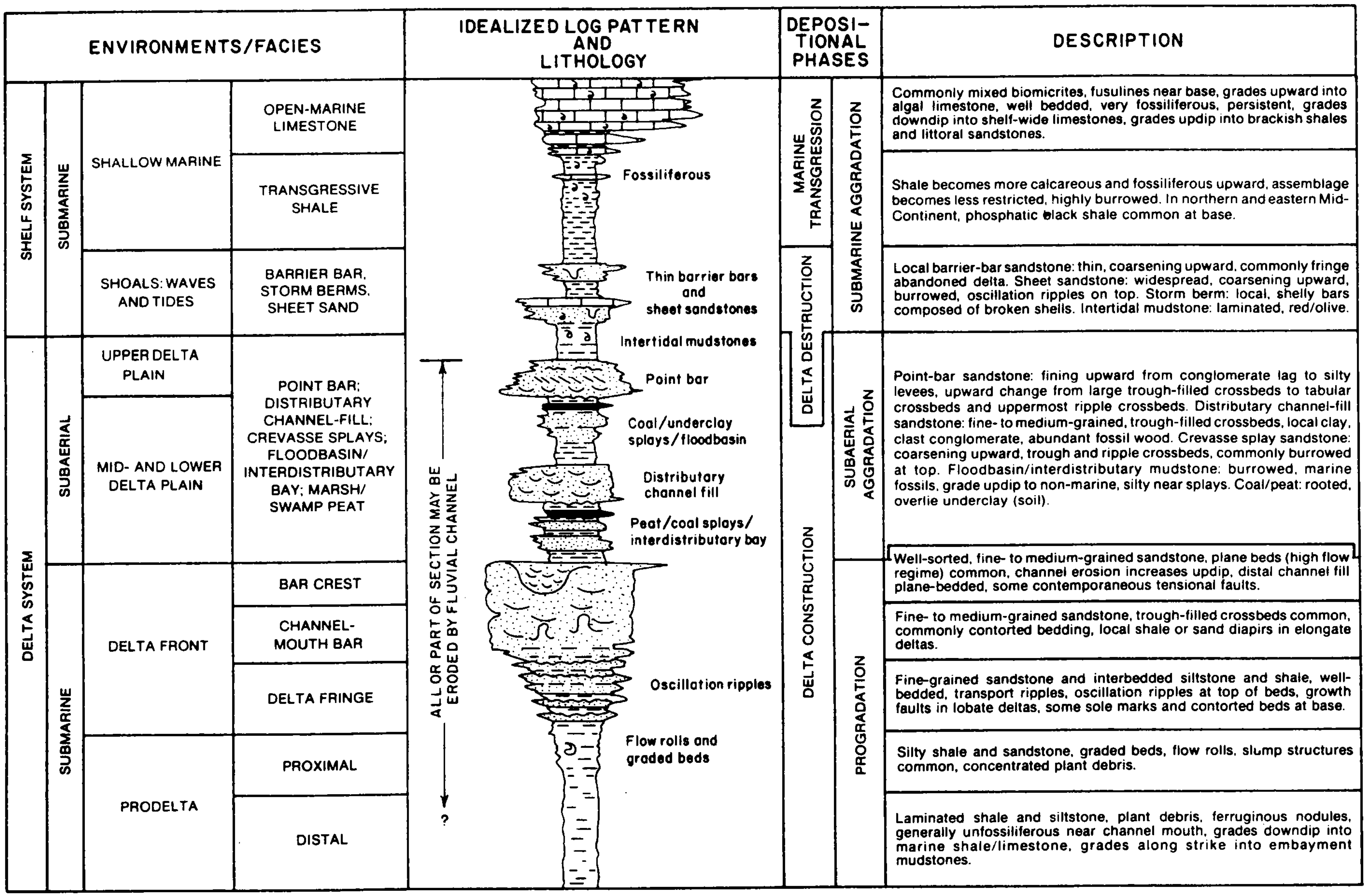


Figure 7. Idealized cratonic delta sequence showing principal depositional phases, idealized electric log pattern, and facies description. From Brown (1979).

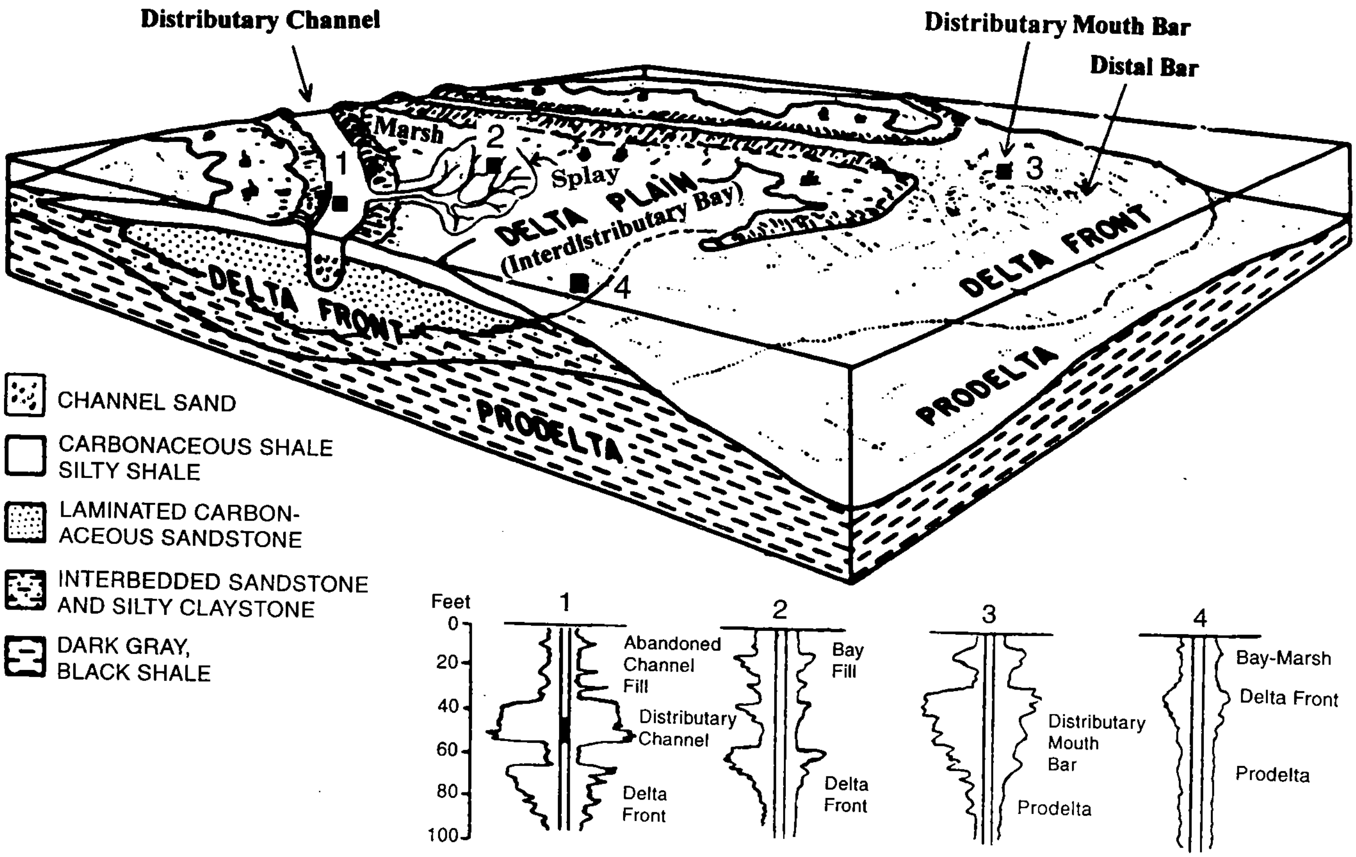


Figure 8. Schematic model of deltaic depositional environments. Idealized electric log responses and inferred facies are shown for locations Nos.1–4. Modified from Brown (1979).

and lateral relationships of rock facies and by faunal content. In the lower delta plain, sediments are influenced highly by marine conditions, which extend from the subaqueous delta front to the landward limit of marine (tidal) influence (Fig. 1). The lower delta plain consists primarily of bay-fill deposits, which occur between or adjacent to major distributaries, and secondarily of distributary-channel deposits. Distributary mouth bars and bar-finger deposits are the principal components of the subaqueous delta front (Fig. 1) and are attached to the lower delta plain. These environments and idealized electric log patterns of associated clastic facies are illustrated in Figure 8.

Lower-delta-plain sediments characteristically overlie delta-front sands and prodelta shale. In the upper reaches of the lower delta plain, coal commonly is associated with marshy areas that are insulated from rapid sedimentation or destructive marine events that typify the lower reaches of the delta plain. Through continued progradation of a delta, the lower delta plain is overlain by upper-delta-plain sediments. Unless the stratigraphic relationship is unconformable, coastal flood-plain sediments commonly are not recognized in succession above delta-plain deposits.

Bay Fill and Splays

Bay-fill sediments originate from several sources including effluent plumes of major distributaries and crevasse splays. Splays, however, are the dominant source of bay-fill sandstone and constitute much of the sediment in fluvial-dominated deltas as shown in Figure 9, which identifies the distribution of principal sand facies in the modern Mississippi River delta. Splays originate during flooding events when sediment is carried through a breach in a distributary levee and distributed into shallow bays through a branching network of smaller channels. The lenticular, fan-shaped deposits (crevasse splays) commonly are 10–40 ft thick and consist of individual sequences of sand and mud that increase in grain size upward. This stratigraphic characteristic is caused by the rapid deposition of suspended sediments ahead of current-induced bed-load transport of coarser sand. However, because splays are driven by fluvial processes, thin distributary-channel deposits also are constituents of every splay. The thickness of a splay deposit commonly is proportional to the depth of the interdistributary bay and the hydraulic advantage between the distributary channel and the receiving area. Thus, splays characteristically are thinner than distributary mouth bars and contain less sand. After abandonment of a crevasse system and subsequent subsidence, the area reverts to a bay environment when marine waters encroach. This entire cycle lasts about 100–150 years (Coleman and Prior, 1982) and may be repeated several times to form a stacked assemblage such as that shown in log signature on Fig-

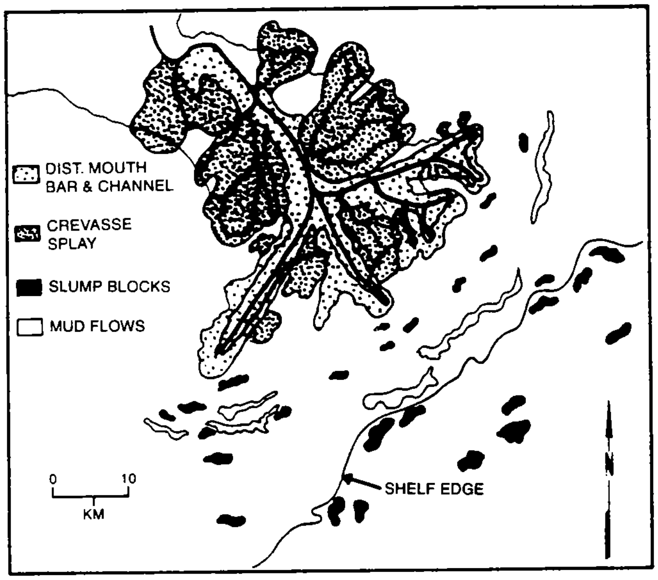


Figure 9. Distribution of principal sand facies in the modern Mississippi River fluvial-dominated delta. From Coleman and Prior (1980).

ure 8. Splay deposits are not considered to be good reservoirs because they contain large amounts of detrital clay, which reduce the effective porosity and permeability of the sandstone beds.

Distributary Channels

Distributary channels are responsible for the primary distribution of nearly all sediments within the lower delta plain. Despite their conspicuous presence, however, they account for a relatively small volume of sediment in the delta, as is illustrated in the schematic model of a delta (Fig. 8) and in the sand facies distribution map of the modern Mississippi River delta (Fig. 9).

Distributary channels typically are incised upon preexisting interdistributary or delta-front sediments. Because they occur at the end of a fluvial transport regime, distributary-channel sands commonly are uniformly fine grained and well sorted. As shown in Figure 3, distributary-channel sand bodies commonly are 10–50 ft thick and 100–1,000 ft wide. Sedimentary structures consist of tabular and trough cross-bedding, clay clasts, and contorted beds (Fig. 10).

The extension of distributary channels into the subaqueous marine environment and the concurrent deposition of levee structures help prevent lateral migration of distributary channels. This stabilizing condition inhibits the formation of point bars that characterize coastal flood-plain meander-belt systems. Since distributary channels occur within, or in close proximity to, marine conditions, they may incorporate marine constituents such as shell fragments, fossils, and glauconite.

Distributary Mouth Bars and Bar Fingers

The progradation of a fluvial-dominated system such as the modern Mississippi River delta is sustained by a series of finger-like sand bodies that are deposited ahead of the main river distributaries. These sand bars are the subaqueous extensions of major distributary channels formed because of confined flow and directed transport of suspended sediments into the open gulf. The tendency of distributary channels and accompanying bar-finger sands to be nonbranching seems to be a result of several factors such as sediment load characteristics of the river, water depth and salinity contrasts in the receiving basin, and river discharge rates. Most investigators believe that bar fingers form when river discharge is confined by the development of subaqueous levees and when sediment transport is aided by the buoying effect of saline water. Conversely, non-directed dispersal of river-mouth sediment in shallow, fresher water bays causes multiple branching distributaries

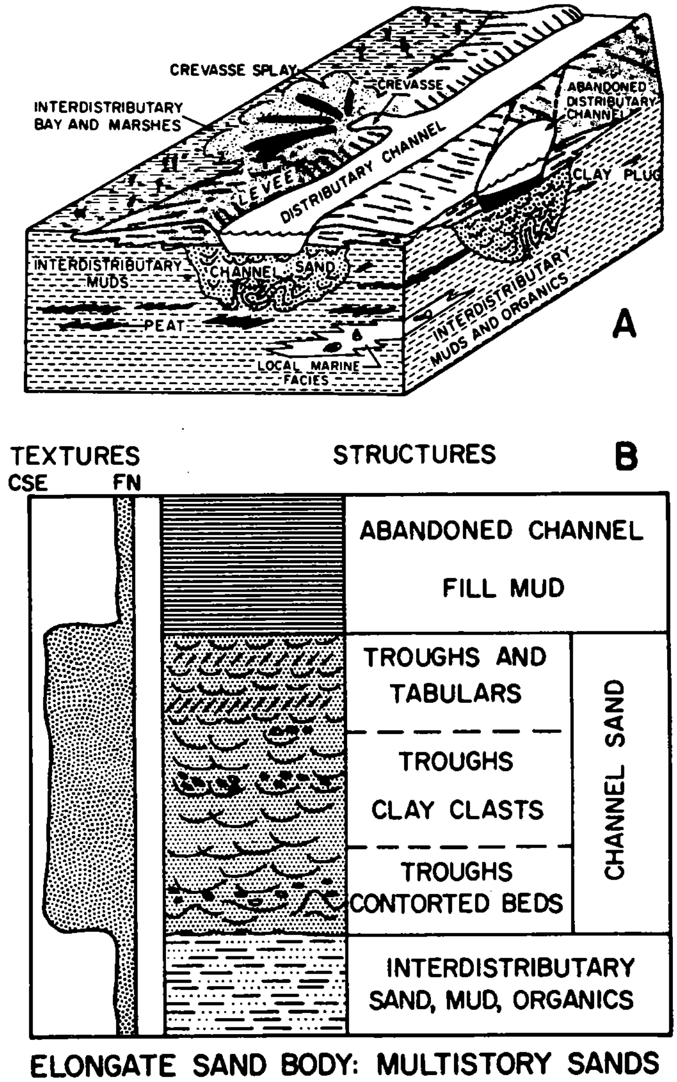


Figure 10. Distributary channel model. (A) Schematic model of channel-fill sands, lower delta plain setting; (B) idealized vertical sequence of distributary channel-fill sandstones. Modified from Brown (1979).

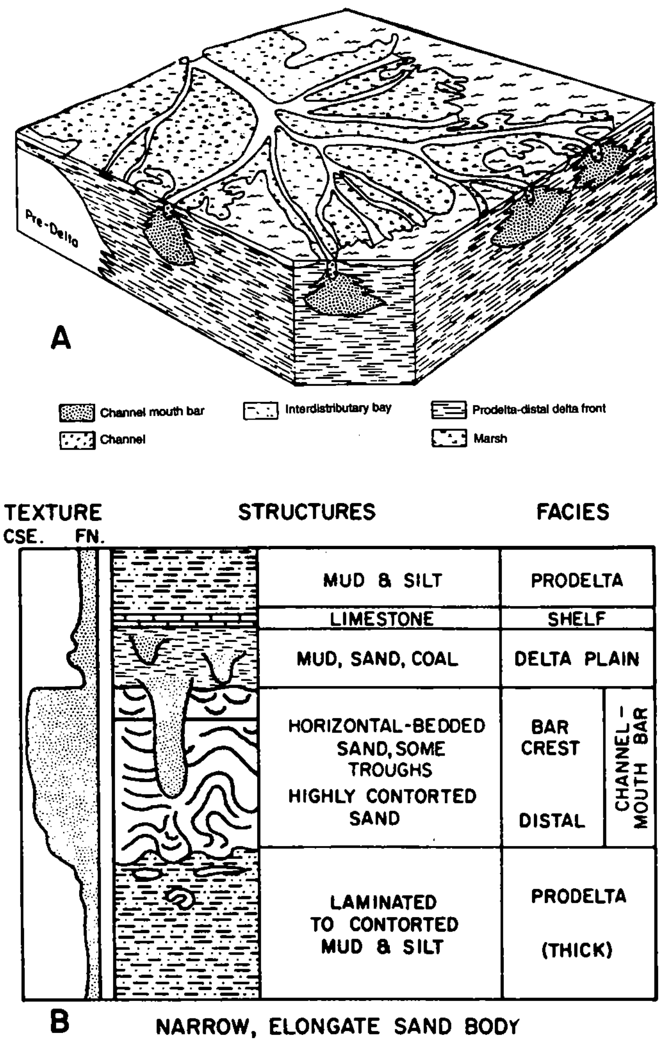


Figure 11. Elongate-delta model. (A) Birdfoot lobe, Holocene Mississippi delta; (B) idealized vertical sequence of a distributary mouth bar and associated deposits in an elongate delta. Modified from Brown (1979).

such as those that characterize other parts of the Mississippi River delta. In the latter case, distributary mouth bars are lobate rather than elongate and become progressively finer grained seaward.

Distributary mouth bars have the highest rate of deposition in the subaqueous portion of a delta. They are composed of the same sediments that constitute splays and distributary channels in the lower delta plain but are distinctly different morphologically. In the upper portion of the bar (bar crest), sands are reworked continually by wave and storm currents to produce some of the best and most laterally extensive reservoirs in delta environments. Large-scale sedimentary structures, such as high-angle and trough cross-bedding, are the result of this energy. The rapid clastic buildup also causes soft-sediment instability in the form of mud diapirs and contorted beds. These types of sedimentary structures are illustrated in Figure 11.

Distributary mouth bars make up most of the delta front and may be >200 ft thick, but commonly they are ~100 ft thick. Redistribution of the same sand by marine currents may promote the deposition of distal bars; in the event of eustatic sea level rise (transgression), barrier islands may form. Characteristically, distributary mouth bars have serrated, coarsening-upward logs and textural profiles (Figs. 8,11). In places, the facies are subdivided into a distal bar facies (lower, shaly part of profile) and a proximal bar facies (upper, sandy part of profile). The coarsening-upward stratigraphic profile is caused by the dispersal of buoyed sediment and progressive deposition of coarse-grained sediment on top of previously dispersed fine-grained sediment. Additionally, carbonaceous debris from continental sources commonly is interbedded with the sand. Distributary mouth bars commonly overlie prodelta muds and provide a relatively stable foundation over which delta-plain sediments are deposited during regressive depositional periods.

NOTE TO READERS

Industry participation in the FDD program is heartily encouraged. We welcome any comments that you may have about the content of this publication and about the ongoing needs of industry with respect to information and technology relating to FDD reservoirs. Please contact Charles J. Mankin at the Oklahoma Geological Survey, 100 East Boyd, Room N-131, Norman, OK 73019 with your questions or comments.

PART II

The Morrow Play

Richard D. Andrews
Geo Information Systems

INTRODUCTION

Pennsylvanian Morrow sandstones are some of the most important oil and gas reservoirs in Oklahoma. Although the original purpose of this project was to study only FDD oil reservoirs and secondary recovery techniques, it has been expanded to include areas prone to both oil and gas if they occur as logical extensions of FDD oil reservoir mapping. Also, because of the often complex and controversial nature of many sandstone bodies in the Midcontinent, this project is designed to investigate areas containing fluvial or channel-like deposits whether or not the depositional environment is known to be deltaic. Due to the large areal extent of this project, regional maps sometimes are generalized to preserve their effectiveness, while field mapping is presented in much greater detail. As shown in Figure 12 and Plate 1, the entire study area for the Morrow play consists of western Oklahoma, including most of the Panhandle.

Morrow sandstones are probably some of the most difficult rock units to interpret when one is considering correlation of individual sandstone beds and depositional environments. Early investigators commonly thought that sandstones in the upper Morrow were mostly fluvial-deltaic, while sandstones in the lower Morrow were considered to be almost entirely of a transgressive marine origin. Ideas about Morrow deposition have changed significantly since the 1960s and early 1970s, and they currently involve concepts of fluvial valley infilling, marine tidal processes, and sequence stratigraphy (South, 1983; Harrison, 1990).

MORROW STRATIGRAPHY

Morrow sediments are Lower Pennsylvanian in age and consist of sandstone, shale, and limy clastics. The name is primarily a subsurface term that is used by the oil and gas industry in northwestern Oklahoma, even though it is a formal group and formation name originating in western Arkansas. In this report, the term Morrow is applied to the section of rock that extends from the base of the Atokan Thirteen Finger lime to the top of the Mississippian Chester limestone. This interval is usually about 200–400 ft thick throughout much of the Anadarko shelf but thickens in the basin depocenter to >4,000 ft in western Oklahoma. Type logs for three areas are shown as part of the field studies included in this report.

For this study, the Morrow is subdivided into two units based on generalized wireline log characteristics that are observed over much of the shelf area. Although no formal divisions of the Morrow are established, most investigators accept the usage of an upper and lower Morrow. The top of the lower Morrow also is informally called the "Squaw Belly"; it consists of a relatively thin stratigraphic section of limestone or limy sediments and is most prevalent in Beaver, Harper, and Texas Counties, Oklahoma. Occasionally, the "Squaw Belly" also is referred to as the middle Morrow. Many of the sandstones in the Morrow have been given informal names by operators, and the most common and accepted ones are included in the stratigraphic nomenclature chart of Figure 13.

There remains some controversy regarding the actual base of the Morrow in portions of the Anadarko basin, including the Canton FDD area, because of an unconformable(?) contact between the Morrow and the older Springer which is not always readily apparent from well logs. Additionally, both rock groups contain similar lithologies, and cyclic clastic deposition appears to be relatively continuous across both zones. Some geologists believe that the Springer is distinguished by low resistivity shales (less than a few ohm-meters) and that the sands are strictly deep marine in origin. However, these criteria are not always easily discernible, nor are they widely accepted; in many places where Morrow terminology has long since been accepted, low resistivity shales are also observed. Additionally, the pre-Morrow surface is complicated further when a shale-on-shale contact occurs between the Pennsylvanian and Mississippian. The resolution of this controversy is beyond the scope of this study. Thus, it is possible that some sandstones that are interpreted in this report to be lower Morrow may actually belong to the Springer Formation. For this project, it was not considered necessary to discriminate between the Morrow and Springer.

MORROW DEPOSITIONAL ENVIRONMENT CONSIDERATIONS

The interpretation of depositional environments is very important to the exploration and development of

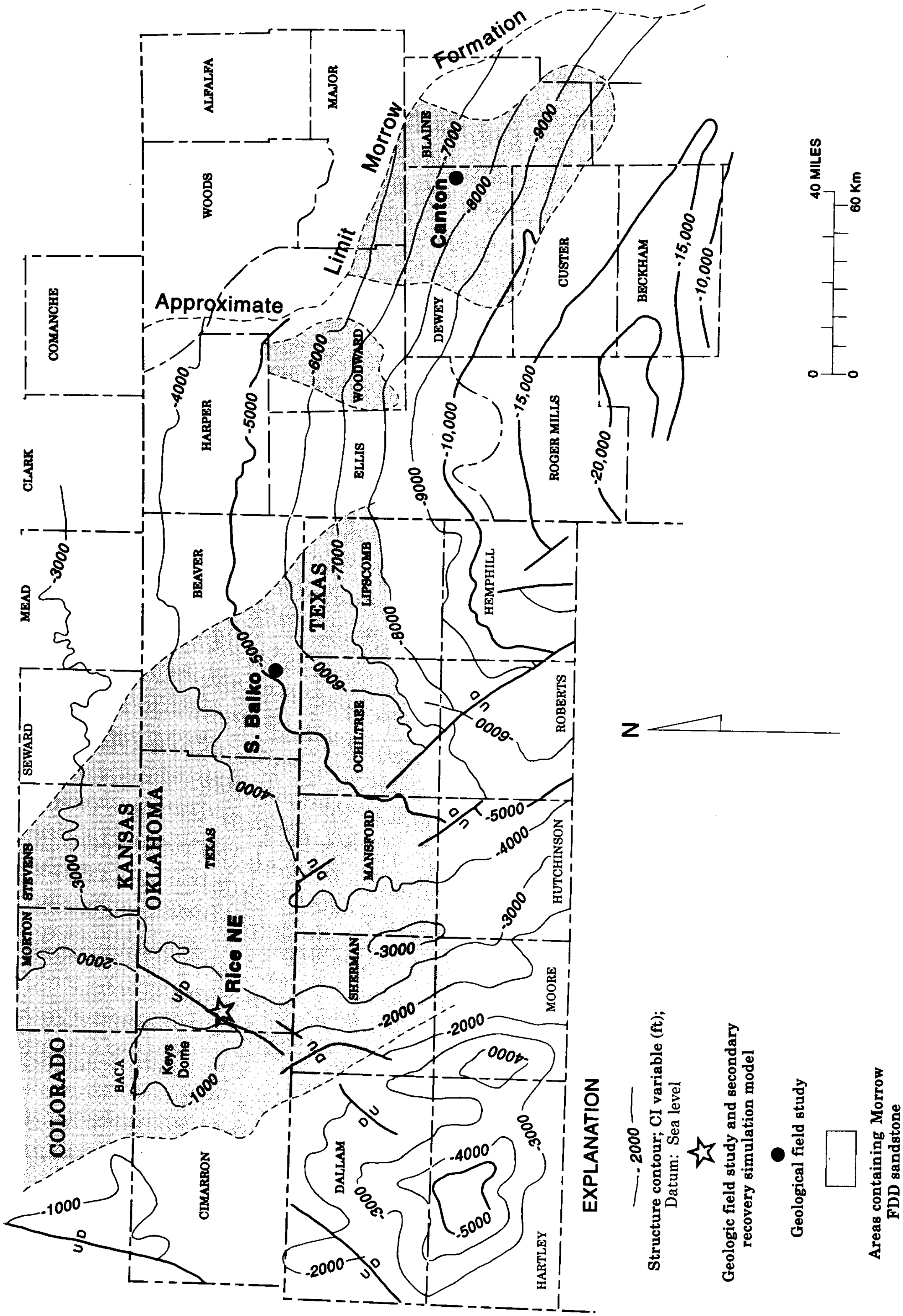


Figure 12. Generalized location map showing Morrow FDD areas and structure of the Morrow Formation. Modified from Swanson (1979), east part, and Forgotson (1969), west part.

SYSTEM	SERIES	GROUP	FORMAL SURFACE NAMES (FORMATION)		INFORMAL SUBSURFACE NAMES
PENNSYLVANIAN	Atokan	Atoka	Atoka (surface name where exposed in eastern Oklahoma)		Thirteen Finger lime
	Morrowan	Morrowan (Lower Dornick Hills)	Morrow (surface name where exposed in Arkansas) Kearny Formation (subsurface name used in Kansas)	upper Morrow	(The following names are sometimes used interchangeably and are not necessarily in stratigraphic order)
					Purdy sand (Keyes and Sturgis field area)
					Sturgis sand
					Bowles sand (Camrick field)
					Kelly sand (Eva NW field)
					Lips sand (Camp creek, Camrick, and Keyes fields)
					A, B, C, D, etc, sand
					Puryear (deep Anadarko basin)
				lower Morrow	"Squaw Belly" (limy sediments and limestone, sometimes called middle Morrow)
			Cromwell Sandstone; of the Union Valley Formation in the Arkoma basin		Mocane - Laverne sand
					Keyes or Basal sand
					Jefferson sand (Arkoma basin)
MISSISSIPPIAN	Chesterian	Mayes	Pitkin Limestone (surface names when exposed in eastern Oklahoma)		Chester (Manning, Mississippi)
			Fayetteville Shale		
			Hindsville Limestone		

Figure 13. Stratigraphic nomenclature chart of the Morrow Formation in the Panhandle and northwest Oklahoma.

the Morrow. Correctly interpreting a depositional environment can help identify trends of reservoir sands, which then can be mapped (using electric well-log data) in the subsurface. Understanding a depositional environment also helps in the interpretation of such reservoir characteristics as sand thickness and extent, clay content, and reservoir quality. Inferences of depositional origin are made routinely using gamma ray or resistivity log profiles in addition to other data.

It is important to consider the areal distribution or continuity of individual sandstone beds when interpreting the depositional environment of any rock unit. In the Morrow, sandstones tend to be highly variable in thickness, lateral extent, and depositional origin. Wireline log responses change suddenly and correlations can be difficult even over very short distances. Additionally, fluvial (nonmarine) sandstones often are interbedded with marine sediments and limestone. These characteristics indicate an unstable geological setting involving the interaction of several depositional environments in close proximity to one another.

GENERALIZED MORROW DEPOSITIONAL MODEL (FDD AREAS)

Throughout most of the Anadarko shelf and shallow basin, the Morrow Formation simply does not fit into a simple depositional model, a fact that quickly becomes apparent when electric logs are used to correlate sandstones or interpret depositional environments. The complexity of the Morrow becomes even more apparent as the number of wells in any one area increases. On a regional scale, however, a generalized depositional model of the upper and lower Morrow can be used.

Core and/or well log interpretations in all field study areas show that marine and nonmarine sediments are in close proximity to each other both stratigraphically and laterally, which suggests that the principal sandstone horizons in the Morrow Formation were affected by repeated changes in sea level. The relationship of sediments indicates that the position of Morrow shorelines fluctuated significantly and that depositional environments of the sandstones were highly interactive. Under such conditions, relatively short-lived and sand-poor depositional episodes prevented the occurrence of widespread, uniform depositional sequences (both marine and nonmarine). Individual sandstone beds in the Morrow are relatively thin (generally <50 ft), and the total sandstone in any one depositional cycle commonly is <150 ft. Thus, a dynamic system containing several different, but spatially interactive, environments is an appropriate generalized depositional model for the Morrow.

Lower Morrow: Western Oklahoma, Anadarko Basin

Evolution of the lower Morrow in western Oklahoma is not clearly understood, and there is disagreement about what constitutes the basal Morrow, primarily because of uncertainties about formation boundaries and the stratigraphic relationships between the Morrow, Springer, and Mississippian. On regional stratigraphic cross sections A–A′ and B–B′ (Pl. 2), the Morrow–Mississippian contact is shown to be on top of the "upper" Chester. The cross sections also identify the Chester "solid," which could be interpreted alternatively to be the Pennsylvanian–Mississippian unconformity. In addition, some of the lower sands in the interval between the Chester and Morrow are identified as Springer, and, in many cases, the relationship between the Morrow and the Springer is interpreted to be unconformable. Nevertheless, in the shallow Anadarko basin and the Canton study area, the Springer and Morrow intervals seem to constitute a continuous depositional sequence without any clear-cut division or unconformable relationship due to erosion or nondeposition. This problem, in turn, makes it difficult to identify the transgressive interval of the lower Morrow especially where marine lithologies of the upper Chester (or Springer) already account for much of the transgressive section within the Anadarko basin.

FDD areas identified in the Canton and Woodward "trench" areas (Pl. 1) have stratigraphic sequences which depart from the persistent marine depositional patterns that characterize the lower Morrow. In these localized areas, the sedimentary record indicates a shallowing-upward depositional trend that is transitional from marine shelf to subaerial environments. This interpretation is supported by core descriptions

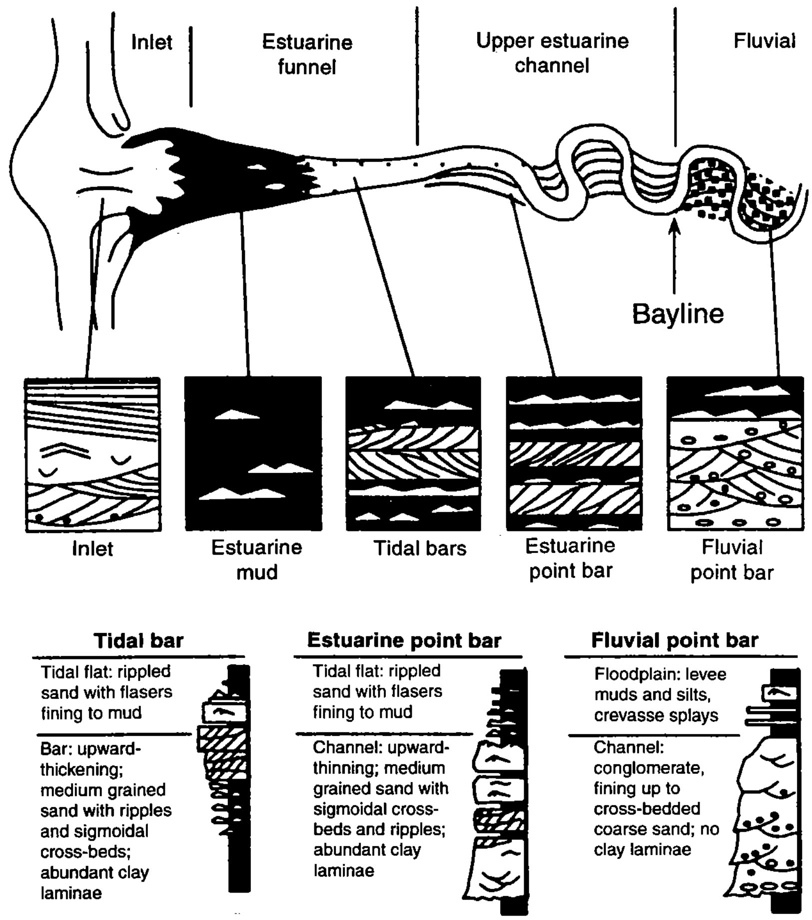


Figure 14. Schematic illustration of the longitudinal facies within a macrotidal estuary. Each morphological zone is represented by a characteristic facies type indicating a downstream evolution from fluvial to estuarine channels and bars. From Shanley and McCabe (1994).

by Bentkowski (1985), South (1983), and Godard (1981), and from numerous well log interpretations. In areas where deltaic sediments are interpreted, a typical vertical sequence in a portion of the lower Morrow includes in ascending order: marine shale (prodelta shelf?), shallow marine sand (delta front?), and subaerial exposed sediments consisting of fluvial point bars, marsh, and carbonaceous material (delta plain?). Quite often, sandstone beds have a fluvial geometry but contain marine constituents such as shell fragments or glauconite. This could indicate a redistribution of preexisting marine sediments during a period of transgression or the extension of a channel into a marine environment (distributary channel). Fluctuating shorelines or tidal currents may also be responsible for the incorporation of marine sediments. This type of deposition model is shown in Figure 14 and is particularly applicable to the Morrow, which may have been affected by periodic changes in sea level. As shown on Plate 1, fluvial depositional systems in the Canton area are interpreted to consist of both coastal plain deposits (no underlying delta-front deposits) and deltaic sequences.

Ultimately, lower Morrow fluvial systems were inundated by marine conditions, which caused the redistribution of existing sands and the deposition of shale and discontinuous, nearshore sand bodies. The aggraded sediments became predominantly shale, now interpreted to be the upper Morrow interval. Since limy sediments attributable to the "Squaw Belly" were not identified clearly from well logs in the Canton and Woodward areas, the approximate stratigraphic position of the upper Morrow/lower Morrow boundary is interpreted to be near the top of the principal lower Morrow sandstone zone, as shown on regional cross sections A–A′ and B–B′ (Pl. 2).

Coarse-grained clastics in the lower Morrow are most apparent in the Canton and Woodward FDD areas. However, this same stratigraphic interval becomes increasingly finer grained to the northwest in the Mocane-Laverne field where it is entirely marine or semimarine in origin. Further west in the principal FDD areas of Texas County, Oklahoma, the lower Morrow interval consists mostly of marine shale overlying basal marine sands. This regional distribution of fine- and coarse-grained sediment indicates a clastic source area to the north–northeast as opposed to a source area for upper Morrow FDD areas to the west–northwest. The distribution pattern of clastic material in the lower Morrow also indicates that the regional extent of the Morrow to the northeast is partly a depositional limit and that the early Morrow seaway was deeper to the southwest.

Upper Morrow: Oklahoma Panhandle, Anadarko Shelf

The upper Morrow consists mostly of marine shale with discontinuous sand bodies scattered throughout its regional extent. Within FDD areas of the Oklahoma Panhandle, these sand bodies occur in elongate or sinuous patterns that are interpreted to have originated primarily in fluvial channels. Previous investigators attributed the occurrence of sand bodies to deltaic conditions, and they appear to be correct for certain parts of Texas County, Oklahoma. Swanson (1979) constructed a well-known fluvial-deltaic model of the upper Morrow largely from his work in the Postle field area. However, other areas west of Postle field and to the east in southwest Beaver County have fluvial constituents that probably are not deltaic in origin. Within these areas, detailed studies of Rice NE and South Balko fields indicate that upper Morrow sands originated from fluvial valley-fill systems that were incised in the preexisting marine shale of the upper Morrow

(Fig. 15). Distinctive delta-front or delta-plain sediments are characteristically absent in these areas although sediments immediately above and below the channel sands have marine characteristics.

Deposition of fluvial sediments within the upper Morrow appears to be controlled by a series of incised drainage systems that trend in a northwest-to-southeast direction. In certain areas, such as in Postle field, depositional rates may have temporarily exceeded sea-level rise, resulting in deltaic areas of limited size. Other depositional sites appear to be flood-plain equivalents where there was insufficient sediment load to overcome the effects of rising sea water. In these areas, fluvial deposits (consisting of point bars and possibly some braided river deposits) were immediately reworked by transgressive marine processes. Although their clastic components basically are the same, sandstones of delta or coastal flood-plain origin may have facies and morphologies different from those of sandstones composed of sediments reworked by tides in a coastal inlet. Figure 14 shows the different facies that develop in a macrotidal estuary, such as tidal bars (bidirectional cross-bedding), estuarine point bars, and fluvial point bars.

In a valley-fill model such as in Figure 15, fluvial sandstone of the upper Morrow is interpreted to have

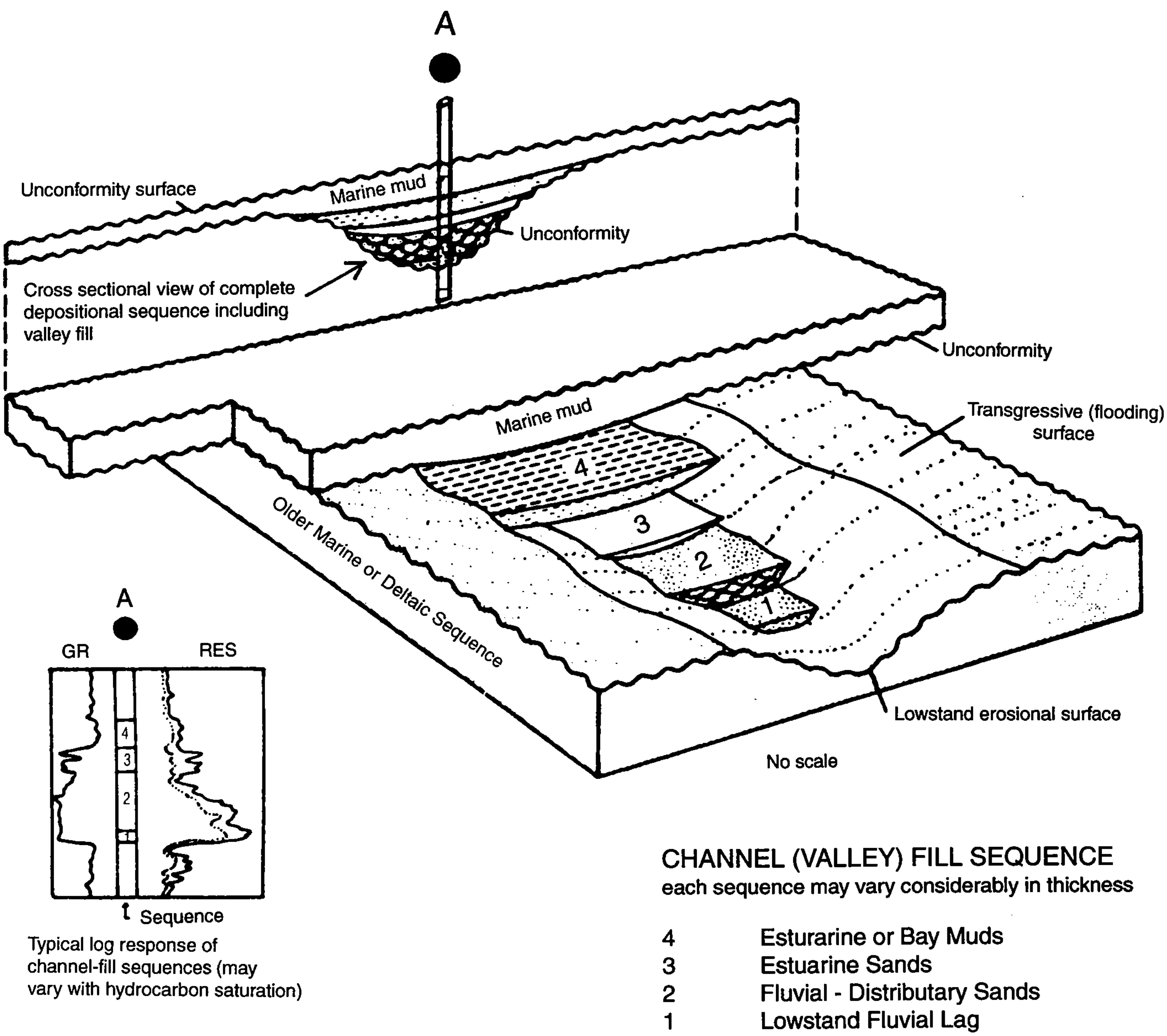


Figure 15. Schematic block diagram illustrating depositional style and vertical sequence of clastic rock facies that characterize many Morrow valley-fill deposits. Such sequences commonly are called channel fills, and they may represent fluvial and/or distributary deposits that were affected by marine processes such as those in estuarine or tidal environments. Fluvial channels commonly cut through preexisting marine sediments or, in some cases, fluvial deposits are reworked during a sea level rise, causing fossils and accessory minerals normally attributed to marine environments to be incorporated in fluvial sediments. Modified from Wheeler and others (1990).

been deposited upon an erosional surface that formed in response to a drop in sea level. Evidence that this condition reversed itself is indicated by marine fossils and trace fossils that occur in sediments above the principal channel deposits. Since the distribution of upper Morrow sandstone was apparently controlled by the arrangement of paleo-valleys, it seems likely that initial marine influences during sea level rise could have favored tidal or estuarine conditions. Continued marine transgression resulted in complete marine inundation. The position of relative sea level in this case has a direct relationship to facies development in the Morrow and is the basis of sequence stratigraphy.

An incised valley-fill system, such as the Morrow, forms in response to sea level drop. Channel deposits that occur within the eroded paleo-valleys belong to a lowstand system tract (LST) whereas the underlying shelf sediments were deposited earlier when sea level was relatively high and belong to a highstand system tract (HST). In the case of the upper Morrow, shelf sediments were mostly marine shale since there was no highstand delta. Limestone beds above the LST channels indicate a transgressive event and their facies represent a transgressive system tract (TST). These relationships of deposition and relative sea level are shown in Figure 16 and are applicable to the depositional model of the upper Morrow. Limestone in the overlying Atoka is analogous to the TST carbonates identified in Figure 16 and is related to sea level rise (marine transgression).

Work by Harrison (1990) indicates that the valley-fill sequences, including point-bar sandstones, are completely surrounded by marine shale. Prerequisites for such a model are lowering of relative sea level (lowstand), incisement of exposed shelf (preexisting Morrow marine shale), extension of fluvial processes, and rise in relative sea level (transgression). Such a sequence of events is in agreement with the valley-fill diagram in Figure 15 and the diagram of depositional systems tracts in Figure 16.

Regional stratigraphic cross sections C–C′ and C′–C″ (Pl. 3) have been constructed across the entire FDD portion of the Oklahoma Panhandle. These sections show the electric log character and stratigraphic position of the principal sandstone zones that occur in this region. Although most of the oil production comes from the upper Morrow, there are some sandstone bodies in the middle to lower portion of the Morrow that have electric log profiles characteristic of fluvial channels. However, these lower sandstones are prone to gas production and are not of primary importance in this study.

FDD IN THE MORROW

Morrow fluvial systems (Pl. 1) are found principally in three regions within Oklahoma. The first area is the *Dewey–Blaine Counties embayment.* A second area, located within a north–south-trending paleo-valley in central Woodward County, is called informally the *Woodward "trench."* The most extensive area of fluvial domination, however, occurs in the *Panhandle region* comprising Texas, western Beaver, and eastern Cimarron Counties. All three areas contain more than one sequence of fluvial sandstone in addition to nearshore and shallow marine sandstone deposits.

The distribution of fluvial or FDD sediments is related directly to the type of hydrocarbon produced from the Morrow. Morrow oil production (Pl. 4) occurs almost entirely in areas identified as FDD, whereas areas with other depositional environments produce more natural gas. One reason this occurs is that sediments of fluvial or FDD origin have better reservoir properties. The properties of a reservoir are related to depositional environment. For the most part, sand in FDD areas is coarser grained than the relatively tight marine sands in areas that mainly produce gas.

The map in Plate 5 shows the boundaries of all significant Morrow fields in Oklahoma, whether or not they are FDD in origin. Any field that has produced at least 5,000 barrels of Morrow oil, or at least 3 billion cubic feet of gas, in the past 15 years (since 1979) is included on this plate. Field names and boundaries are consistent with field designations by the Oklahoma Nomenclature Committee of the Midcontinent Oil and Gas Association. In some cases, Morrow production is found only in one portion of the field; in other cases, Morrow production is found outside of the formal field boundaries. This occurs because the effort to formally extend field boundaries lags behind the extension of producing areas. The shaded pattern used in the Morrow field map indicates all areas of Morrow oil production regardless of depositional origin.

All available sources of information were used in identification of Morrow fluvial and FDD areas, including theses, articles in *Shale Shaker,* consultants, and personal investigations by the author. Selected references used for Morrow sandstone mapping are listed on Plate 6. A more complete list of references is included as part of this volume.

Dewey–Blaine Counties Embayment (FDD–Oil)

This area has been mapped in detail by South (1983) and Bentkowski (1985) and is discussed in field reports by Colton (1974a,b,c) and Cochrane (1974). It occurs in the shallow portion of the Anadarko basin updip from the shelf break and lies at depths of about 8,500–11,000 ft. Characteristic of this area is a stratigraphic assemblage of several sandstones belonging to the lower Morrow (or upper Springer?). Many of these sandstones are interpreted to be deposited in some form of "channel" and, on a regional scale, they trend to the south and southwest (Pl. 1). Depositional trends of channel deposits indicate the paleodip of the pre-Pennsylvanian erosional surface and the direction to the source area for lower Morrow sediments (Bentkowski, 1985). This source area is interpreted by most geologists to be the Transcontinental arch, which is a structural element largely located in western Nebraska.

The Dewey–Blaine Counties area is unusual for the Morrow in the Anadarko basin since many of the wells are classified as oil wells (Pl. 4). Although gas is found basinward and along depositional strike, a significant oil fraction is trapped in the best reservoirs which are fluvial in nature. These rocks have porosities of about 10–20% and permeabilities of 10 to >100 md (South, 1983). The fluvial facies are generally fine grained, but basal portions of individual beds may be coarse grained to conglomeratic. In composition, the sandstones are quartz arenites with varying amounts of skeletal and clay material (South, 1983). Thin sequences of lagoonal or flood-plain material consisting of black, carbonaceous shale are interbedded in the sandstones or extend laterally from the sandstone channels (South, 1983). These sediments were probably de-

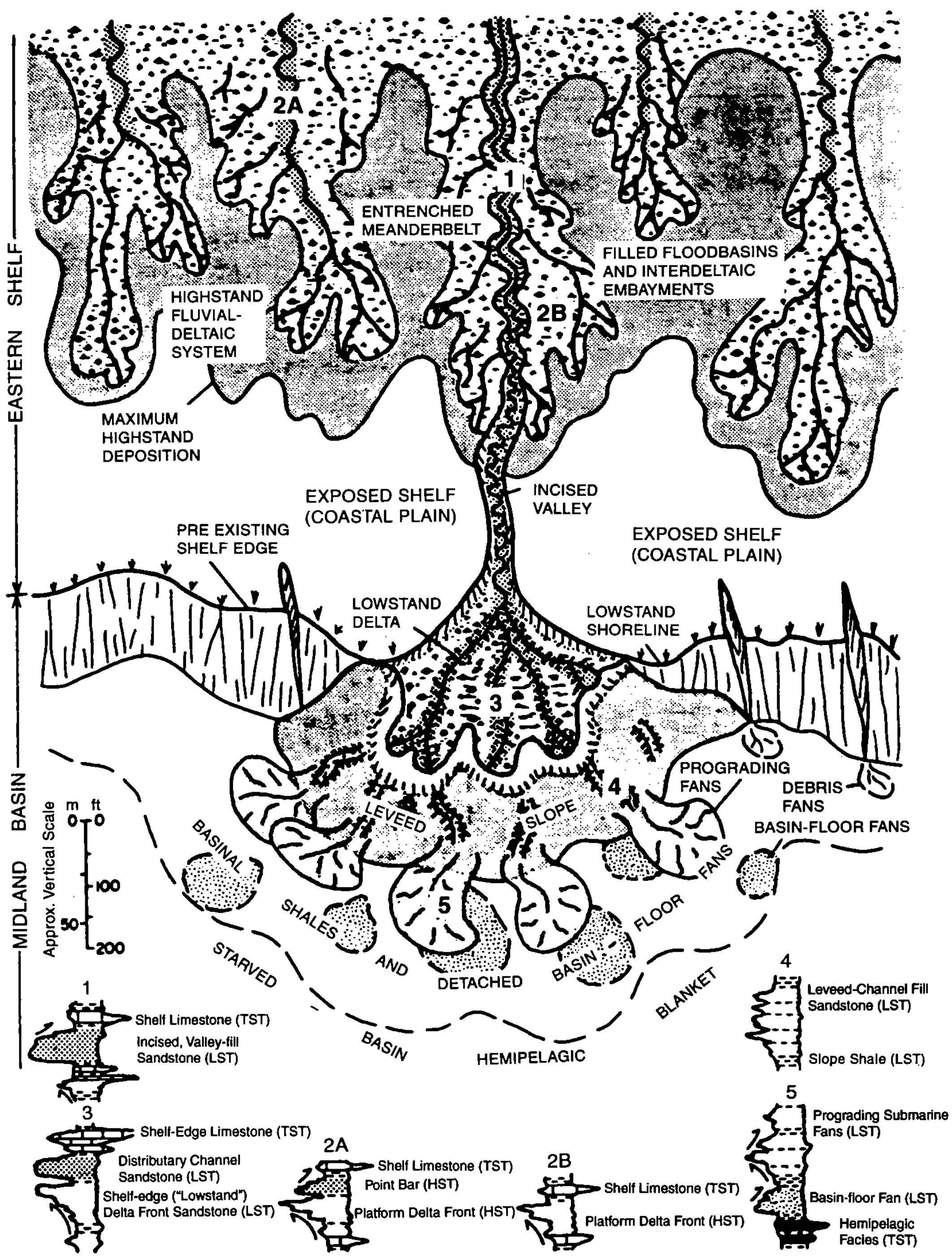


Figure 16. Depositional systems tracts—highstand system tract (HST), lowstand system tract (LST), transgressive system tract (TST)—at maximum progradation of terrigenous clastic systems. Representative logs illustrate facies within various systems comprising the tracts. From Brown (1979).

posited in a lower, subaerial coastal plain or deltaic environment. Conspicuously absent, however, are coal beds that usually occupy a portion of most deltaic sequences.

Several early investigators of the Morrow indicated that basal Morrow sandstone deposition was related to dendritic erosional patterns incised on the pre-Morrowan carbonate surface (Khaiwka, 1973a,b; Busch, 1959). Such a relationship was not observed; a pronounced erosional unconformity was not identified in this area, and lower Morrow shale largely fills any irregularities occurring on top of the Chester.

Canton Study Area

(secs. 22, 23, 26, 27, T. 18 N., R. 14 W., Dewey County, Oklahoma)

The Canton study area is ~6 mi southwest of the town of Canton. It consists of four sections that were originally part of Canton Southwest field before their assignment to the Watonga–Chickasha trend. Selection of this specific site was based upon oil production characteristics of the Morrow that are unique to the geologic province in which it occurs (Anadarko shelf-transition). It also has favorable well spacing (40 acres) and availability of current data such as cores, modern well logs, and production information. Table 1 gives a summary of geological/engineering data for the Canton study area; characteristics of the study area are discussed in more detail in the following sections.

Stratigraphy: Sandstone beds in the Canton study area constitute one of the most complicated assemblages of sediments in the entire Morrow FDD play. Numerous sand zones occur in a stratigraphic interval of only a few hundred feet and their thickness and lateral continuity is highly variable. This often makes correlation of individual sandstone beds very difficult, even within the same section. Depositional origin apparently is very complicated since facies representative of marine, semimarine, and subaerial environments are in close proximity both vertically and laterally.

The principal Morrow sandstone beds identified in the Canton study area informally are called, in descending order, the "B," "C," and "D" sands (Fig. 17). They generally are stacked upon one another in the middle portion of the lower Morrow interval. The division between the upper and lower Morrow is not precise, however, and is generally picked just above a poorly developed sandy interval that may belong to the "Squaw Belly." Regional correlations indicate that the "D" sand may be stratigraphically equivalent to the Springer zone identified on regional cross sections that extend deeper into the Anadarko basin (Pl. 2). This relationship generally is unimportant since nearly all production in the Canton study area is attributable to the "B" and "C" sands.

The spatial relationship and stratigraphy of lower Morrow sandstones in the Canton area are shown in detailed cross sections of the four-section study area. Cross section A–A′ (Fig. 18, in envelope) is a strike line oriented northwest–southeast and best shows the char-

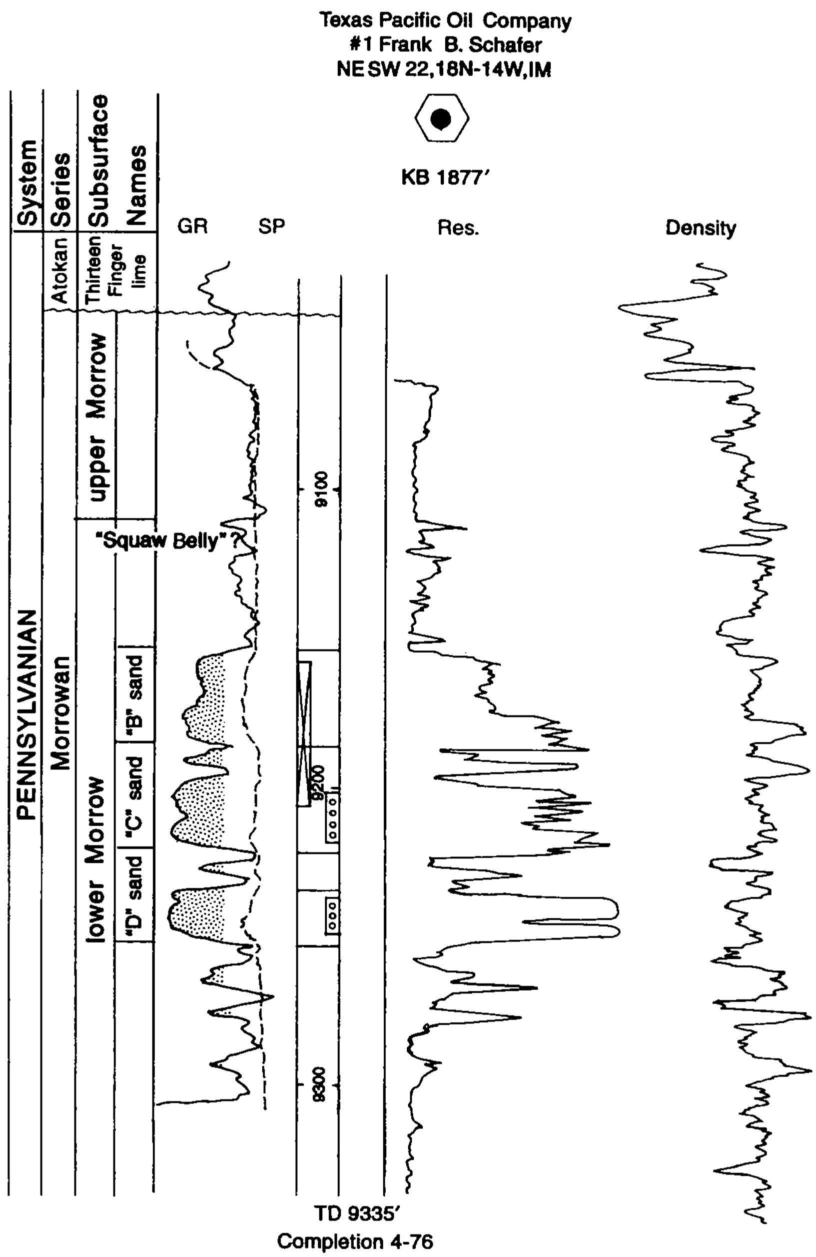


Figure 17. Morrow type log in the Canton study area showing log patterns of gamma ray (GR), spontaneous potential (SP), resistivity, and density measurements.

TABLE 1. – Geological/Engineering Data for the Lower Morrow Sandstones in the Canton Study Area, Dewey County, Oklahoma

	lower Morrow "B" sand	lower Morrow "C" sand
Reservoir size	1,503 acres	1,960 acres
Well spacing (oil)	40 acres	40 acres
Oil/water contact	none	none
Gas/oil contact	none	none
Porosity	5–20% (10% avg)	5–20% (10% avg)
Permeability	1–200 md (1–10 avg)*	1–200 md (2–10 avg)*
Water saturation	20–45%	20–45%
Thickness (net sand in field) ($\phi \geq 8\%$)	10–20 ft (10.2 ft avg)	10–30 ft (12 ft avg)
Reservoir temperature	160–170° F	160–170° F
Oil gravity	40–47° API	40–47° API
Initial reservoir pressure	4,200 PSI**	4,200 PSI**
Initial formation-volume factor	1.2 reservoir barrels/stock tank barrels**	
Original Oil in Place (volumetric)	6,442 MSTBO	9,884 MSTBO
Cumulative primary oil	2,360 MSTBO (combined)	
Recovery efficiency (oil)	14.5% (combined)	
Cumulative gas	12.4 BCF (combined since 1979)	

*Source: South (1983). **Source: Colton (1974a).

acter of the "B" sand. In the northwest part of the study area, the "B" sand has a multicomponent electric log profile (Fig. 18) such as in the No. 3 Tidball well in the SW¼NW¼ of sec. 22, T. 18 N., R. 14 W. (Fig. 19). The log pattern from this well indicates several closely related depositional environments that probably involved marginal-marine processes. From ~42 ft in this well, the "B" sand thins to ~19 ft in the No. 1 Gundlach well in the N½SE¼ sec. 22, T. 18 N., R. 14 W. The log character in the No. 1 Gundlach well is more uniform and the consistent coarsening-upward textural profile is suggestive of a single depositional origin. Farther to the southeast, the "B" sand is almost entirely absent in the W½ sec. 26, T. 18 N., R. 14 W. In cross section B–B′ (Fig. 20, in envelope), the "C" sand has a well-developed fluvial log signature in the No. 2 Schafer "B" well in the NW¼NE¼ of sec. 27, T. 18 N., R. 14 W. (Fig. 19). This sand is absent ~1 mi to the northeast in the No. 2 Schafer well in the SW¼NW¼ of sec. 23, T. 18 N., R. 14 W., but it reappears farther to the northeast in the No. 1 Frank Schafer well in the N½ NE¼NW¼ of sec. 23, T. 18 N., R. 14 W.

Other important characteristics shown on these cross sections are the nature of sand bodies, their relative thicknesses, the multicomponent stacking arrangement (as seen on log traces), productive zones, and general log character of reservoir-grade sandstones.

Structure: The structure of the Canton area is characteristic of a stable shelf or shelf-transition environment (Fig. 21). Structure contours indicate basinward dip to the southwest at ~100 ft per mile which is equivalent to a 1° dip. There are no known faults or structural closures in the four-section study area.

Isopach Mapping: Basic sandstone mapping includes gross and net isopach maps for both the lower Morrow "B" and "C" sands. These maps were prepared using an 8% porosity cutoff for net values and GR-resistivity log deflections for determination of sand body thickness regardless of porosity (gross thickness). In some cases, more than one sand bed was judged to belong to a particular sandstone zone.

Lower Morrow "B" Sand: The "B" sand is the youngest Morrow sand to produce within the Canton study area. It is found in almost every well in the four-section study area but trends are preferentially to the north, northwest, and northeast in certain portions of secs. 22, 23, and 26, T. 18 N., R. 14 W. Within these trends, the gross thickness is generally 20–40 ft (Fig. 22). Reservoir quality of this zone often is affected adversely by shale partings, high clay content, and depositional heterogeneities attributable to marine processes. As a result, the net sand distribution is considerably more limited and is confined to relatively narrow, winding areas that commonly are only about 10–20 ft thick and 0.5 mi wide (Fig. 23). The dominant northerly orientation of these sandstone bodies is an important consideration in exploration or development infill drilling, especially since many geologists maintain that all sands in the Morrow trend northwest–southeast.

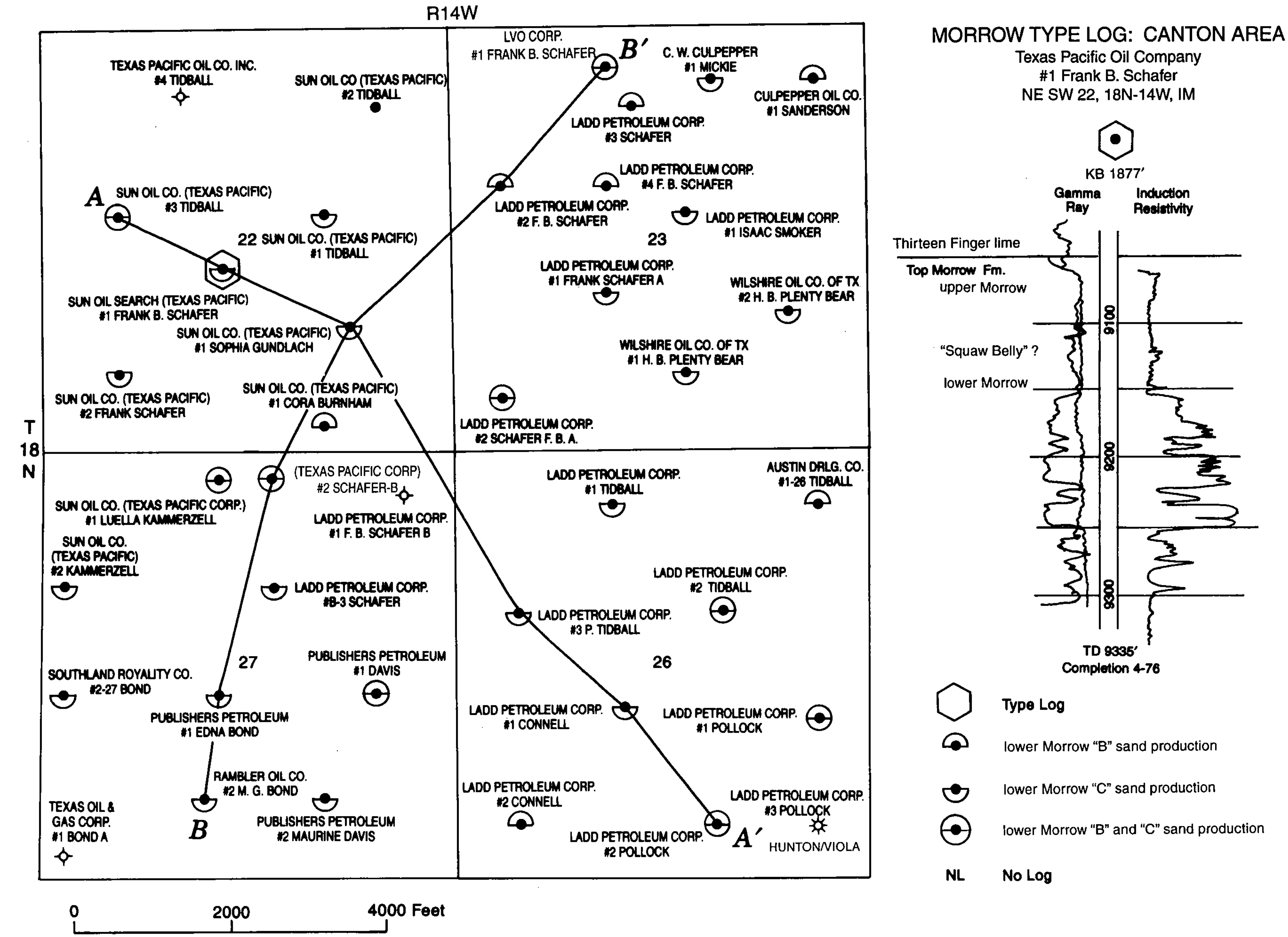


Figure 19. Information map showing operator, lease, and well number for wells in the Canton study area, secs. 22, 23, 26, 27, T. 18 N., R. 14 W., Dewey County, Oklahoma.

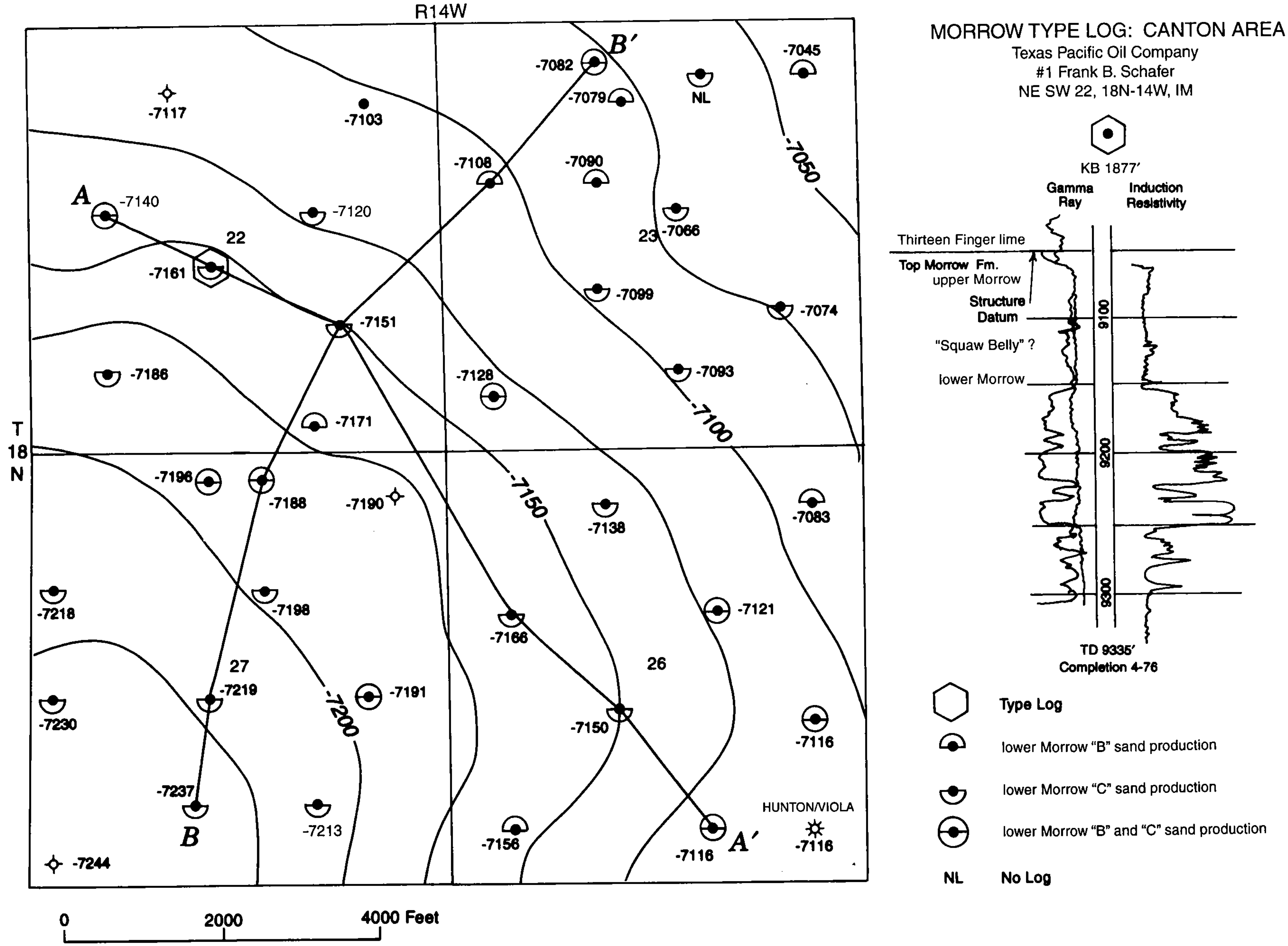


Figure 21. Structure map of the top of the Morrow Formation in the Canton study area, secs. 22, 23, 26, 27, T. 18 N., R. 14 W. Contour interval = 25 ft. See Figure 19 for names of wells.

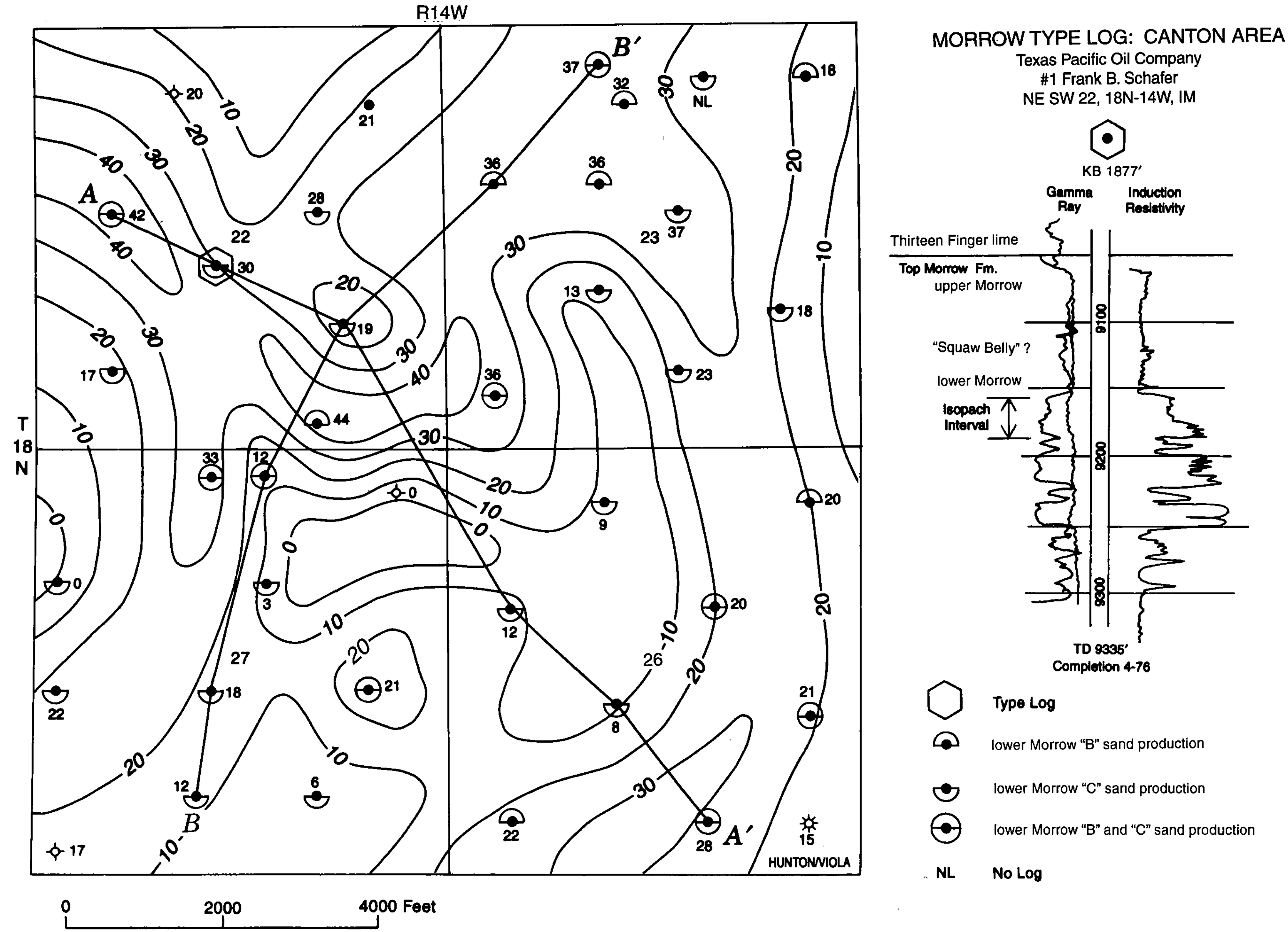


Figure 22. Isopach map of the gross lower Morrow "B" sand in the Canton study area, secs. 22, 23, 26, 27, T. 18 N., R. 14 W. Contour interval = 10 ft. See Figure 19 for names of wells.

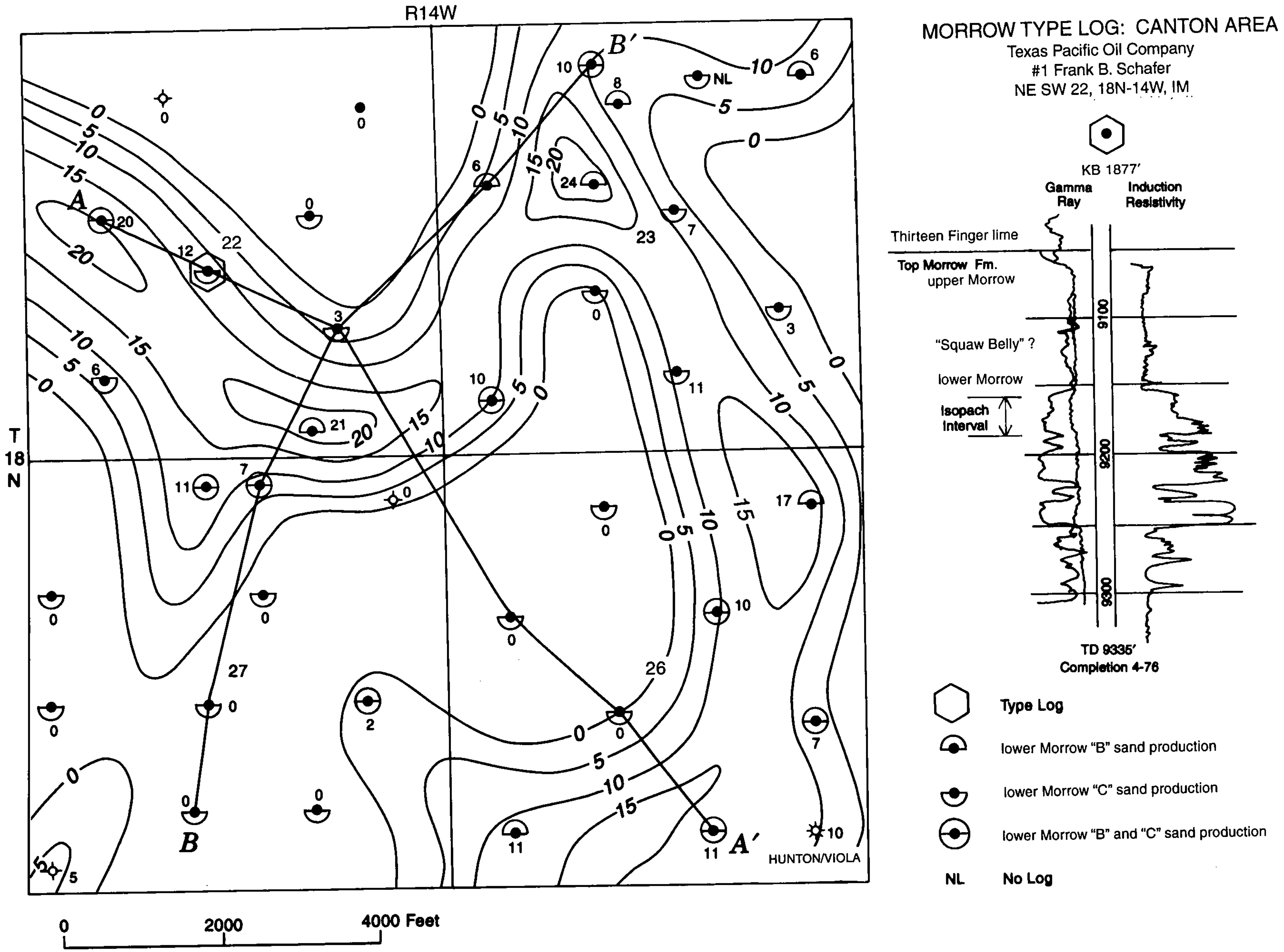


Figure 23. Isopach map of the net lower Morrow "B" sand (porosity: ≥8%) in the Canton study area, secs. 22, 23, 26, 27, T. 18 N., R. 14 W. Contour interval = 5 ft. See Figure 19 for names of wells.

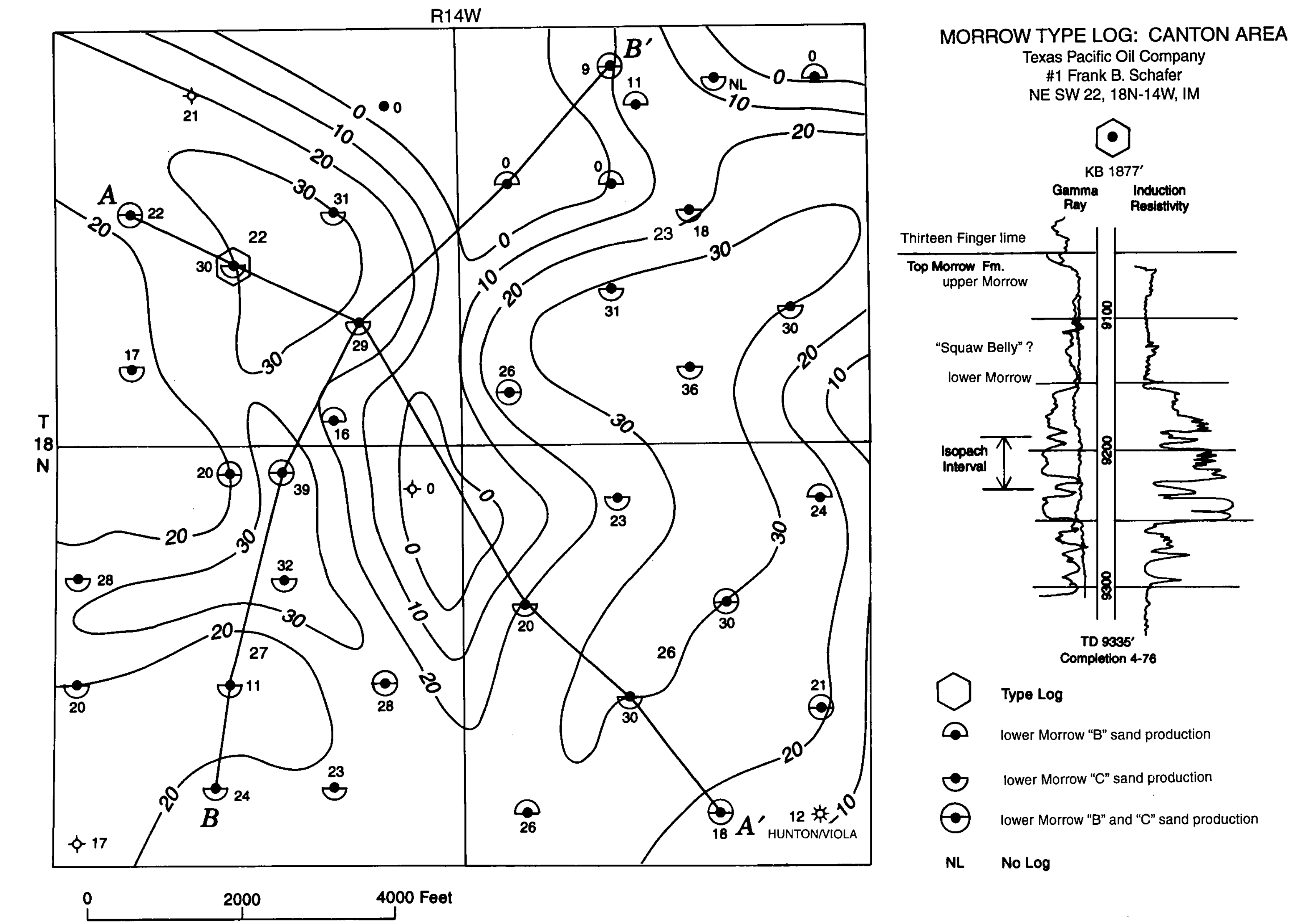


Figure 24. Isopach map of the gross lower Morrow "C" sand in the Canton study area, secs. 22, 23, 26, 27, T. 18 N., R. 14 W. Contour interval = 10 ft. See Figure 19 for names of wells.

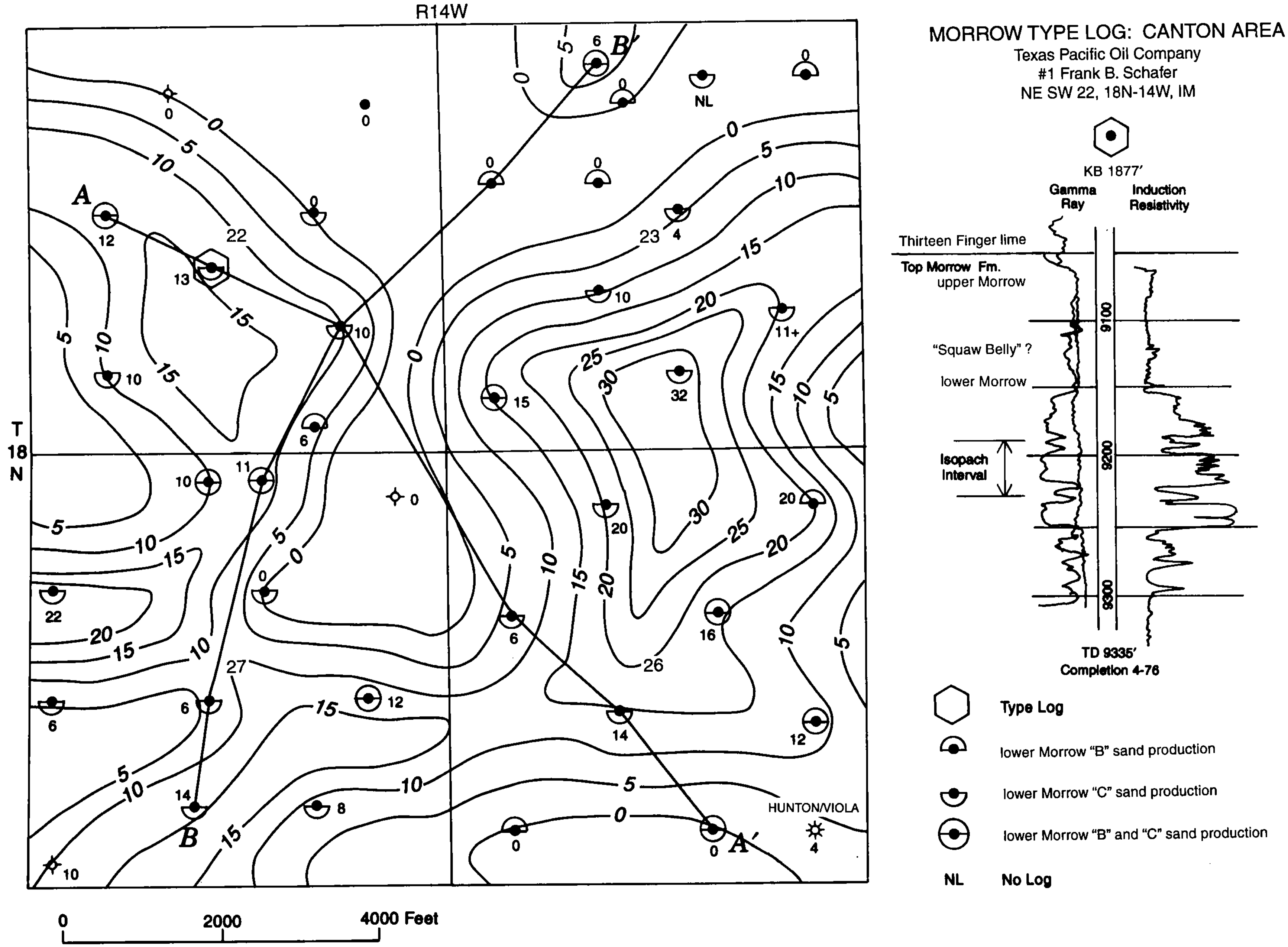


Figure 25. Isopach map of the net lower Morrow "C" sand (porosity: >8%) in the Canton study area, secs. 22, 23, 26, 27, T. 1 8 N., R. 14 W. Contour interval = 5 ft. See Figure 19 for names of wells.

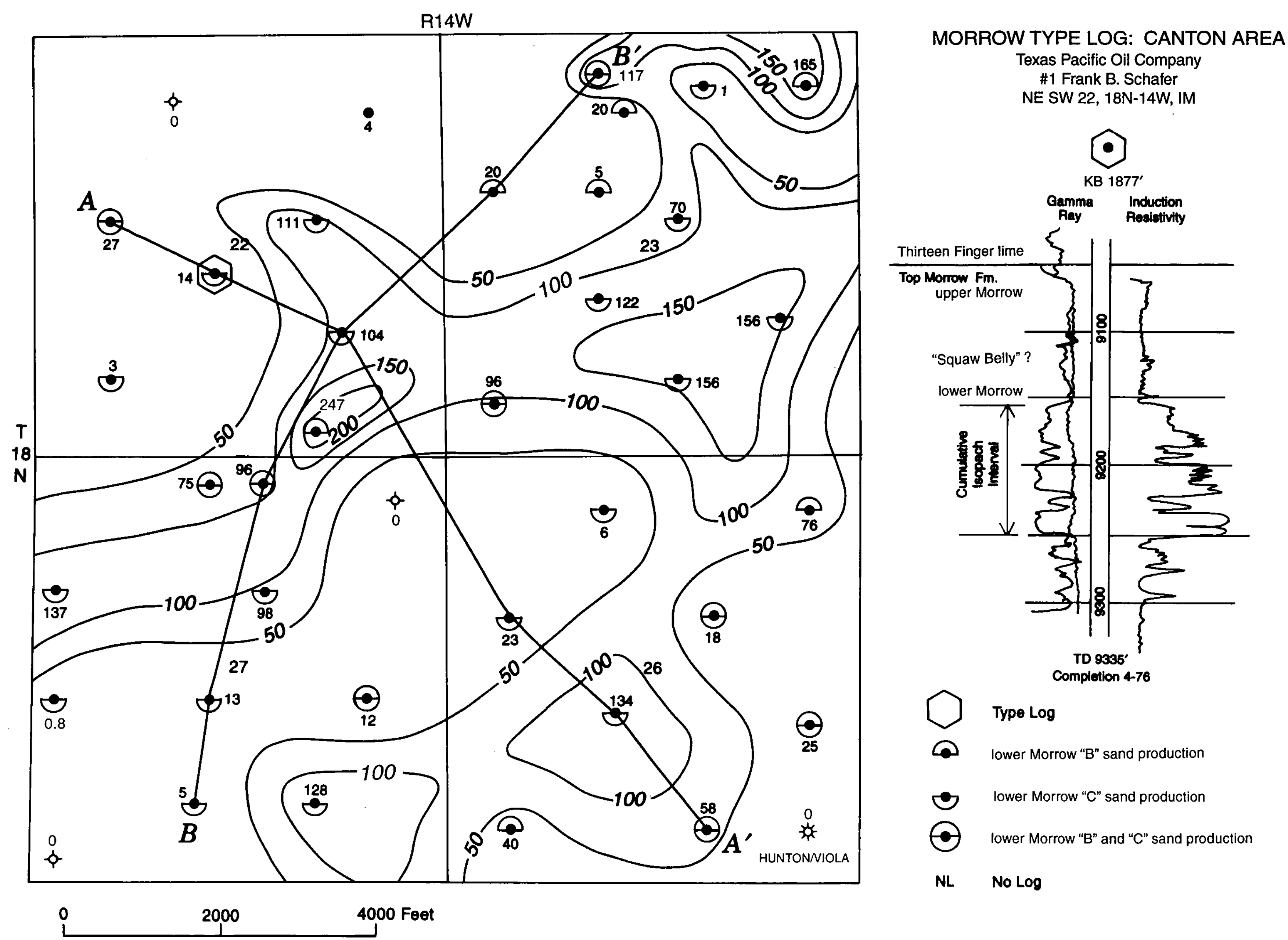


Figure 26. Map of cumulative lower Morrow oil production in the Canton study area, secs. 22, 23, 26, 27, T. 18 N., R. 14 W. Contour interval = 50 MBO. See Figure 19 for names of wells.

The "B" sand appears to be channel-form in map view but log signatures and core descriptions indicate a significant, if not dominant, marine influence. Sands in sec. 23, T. 18 N., R. 14 W. are interpreted to be mostly fluvial in origin, whereas stratigraphically similar sands to the west and south (basinward) are believed to be highly marine influenced. This conclusion is supported by textural analysis, sedimentary structures, and fossil evidence from several sandstone cores described by South (1983). Depositional facies of the marine and marginal-marine sands include tidal channels (estuarine), tidal bars and flats, and nearshore bars. Overall, the "B" zone is a multicomponent sand body comprised of a stacked assemblage of individual beds, each with a different depositional origin. As a stratigraphic package, the "B" sand zone shows evidence of more frequent marine intrusion. Stratigraphically higher sediments are entirely of marine origin and represent the dominant transgressive nature of the lower Morrow.

The "B" sand is usually only several feet above the "C" interval and occasionally is in direct contact with the underlying "C" sand. However, both sandstone horizons seem to have somewhat distinct stratigraphic zones, and deep scour is not often observed in either sand body.

Lower Morrow "C" Sand: The "C" sand also is widely distributed throughout the map area and the direction of depositional trends is northward. Stratigraphically, the "C" sand generally is the first well-developed sandstone in the lower Morrow, and distinctive fluvial attributes are seen in wireline log profiles and in core descriptions (South, 1983). Such data suggests that the "C" sand was deposited predominantly by a single process, which tended toward the development of fluvial point bars. The resulting lithology has better reservoir characteristics and is more uniform both vertically and laterally than the extremely heterogeneous lithology of the younger "B" sand.

Isopach mapping in the four-section Canton study area identifies two basic sandstone trends in the lower Morrow "C" zone. Where present, the trends have about 20–30 ft of gross sandstone, although sandstone is totally absent in several areas (Fig. 24). The most prominent sandstone trend is ~0.75 mi wide and occurs in a meandering pattern that is oriented in a northeast to southwest direction in the eastern part of the study area. In the western half of the study area, the lower Morrow "C" sand trends to the northwest; a bend causes the trend to change direction, however, and to extend to the southwest outside the study area.

Net isopach mapping of the lower Morrow "C" sand (Fig. 25) shows that the best reservoir occurs in a relatively narrow, sinuous pattern that extends across the study area in a northeast to southwest direction. This trend corresponds very well with the principal oil-production patterns in the study area. Net sandstone generally is absent in the northern, central, and southeastern parts of the mapped area. Where present, the net "C" sand thickness typically is about 10–20 ft, although locally it is ~30 ft thick in the east-central part of the study area.

Core Analysis: Several core studies were completed by South (1983) and Bentkowski (1985) in areas within or surrounding the Canton study area. Their work indicates that several different types of coarse-grained clastics occur within the lower Morrow, including quartz-dominated sands, skeletal sands, and lithic pebble conglomerates. Sands are usually fine to medium grained, and sometimes coarse grained to conglomeratic. Individual beds often have sharp basal contacts and fine upwards. Sedimentary structures include massive to horizontal bedding, in addition to wavy and inclined cross-bedding. Bedding surfaces may have carbonaceous debris. Sandstones of marine origin are significantly bioturbated and have a coarsening-upward vertical profile. Hydrocarbon production generally is limited to the quartz-dominated sands that characteristically belong to fluvial or FDD depositional systems.

Constituents of the principal reservoir rocks are extremely variable and depend upon which facies is analyzed. Quartz-dominated channel sands usually have 80–90% quartz and 1–15% clay matrix although upper point bar facies may have >20% clay matrix (South, 1983). The quantity of carbonate matrix (consisting of calcite, dolomite, and siderite) is highly variable in these sands and usually ranges from 1% to 10%. Skeletal material is facies-dependent and is most common in transitional fluvial deposits of tidal (estuarine) origin. Quartz overgrowths and silica cements are common diagenetic materials filling voids. Small amounts of glauconite, carbonaceous debris, and other minerals (chlorite, biotite, plagioclase) also are found in samples.

Reservoir Characteristics: Reservoir characteristics of lower Morrow sandstones in the Canton study area are very different from those of the upper Morrow fluvial deposits in the Oklahoma Panhandle. The lower porosity of sandstones in the Canton area is a function of greater depth, ~9,000 ft in the Canton area versus ~5,000 ft in the Rice NE study area. Effective porosity in productive sandstones in the Canton study area, as determined from density-neutron cross-plot analyses, is in the general range of 5–20%, but commonly is only 8–15% for most reservoir sands. The lower limit of porosity associated with production appears to be ~5% for gas and 8% for oil, and a "ball park" average for productive sands is ~10%. Extreme porosity values >20% are uncommon. Permeability values are in the range of 1–200 md but the range in a typical good well commonly is about 2–10 md (South, 1983).

Formation Evaluation: Lower Morrow sandstones in the Canton area respond reasonably well to established methods of formation evaluation using electric logs. All wells have modern resistivity measurements and most wells have porosity determinations incorporating density-neutron logging techniques. As a rule, oil production is limited to sandstones having at least 8% porosity and "deep" resistivity values of 40–150 ohm-meters. In well-developed sandstones, resistivity logs also characteristically have strong separation between the short and deep resistivity curves, an indication of mud-cake buildup on the walls of the borehole due to drilling-fluid invasion. Such a strong separation between curves, therefore, indicates permeability.

Calculated water saturation ($Sw = \sqrt{F \times Rw/Rt}$) in productive zones has a range of about 20% to 45%, assuming a Rw (resistivity of formation water) of 0.04 at formation temperature and using the Archie equation for formation factor ($F = 1/\phi^2$). Rt (true resistivity) is determined from the deep resistivity log curve. Porosity (ϕ) is determined from any porosity measuring tool. On the average, water saturations appear somewhat lower in the Canton area than in the upper Morrow sandstones in the Oklahoma Panhandle. The primary difference is that Morrow sandstones in the Canton area have lower average porosity but significantly higher true resistivities. Additionally, there is no water leg in any of the lower Morrow sandstones in the Canton area. As a general rule, if a sandstone has effective porosity, it probably will produce hydrocarbons.

Reservoir Sensitivity and Formation of Porosity: Porosity in the lower Morrow sandstones is mainly secondary and is related to the dissolution of the original detrital clay matrix (South, 1983). Porosity is also enhanced by the dissolution of quartz grains and other unstable framework constituents such as glauconite, certain accessory minerals, and silica cements. Although carbonate, primarily in the form of calcite, is a common cement, carbonate dissolution is noted infrequently. The highest porosities occur in the quartz-dominated channel sandstones whereas skeletal sands and conglomerates usually are tight.

Diagenetic by-products such as chlorite, kaolinite, and small amounts of detrital(?) glauconite can cause formation damage in the Canton area. Kaolinite is easily dispersed during turbulent fluid surges brought on by drilling, oil production, or water injection. The dislodged clay particles migrate short distances to form "brush-pile" obstacles within pore throats and, thus, seriously reduce reservoir performance. Acid treatment may also do more harm than good because of the reaction of acid with iron-rich minerals such as chlorite and glauconite; the insoluble residue will permanently reduce reservoir permeability.

Oil and Gas Production and Well Completion: Field development in the Canton area took place in the late 1970s and early 1980s. There was a success rate of 92% for the 39 wells drilled: 35 produced from the Morrow, three were dry, and one produced from a deeper horizon. Of particular interest for the Morrow is the fact that nearly all completions are classified as oil wells since they generally have a gas/oil ratio of <5,000:1.

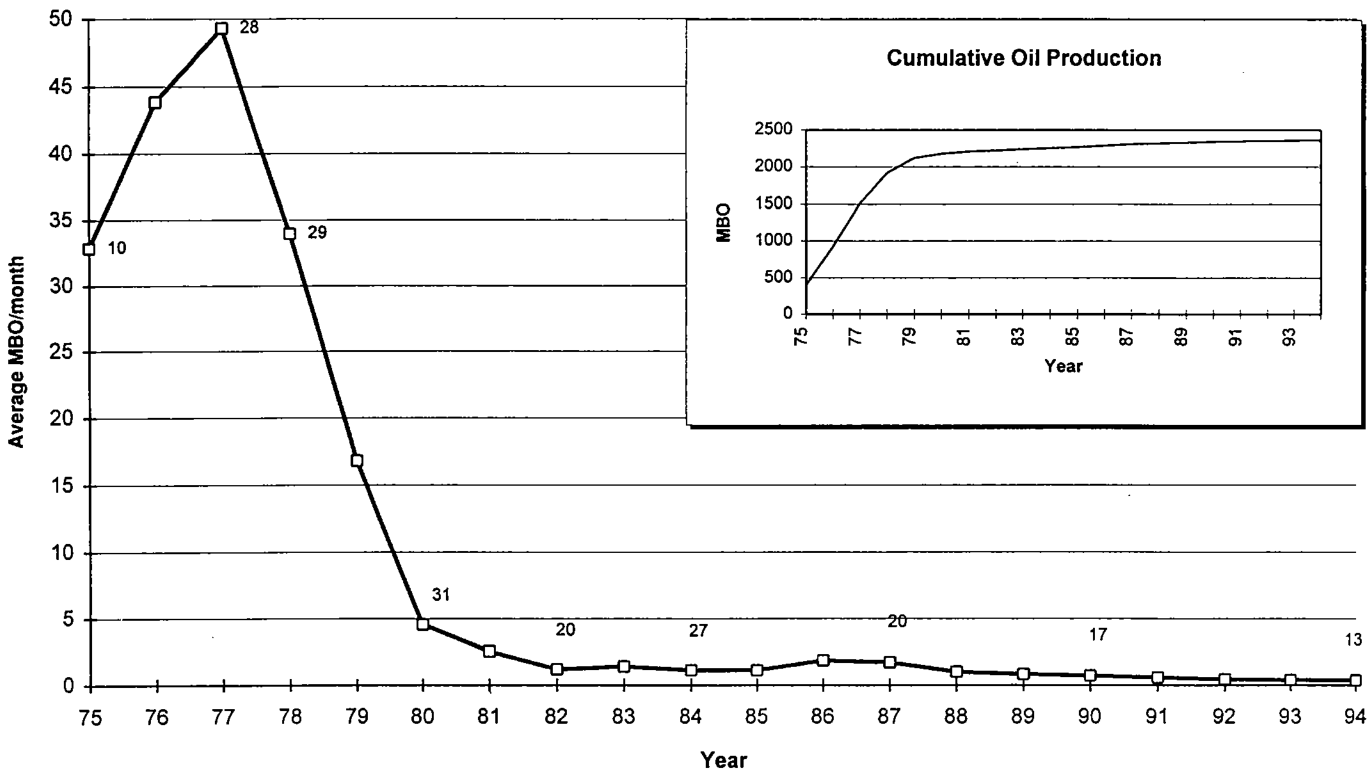


Figure 27. Oil-production decline curve for lower Morrow sandstones in the Canton study area, secs. 22, 23, 26, 27, T. 18 N., R. 14 W. Numbers on the curve designate the number of wells that had Morrow oil production at various years. Inset plot shows cumulative oil production from the "B" and "C" sands combined.

Most of the Morrow wells were completed with fracture treatment using oil-based fluids and sand as a proppant. Some operators used gelled acid (which probably did formation damage). It is difficult to quantify formation damage in terms of lost production, however, because reservoirs vary from one location to another. Production tests showed that most wells initially flowed 100–500 BOPD regardless of treatment procedures. Cumulative production for individual wells was affected most by the thickness, extent, and initial quality of the reservoir sandstone. For most Morrow wells, cumulative production was 50–150 MBO (Fig. 26). Flowing pressures (surface) also reflected lithologic characteristics and varied from several hundred PSI to a maximum of 2,600 PSI. The original bottom-hole pressure for the reservoir was 4,200 PSI (Colton, 1974a).

Cumulative primary oil production from all lower Morrow sandstones in the four-section study area is estimated at 2,360 MSTBO, which is 14.5% of the estimated 16,326 MSTBO in place originally. The initially rapid recovery rate of oil followed by a quick decline in production is attributable to a strong solution-gas-drive mechanism within the reservoir. Once this energy was lost, oil production was reduced to very small quantities (Fig. 27). The inset plot on Figure 27 shows the cumulative annual oil production from the Morrow. The large increase in production from 1975 to 1979 coincides with field development which took place during the late 1970s.

Significant oil production in the Canton area lasted only about five years; by 1981, individual wells produced <3 BOPD on the average. However, following oil depletion, most wells produced substantial amounts of gas. Figure 28 shows annual gas production and cumulative gas production for the Canton study area. Cumulative gas production since 1979 is an estimated 12.4 BCF. Additional production data for both oil and gas are summarized in Table 2.

Technically, secondary recovery of oil is possible from this type of reservoir, with some qualification. A significant reduction in the amount of reservoir oil probably occurred with the rapid initial oil recovery and production of associated gas. This shrinkage of reservoir oil in addition to primary oil production may diminish the amount of secondary oil recoverable through a waterflood.

Woodward "Trench" Area (FDD–Gas)

The Woodward "trench" is a north–south-oriented channel-fill system. Prior to or during deposition of the Morrow, there was a large erosional valley on the Mississippian surface. This valley was ~30 mi long, 3–6 mi wide, and >150 ft deep (Godard, 1981). It probably was one of the principal sediment supply corridors for the lower and upper Morrow in the eastern Anadarko basin. (Another supply corridor was the Dewey–Blaine Counties embayment area.) Only a brief summary of

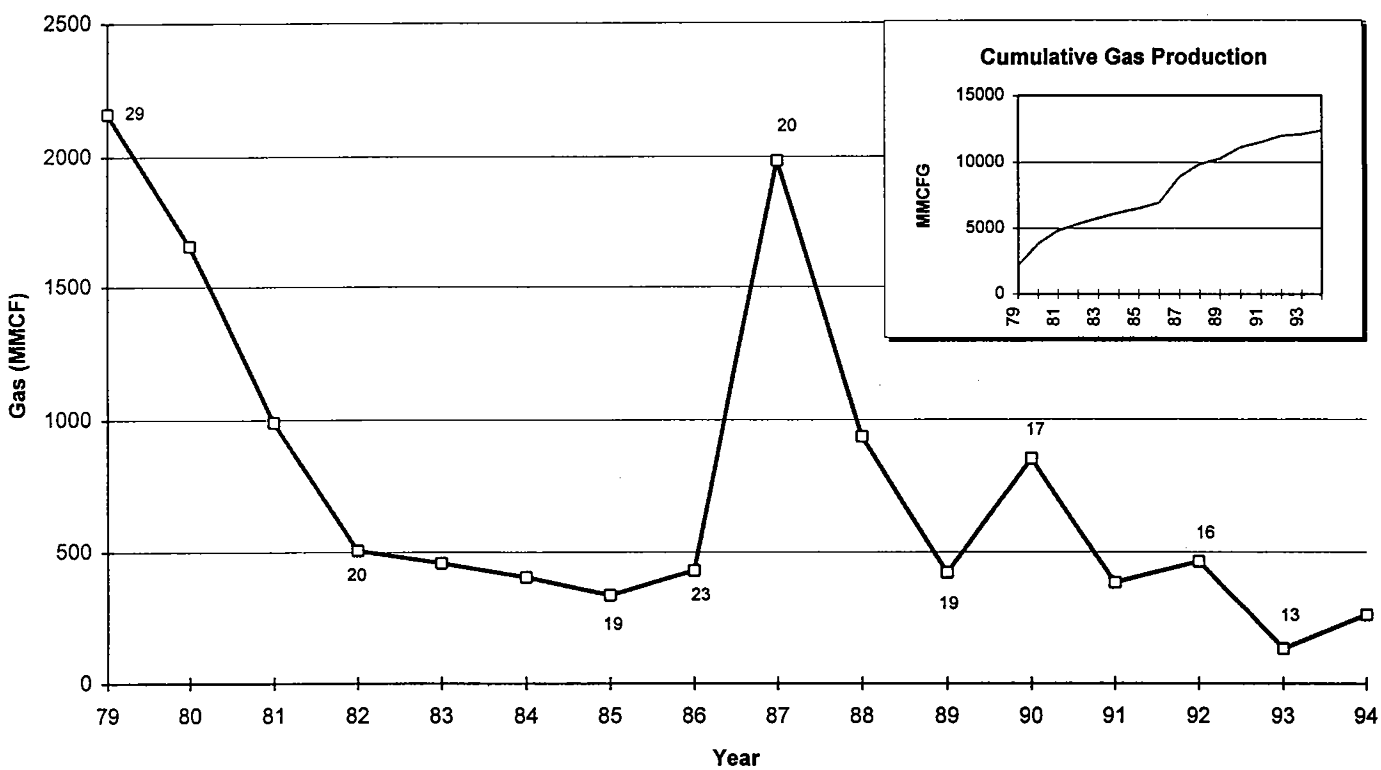


Figure 28. Gas-production decline curve for lower Morrow sandstones in the Canton study area, secs. 22, 23, 26, 27, T. 18 N., R. 14 W. Numbers on the curve designate the number of wells that had Morrow gas production at various years. Inset plot shows cumulative gas production from the "B" and "C" sands combined.

TABLE 2. – Oil and Gas Production Statistics for the Lower Morrow Sandstones in the Canton Study Area, Dewey County, Oklahoma

OIL						GAS					
Year	Number of Oil Wells* (estimated)	Annual Oil Production (Barrels)	Average Monthly Oil Production (Barrels)	Average Daily Oil Production Per Well (BOPD)	Cumulative Oil Production (Barrels)	Year	Number of Gas Wells* (estimated)	Annual Gas Production (MCF)	Average Annual Gas Production Per Well (MCF)	Average Daily Gas Production Per Well (MCF)	Cumulative Gas Production (MCF)
75	10	394,041	32,837	108.0	394,041						
76	18	526,339	43,862	80.1	920,380						
77	28	591,480	49,290	57.9	1,511,860						
78	29	407,299	33,942	38.5	1,919,159	No gas production data prior to 1979					
79	29	201,669	16,806	19.1	2,120,828	79	24	2,163,059	90,127	247	2,163,059
80	31	54,426	4,536	4.8	2,175,254	80	26	1,656,665	63,718	175	3,819,724
81	31	30,727	2,561	2.7	2,205,981	81	24	990,152	41,256	113	4,809,876
82	20	14,613	1,218	2.0	2,220,594	82	24	505,672	21,070	58	5,315,548
83	21	17,160	1,430	2.2	2,237,754	83	23	457,770	19,903	55	5,773,318
84	27	13,471	1,123	1.4	2,251,225	84	21	403,326	19,206	53	6,176,644
85	19	13,501	1,125	1.9	2,264,726	85	23	335,234	14,575	40	6,511,878
86	23	22,397	1,866	2.7	2,287,123	86	21	429,309	20,443	56	6,941,187
87	20	20,800	1,733	2.8	2,307,923	87	21	1,984,192	94,485	259	8,925,379
88	16	12,143	1,012	2.1	2,320,066	88	20	935,711	46,786	128	9,861,090
89	19	10,148	846	1.5	2,330,214	89	21	421,423	20,068	55	10,282,513
90	17	8,725	727	1.4	2,338,939	90	18	852,318	47,351	130	11,134,831
91	15	6,917	576	1.3	2,345,856	91	18	382,885	21,271	58	11,517,716
92	16	5,273	439	0.9	2,351,129	92	17	463,141	27,244	75	11,980,857
93	13	4,767	397	1.0	2,355,896	93	17	131,354	7,727	21	12,112,211
94	13	4,422	369	0.9	2,360,318	94	16	260,473	16,280	45	12,372,684

*Based on the number of producing leases. Individual leases may contain more than one producing well.

the Woodward "trench" area is provided because, although it contains excellent examples of FDD reservoirs, the associated field(s) are prone to gas rather than oil production. In this area, iodine also is extracted from water pumped from the Morrow.

The Woodward "trench" contains mostly lower Morrow sediments of fluvial and mixed-marine origin. Depositional histories of these sandstones are probably similar to those in the Canton area except that their areal distribution was largely predetermined by paleogeographic constraints of the "trench." A suitable model incorporates a fluvial meander belt with areal dimensions of the "trench" and discharge facies that extend to the south and southwest in a branching pattern. Depositional processes beyond the geographic area of the "trench" may have been deltaic. However, because of the spatial geometry within the incised valley, depositional processes within the "trench" probably were fluvial coastal plain in nature rather than deltaic. Additionally, even fluvial sediments may have been affected by marine processes in an estuarine environment since the paleogeographic setting of this depositional system seems to have been especially suited for tidal influence (i.e., a coastal inlet). These interpretations of the depositional environment are supported by core descriptions by Godard (1981), which show glauconite and marine skeletal material intermixed with channel deposits.

The discharge facies of the Woodward "trench" extend to the south and southwest and are correlative with the sediment package in the Canton area. These sediments consist of both upper and lower Morrow deposits but only the lower unit contains elements characteristic of fluvial-deltaic deposition. This lower Morrow unit is a progradational sequence similar to that at Canton and contains genetically related facies such as fluvial point bar deposits, distributary channels, interdistributary bay deposits (splays, marsh, and lagoonal material) and shallow marine distributary mouth bar sequences. In addition, core descriptions by Godard (1981) provide evidence of estuarine channels and tidal deposits formed in the bay head areas of the Woodward "trench."

Fluvial sandstones within the Woodward "trench" generally are multistoried and attain a maximum aggregated thickness of >75 ft (Godard, 1981). They are classified primarily as fine- to medium-grained quartz arenites that are moderately to poorly sorted and conglomeratic at the base. According to Godard (1981), typical sedimentary structures include ripple and medium-scale cross-bedding and soft-sediment deformation. Wireline well logs show that individual units commonly contain sharp basal contacts and have blocky to fining-upward profiles. The channel sandstones are largely free of glauconite, bioturbation, and skeletal material although some do have these marine characteristics. Porosity ranges from about 5% to 15% and is dependent mostly on grain size and calcite cementation.

The Woodward "trench" still existed during deposition of the upper Morrow although, by then, it was largely filled by the lower unit. As in the Canton area, the upper Morrow began with a major transgression over most of the Anadarko basin. Sediments associated with this event consist mostly of marine shale (also found farther to the northwest in Mocane-Laverne field). However, several fine-grained sandstones of marine origin are contained in the upper Morrow in the Woodward area. Godard (1981) indicates that there is >60 ft of upper Morrow sand within the channel area and that it thickens to >180 ft of sand in the discharge facies in the southwest portion of his study area.

Oklahoma Panhandle, Upper Morrow (FDD–Oil)

The Oklahoma Panhandle in Cimarron, Texas, and Beaver Counties contains the most extensive accumulation of Morrowan FDD sediments in the State (Pl. 1). In this area, sandstones of fluvial and nearshore marine origin are found within the upper Morrow at depths generally <6,000 ft. Since these deposits often have excellent reservoir properties, many of these sandstones produce oil, gas, or a combination of both (Pl. 4).

Stratigraphic nomenclature for the Morrow in the Oklahoma Panhandle consists of an upper and lower unit. The lower Morrow contains no known FDD deposits although basal sands of marine origin produce gas throughout the area. Upper Morrow sediments also are mostly marine in origin and consist primarily of marine shale. However, the presence of localized sand in the middle and upper part of the upper Morrow is largely the result of a southeastward-trending fluvial system. Farther to the south–southeast, toward the axis of the Anadarko basin, this fluvial system shows increasing marine influence. Stratigraphically equivalent deposits to the east in Beaver and Harper Counties are entirely marine in origin, whereas upper Morrow deposits in western Cimarron County consist of semicontinental mudstones.

In the Oklahoma Panhandle, upper Morrow fluvial sandstones lithologically are very different from lower Morrow fluvial sandstones in the Canton area. Typically, upper Morrow fluvial sandstones in the Panhandle are arkosic, whereas lower Morrow sandstones in western Oklahoma are predominantly quartz arenites. This lithologic distinction is evidence for a major difference in source areas: the source area for the upper Morrow in the Panhandle was to the west–northwest and the source area for the lower Morrow in FDD areas of western Oklahoma was to the north–northeast.

The sandstones in the upper Morrow of the Panhandle are classified as subarkose in composition, but they vary from true arkose to lithic arkose (Harrison, 1990). Individual deposits have granule- to pebble-size conglomerates at the base and grade upward into coarse- to medium-grained sand. Higher in the section, the sand becomes increasingly finer grained and grades into very fine grained, micaceous sandstone, siltstone, and shale. Coarse-grained detrital material consists mainly of quartz (40–68%), feldspar (mostly K and low Na [4–14%] varieties), and rock fragments (granite, chert, siltstone, shale, schists, chlorite [<11%]) (Harrison, 1990). A typical point-bar/channel-fill sandstone is poorly sorted, medium to coarse grained (fining upward), tan to gray in color, and has an abundance of carbonaceous plant debris. Porosity from samples and well logs is 10–25%. Kaolinite is the predominant diagenetic constituent affecting porosity but chlorite and feldspar alteration clays also affect it (Harrison, 1990). Common cements include quartz overgrowths and carbonates (dolomite, siderite, and calcite?).

South Balko Field Study

(Ts. 1, 2 N., R. 23 E. CM, western Beaver County, Oklahoma)

Production from the main part of S. Balko field was established December 4, 1959, with the discovery of gas in the Oklahoma Natural Gas Co. No. 1 Custer well in the C SW¼NE¼ sec. 31, T. 2 N., R. 23 E. CM. Earlier production from a well in the NW¼SE¼ sec. 9, T. 1 N., R. 23 E. CM predated this well by a few months, but production is not considered to be from the same oil pool that constitutes the main reservoir in S. Balko field.

The accredited discovery well was completed as a gas well in the western updip part of the field. This portion of S. Balko is now known to be the gas cap. Production from this well is from the upper Morrow "A" sand at a depth of ~7,400 ft. Initial calculated open flow was estimated at 15 MMCFGPD with a shut-in tubing pressure of 1,667 PSI (Dowds, 1963). As was the case with most subsequent wells, the reservoir was fractured and treated with acid. Total cumulative production from the No. 1 Custer well is estimated at 1.7 BCFG. Prior to production assignments by the stratigraphic nomenclature committee, S. Balko was named W. Elmwood and S.W. Elmwood. Table 3 gives a summary of geological/engineering data for the S. Balko field; characteristics of the field are discussed in more detail in the following sections.

Stratigraphy: There are three main sandstone intervals in the upper Morrow section of the S. Balko field (Fig. 29). In descending stratigraphic order, they are called informally the "A," upper "B," and lower "B" sands. At a few locations, there is another sandstone that appears to lie immediately beneath the lower "B" and it is called the "C" sand. The "C" sand does not occur in the type section, nor is it productive. Therefore, it is not included in this study.

The spatial relationship and stratigraphy of the upper Morrow sandstones in S. Balko field are shown in detailed cross sections of the area. Cross section A–A′ (Fig. 30, in envelope) is oblique to strike in an east–west direction and best shows the character of the "A" sand, which is the principal reservoir in the field. The "A" sand commonly has a blocky log signature and is 30–40 ft thick in the central wells of the cross section. The "A" sand pinches out against shale in both directions, and there are no laterally equivalent sandstone facies that would indicate deltaic or marine depositional environ-

TABLE 3. – Geological/Engineering Data for the Lower Morrow Sandstones in the South Balko Field, Western Beaver County, Oklahoma

	Morrow "A" sand	Morrow Upper "B" sand
Reservoir size	1,423 acres (below gas cap)	not determined
Well spacing (oil)	80 acres	80 acres
Oil/water contact	about –4,703 ft	several (not determined) (lower "B" about –4,707 ft)
Gas/oil contact	about –4,610 ft	about –4,590 ft
Porosity	10–20% (~15% avg)	10–20% (~15% avg)
Permeability	variable to 6,000 md*	variable to 6,000 md*
Water saturation	24–40%	24–40%
Thickness (net sand) ($\phi \geq 10\%$)	about 10–35 ft (19.3 ft avg)	about 10–40 ft (gross)
Reservoir temperature	140° F	140° F
Oil gravity	35–45° API	35–45° API
Initial reservoir pressure	~2,300 PSI	~2,300 PSI
Initial formation-volume factor	1.19 (est.)	1.19 (est.)
Original Oil in Place (volumetric)	17,312 MSTBO	not determined
Cumulative primary oil	~2,144 MSTBO (78 BO/acre-ft)	~2,667 MSTBO
Recovery efficiency (oil)	~12.4%	not determined
Cumulative gas	4,753 MMCF	69.4 MMCF

*Dowds (1963).

ments. The "A" sand occurs as just one sand bed of variable thickness, which makes identification of fluid contacts easy. In the Phillips No. 1 Cates-B well (Fig. 31) in the SW¼NW¼ sec. 5, T. 1 N., R. 23 E. CM, the oil/water contact of the "A" sand is easily determined from examination of the resistivity log trace (Fig. 30). The "B" sand in cross section A–A′, on the other hand, shows a very broken log character for both the upper and lower zones. This indicates that individual sandstone beds of the "B" horizon may have been deposited in different depositional environments and may have distinctly different reservoir characteristics. Usually, only the lower part of the upper "B" sand is productive, which indicates that this zone is a facies very different from the rest of the sand body. Characteristically, the lower "B" sand is wet in all areas except the extreme northern part of the field, as determined by production tests or drill-stem tests in several wells. The "C" sand in cross section A–A′ is well developed in the No. 1 Ollie Cates well in the SE¼NW¼ sec. 5, T. 1 N., R. 23 E. CM. Although the stratigraphic position of the "C" sand is easily identified in other well logs, it is generally absent throughout most of the field.

Cross section B–B′ (Fig. 32, in envelope) is oblique to dip in a north–south direction. It best shows the relationship of oil versus gas production in the northern part of S. Balko field. The four wells in the northern half of the cross section have Morrow oil and gas production in the "A" and upper "B" sands within or near the gas cap of the field. In Figure 32, producing intervals are marked on well logs and production figures (shown beneath the well logs) indicate the nature and quantity of the hydrocarbon produced.

Structure: The structural configuration of the S. Balko field is uncomplicated by any structural irregularities such as faults or folds (Fig. 33). The dip to the southeast, at about 100–150 ft/mi, is <2°.

Isopach Mapping: Because of the large number of individual sandstone beds in S. Balko field, only selected intervals were mapped, including the "A" sand from which both net and gross maps were constructed, and the upper and lower "B" sand intervals from which only gross isopach maps were made. Thicknesses of the upper and lower "B" sands were also combined to make one gross sandstone isopach map. Making net sandstone isopach maps of the various productive intervals in the upper "B" horizon would be a logical extension of this field study. However, porosity logs in S. Balko field often are not available, and net thickness determinations of thin beds would be more speculative. When porosity data were available, a net cutoff of 10% was used since this value appeared to be the minimum porosity necessary for good oil production.

Upper Morrow "A" Sand: The upper Morrow "A" sand is the most continuous and uniformly deposited sandstone in the S. Balko area. It is present in two general areas in the 16-section study area and usually oc-

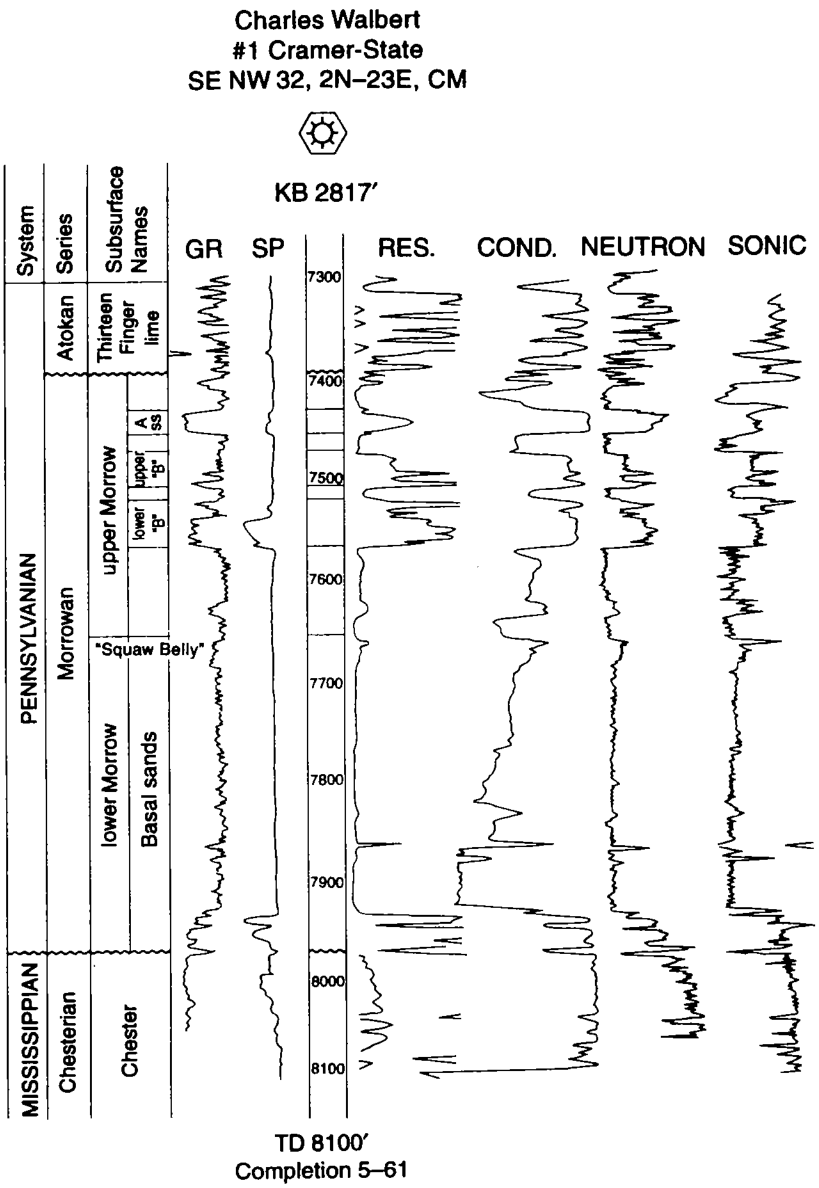


Figure 29. Morrow type log in S. Balko field, western Beaver County, Oklahoma, showing log patterns of gamma ray (GR), spontaneous potential (SP), resistivity (RES), conductivity (COND), neutron, and sonic measurements.

curs as a single bed with a gross thickness of 20–40 ft (Fig. 34). There appear to be few significant shale partings within the "A" sand, and detailed log profiles show that it has a very gradual fining-upward texture (Figs. 30,32). The characteristic log profile on large-scale logs, however, appears blocky with little indication of facies variations. The lower bed boundary consists of sand on shale, and the boundary is always sharp due to fluvial scouring (Fig. 30, eastern half of cross section A–A′). Upper bed boundaries may appear to have a rapid transition to shale but, actually, there usually is a gradual upward-fining texture. On cross section B–B′ (Fig. 30), one bed form in the SW¼ SW¼ sec. 32, T. 2 N., R. 23 E. CM takes on the classic bell-shaped electric log profile of a point bar. Apparently, stream morphology and the predominance of coarse-grained sand influenced the development of fluvial deposits, which probably consist of point bars predominantly and braided stream deposits to a lesser degree.

The distribution of net Morrow "A" sand (Fig. 35) is similar to that of the gross sandstone, and indicates that when the "A" sand is present, it usually has porosity development. Typically, the net "A" sand is about 10–35 ft thick and is best developed within a meandering thalweg that is oriented in a northwest–southeast direction. Within this trend, the "A" sand reservoir has a oil/water contact at about –4,703 ft and a gas/oil contact at about –4,610 ft. The thickest part of this sand body is about a mile wide although sandstone is distributed across a meander belt that is probably close to 2 mi wide. The "A" sand lies about 50 ft beneath the Atoka–Morrow contact and is separated from the underlying upper "B" sand horizon by about 10–20 ft of shale.

Upper Morrow "B" Sands: This horizon is composed of several individual sandstone beds that occupy a stratigraphic interval of about 80–120 ft. Predominant sandstones appear to be fluvial channel-fill in nature, are lenticular in areal extent, and have scoured basal contacts (Fig. 30). A single letter ("B") identifies this stratigraphic assemblage. Nevertheless, there are two main subdivisions within this sandstone sequence, the upper "B" and the lower "B" sands. The combined gross sandstone isopach of the entire Morrow "B" interval is shown in Figure 36. The upper "B" and the lower "B" zones were also mapped separately.

The gross isopach map of the upper "B" sand (Fig. 37) shows a deposition pattern that is oriented in a north–south direction. The combined thickness of one or more individual sandstone beds, as determined from GR and resistivity logs, were used to construct this map. The upper "B" sand map shows that the main sandstone body is contained within a straight to slightly curving channel belt that is ~1 mi wide and often 20–40+ ft thick. However, only the lowermost sandstone bed in the upper "B" interval is productive; this zone seems to be the direct result of fluvial channel deposition. Stratigraphically higher sand zones within the upper "B" interval are interpreted to be of a different depositional facies because their log profiles indicate different textural patterns, higher concentrations of clay, less sand, and lower porosity than log profiles for a classic fining-upward fluvial sequence (Fig. 30).

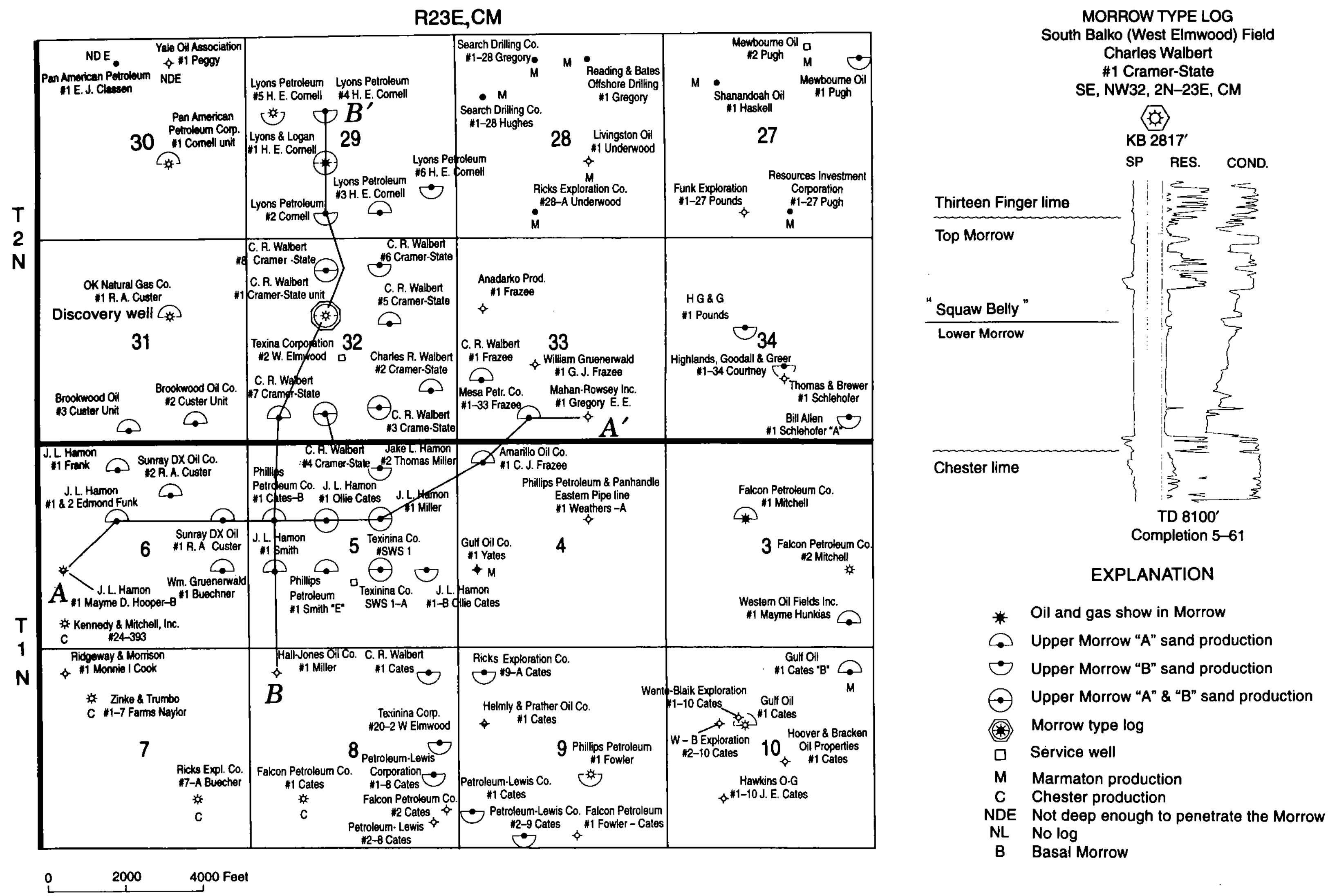


Figure 31. Information map showing operator, lease, and well number for wells in S. Balko (West Elmwood) field, western Beaver County, Oklahoma.

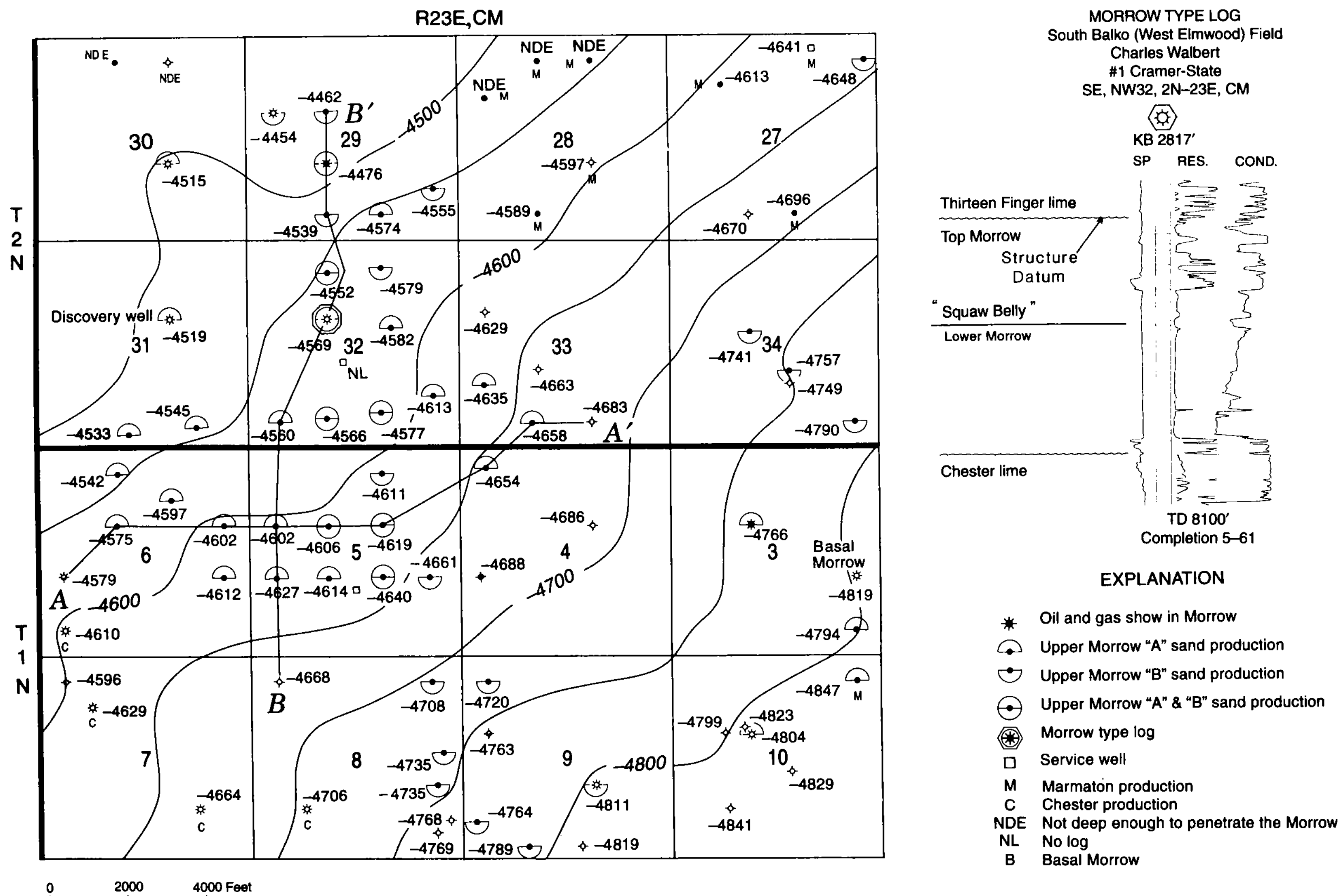


Figure 33. Structure map of the top of the Morrow Formation in the S. Balko field, Ts. 1, 2 N., R. 23 E. CM, western Beaver County, Oklahoma. Contour interval = 50 ft. See Figure 31 for names of wells.

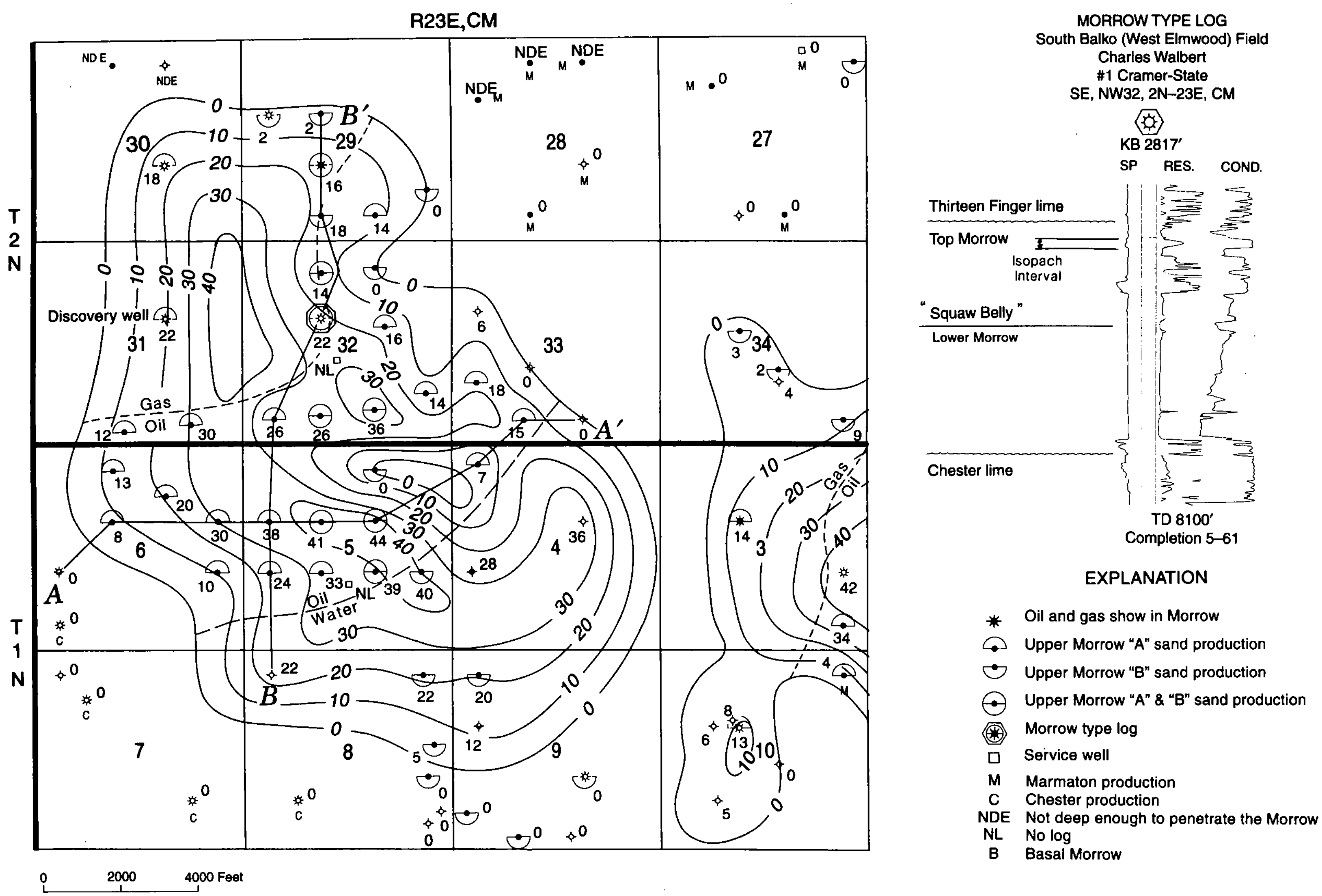


Figure 34. Isopach map of the gross upper Morrow "A" sand in the S. Balko field, Ts. 1, 2 N., R. 23 E. CM, western Beaver County, Oklahoma. Contour interval = 10 ft. See Figure 31 for names of wells.

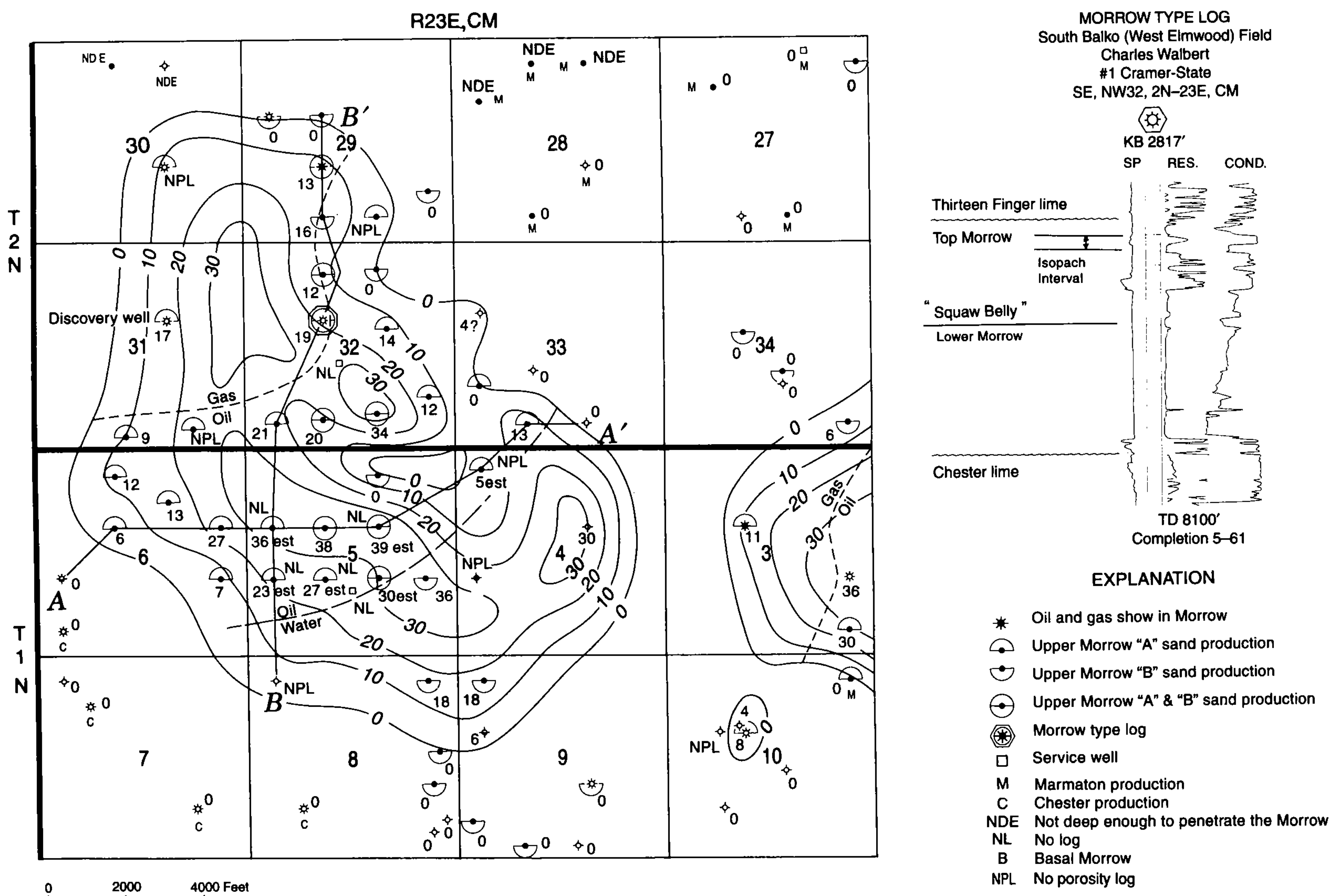


Figure 35. Isopach map of the net upper Morrow "A" sand (porosity: ≥10%) in the S. Balko field, Ts. 1, 2 N., R. 23 E. CM, western Beaver County, Oklahoma. Contour interval = 10 ft. See Figure 31 for names of wells.

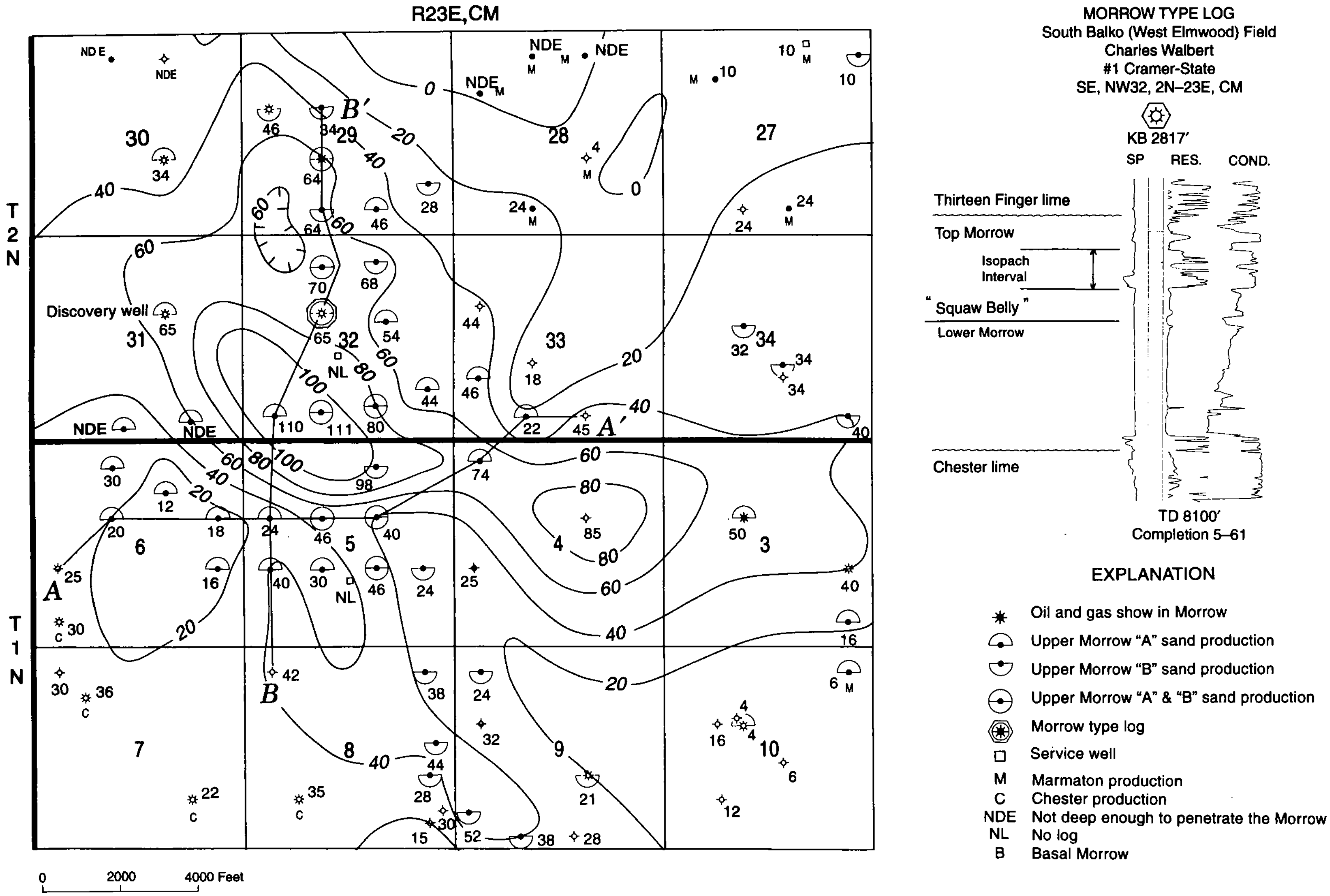


Figure 36. Isopach map of the gross upper Morrow upper and lower "B" sands combined in the S. Balko field, Ts. 1, 2 N., R. 23 E. CM, western Beaver County, Oklahoma. Contour interval = 20 ft. See Figure 31 for names of wells.

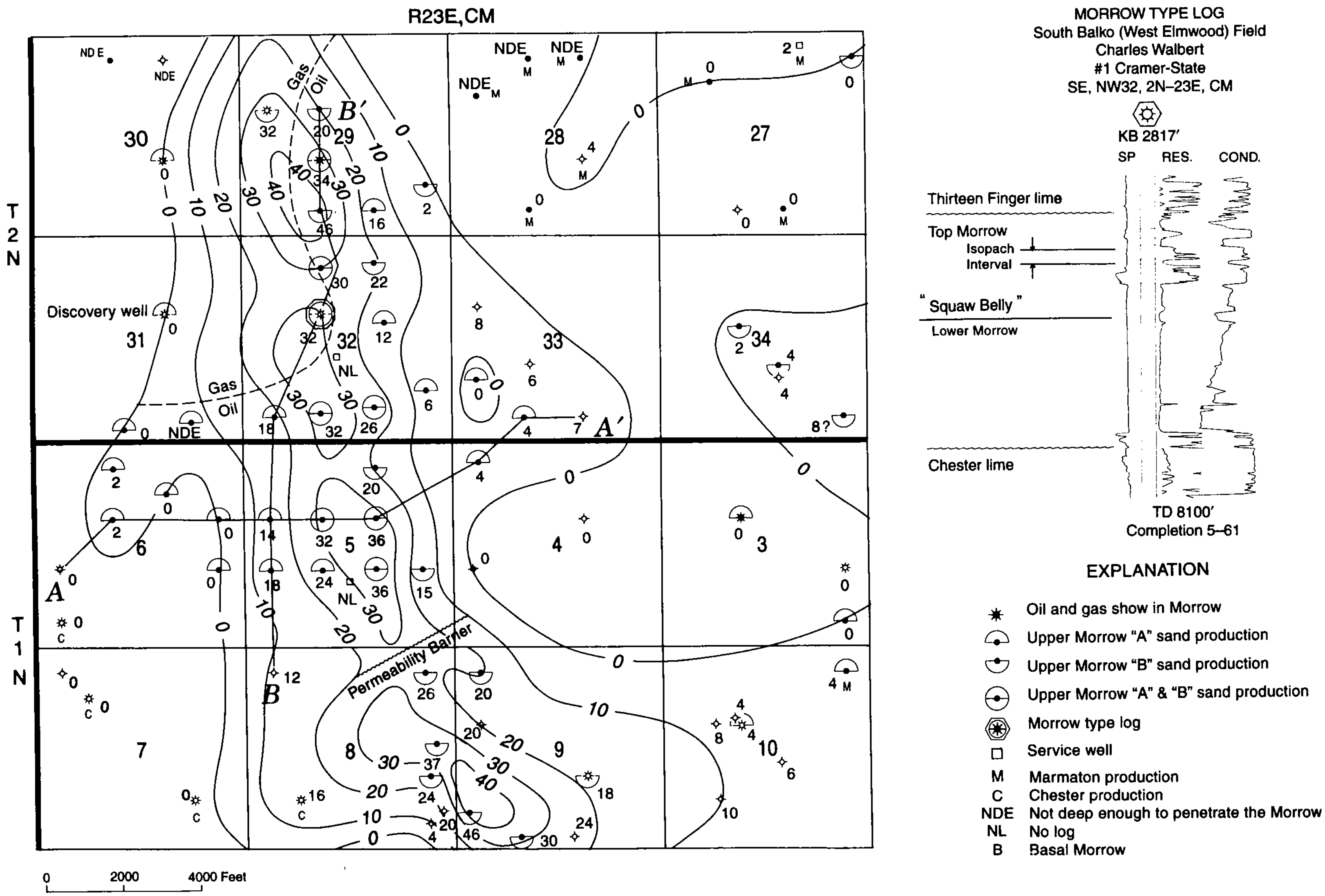


Figure 37. Isopach map of the gross upper Morrow upper "B" sand in the S. Balko field, Ts. 1, 2 N., R. 23 E. CM, western Beaver County, Oklahoma. Contour interval = 10 ft. See Figure 31 for names of wells.

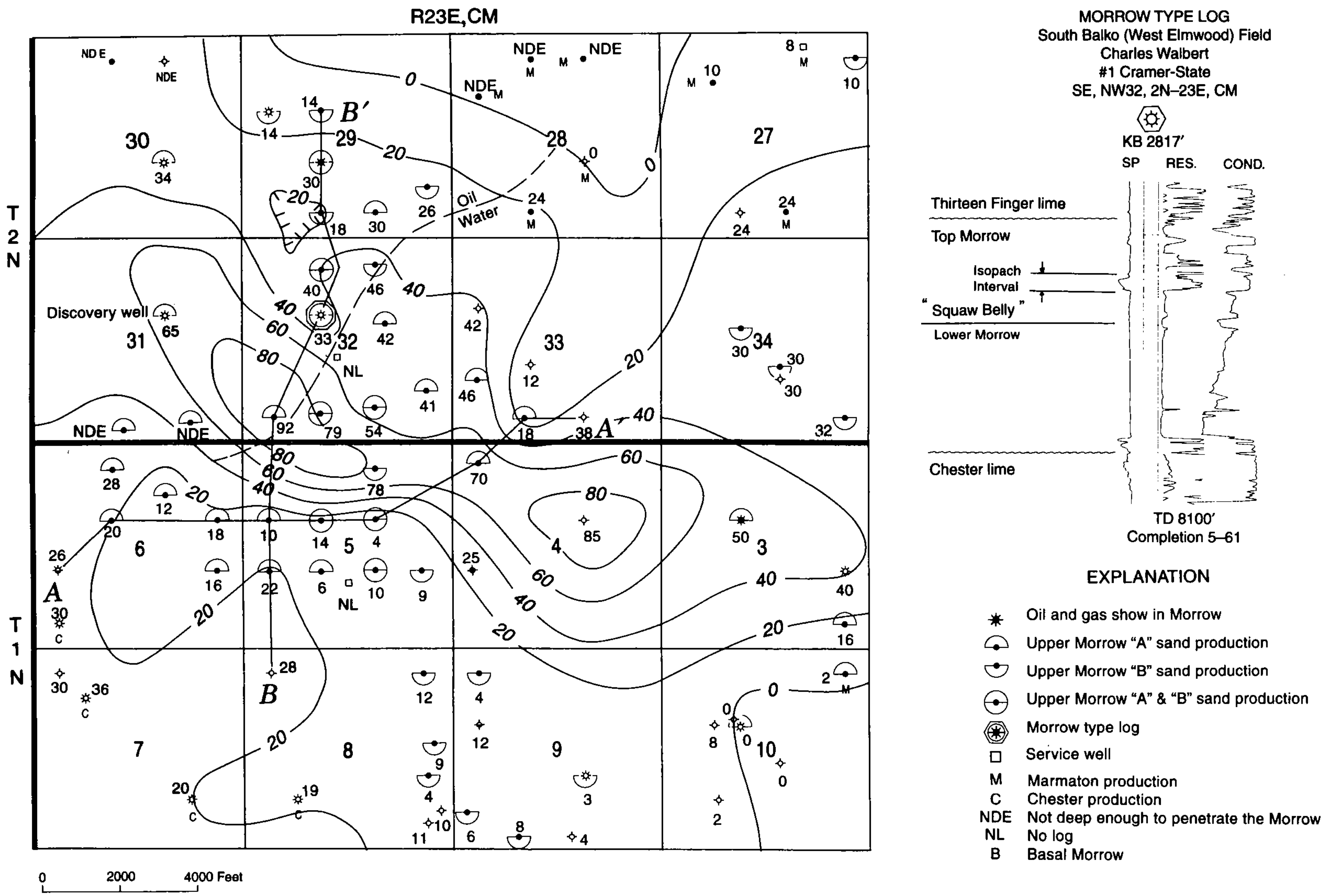


Figure 38. Isopach map of the gross upper Morrow lower "B" sand in the S. Balko field, Ts. 1, 2 N., R. 23 E. CM, western Beaver County, Oklahoma. Contour interval = 20 ft. See Figure 31 for names of wells.

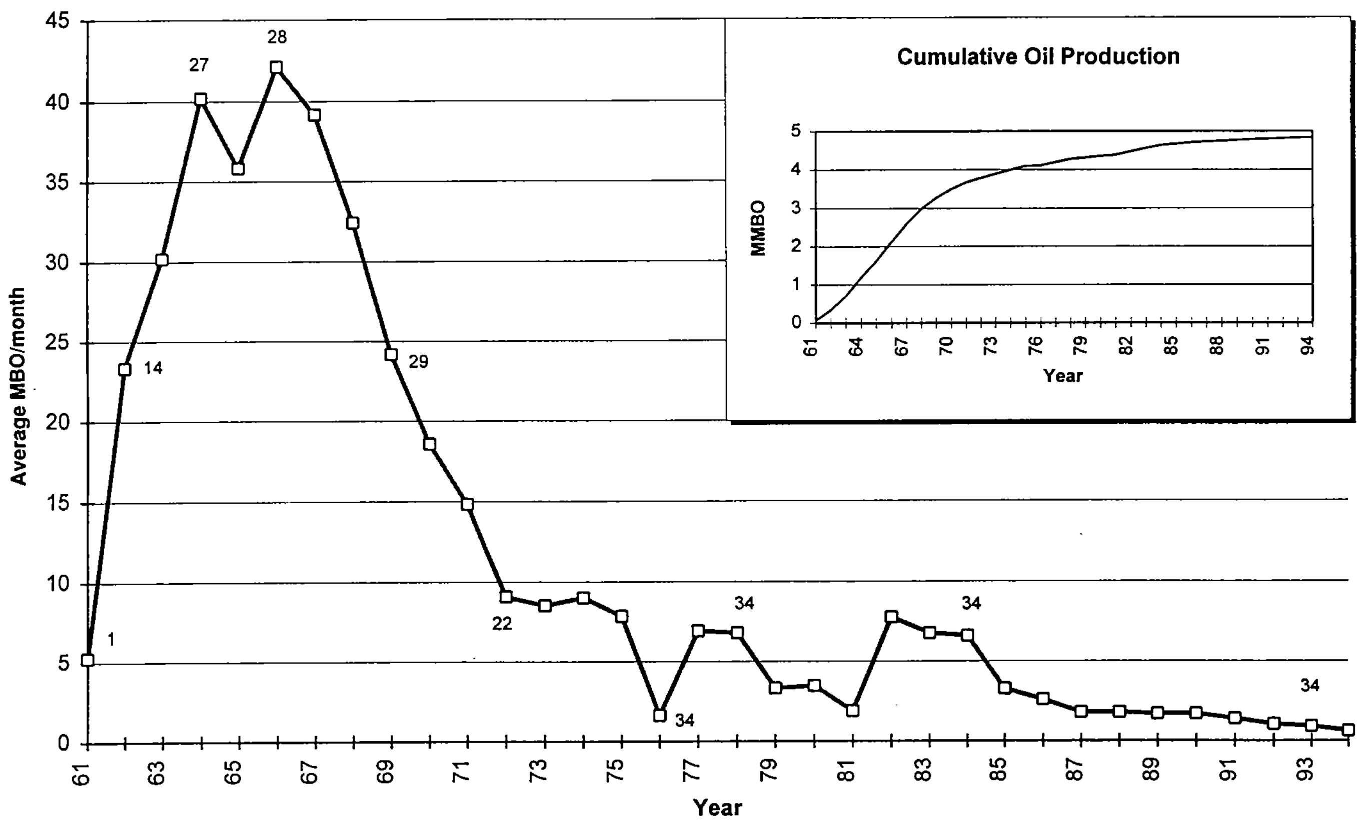


Figure 39. Oil-production decline curve for upper Morrow sandstones in S. Balko field, western Beaver County, Oklahoma. Numbers on the curve designate the number of wells that had Morrow oil production at various years. Inset plot shows cumulative oil production from the "A" and "B" sands combined.

Within the upper "B" sand interval, there appears to be a single gas/oil contact at about –4,590 ft in the northwest part of S. Balko field (Fig. 37). This gas/oil contact was determined from a combination of production histories of several wells, production and drill-stem tests, and well log analyses. However, oil/water contacts in the upper "B" interval are not as apparent since production is attributable to small bodies of net sandstone that are equivalent stratigraphically but are discontinuous from one another. Figure 37 shows this depositional pattern in the southern part of the field and indicates a permeability barrier between two main sand bodies.

The lower "B" sand contains the most extensive distribution of sandstone in the S. Balko field. The gross sandstone isopach map shows that this interval is present in nearly every Morrow penetration and is commonly >40 ft thick (Fig. 38). However, this thickness includes many intervals that are shaly and that do not show significant GR or SP log responses. Thus, much of the lower "B" appears to contain several individual sands interbedded with shale, and the net thickness of the lower "B" (not mapped) would undoubtedly be much less than its gross thickness. In a number of places, the lower "B" is uniformly 20–30 ft thick and has textural and log profiles that are characteristic of fluvial point bar deposits. The profiles for the northern wells of cross section B–B′ (Fig. 32) are good examples. The overall trend of the lower "B" sand is northwest–southeast.

The lower "B" sand is productive from only a few wells in the extreme northern part of S. Balko field. Many additional wells in this area had good oil shows and actually tested or produced small amounts of Morrow oil. However, commercial production of oil is influenced largely by the location of the oil/water contact and the distribution of thick sand. As shown in the gross isopach map, most of the thickest sandstone of the lower "B" interval occurs below the oil/water contact, which is at about –4,707 ft (Fig. 38). This oil/water contact was determined from drill-stem tests, production data, and well log analyses. Although several wells lie updip from the generalized oil/water contact, the actual oil column in most of these wells is too thin for commercial interests. Also, in many wells drilled in the oil-saturated portion of the lower "B" sand, the sandstones were too tight for sustained oil production. For these reasons, the lower "B" sand is not considered a significant reservoir and discussion about it will be limited.

Core Analysis: Not available in this field.

Reservoir Characteristics: Reservoir characteristics of the upper Morrow sandstones in the S. Balko field

TABLE 4. – Oil Production Statistics for the Upper Morrow Sandstones in South Balko Field, Western Beaver County, Oklahoma

Year	Number of Oil Wells* (estimated)	Annual Oil Production (Barrels)	Average Monthly Oil Production (Barrels)	Average Daily Oil Production Per Well (BOPD)	Cumulative Oil Production (Barrels)
61	1	62,995	5,250	172.6	62,995
62	14	279,886	23,324	54.8	342,881
63	20	362,148	30,179	49.6	705,029
64	27	482,139	40,178	48.9	1,187,168
65	28	430,009	35,834	42.1	1,617,177
66	28	505,439	42,120	49.5	2,122,616
67	29	469,826	39,152	44.4	2,592,442
68	30	389,193	32,433	35.5	2,981,635
69	29	289,898	24,158	27.4	3,271,533
70	28	223,030	18,586	21.8	3,494,563
71	30	178,013	14,834	16.3	3,672,576
Unitized 1-72 by Texinia Corporation as Upper Morrow Sand Unit					
72	22	108,871	9,073	13.6	3,781,447
73	22	102,320	8,527	12.7	3,883,767
74	22	108,085	9,007	13.5	3,991,852
75	22	94,319	7,860	11.7	4,086,171
76	34	19,508	1,626	1.6	4,105,679
77	34	82,947	6,912	6.7	4,188,626
78	34	81,489	6,791	6.6	4,270,115
79	34	39,969	3,331	3.2	4,310,084
80	34	41,719	3,477	3.4	4,351,803
81	34	22,725	1,894	1.8	4,374,528
82	34	92,920	7,743	7.5	4,467,448
83	34	81,068	6,756	6.5	4,548,516
84	34	79,181	6,598	6.4	4,627,697
85	34	39,364	3,280	3.2	4,667,061
86	34	31,125	2,594	2.5	4,698,186
87	34	21,513	1,793	1.7	4,719,699
88	34	21,531	1,794	1.7	4,741,230
89	34	20,353	1,696	1.6	4,761,583
90	34	20,211	1,684	1.6	4,781,794
91	34	16,656	1,388	1.3	4,798,450
92	34	12,419	1,035	1.0	4,810,869
93	34	10,919	910	0.9	4,821,788
94	34	7,484	624	0.6	4,829,272

* Based on number of producing leases. Individual leases may contain more than one producing unit.

are similar to those of other fluvial deposits in the Oklahoma Panhandle. Effective porosity, as measured primarily from sonic logs, is 10–20% with an estimated average of 15%. This porosity is slightly lower than values recorded in Rice NE field in western Texas County, but generally better than for the deeper lower Morrow production zones in the Canton area. According to Dowds (1963), permeability is highly variable and ranges from ~0 md to 6,000 md. This variability is caused by diagenetic leaching of unstable constituents and the formation of secondary porosity. Calculated water saturations commonly are in the range of 24–40%, which is lower than values in Rice NE field.

Formation Evaluation: Wireline logs can be used very effectively in reservoir evaluation of the Morrow sandstones in the Balko area. Most of the wells were drilled in the 1960s but have some form of resistivity measurement. Porosity measurements frequently were done using sonic or neutron tools. Density porosity measurements were completed for only a few wells, and modern litho-density measurements generally are unavailable in the mapped area.

Calculated water saturation $Sw = \sqrt{F \times Rw/Rt}$ in productive zones varies from about 24% to 40%, assuming a Rw (resistivity of formation water) of 0.04 at formation temperature and using the Archie equation for formation factor ($F = 1/\phi^2$). Rt (true resistivity) is determined from the deep resistivity log curve. Porosity (ϕ) generally was determined from sonic logs by using a standard conversion of travel time to porosity. It was found that productive zones within the upper Morrow had relatively clean GR curves and a true or "deep" resistivity of at least 20 ohm-meters. Resistivity of many oil-producing sandstones is >50 ohm-meters.

Reservoir Sensitivity and Formation of Porosity: Porosity associated with upper Morrow sandstones in the S. Balko area is mainly secondary and is related to dissolution of unstable constituents and enhancement of preexisting pores. Original carbonate cement, feldspars, and rock fragments were chemically altered or dissolved after deposition. The voids created or redeveloped during chemical alteration of these constituents provided the space necessary for hydrocarbon migration and containment. Diagenesis was also a probable source for the kaolinite and chlorite that are abundant in most of the sandstones.

The abundance of kaolinite and chlorite characterizes most of the upper Morrow sandstones in the Oklahoma Panhandle and makes them sensitive to formation damage. Kaolinite is easily dispersed during any fluid surge brought on by drilling, oil production, or water injection. The dislodged clay particles migrate short distances and are trapped in pore throats, adversely affecting most of the reservoir. Chlorite also can cause serious formation damage if the reservoir is treated with acid during well completion. The chemical reaction between the acid and chlorite produces an insoluble precipitate of iron hydroxide that reduces reservoir permeabilities.

Oil and Gas Production and Well Completion: Cumulative oil production through 1994 from the upper Morrow sands in S. Balko field is estimated at 4.8 million barrels (Table 4). Table 4 also identifies the average monthly production and annual production for the field. The number of producing wells and the average daily oil production per well also are given in this table. S. Balko field was unitized in 1972, but it is not known whether it was successfully water flooded. A sharp decrease in the slope of the oil production decline curve (Fig. 39) occurred during this time, and the number of producing wells dropped from 30 to 22. During the next four years, production stabilized at about 8–9

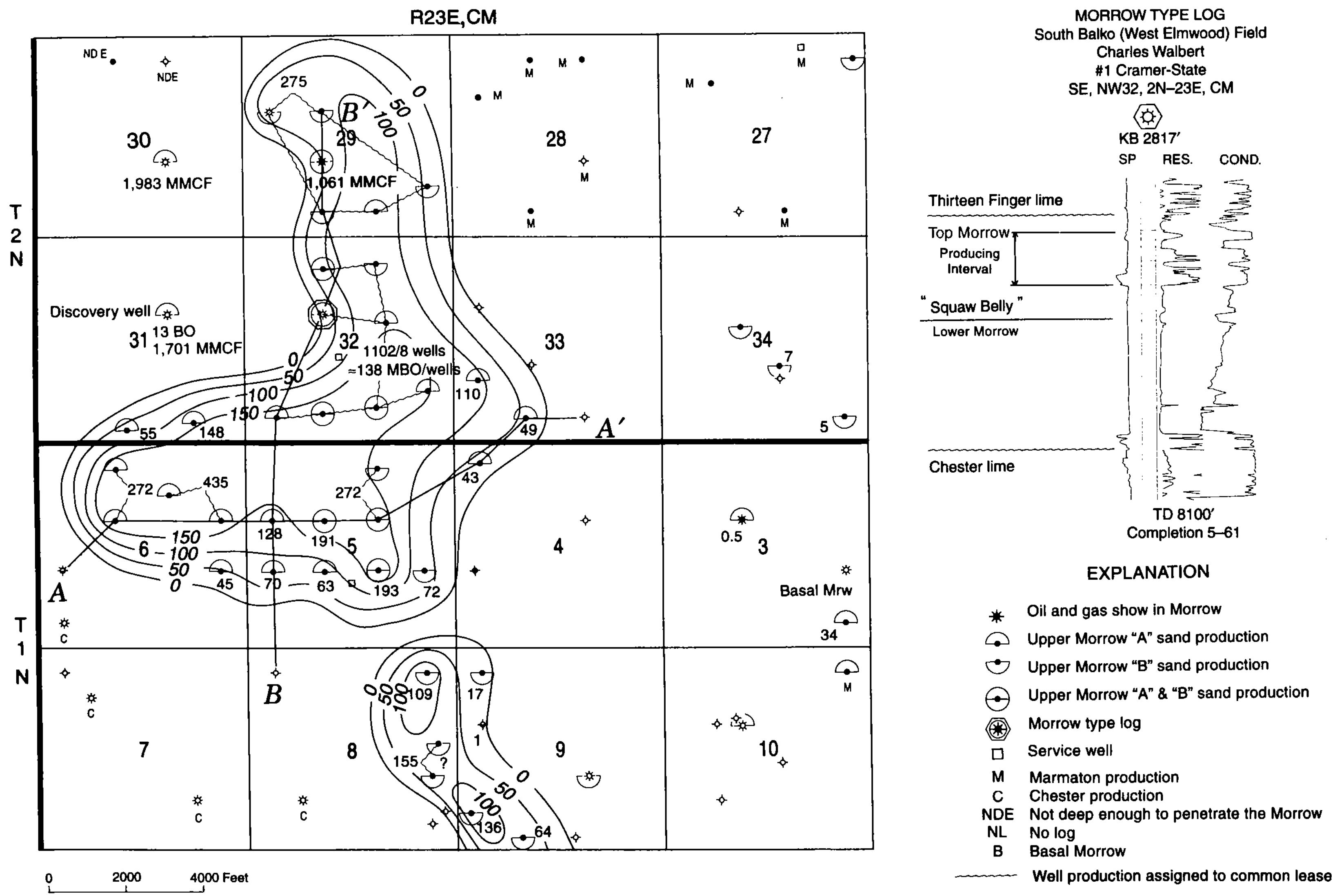


Figure 40. Map of cumulative oil production in the upper Morrow, S. Balko field, Ts. 1, 2 N., R. 23 E., western Beaver County, Oklahoma. Contour interval = 50 MBO. See Figure 31 for names of wells.

MBO/month. Thereafter, oil production varied by year, probably in response to field development and production reporting practices. Since mid-1985, average production for individual wells has been <3 BOPD. The inset plot on Figure 39 shows the cumulative annual oil production of the Morrow. The large increase in production from 1961 to 1970 coincides with field development which took place during the early and middle 1960s.

Most of the oil wells in S. Balko field had a gas/oil ratio of <1,000:1. They were routinely acidized and completed with fracture treatment using sand as a proppant. Initial production was about 100–200 BOPD although several wells had initial potential measurements of several hundred BOPD. Most wells had flowing pressures (surface) of 100–400 PSI but occasionally, flowing pressures >1,000 PSI were recorded. The bottom-hole (or initial reservoir) pressure was ~2,300 PSI but measurements varied depending on their structural position within the field. Cumulative production for individual wells varies from ~50 MBO to 200 MBO. The production trend of individual wells identifies the principal "sweet" spots within S. Balko field and is mapped in Figure 40.

Rice NE Field Study

(T. 3 N., R. 10 E. CM, western Texas County, Oklahoma)

Rice NE field is located along the east flank of Keyes dome which is part of the north–south-trending Cimarron uplift that crosses the Oklahoma Panhandle (Pl. 1, Fig. 12). It was discovered by Apache Corp. on April 18, 1963, with the completion of the Gaither No. 1 well in the NW¼ NW¼ sec. 23, T. 3 N., R. 10 E. CM. That well was perforated from 5,192–5,204 ft and 5,208–5,220 ft and had an initial potential flowing of 140 BOPD. Reservoir data of the Gaither No. 1 well includes: a gross sand thickness of the upper Purdy "B" sand of 22 ft, final flowing pressure of 774 PSI, final shut-in pressure of 1,265 PSI, and gas/oil ratio of 400:1. The oil gravity was 36° API. Cumulative production from this well is estimated at 82 MBO, which is generally better than average for this field. Table 5 gives a summary of geological/engineering data for the upper Purdy "B" sand and the lower Purdy "C" sand, the main hydrocarbon-producing sandstones in the Rice NE field. Characteristics of the field are discussed in more detail in the following sections.

Stratigraphy: Stratigraphy in the Rice NE field area is illustrated on the type electric log (Fig. 41). This log shows that the Morrow is subdivided into two intervals that are called informally the upper and lower Morrow. The lower Morrow is entirely marine in origin and consists mostly of shale. Basal portions of the lower Morrow often have calcareous sands of the Keyes interval. These sandstones lie unconformably on the Mississippian Chester limestone and locally produce gas from relatively tight, fine-grained reservoirs. The upper part of the lower Morrow is defined by a limy interval that is called the "Squaw Belly."

The upper Morrow contains multiple sands of both marine and nonmarine origin. However, there are only two main sandstones which produce hydrocarbons and they are identified informally as the upper Purdy "B" and the lower Purdy "C" sands. Both of these reservoir sandstones are oil prone and are interpreted to

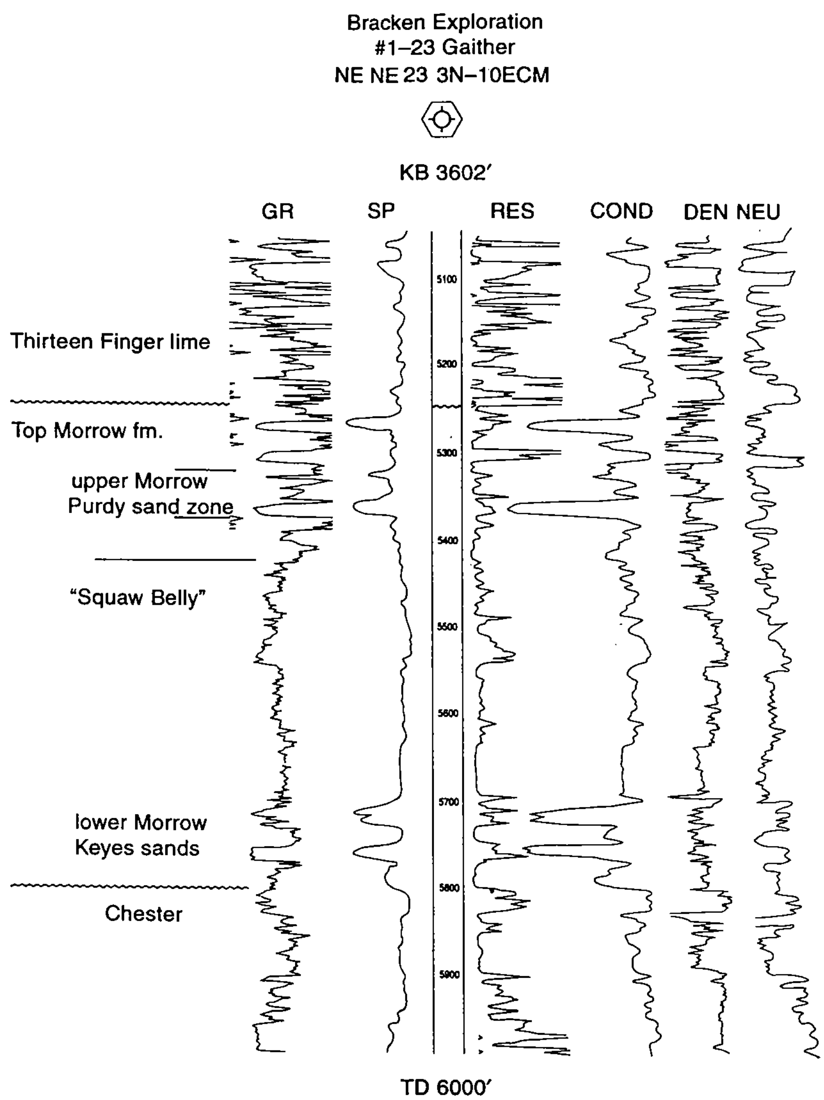


Figure 41. Morrow type log in Rice NE field showing log patterns of gamma ray (GR), spontaneous potential (SP), resistivity (RES), conductivity (COND), density (DEN, solid line), and neutron (NEU, dashed line) measurements.

TABLE 5. – Geological/Engineering Data for the Lower Morrow Sandstones in the Rice NE Field, Texas County, Oklahoma

	upper Purdy "B" sand	lower Purdy "C" sand
Reservoir size	450 acres	940 acres
Well spacing (oil)	40 acres	40 acres
Oil/water contact	about –1,650 and –1,655 ft	about –1,708 ft
Gas/oil contact	about –1,587 ft	about –1,540 ft
Porosity	5–24 % (~14% avg)	5–24 % (~17% avg)
Permeability	1–184+ md (12 md avg)*	1–184+ md (20 md avg)*
Water saturation	25–50% (35% avg)	22–50% (35% avg)
Thickness (net sand in field) ($\phi \geq 10\%$)	5–20 ft (9 ft avg)	5–38 ft (14 ft avg)
Reservoir temperature	130° F	130° F
Oil gravity	30–39° API	34–42° API (37° avg)
Initial reservoir pressure	1,320 PSI (from DST)	1,335 PSI*
Initial formation-volume factor	1.156 reservoir barrels/stock tank barrels*	
Original Oil in Place (volumetric)	2,473 MSTBO	9,759 MSTBO
Cumulative primary oil	333 MSTBO (82 BO/acre-ft)	656 MSTBO* (50 BO/acre-ft)
Recovery efficiency (oil)	13.5%	6.7%
Cumulative gas	117 MMCFG?	3,243 MMCFG

*Data supplied by Ensign Operating Co.

have fluvial origins in a transgressive valley-fill depositional setting. They are separated from one another stratigraphically by about 10 to 40 ft of shale, but thick sandstone seldom occurs both in the upper Purdy and the lower Purdy in the same geographic area.

Cross section A–A′ (Fig. 42, in envelope) is an east–west strike line in the northern part of Rice NE. It principally shows the character of the upper Purdy "B" sand which is best developed in the No. 1-15 Cline well in the SE¼SE¼NW¼ of sec. 15, T. 3 N., R. 10 E. CM (Fig. 43). Although this sand is wet (notice the 1 ohm-meter resistance on deep curve [Fig. 42]), it shows the typical blocky channel-fill log profile that characterizes these sandstones. The lower Purdy "C" interval is mostly shale in this line of section, but the "C" sand is present in the easternmost well.

Cross section B–B′ (Fig. 44, in envelope) is also an east–west strike line through the southern part of Rice NE field. In this portion of the field, the lower Purdy sand is best developed and its characteristic pattern of thinning and thickening is well illustrated. The lower Purdy sand also has a blocky log profile, and the deep resistivity is 5–30 ohm-meters in productive wells. On this line of section, the lower Purdy is shown to pinch out against shale between the two easternmost wells.

Cross section C–C′ (Fig. 45, in envelope) is a north–south dip-oriented line that ties the upper Purdy producing area in the northern part of the field with the lower Purdy producing area in the southern part of the field. The spatial relationship of these two sands is such that they are rarely well developed in the same geographic location. Also shown in this line of section are the numerous hot shale beds in the upper Morrow section that make the identification of thin sandstones difficult.

Structure: Field mapping in the Rice NE field area indicates that the Morrow structure is moderately more complex than other areas within the stable Anadarko shelf. Rice NE is bounded by major fault blocks that trend in a northeast–southwest direction (Fig. 46). Displacement varies from about 500–800 ft along the updip fault (west), to ~250 ft along the downdip fault (east). As is typical for the area, displacement is down to the east. The updip fault is interpreted to be the principal trapping mechanism for the upper Purdy "B" sand, but it is not directly responsible for entrapment of the lower Purdy "C" sand which is predominantly stratigraphic. Between the two major fault blocks, the structure is somewhat anticlinal, and dips extend both to the east and to the north in direct response to structural readjustments that occurred along the east flank of the Cimarron uplift. The reversal of dip from east to north has been used as evidence of additional faulting by some geologists. However, the maximum dip to the north is only ~200 ft/mi, or 2°, a very small inclination that probably is not due to displacement. There is an understandable tendency to interpret relatively "tight" structure contours as faults if the contour interval (only 50 ft on Fig. 46) is ignored.

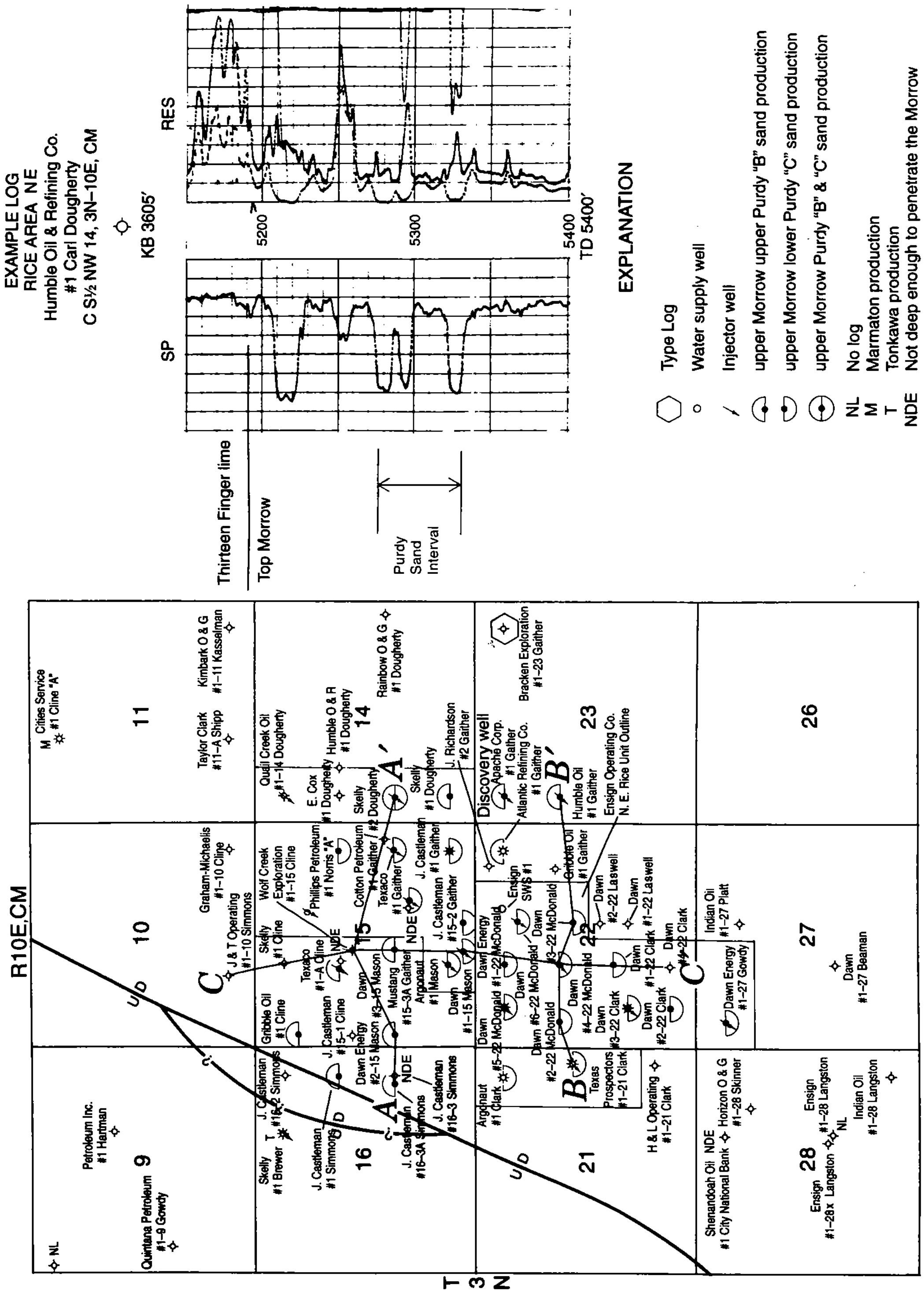


Figure 43. Information map showing operator, lease, and well number for wells in Rice NE field, western Texas County, Oklahoma.

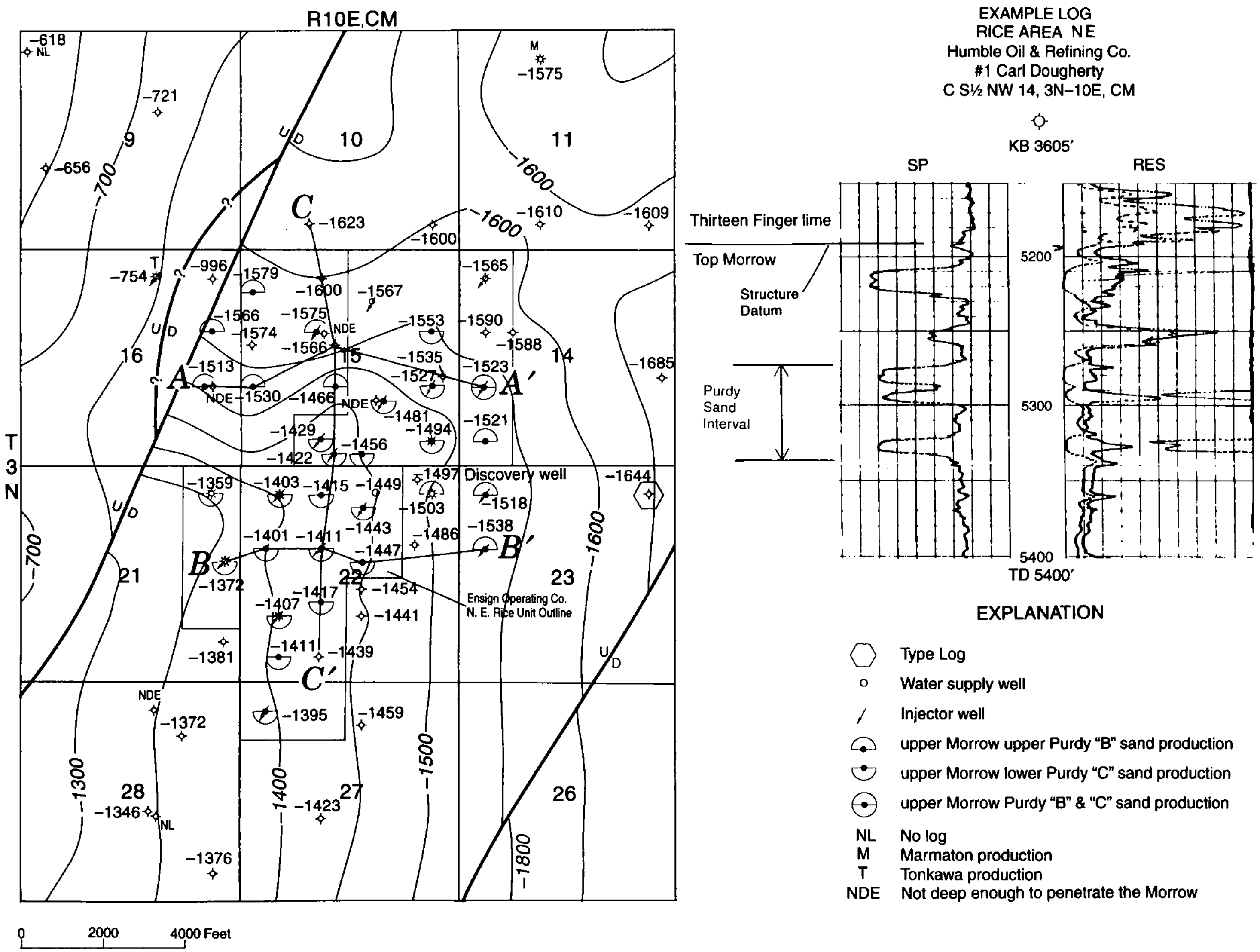


Figure 46. Structure map of the top of the Morrow Formation in the Rice NE field, western Texas County, Oklahoma. Contour interval = 50 ft. (Modified from Ensign Operating Co., 1995.) See Figure 43 for names of wells.

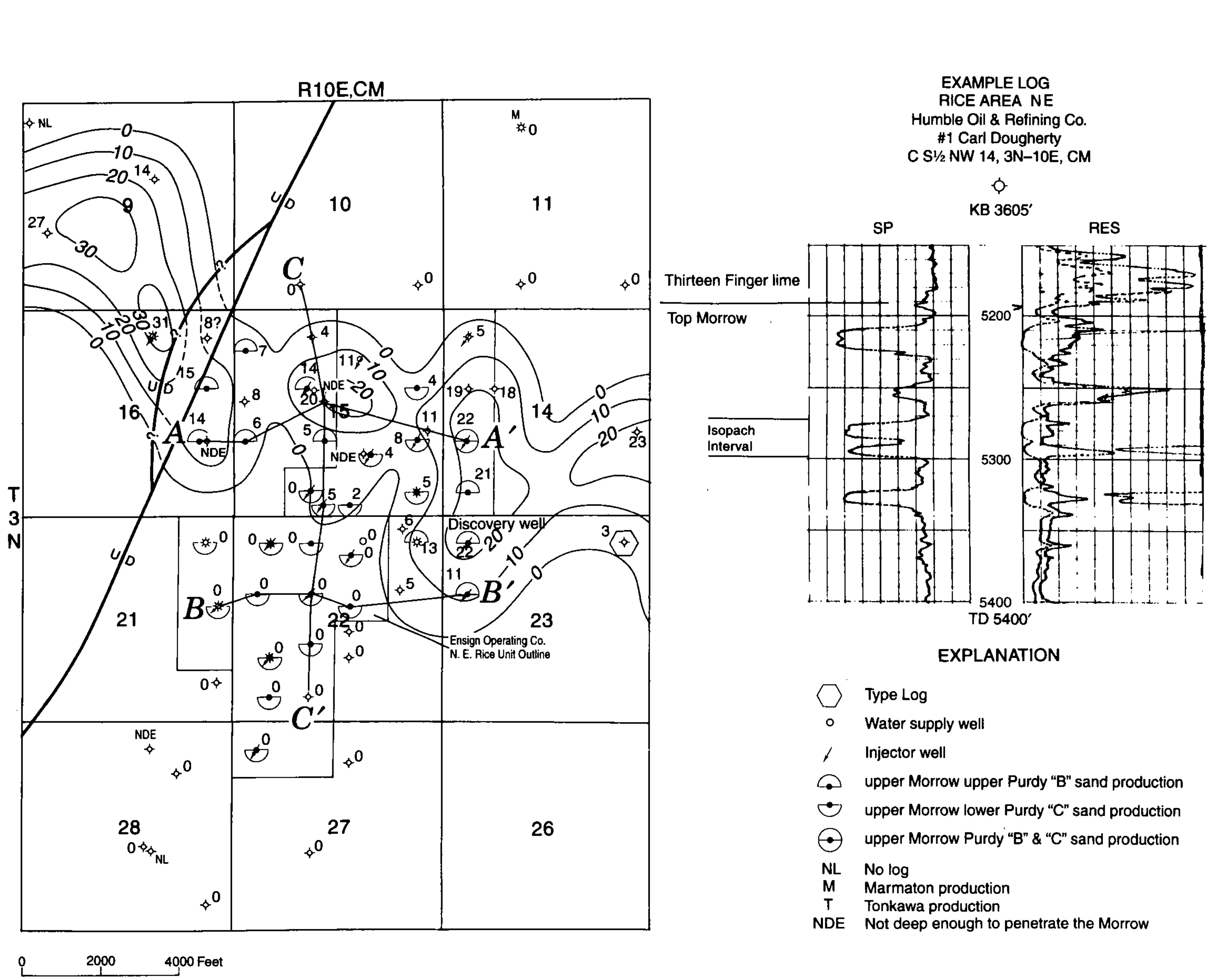


Figure 47. Isopach map of the gross upper Purdy "B" sand in the Rice NE field, western Texas County, Oklahoma. Contour interval = 10 ft. See Figure 43 for names of wells.

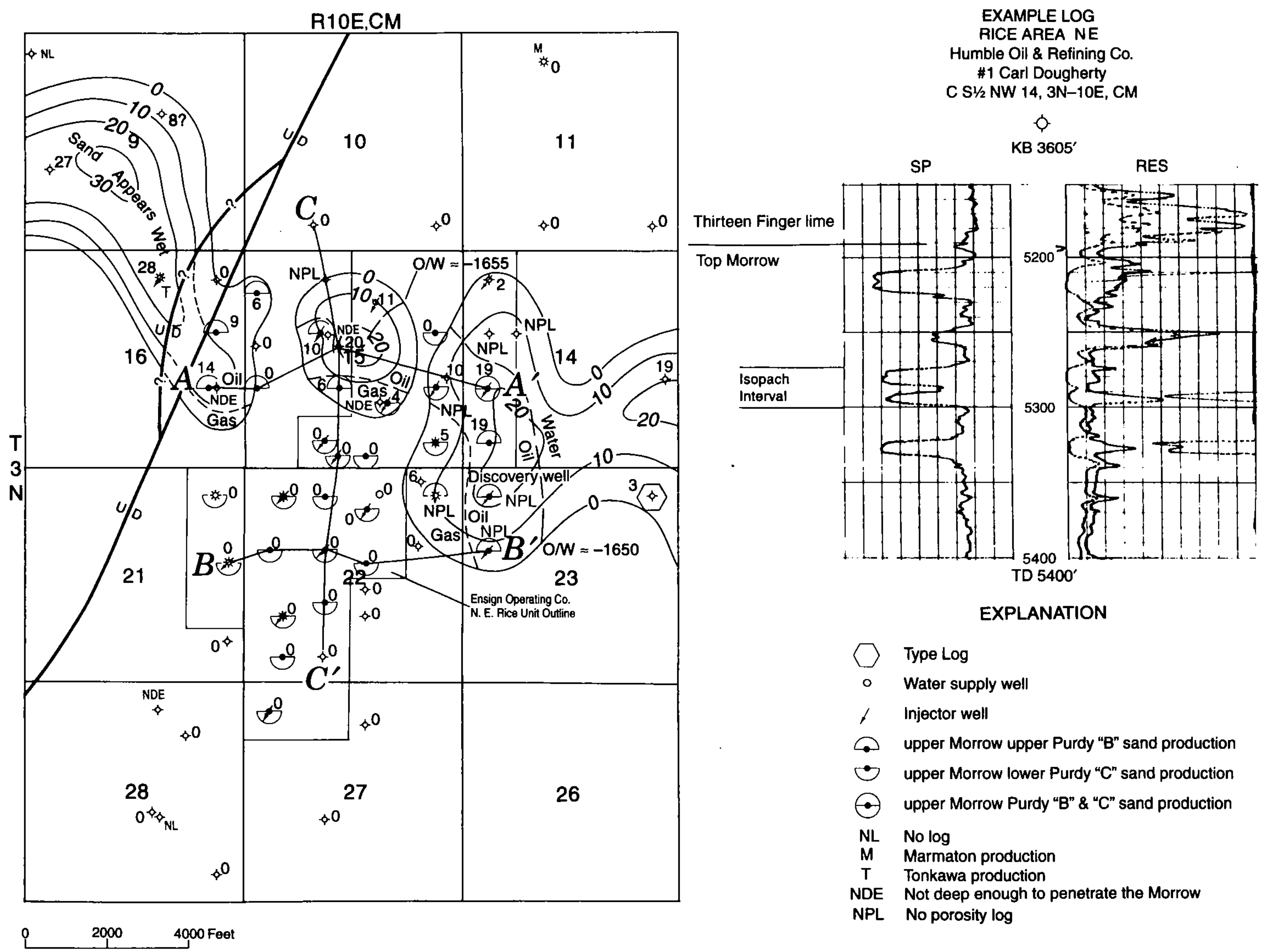


Figure 48. Isopach map of the net upper Purdy "B" sand (porosity: ≥10%) in the Rice NE field, western Texas County, Oklahoma. Contour interval = 10 ft. See Figure 43 for names of wells.

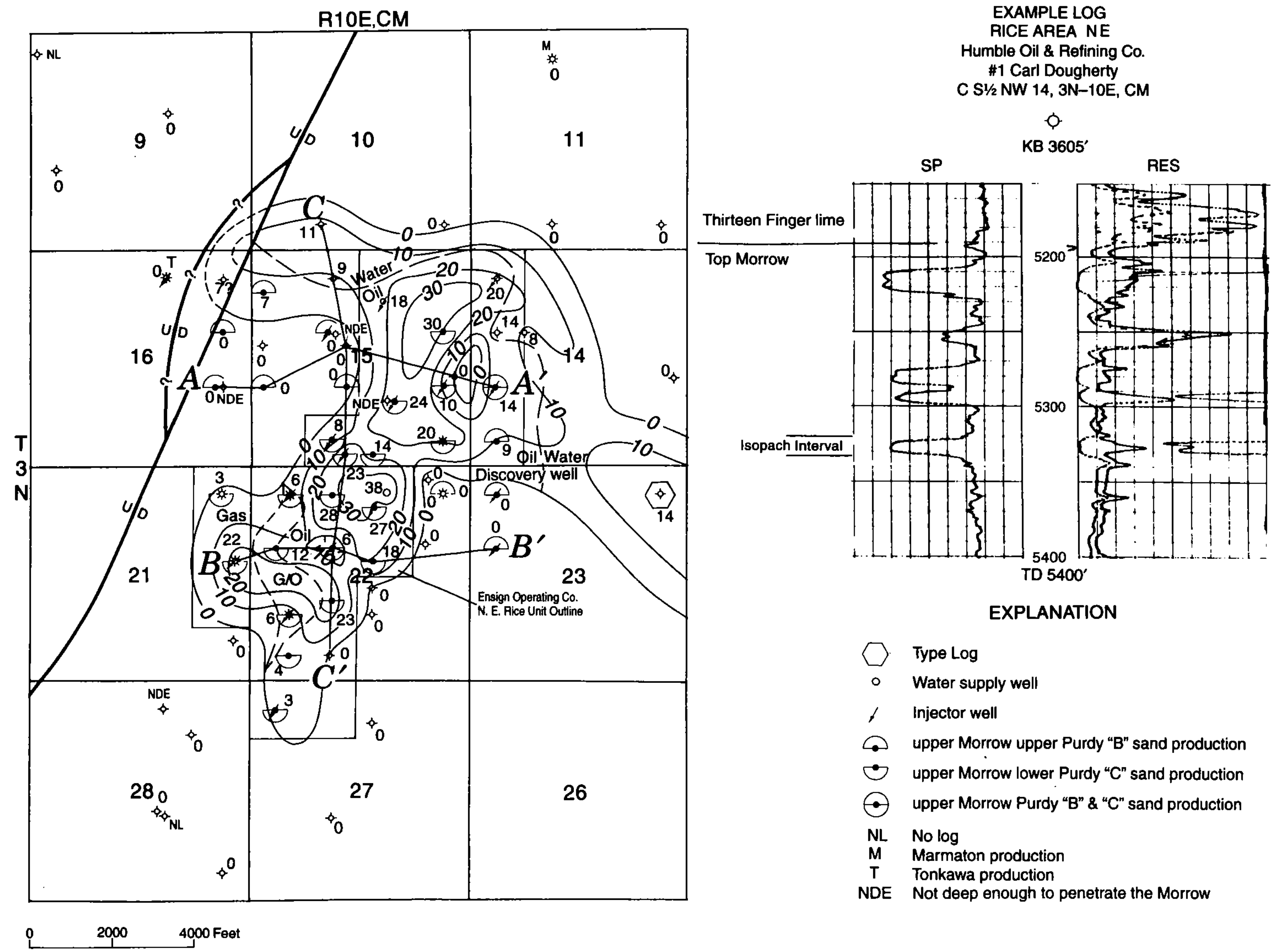


Figure 49. Isopach map of the net lower Purdy "C" sand (porosity: ≥10%) in the Rice NE field, western Texas County, Oklahoma. Contour interval = 10 ft. See Figure 43 for names of wells.

Isopach Mapping: Basic sandstone mapping includes both gross and net isopach maps of the upper Purdy "B" sand, and a net isopach map of the lower Purdy "C" sand. These maps were prepared using a 10% porosity cutoff for net values and GR-resistivity log deflections for determination of sand-body thickness regardless of porosity (gross thickness). In some cases, more than one sand bed was judged to belong to a particular Purdy zone.

TABLE 6. – Oil Production Statistics for Upper Morrow Purdy Sands (Combined) in Rice NE Field, Western Texas County, Oklahoma

Year	Number of Oil Wells* (estimated)	Annual Oil Production (Barrels)	Average Monthly Oil Production (Barrels)	Average Daily Oil Production Per Well (BOPD)	Cumulative Oil Production (Barrels)
63	4	28,750	2,396	19.7	28,750
64	5	40,896	3,408	22.4	69,646
65	4	35,721	2,977	24.5	105,367
66	4	40,458	3,372	27.7	145,825
67	4	33,617	2,801	23.0	179,442
68	4	27,873	2,323	19.1	207,315
69	4	25,411	2,118	17.4	232,726
70	6	26,029	2,169	11.9	258,755
71	5	25,622	2,135	14.0	284,377
72	5	24,294	2,025	13.3	308,671
73	4	21,052	1,754	14.4	329,723
74	4	20,825	1,735	14.3	350,548
75	5	18,076	1,506	9.9	368,624
76	5	16,288	1,357	8.9	384,912
77	5	13,100	1,092	7.2	398,012
78	6	15,465	1,289	7.1	413,477
79	6	12,506	1,042	5.7	425,983
80	6	10,081	840	4.6	436,064
81	5	8,655	721	4.7	444,719
82	8	26,403	2,200	9.0	471,122
83	12	94,978	7,915	21.7	566,100
84	14	138,648	11,554	27.1	704,748
85	12	83,199	6,933	19.0	787,947
86	12	68,463	5,705	15.6	856,410
87	13	46,971	3,914	9.9	903,381
88	13	32,085	2,674	6.8	935,466
89	11	25,002	2,084	6.2	960,468
90	12	20,452	1,704	4.7	980,920
91	12	17,598	1,467	4.0	998,518
92	11	16,206	1,351	4.0	1,014,724
93	10	9,938	828	2.7	1,024,662
94	10	7,525	627	2.1	1,032,187

*Based on number of producing leases. Individual leases may contain more than one producing unit.

Upper Purdy "B" Sand: The upper Purdy "B" sand is part of a meandering fluvial system that extends at least 12 mi to the east beyond the Rice NE field and equally as far to the northwest (Pl. 1). Within the Rice NE field area, isopach mapping shows that this sand interval is oriented basically east–west and that the western portion is displaced by the updip fault (Fig. 47). Where present, the gross sand often has a thickness of 10–30 ft, whereas the thickness of net porous sand (Fig. 48), usually is 5–20 ft. The reduction in thickness of the net sandstone is due to a high proportion of diagenetic constituents or shale partings. As shown on either isopach map, the sand body is seldom more than a mile across, and it widens and narrows repeatedly throughout the mapped area. The bulges within the isopach map may indicate the meander amplitude of the fluvial system.

Because of the highly variable nature of the upper Purdy "B" sand, at least four different "compartments" of clean sand are mapped within the basic sand trend. These areas may represent the principal areas of point-bar development within the central portion of a meander belt. As shown in Figure 48, porosity development within the eastern two areas produced individual oil/water contacts at about –1,650 ft. The three "B" sandstone reservoirs east of the updip fault also have individual gas/oil contacts, at about –1,587 ft, which may be coincidental, or it may indicate that reservoir communication existed between the three areas during hydrocarbon migration. The sand that is immediately east of the updip fault appears truncated by the fault and does not have an apparent water column. The sand farthest to the west on the updip fault block is completely wet within the mapped area and is not productive.

Lower Purdy "C" Sand: Regional distribution of the lower Purdy "C" sand is similar to that of the upper Purdy sand even though the meander-belt patterns of the two systems are oriented in different directions locally. This may imply that avulsion occurred during the evolution and aggradation of the two Purdy sand intervals. The net lower Purdy "C" sand occurs in a sinuous pattern that is ~0.75 mi wide (Fig. 49). The lower Purdy sand is interpreted to extend beyond the mapped area for several more miles to the southwest and northeast (Pl. 1) and is believed to be one of the principal reservoirs in Rice and S. Eva fields. The lower Purdy "C" sand is stratigraphically 10–40 ft below the upper Purdy "B" sand, and it is uncommon to find good sand development in both the lower and upper Purdy zones within precisely the same geographic area.

Because the isopach map of the net lower Purdy "C" sand (Fig. 49) is very similar to the map of the gross interval thickness, only the net map has been included here. The net lower Purdy "C" sand thickness varies from 10–30 ft throughout most of the mapped area, although thicker net sand accumulations are found locally within the field. There are several places within the main trend, however, where the sand is absent or very nearly so. Such a pattern is typical for fluvial de-

TABLE 7. – Oil Production Statistics for the Upper Purdy and Lower Purdy Sands in the Rice NE Field, Western Texas County, Oklahoma

UPPER PURDY "B" SAND PRODUCTION						LOWER PURDY "C" SAND PRODUCTION					
Year	Number of Oil Wells* (estimated)	Annual Oil Production (Barrels)	Average Monthly Oil Production (Barrels)	Average Daily Oil Production Per Well (BOPD)	Cumulative Oil Production (Barrels)	Year	Number of Oil Wells* (estimated)	Annual Oil Production (Barrels)	Average Monthly Oil Production (Barrels)	Average Daily Oil Production Per Well (BOPD)	Cumulative Oil Production (Barrels)
63	3	20,780	1,732	19.0	20,780	63	1	7,970	664	21.8	7,970
64	3	25,796	2,150	23.6	46,576	64	2	15,832	1,319	21.7	23,802
65	2	14,576	1,215	20.0	61,152	65	2	21,145	1,762	29.0	44,947
66	2	19,781	1,648	27.1	80,933	66	2	20,677	1,723	28.3	65,624
67	2	14,506	1,209	19.9	95,439	67	2	19,111	1,593	26.2	84,735
68	2	9,529	794	13.1	104,968	68	2	18,345	1,529	25.1	103,080
69	2	6,705	559	9.2	111,673	69	2	18,707	1,559	25.6	121,787
70	3	8,014	668	7.3	119,687	70	3	18,016	1,501	16.5	139,803
71	3	8,223	685	7.5	127,910	71	2	17,399	1,450	23.8	157,202
72	3	6,632	553	6.1	134,542	72	2	17,662	1,472	24.2	174,864
73	2	3,998	333	5.5	138,540	73	2	16,862	1,405	23.1	191,726
74	2	4,123	344	5.6	142,663	74	2	16,702	1,392	22.9	208,428
75	3	3,605	300	3.3	146,268	75	3	4,472	373	4.1	212,900
76	3	3,432	286	3.1	149,700	76	3	12,856	1,071	11.7	225,756
77	3	2,189	182	2.0	151,889	77	3	10,912	909	10.0	236,668
78	3	2,638	220	2.4	154,527	78	4	12,828	1,069	8.8	249,496
79	3	2,022	169	1.8	156,549	79	4	10,485	874	7.2	259,981
80	3	1,424	119	1.3	157,973	80	4	8,657	721	5.9	268,638
81	3	1,550	129	1.4	159,523	81	3	7,105	592	6.5	275,743
82	4	11,237	936	7.7	170,760	82	10	15,166	1,264	4.2	290,909
83	5	20,112	1,676	11.0	190,872	83	13	74,867	6,239	15.8	365,776
84	5	29,536	2,461	16.2	220,408	84	17	84,757	7,063	13.7	450,533
85	5	11,992	999	6.6	232,400	85	17	61,310	5,109	9.9	511,843
86	5	17,553	1,463	9.6	249,953	86	16	51,449	4,287	8.8	563,292
87	6	20,758	1,730	9.5	270,711	87	16	26,213	2,184	4.5	589,505
88	6	14,651	1,221	6.7	285,362	88	16	17,435	1,453	3.0	606,940
89	5	12,543	1,045	6.9	297,905	89	14	12,460	1,038	2.4	619,400
90	5	10,089	841	5.5	307,994	90	15	10,363	864	1.9	629,763
91	5	9,540	795	5.2	317,534	91	15	8,058	672	1.5	637,821
92	5	8,243	687	4.5	325,777	92	14	7,963	664	1.6	645,784
93	5	4,679	390	2.6	330,456	93	13	5,260	438	1.1	651,044
94	5	2,554	213	1.4	333,010	94	13	4,971	414	1.0	656,015

*Based on the number of producing leases. Individual leases may contain more than one producing well.

posits and is a recurring problem in reservoir management. Overall, however, the lower Purdy "C" reservoir is interpreted to have certain consistent characteristics, which, in the future, may prove to be oversimplified. These reservoir characteristics are a single oil/water contact at about –1,708 ft and a single gas/oil contact at about –1,540 ft. The gas-filled portion occurs in the extreme southwestern part of the reservoir and is relatively small in comparison to the rest of the field. In general, the lower Purdy "C" sand constitutes a structurally enhanced stratigraphic oil pool. It is the major reservoir within Rice NE field although not necessarily the most laterally extensive sandstone within the upper Morrow.

Core Analysis: Core analysis of the Ensign SWS No. 1 well (NW¼NE¼ sec. 22, T. 3 N., R. 10 E. CM) shows the lower Purdy "C" sand to be a medium- to coarse-grained, arkosic sandstone. Pebbly, conglomeratic zones several inches thick are found near the base of the sand body which becomes increasingly finer grained up section. Conspicuous sedimentary structures include massive to graded bedding, horizontal and inclined bedding, minor clay drapes (which would seriously impede fluid migration), and numerous zones of carbonaceous debris. Sorting is generally poor and grains are mostly subrounded to subangular. There are a few fossil fragments, which most likely were ripped up from the immediately underlying marine deposits.

Whole-rock analysis by TerraTek, Inc. indicates the following mineralogy: quartz (~71%), plagioclase (~17%), and clays (~12%). Rock fragments include metamorphic facies such as schist, metaquartzite, and sheared quartz. Other rock constituents include granitic fragments, chloritic mudstone, and sandstone/

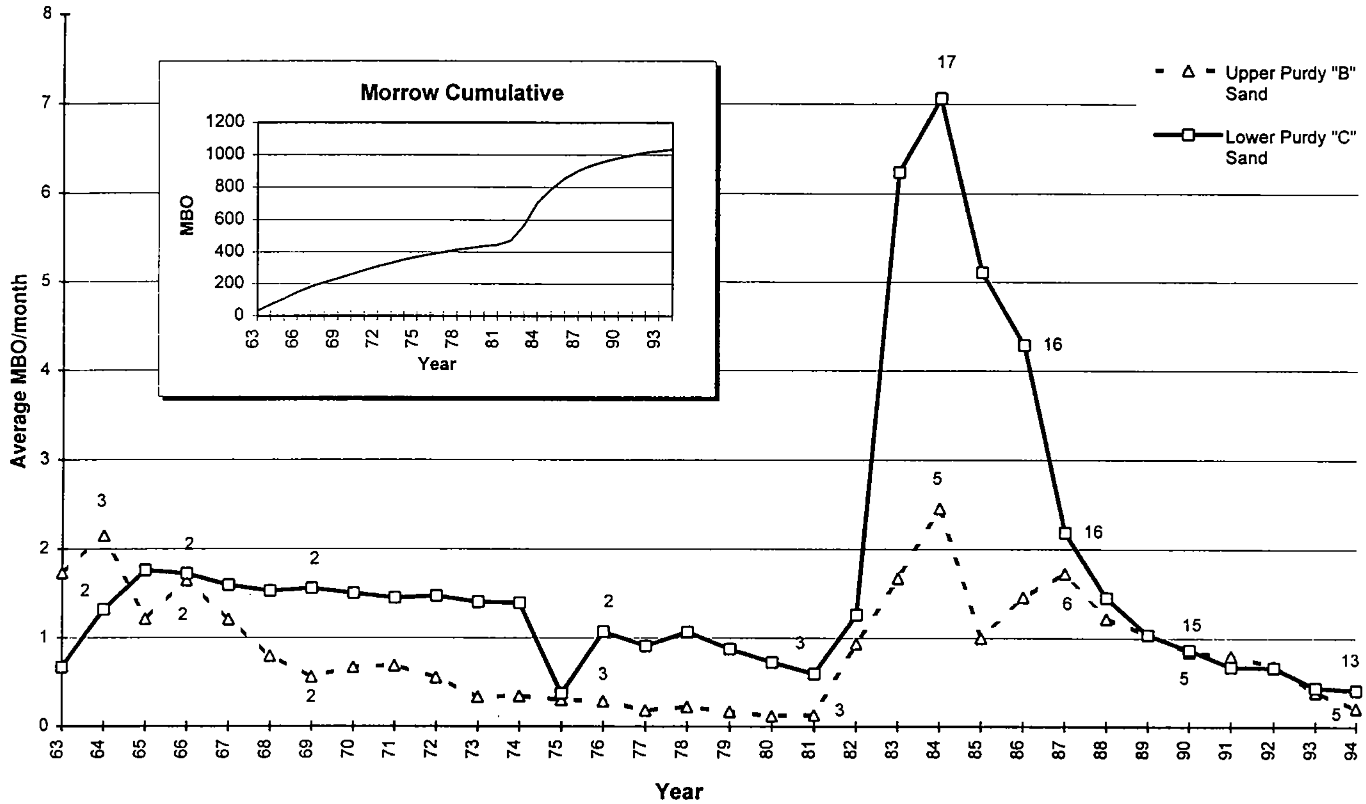


Figure 50. Morrow production decline curves for the upper and lower Purdy sands in Rice NE field, western Texas County, Oklahoma. Numbers along curves designate the number of wells that produced oil from the indicated reservoir at various years. Inset plot shows cumulative oil production from the upper and lower Purdy sands combined.

breccia. Kaolinite constitutes ~75% of the clay fraction, whereas chlorite and smectite concentrations are about 20% and 10%, respectively. The clay content is primarily a function of feldspar and rock-fragment alteration and therefore is considered authigenic. Other secondary minerals that occur in small amounts include dolomite, pyrite, siderite, quartz, chlorite, and limonite. All these constituents can be regarded as cementing agents. Calcite, which initially may have been present as a cement, is not very common due to secondary leaching and porosity enhancement.

Reservoir Characteristics: Reservoir characteristics of the Purdy sands are similar to those of other immature fluvial deposits. Effective porosity is relatively high and ranges from 5% to 24%. Where the sands are productive, porosity is usually >15% and often much higher. Permeability generally varies from about 5 md to 50 md but averages only ~12 md. This low average permeability is due mainly to poorly sorted framework constituents and to large amounts of clay, both products of sourcing and depositional environment. The fact that extreme values of good porosity and permeabilities >100 md occur in the most effective portion of the reservoir in terms of hydrocarbon recovery must be taken into account when one is calculating reserves or planning secondary recovery units.

Formation Evaluation: Purdy sandstones often are difficult to analyze and interpret with common formation evaluation techniques because of the large amount of interstitial clay, the presence of interbedded "hot" shale, and feldspar constituents that make the Purdy reservoirs anomalously radioactive. Many Purdy sands have relatively high GR values that are indistinguishable from the hot shales. When the sands have relatively low GR values, they can be confused with limestone. Porosity determinations (made using either sonic or density-neutron tools) are erroneously high due to the clay effect.

Resistivity is probably the most effective measurement to use for reservoir detection and evaluation. Lithologies in the upper Morrow that have relatively low "deep" resistivity values (about 1 to 5 ohm-meters) and a separation of several ohm-meters between the shallow and deep resistivity are generally water-wet sands. In contrast, hydrocarbon-bearing sands have "deep" resistivities of 5 to 20+ ohm-meters that are distinct from the range for both the shallow and the deep resistivities of the shale baseline, which is about 4–5 ohm-meters.

Calculated water saturation $Sw = \sqrt{F \times Rw/Rt}$ in productive zones varies from about 22% to 50%, assuming a Rw (resistivity of formation water) of 0.04 at formation temperature and using the Archie equation for for-

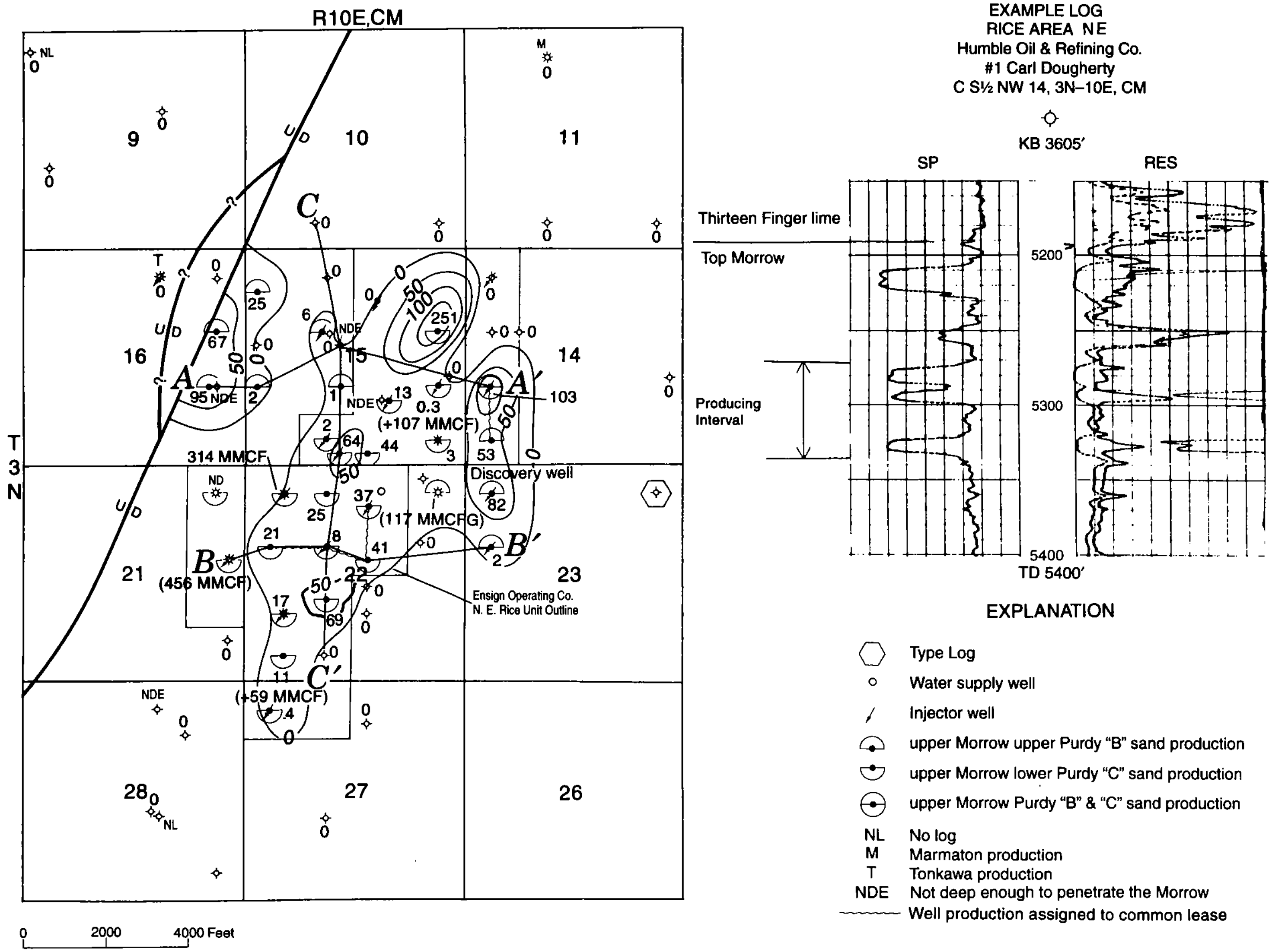


Figure 51. Map of cumulative oil production in the upper Morrow (upper and lower Purdy sands), Rice NE field, western Texas County, Oklahoma. Contour interval = 50 MBO. See Figure 43 for names of wells.

mation factor ($F = 1/\phi^2$). Rt (true resistivity) is determined from the deep resistivity log curve. Porosity (ϕ) is determined from any porosity measuring tool.

Reservoir Sensitivity and Formation of Porosity: Porosity associated with upper Morrow sandstones is mainly secondary and it is related to dissolution of unstable constituents and enhancement of preexisting pores. Original carbonate cement, feldspars, and rock fragments were chemically altered or dissolved after deposition. The voids created or redeveloped during chemical alteration of these constituents provided the space necessary for hydrocarbon migration and containment. Diagenesis was also a probable source for the kaolinite and chlorite that are abundant in most sandstones.

The abundance of kaolinite and chlorite makes the Morrow Purdy sands sensitive to formation damage. Kaolinite is easily dispersed during any fluid surge brought on by drilling, oil production, or water injection. The dislodged clay particles migrate short distances and are trapped in pore throats, adversely affecting most of the reservoir. Chlorite also can cause serious formation damage if the reservoir is treated with acid during well completion. The chemical reaction between the acid and chlorite will produce an insoluble precipitate of iron hydroxide that reduces reservoir permeabilities.

Oil Production and Well Completion: Cumulative primary oil production through 1994 from the Purdy sands (combined) in Rice NE is estimated at ~1 million barrels (Table 6). Table 6 also identifies the average monthly production and annual production for the field as well as the average daily oil production per well for the combined Purdy sands. Table 7 is a compilation of production data for the upper Purdy "B" and lower Purdy "C" sands separately.

The production decline curves in Figure 50 illustrate the development and production histories of individual Purdy sands. There have been two periods of increased production and subsequent decline for the upper Purdy "B" sand; they correspond to the initial discovery in 1963 and to field expansion during the early 1980s. Although oil production from the Purdy "B" sand is considerably less than from the underlying Purdy "C," average production from some individual wells is comparable to production from the lower Purdy sand. In fact, the upper Purdy "B" sand appears to have a slower production decline and higher recovery factor than the "C" sand despite being thinner and smaller in areal extent.

An estimated 66% of the total primary oil recovery in Rice NE is attributed to the lower Purdy "C" sand. This zone had relatively stable oil production from only a few wells until the early 1980s. After this period, expansion of Rice NE field was due largely to completions in the lower Purdy "C" sand in the southern part of the field. The rapid increase in oil production shown on Figure 50 was due to additional wells that had total combined recoverable oil reserves greatly exceeding the reserves of the upper Purdy interval. However, depletion of the lower Purdy "C" sand was much more rapid than depletion of the Purdy "B" and, by 1989, production from both horizons was about equal despite the larger number of producing wells from the Purdy "C." This trend is difficult to explain since completion practices have not changed over time and there is relatively little structural variation of producing horizons within the field. In addition, initial reservoir pressures were nearly equal and oil properties are about the same. The most obvious possible explanations are reservoir character and the manner in which hydrocarbons were produced historically. The lower Purdy "C" is generally thicker than the "B" and initial production rates were generally higher, which led to more rapid declines in "C" production later on. The lower Purdy "C" sand also had a significant gas cap in the southwestern part of the field that was drawn upon extensively. The production of gas combined with pressure reduction may have affected the mobility of oil in the oil-saturated portion of the reservoir below the gas/oil transition zone. Additionally, small amounts of oil from the Purdy "C" may have been drawn into the gas cap area and, thus, become unrecoverable.

The inset plot on Figure 50 shows the cumulative annual Morrow oil production from the upper and lower Purdy sands combined. The large increase in production after 1982 coincides with development of the lower Purdy "C" sand in the southwestern part of Rice NE field.

Most of the wells were acidized and completed with fracture treatment using sand as a proppant. These completion practices were used for the upper Purdy sands during the 1960s when they were developed and during the 1980s when the lower zone was brought on line. Therefore, differences in recovery efficiency and production decline are not due to completion practices and must be related to production methods or reservoir characteristics. Wells usually had flowing tubing pressures that ranged from 100 to 700 PSI; initial potential measurements generally were <100 BOPD. Cumulative production per well is generally <50 MBO, although a few wells have produced much more. Since oil production from more than one well may be assigned to a single lease, individual well production is often unavailable. However, the production trend of individual wells or leases can be used to identify the principal "sweet" spots within Rice NE field(Fig. 51).

PART III

Reservoir Simulation of the Upper Morrow Reservoirs (upper and lower Purdy), Rice NE Field, Texas County, Oklahoma

R. M. Knapp and Zahid Bhatti
School of Petroleum and Geological Engineering
University of Oklahoma

The Rice NE field is located in secs. 14–16, 21–23, and 27, T. 3 N., R. 10 E. CM, Texas County, Oklahoma (Fig. 43). The upper Morrow has two main sandstone units that produce oil, identified informally as the upper and lower Purdy sands. They have been characterized as trangressive fluvial valley-fill sequences deposited in marine shales.

The Morrow (Purdy) reservoirs have highly variable properties and appear to have four different, isolated flow units. The upper Purdy appears to be partitioned into three separate lobes, each with individual oil/water contacts and gas/oil contacts. The average net thickness of the upper Purdy is 9 ft and the lobes have a combined area of 450 acres. The lower Purdy appears to be a single connected sandstone unit with an oil/water contact at 1,708 ft subsea (below mean sea level) and a gas-oil contact at 1,540 ft subsea. It has an average net thickness of 14 ft and an areal extent of 940 acres. Average reservoir properties for both units are given in Table 8.

The oil in the Purdy reservoirs is a very low shrinkage oil with an initial formation-volume factor of 1.156 RB/STB and an estimated initial oil viscosity at reservoir conditions of 2.03 cp. The initial oil in place was estimated to be 12.0 MMSTB. This estimate is based on an initial oil saturation of 67%. The maximum recovery, based on an estimated residual oil saturation of 28%, could be as much as 7.0 MMSTB. The unrecoverable immobile oil is estimated to be 5.0 MMSTB. Primary recovery through June 1994 was 1.03 MMSTB.

Behavior of the Morrow reservoirs has conformed to that of saturated, low-shrinkage oil reservoirs with small gas caps, which suggests that water drive has not been a significant source of reservoir energy. A waterflood has been initiated by the operator, Ensign Operating Co., but no water was injected into the formation prior to October 1994. Thus, only primary depletion of the reservoir had occurred during the period for which reservoir history was matched. Ensign Operating Co. cooperated in this study, and extensive use was made of data provided by the company.

A typical well-log response for the Rice NE field area is shown in Figure 41 (Part II of this volume). One well, the Ensign NERMU SWS No. 1, NW¼NE¼ sec. 22, T. 3 N., R. 10 E. CM, was cored and special core analyses were run on the core to provide water-oil relative permeability data as well as absolute porosity and permeability information. Nearly all wells were logged and the well-log suites included resistivity, SP, gamma ray, neutron, bulk density and density porosity logs. Drill stem tests from the Carl Dougherty No. 1 and No. 2, Norris No. 1-A, Gaither No. 1-23, and D.R. Gaither 1-23 wells were available for initial pressures and productive capacities.

The Rice NE wells that have been completed in the Purdy reservoirs are shown in Table 9. All depths are true depths as interpreted from the logs and scout tickets. A total of 43 wells were within the field boundaries. Of these, 29 were completed in one or both of the Purdy reservoirs. The first three wells were completed in 1963 and development of the Rice NE field was relatively steady with nine more wells completed through 1982. An additional 17 wells were drilled in a period of rapid development from 1983 to 1985, 11 of which were completed in the lower Purdy sand. Just before Ensign initiated its waterflood in October 1994, eight wells were producing from the upper Purdy and 14 wells were producing from the lower Purdy.

The oil production and producing gas-oil ratio for the Rice NE field during the period for which reservoir history was matched are shown in Figure 52. During the first 20 years from 1963 to 1983, production declined smoothly and steadily. During the extensive development period from 1983 through 1985, production rates dramatically increased as additional wells were completed in the lower Purdy reservoir; after that production rapidly declined. At the start of the waterflooding in October 1994, production from five producing wells was ~15 STB/day. By the end of December 1994, 1,032 MSTB of oil had been produced and 2,440 MMCF of gas had been sold. This represents a recovery of 8.3% of the initial oil in place based on volumetric estimates.

The Morrow sandstone has been successfully waterflooded in other fields, and the Rice NE lower Purdy reservoir is considered to be an attractive candidate for

TABLE 8. – Average Reservoir Properties for the Purdy Reservoir

Properties	upper Purdy values	lower Purdy values
Porosity	14 %	17 %
Permeability	12 md	20 md
Gross Pay	20 ft	38 ft
Net Pay (ϕ > 8%)	9 ft	14 ft
Reservoir Temperature	130 °F	130 °F
Specific Gas Gravity	0.789	0.789
Oil Gravity	38.5 °API	38.5 ° API
Initial Water Saturation	33 %	33 %
Initial Bottom Hole Pressure	1320 PSIA	1335 PSIA
Initial Solution Gas Oil Ratio	270 SCF/STB	270 SCF/STB
Initial Oil Formation Volume Factor	1.156 RB/STB	1.156 RB/STB
Initial Oil in Place	3220 MSTB	8780 MSTB

waterflooding even though the permeability is low. This reservoir simulation study was carried out to estimate initial oil and gas in place, recovery factors, and waterflood recovery for the operator's planned waterflood project.

Reservoir fluid properties were estimated by Western Atlas using PVT simulation as part of a study of fluids produced from Ensign Operating Co's Rice No. 1 well completed in the upper Morrow and located 4 mi southwest of the Rice NE field in sec. 4, T. 2 S., R. 10 E. CM. Early gas-oil ratio production data and PVT simulation suggested that the reservoir was saturated initially. From the initial gas-oil ratio and gas solubility correlation, the Rice No. 1 bubble-point pressure was estimated to be 1,317 PSIA. Pressure measurements reported on the scout tickets suggest that the initial pressure of the upper Purdy in the Rice NE field was 1,320 PSIA at the 1,587-ft subsea gas/oil contact and the initial lower Purdy pressure in the Rice NE field was 1,335 PSIA at the 1,708-ft subsea oil/water contact. Since no measured pressures were available for the end of the primary production, the goal of the history matching part of the study was to calculate well pressures for the producing wells that would suggest that they were just "making" their specified production rates on September 30, 1994. This was accomplished for all 19 producing wells. The history matching portion of the reservoir study seemed to confirm the complex nature of the reservoirs.

After primary production from 1963 through 1994 was matched, a forecast of expected waterflood performance was prepared (Fig. 53A,B). The petrophysical data measured on the NERMU SWS No. 1 included two-phase water-oil relative permeabilities. The Corey correlation was used to estimate the gas relative permeabilities (Chrichlow, 1977, p. 35–36). The average residual oil saturation of 28% was based on the core analysis. In accordance with Ensign Operating Co.'s plan, in the simulation study the Carl Daugherty No. 2, Mason No. 1-15, McDonald Nos. 4, 5 and 6, Clark Nos. 1-21 and 3-22, and Gaither No. 3A wells were converted to injection wells. Two new wells, the NERMU Nos. 1

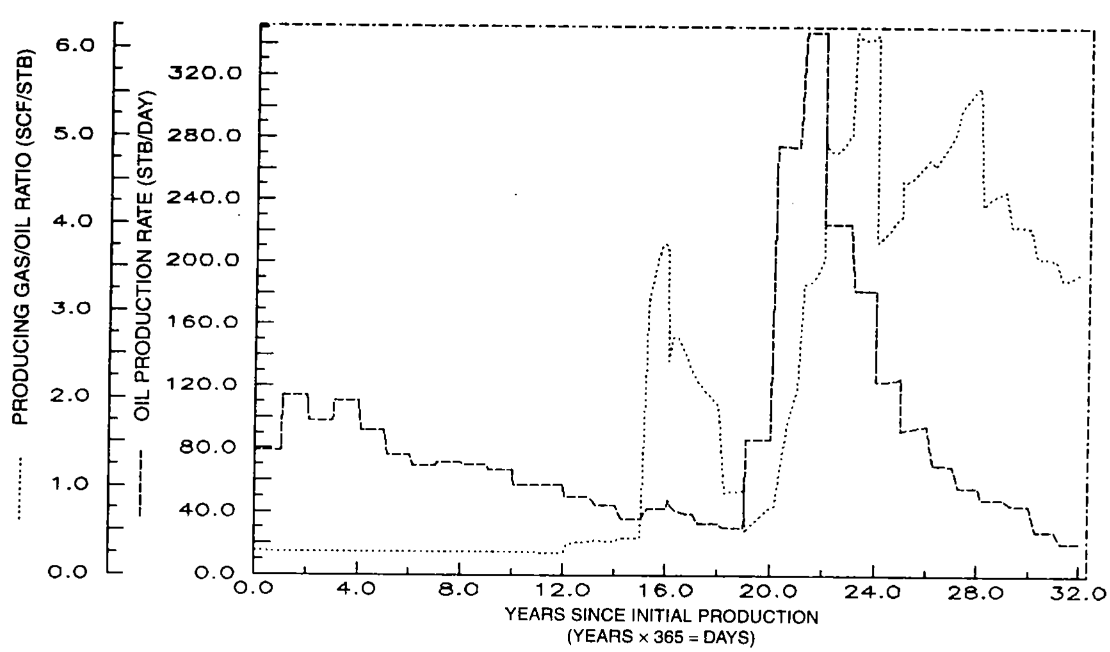


Figure 52. Oil production rates and simulated gas/oil ratios for Rice NE field during the period for which reservoir history was matched, May 1963 to September 1994. Total gas produced = 2,440 MMSCF; total oil produced = 1,032 MSTB.

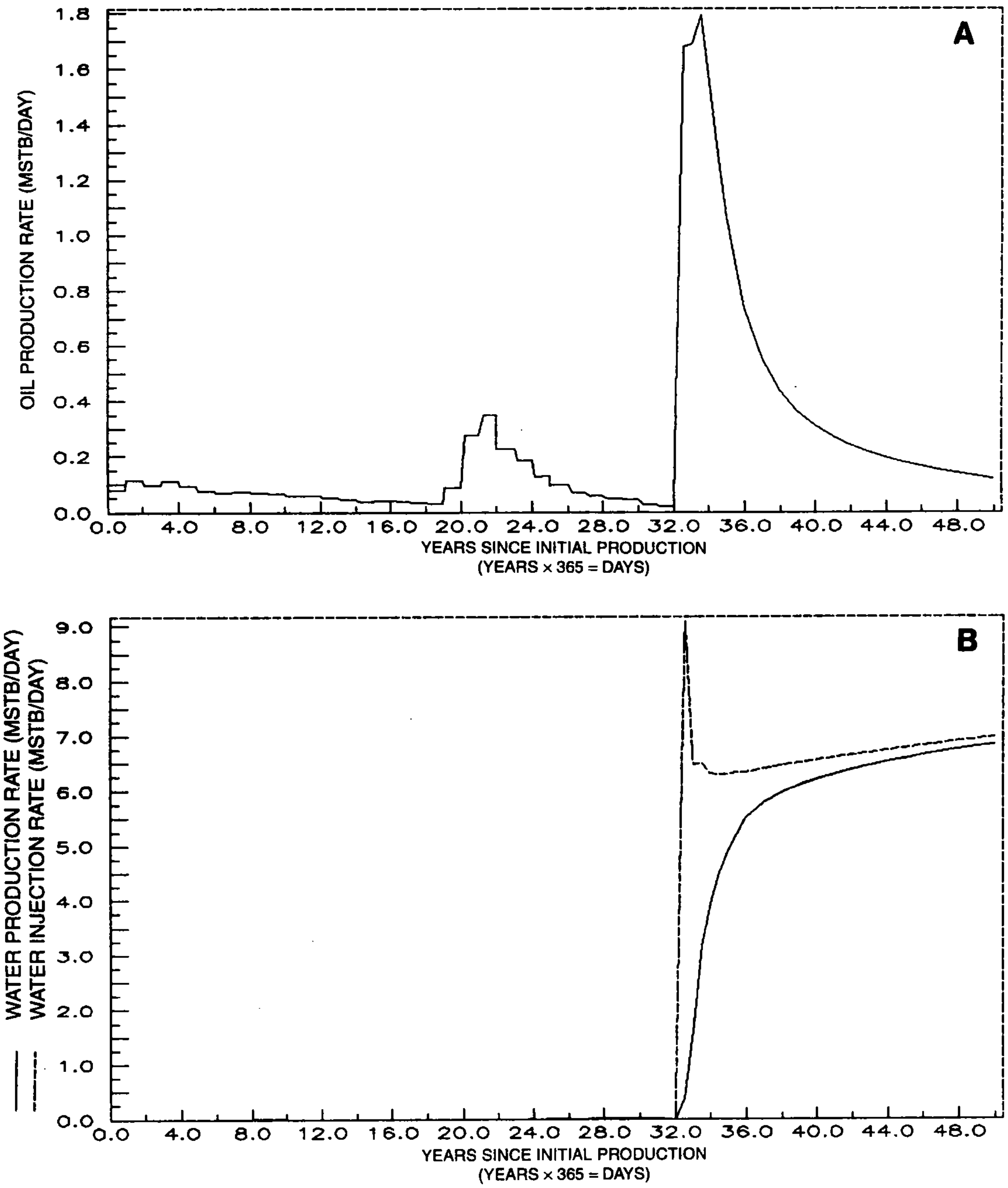


Figure 53. (A) Waterflood forecast for Rice NE field. (B) Simulated waterflood production and injection of Rice NE field.

and 2, were drilled and completed as injection wells also. The nine remaining wells, the Norris No. 1-A, Gaither No. 2-15 and Texaco 1-15, Carl Dougherty No. 1, McDonald Nos. 1, 2 and 3, Clark Nos. 1-22 and 2-22, were continued as production wells. In the information provided by Ensign, no provision was made for the Cline No. 1-15 well. The net formation thickness maps suggest that there should be oil in the lower Purdy at this well, and the scout ticket reported that it was initially completed in the lower Purdy. Therefore, it was retained as a producer in the simulation study.

The "policy" followed for waterflood simulation was to control both injection and production well bottom-hole pressures. Actual pressure data were available through 1994. From the beginning of 1995, the bottom-hole pressure for injection wells was held at 3,500 PSIA and the bottom-hole pressure for production wells was held at 350 PSIA. The first oil-production response to the waterflood is expected to occur a few months after injection begins. For the field simulation, an initial water-injection rate of 9,000 STB/day was used to conform with Ensign operations in 1994.

TABLE 9. – Morrow (upper and lower Purdy) Sandstone Wells, Rice NE Field

Well Name/ Map Identification	Well Location T3N R10ECM	Initial Production Date	Cumulative production since 1963	Formation Top-Bottom (ft)	Perforation Upper-Lower (ft)
Apache Corp./ Gaither # 1	NW NW 23	4-18-63	81726 STB	5190-5220	5191-5219
Skelly Oil Co./ Carl Dougherty 1	SW SW 14	10-10-63	52815 STB	5196-5225	5204-5225
Skelly Oil Co./ Carl Dougherty 2	NW SW 14	10-10-63	102523 STB	5216-5250 5260-5270	5220-5242 5260-5270
Humble Oil/ D R Gaither 1	C SW NW 23	3-5-64	2370 STB	5217-5224	5218-5224
Phillips Pet./ Norris 1-A	C SE NE 15	8-6-64	249825 STB	5300-5332	5300-5332
Texaco Inc. / Carl Cline 1-A	SE NW 15	8-7-70	5614 STB	5270-5285	5270-5284
Texaco Inc./ Gaither # 1	NE SE 15	7-23-70	251 STB	5275-5285	5278-5284
J. Castelman / Gaither #1	SE SE 15	1-24-75	2581 STB	5200-5222	5203-5221
Argonaut / Mason #1	SE SW 15	6-29-78	2374 STB	5168-5188	5168-5188
Atlantic Refining/ Gaither #1	NE NE 22	3-15-84	21362 MSCF	5142-5176	5142-5157
Dawn Energy / McDonald 1-22	NE NW 22	9-21-81	25304 STB	5157-5190	5158-5190
Dawn Energy / McDonald 2-22	SW NW 22	2-25-83	20594 STB	5148-5168	5152-5163
Dawn Energy / McDonald 3-22	SW SW NE 22	4-16-83	40961 STB	5184-5202	5184-5202
Dawn Energy / McDonald 4-22	SE NW 22	6-17-83	8414 STB	5162-5170	5162-5170
Dawn Energy / McDonald 5-22	E2 NW NW 22	5-20-84	314349 MSCF	5150-5160	5150-5160
Dawn Energy / McDonald 6-22	SW NW NE 22	5-20-84	37346 STB	5174-5200	5174-5200
J. Castleman / Simmons 1	SE NE 16	2-16-82	66815 STB	5295-5305	5296-5305
J. Castleman / Simmons 16-3A	NE SE 16	6-23-83	95205 STB	5225-5240	5226-5240
Dawn Energy / Mason 1-15	SE SE SW 15	10-19-82	60045 STB	5167-5192	5167-5192
Dawn Energy/ Mason 2-15	NW SW 15	11-29-83	1987 STB	5246-5256	5246-5256
Dawn Energy / Mason 3-15	NE NE SW 15	5-16-86	1417 STB	5168-5176	5170-5176
Dawn Energy / Clark 1-22	NE SW 22	4-2-83	69042 STB	5150-5176	5151-5176
Dawn Energy / Clark 2-22	E2 SW SW 22	9-29-83	10259 STB	5162-5172	5167-5170
J. Castleman / Gaither 2-15	SW SW SE 15	12-15-83	44282 STB	5187-5201	5187-5201
Dawn Energy / Clark 3-22	SE NW SW 22	1-19-84	17014 STB	5136-5150	5136-5150
Dawn Energy / Gowdy 1-27	NW NW 27	5-31-84	371 STB	5146-5149	5146-5148
Mustang / Gaither 15-3A	S2 NW SE 15	12-12-85	12303 STB	5211-5234	5212-5234
Gribble Oil / Cline 1-15	SW NW NW 15	6-5-87	25326 STB	5298-5306	5299-5306
Texas Prospectors/ Clark 1-21	SE SE NE 21	2-28-85	440901 MSCF	5124-5150	5124-5150

Simulated field water-injection and production rates are shown in Figure 53B. A maximum oil production rate of 1,800 STB/day is expected one year after the injection begins (Fig. 53A). The additional oil recovery is expected to be 3.2 MMSTB or three times the primary recovery. Early production and injection should be monitored closely to ensure that the reservoir is being swept adequately by the injected water. After waterflooding, the total recovery for both primary and secondary production should be 4.2 MMSTB or 35% of the initial oil in place. The large difference between the maximum potential recovery and expected recovery is due to the omission of the upper Purdy lobes from the waterflood simulation and shrinkage caused by the production of solution gas during primary recovery. The reservoir simulation shows that the results of the waterflood should be good. More than half of the total lower Purdy reservoir volume thought to exist should be swept to residual-oil saturation by the proposed injection plan.

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APPENDIX 1

Various Size Grade Scales in Common Use

(from Blatt and others, 1980)

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

†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

API	American Petroleum Institute
BCF	billion cubic feet (of gas)
BCFG	billion cubic feet of gas
BO	barrels of oil
BOPD	barrels of oil per day
BHP	bottom-hole pressure
cp	centipoise (a standard unit of viscosity)
MBO	thousand barrels of oil
MCF	thousand cubic feet (of gas)
md	millidarcies, or 0.001 darcy
MMBO	million barrels of oil
MMCF	million cubic feet (of gas)
MMCFG	million cubic feet of gas
MMCFGPD	million cubic feet of gas per day
MMSCF	million standard cubic feet (of gas)
MMSTB	million stock tank barrels
MSCF/STB	thousand standard cubic feet per stock tank barrel
MSTB	thousand stock tank barrels
OOIP	original oil in place
PSI	pounds per square inch
PSIA	pounds force per square inch, absolute
PVT	pressure volume temperature
RB	reservoir barrels (unit of measurement of oil in the subsurface where the oil contains dissolved gas); see STB or STBO
RB/STB	reservoir barrels per stock tank barrels
SCF/STB	standard cubic feet per stock tank barrel
STB or STBO	stock tank barrels of oil (unit of measurement for oil at the surface in a gas-free state rather than in the subsurface reservoir where the oil contains dissolved gas); see RB
STB/DAY	stock tank barrels (of oil) per day

APPENDIX 3

Glossary of Terms

(as used in this volume)

Definitions modified from Bates and Jackson (1987), Sheriff (1984), and Van Wagoner and others (1990).

allogenic—Formed or generated elsewhere.

anastamosing stream—A fluvial depositional system characterized by a branching network of shallow channels. Similar in form to braided river systems except that anastomosing rivers have alluvial islands covered by dense and permanent vegetation that stabilizes river banks.

authigenic—Formed or generated in place.

avulsion—A sudden cutting off or separation of land by a flood or by an abrupt change in the course of a stream, as by a stream breaking through a meander or by a sudden change in current whereby the stream deserts its old channel for a new one.

bar finger—An elongated, lenticular body of sand underlying, but several times wider than, a distributary channel in a bird-foot delta.

bed load—The part of the total stream load that is moved on or immediately above the stream bed, such as the larger or heavier particles (boulders, pebbles, gravel) transported by traction or saltation along the bottom; the part of the load that is not continuously in suspension or solution.

braided stream—A stream that divides into or follows an interlacing or tangled network of several small branching and reuniting shallow channels separated from each other by branch islands or channel bars.

centipoise—A unit of viscosity equal to 10^{-3}kg/s.m. The viscosity of water at 20°C is 1.005 centipoise.

channel deposits—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.

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 it 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.

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

diapir—A dome or anticlinal fold in which the overlying rocks have been ruptured by the squeezing-out of plastic core material. Diapirs in sedimentary strata usually contain cores of salt or shale.

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.

distributary mouth bar—The main sediment load of a distributary channel in the subaqueous portion of a *delta* (also called the *delta front*). It consists predominantly of sand and silt; grain size decreases seaward.

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

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

formation-volume factor—The factor applied to convert a barrel of gas-free oil in a stock tank at the surface into an equivalent amount of oil in the reservoir. It generally ranges between 1.14 and 1.60. See also: *shrinkage factor.*

highstand—The interval of time during one or more cycles of relative change of sea level when sea level is above the shelf edge in a given local area.

highstand system tract (HST)—The stratigraphically higher (or younger) depositional system(s) in a succession of genetically related strata bounded by unconformities or their correlative counterparts.

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

infilling—A process of deposition by which sediment falls or is washed into depressions, cracks, or holes.

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

lacustrine—Pertaining to, produced by, or formed in a lake or lakes.

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

lowstand—The interval of time during one or more cycles of relative change of sea level when sea level is below the shelf edge.

lowstand system tract (LST)—The stratigraphically lower (or older) depositional system(s) in a succession of genetically related strata bounded by unconformities or their correlative counterparts.

meander—One of a series of regular freely developing sinuous curves, bends, loops, turns, or windings in the course of a stream. See also: *meander belt.*

meander belt—The zone along a valley floor across which a meandering stream shifts its channel from time to time; specifically the area of the flood plain included between two lines drawn tangentially to the extreme limits of all fully developed meanders. It may be from 15 to 18 times the width of the stream.

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

mud cake—A clay lining or layer of concentrated solids adhering to the walls of a well or borehole, formed where the drilling mud lost water by filtration into a porous formation during rotary drilling.

offlap—A term commonly used by seismic interpreters for reflection patterns generated from strata prograding into deep water.

onlap—The progressive submergence of land by an advancing sea.

point bar—One of a series of low, arcuate ridges of sand and gravel developed on the inside of a growing meander by the slow addition of individual accretions accompanying migration of the channel toward the outer bank.

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.

proppant—As used in the well completion industry, any type of material that is used to maintain openings of induced fractures. Proppants usually consist of various sizes of sand, silica beads, or other rigid materials, and they are injected into the formation while suspended in a medium such as water, acid, gel, or foam.

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

residual oil—Oil that is left in the reservoir rock after the pool has been depleted.

ribbon sand—See: *shoestring sand.*

rip-up—Said of a sedimentary structure formed by shale clasts (usually of flat shape) that have been "ripped up" by currents from a semiconsolidated mud deposit and transported to a new depositional site.

river bar—A ridge-like accumulation of alluvium in the channel, along the banks, or at the mouth, of a river.

shoestring sand—A shoestring composed of sand or sandstone, usually buried in the midst of mud or shale; e.g., a buried distributary mouth bar, coastal beach, or channel fill.

shrinkage factor—The factor that is applied to convert a barrel of oil in the reservoir into an equivalent amount of gas-free oil in a stock tank at the surface. It generally ranges between 0.68 and 0.88. See also: *formation-volume factor.*

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.

stillstand—Stability of an area of land, as a continent or island, with reference to the Earth's interior or mean sea level, as might be reflected, for example, by a relatively unvarying base level of erosion between periods of crustal movement.

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

tabular cross-bedding—Cross-bedding in which the cross-bedded units, or sets, are bounded by planar, essentially parallel surfaces, forming a tabular body.

thalweg—The line conecting the lowest or deepest points along a stream bed or valley, whether under water or not.

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

transgressive system tract (TST)— A depositional episode that is bounded below by the transgressive surface and above by sediments representing a period of maximum flooding. The depositional environment of a TST becomes progressively deeper upward in the section.

transverse river bar—A channel bar deposit which is generally at an angle across the channel but prograding on the downstream side. This type of river deposit may be lobate, straight, or sinuous in map view.

trough cross-bedding—Cross-bedding in which the lower bounding surfaces are curved surfaces of erosion; it results from local scour and subsequent deposition.

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.

unitized—Consolidating the management of an entire oil or gas pool, regardless of property lines and lease boundaries, in the interest of efficient operation and maximum recovery.

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

water leg—A water-saturated zone that extends below an oil- or gas-saturated zone.

Notes