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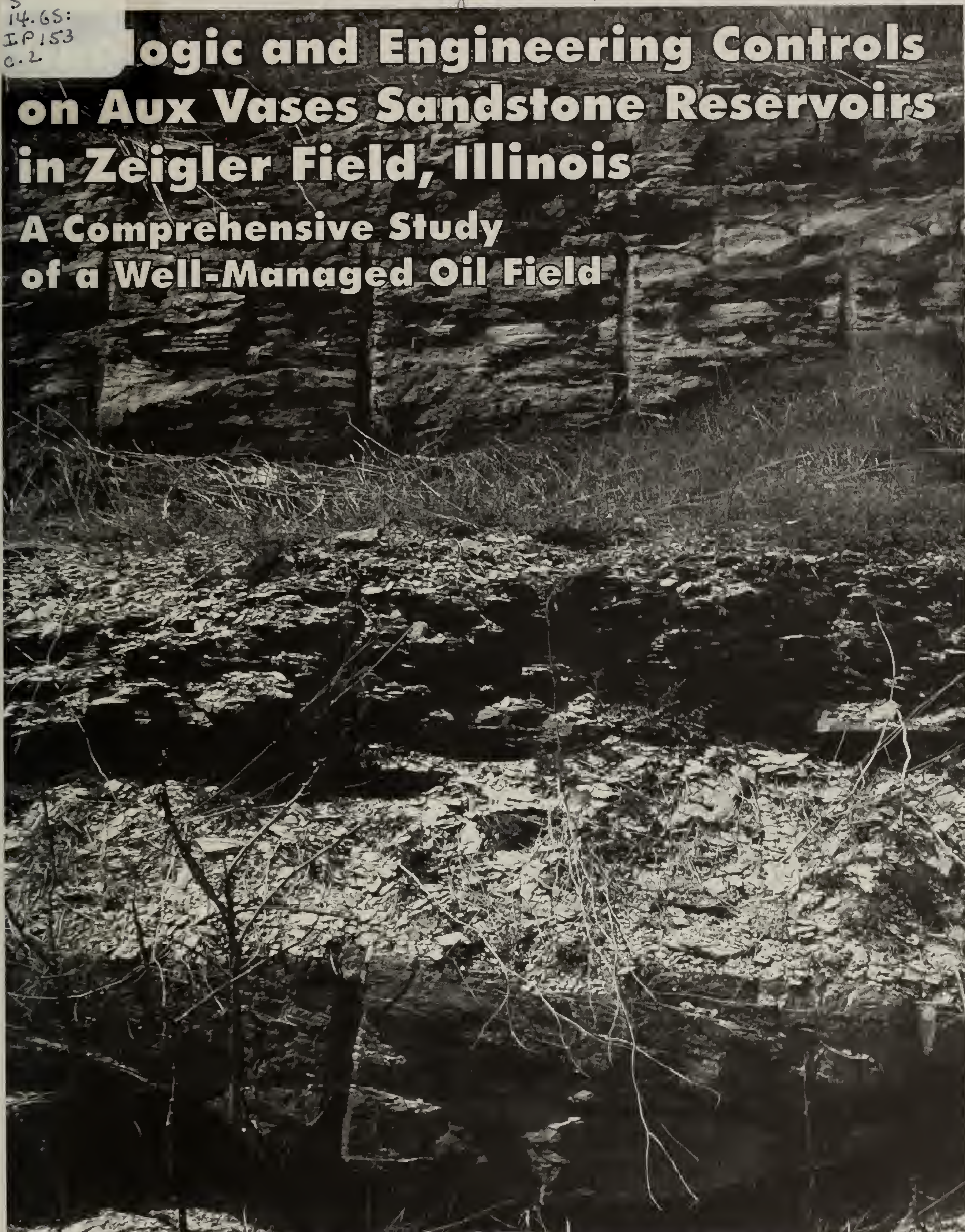
A Comprehensive Study of a Well-Managed Oil Field



Department of Natural Resources
ILLINOIS STATE GEOLOGICAL SURVEY

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A Comprehensive Study of a Well-Managed Oil Field

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EXECUTIVE SUMMARY

Zeigler Field is a typical sandstone reservoir in the Aux Vases and, because of the abundance of geologic and engineering data available, it is ideal for detailed reservoir characterization.

The purpose of this study was to describe the geologic controls on sandstone reservoirs in the Aux Vases at Zeigler Field; place the Aux Vases reservoirs in Zeigler Field in a regional context; develop depositional models (both regional and reservoir scale) for application to exploration and development of similar fields; assess the influence of diagenesis in development of reservoir qualities such as porosity and permeability; and assess the use of engineering data in monitoring reservoir behavior and management of recovery programs.

Core descriptions, porosity and permeability analyses, and cores from several wells drilled in the 1980s were donated to the Illinois State Geological Survey by Gallagher Drilling Company. These and other data were synthesized to interpret reservoir and nonreservoir facies, create isopach maps of reservoir sandstones, show and explain reservoir characteristics, locate and assess permeability barriers, and determine limits of reservoir compartments in the field.

The Aux Vases Formation at Zeigler Field was deposited by tidal processes in a shallow marine, mixed carbonate-siliciclastic environment. Cross-bedded reservoir sandstones were interpreted to be tidal sand waves deposited in a shallow marine environment. A depositional model developed using core and outcrop data shows tidal mud-flat, sand-flat, and mud-flat deposits associated with reservoir sandstone facies. Reservoir sandstones are effectively sealed by tidal-flat siltstones and shales at the top, by lower energy regime, finer grained, ripple-bedded, nonporous and impermeable sandstone at the base, and by impermeable tidal-flat and interbar deposits laterally. A statewide analysis of deposition of the Aux Vases Formation showed, in general, where sandstone bodies similar to those that produce at Zeigler Field may have been deposited in Illinois.

Two isolated and three narrowly connected and slightly overlapping sandstone bars were identified in Zeigler Field. These bars are isolated by lateral facies changes from porous cross-bedded sandstone to nonporous shaly sandstone or by very thin intervals between bars containing a large amount of interstitial calcite cement that occludes porosity and lowers permeability. The existence and magnitude of permeability barriers that separate the three bars in the main body of Zeigler Field were more readily determined using pressure data rather than using correlations of electric logs or core descriptions. Variations in pressure data documented the existence of a permeability barrier that separates the east part of the field from the west part. Pressure data showed a less complete permeability barrier separating the north part of the Plumfield lease from the south part of the lease. In this instance, fluid communication between the bars slowed through a narrow constriction.

Zeigler Field is located 3.5 miles north of the Cottage Grove Fault System; therefore, a natural system of vertical fractures observed in the underlying Ste. Genevieve Limestone is likely to project into Aux Vases sandstone bars. This natural fracture system is likely oriented subparallel to maximum horizontal compressive stresses. This hypothetical fracture system is interpreted as the control for a directional permeability trend that has led to the channeling of reservoir fluids. Channeling of fluids along fractures, coupled with the limited lateral extent of clean reservoir sandstone bars and encasement in relatively nonporous and impermeable facies, caused banking of fluids against the edges of sandbars. Wells located at bar margins that contain thinner and less porous and permeable reservoir intervals have produced twice as much oil as offsetting wells with thicker, more porous and more permeable reservoir intervals. Zeigler Field is primarily a stratigraphic trap because there is no structural closure in the field.

Diagenetic alterations have played a major role in preserving and enhancing porosity and permeability. Dissolution of feldspar framework grains has led to the formation of diagenetic clay minerals coating virtually every sand grain. These diagenetic clay minerals have prevented the precipitation of porosity-occluding quartz overgrowths and preserved porosities as high as 28% in the reservoir facies. Large amounts of early calcite cement have been dissolved in the thicker central parts of sandstone bars and enhanced porosity and permeability. Pore-lining diagenetic clay minerals present problems during reservoir evaluation and during the design of drilling, completion, and recovery programs. Low resistivities (2 ohm-meter resistivity log deflections) in reservoir sandstone intervals are very common at Zeigler Field as a result of these pore-lining diagenetic clay minerals.

Recovery efficiencies for sandstone bars in Zeigler Field are greater than the industry norm of 30% to 40% after primary recovery and waterflood operations and much greater than the 15% to 30% for other Aux Vases fields, although additional recovery is still possible. In the main body of the field, the three sandbars for which historical production data are available have an average recovery efficiency of 48% (calculated using an average porosity of 21%, a formation volume factor of 1.068, and oil saturation of 65%). The West Plumfield sandstone bar had a recovery efficiency of 45%, and the combined Plumfield and South Plumfield sandstone bars had a recovery of 51%. The greater recovery efficiency of the Plumfield and South Plumfield bars was attributed to the greater sweep efficiency and longer duration of the waterflood. The reservoir management program undertaken at Zeigler shows that much better than average recoveries are possible with an early and effective program of pressure monitoring and maintenance.

INTRODUCTION

Zeigler Field is located in southwestern Franklin County, Illinois (primarily in Sec. 18, T7S, R2E, Sec. 13, T7S, R1E, and Sec. 19, T7S, R2E), approximately 3.5 miles north of the Cottage Grove Fault System (fig. 1). The field produces from the middle Mississippian (Valmeyeran) Aux Vases Formation. It lies in an area of historical mining of the Herrin No. 6 Coal (Pennsylvanian) and is developed over the abandoned Zeigler No. 1 and No. 2 underground coal mines owned by the Zeigler Mining Corporation (fig. 2). The Herrin No. 6 Coal is approximately 10 feet thick and occurs at depths ranging from 340 to 450 feet below the surface. Most wells were drilled over open mining; the room-and-pillar mining method was also used in some areas of the field. Wells were drilled on 10-acre (660-ft) spacing.

The field has produced about 2.1 million barrels of oil from 37 wells in the Aux Vases since its discovery in 1963. It is an outstanding candidate for study because all wells in the field were drilled and completed by a single operator (Gallagher Drilling Company); all wells were cored and routine conventional core analyses were performed; and meticulous pressure and produced fluid records were kept.

Purpose and Scope

This study was sponsored by the State of Illinois and the United States Department of Energy as part of a statewide examination of the controls of reservoir heterogeneity

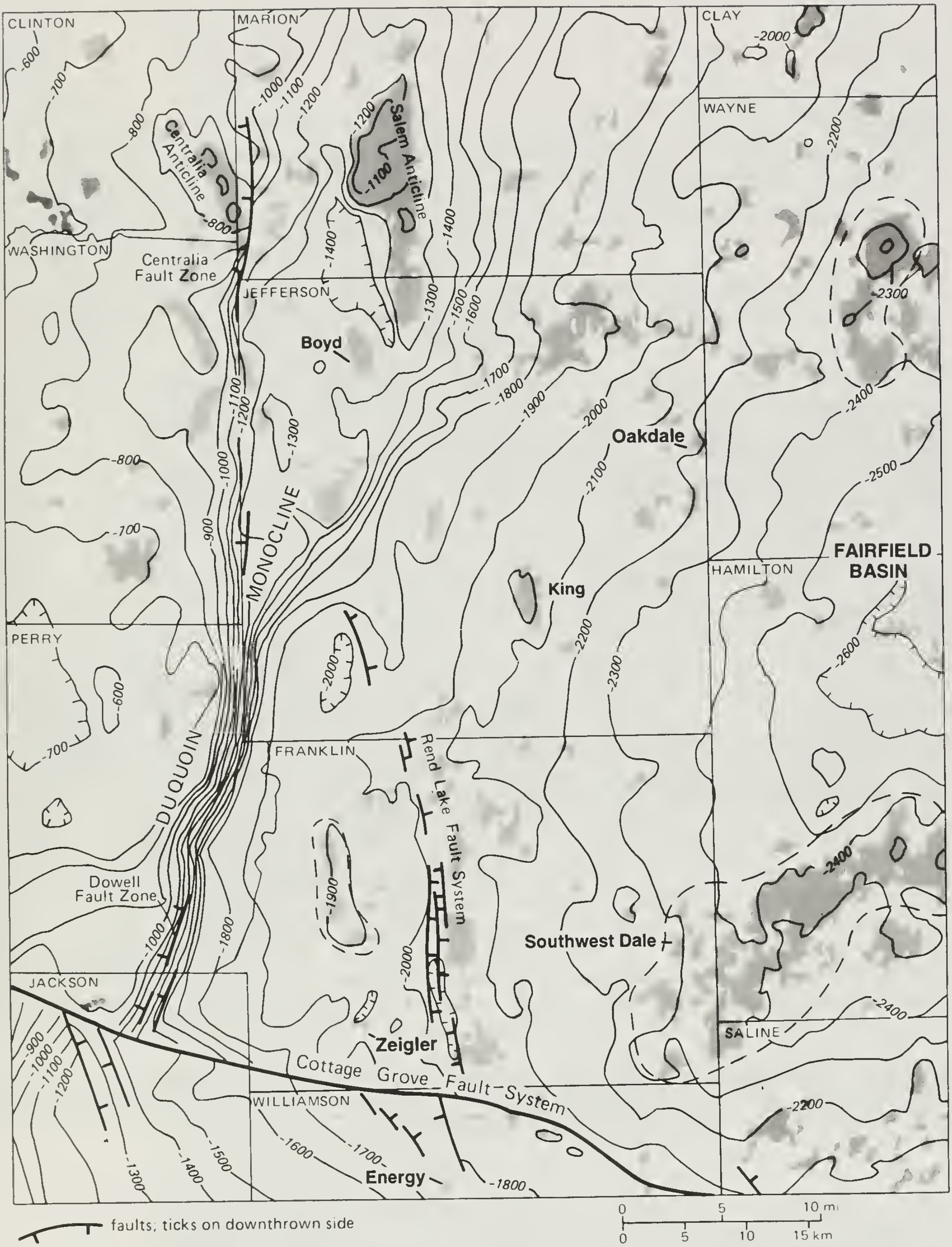


Figure 1 Regional structure map on the Beech Creek Limestone ("Barlow limestone") illustrates the location of major structural features, petroleum production (shaded areas), and Aux Vases fields characterized during reservoir studies for the U.S. Department of Energy (adapted from Nelson 1990 and Seyler and Cluff 1990).

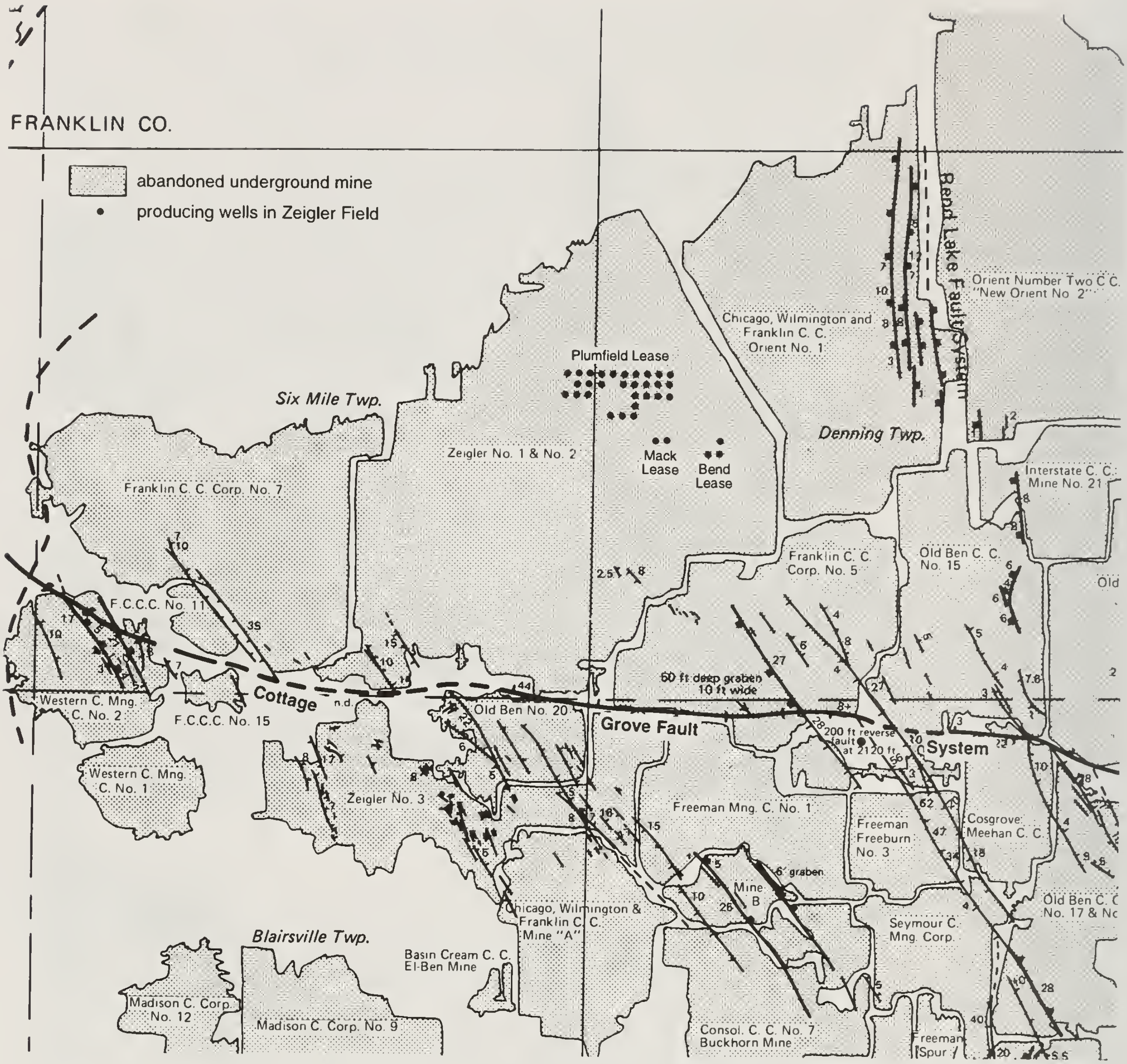


Figure 2 Areas of mined-out coal in the vicinity of Zeigler Field (adapted from Nelson and Krausse 1981). Location of oil wells in Zeigler Field and faults expressed in the coal are shown. The most common secondary faults trend northwest–southeast and intersect the master Cottage Grove Fault.

on oil recovery in two prolific Illinois reservoirs, the Aux Vases and Cypress Sandstone Formations. The sandstones of the Aux Vases Formation have been problematic, yet prolific, producing horizons in the Illinois Basin since the 1940s. In the late 1940s and early 1950s, the introduction of hydraulic fracturing in the basin made the Aux Vases a more viable drilling target. Study of regional facies in the Aux Vases is important because of the similarities found among many Aux Vases reservoirs in southern Illinois. The regional distribution of the more productive versus the less productive facies is a significant factor to consider in exploration and development of Aux Vases reservoirs.

The purpose of this study was to

- describe the geologic controls on the Aux Vases reservoirs at Zeigler Field,
- place the Aux Vases reservoirs in Zeigler Field in a regional context,
- develop depositional models (both regional and reservoir scale) for application to exploration and development of similar fields,
- assess the influence of diagenesis in development of reservoir qualities such as porosity and permeability,
- synthesize engineering and geologic data that best characterize and describe reservoir behavior and use this synthesis to optimize recovery and apply the approach to similar reservoirs.

Zeigler Field was selected because of the availability of cores from closely spaced wells, the availability of abundant data (well logs, core analyses, pressure surveys, and production information), the presence of a single producing horizon (non-commingle), and the location of the field (which allowed comparison with similar characterization studies: Southwest Dale Consolidated Field, Beaty and Fagan, in prep.; Energy Field, Huff 1993).

This and other reservoir characterization studies published as part of this overall project provide geologic input to petroleum engineering models (e.g., see Sim et al. 1994) and have been used for assessment of improved oil recovery opportunities in the Illinois Basin.

Methods of Study

A statewide map was completed to show the general regional distribution of facies and lithologic changes observed in the Aux Vases Formation. Subsurface mapping of Zeigler Field was undertaken to map the thickness, isocapacity, and structure of the reservoir sandstones and cumulative and initial production within the facies.

Subsurface structure maps encompassed a slightly larger area than the field itself and were prepared by interpreting geologic tops from wells with wireline logs. These geologic tops were entered into a spreadsheet database and matched with the Illinois State Geologic Survey (ISGS) digital well database. Well status and location information were obtained through the digital database and then plotted and verified. Elevations of selected limestone marker beds were compiled and contoured by computer and manually edited to make the structure maps. Data for sandstone thickness and elevations of the tops of sandstone bars were generated from core permeability and porosity analyses, core descriptions, and electric-log data, and then hand contoured. Surface elevations that were originally surveyed using other wells in the field for reference were checked against the 7.5-Minute Christopher Quadrangle (which was completed in 1968 and unavailable during development of the main body of Zeigler Field).

The data made available for Zeigler Field by the Gallagher Drilling Company are unmatched in Illinois. Each well drilled was cored. Porosity and permeability were measured directly from core samples at 1-foot intervals through the Aux Vases sandstone units. Cores from the Plumfield lease, the main body of Zeigler Field drilled in the 1960s, are no longer available; but they were described in detail. Cores from wells drilled after the discovery of the Mack lease in 1987 were donated to the ISGS and are in the permanent core collection. Six whole cores from dry and abandoned wells drilled on the margins of Zeigler Field were also available. Four whole cores from the Mack lease, the most prolific reservoir in the field, were described and sampled. These core descriptions were used to interpret environments of deposition of reservoir and nonreservoir facies in the Mack lease. Facies interpretations established from core data were then integrated with electric log data to identify and map reservoir and nonreservoir facies in the Mack lease. Cross sections and maps were constructed using detailed data from the Mack lease. Integration and synthesis of core descriptions, porosity and permeability, petrographic, and electric log data from the Mack lease were used for detailed reservoir characterization and allowed greater insights into reservoir behavior than could electric log data alone.

Core descriptions and electric logs from the Plumfield lease were compared with similar but more detailed data from the Mack lease. Data from the Mack and Plumfield leases were used to construct cross sections and isopachous maps of reservoir and nonreservoir facies in the Plumfield lease. Core descriptions and electric log data were also used to determine the contact of the base of the Aux Vases Formation with the top of the Ste. Genevieve Formation.

Petrographic analyses of the Aux Vases sandstone reservoir in the Mack lease included microscopic study of 61 thin sections made from core samples, in addition to x-ray diffraction (XRD), scanning electron microscope with energy dispersive x-ray spectrometer (SEM/EDX), and cathodoluminescence analyses. Rock textures such as grain size, shape, and sorting were described. Postdepositional alteration, including compaction, cementation, dissolution, fracturing, and porosity types, was studied. The composition of detrital framework grains, precipitation of secondary mineral phases, dissolution phases, and preservation, obstruction, and/or enhancement of porosity in reservoirs were also studied.

Petrographic analyses and core interpretations were compared with deflections in the spontaneous potential and resistivity logs in wells from the Mack lease. Relationships established during this comparison were used to show that subtle changes in electric log deflections may reflect facies changes and differences in reservoir quality.

Engineering data available for Zeigler Field are more complete than they are for any other field in Illinois. Production data, including monthly records of produced water and oil for each well in the field, were meticulously collected,. These data were used to track progress of waterfloods, graph and track production in the field, show sweep efficiency, and calculate recovery efficiencies. Data from pressure surveys were used to determine the limits of reservoirs, locate permeability barriers within the field, and determine efficiency of injection wells. Syntheses of pressure survey data with core descriptions and facies interpretations in the Plumfield and Mack leases were used to construct isopach, isocapacity, and reservoir facies maps, in addition to detailed descriptions of individual reservoirs at Zeigler Field. Reservoir fluids were analyzed to provide information on brine and oil characteristics.

History of Production in Zeigler Field

The discovery well, the Gallagher Drilling Company no. 1 South Plumfield, was drilled in June 1963. During 1963 and 1964, the Plumfield, South Plumfield, and West Plumfield leases were developed, and they constitute the main body of Zeigler Field (fig. 3). The field was expanded a decade later with a discovery on the Bend lease located approximately 1 mile southeast of the Plumfield leases. The three producing wells on the Bend lease are surrounded by dry and abandoned wells, which define an isolated Aux Vases sandstone bar.

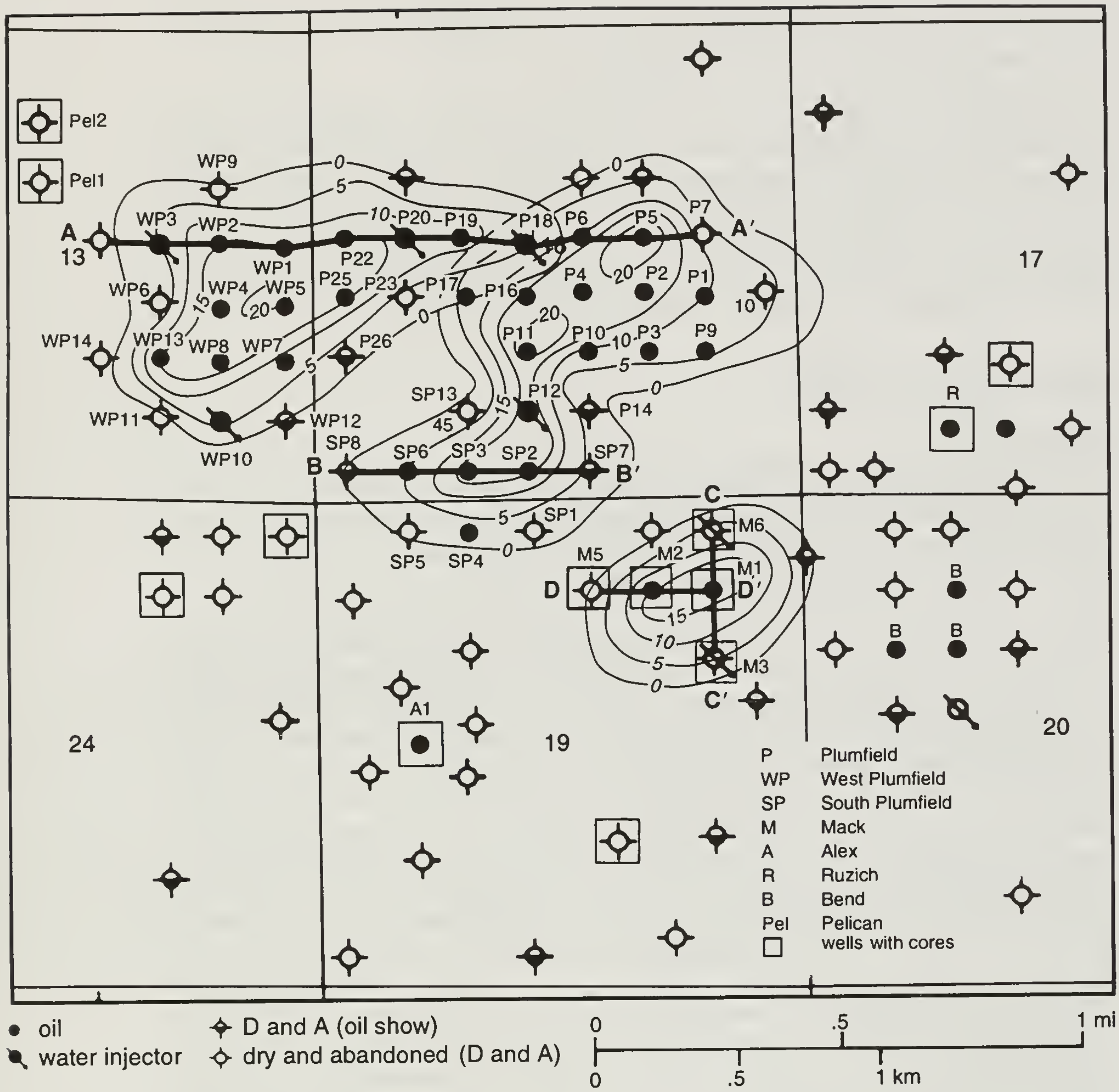


Figure 3 Zeigler Field reservoir sandstone isopach map shows well, cross-section, and available core locations. Leases are indicated by farm name in legend.

The field was further expanded in 1987 with the drilling of the Gallagher Drilling Company no. 1 Mack well. The Mack lease is another isolated pod of production in Zeigler Field. It is surrounded by dry and abandoned wells and water injection wells. The Gallagher Drilling Company no. 2 Mack is the only other producing well in this sandstone body. Improved knowledge of the small size, degree of isolation, and possibilities for discovery of other sandstone bodies has led the Gallagher Drilling Company to continue exploration nearby.

Most wells were completed open hole without stimulation. Some were shot with 10 to 60 quarts of nitroglycerin gel and placed on waterflood shortly after completion. Some peripheral producing wells that had reached their economic limit were converted into salt-water injection wells. Injected salt water was from Pennsylvanian and Cypress sandstones, and produced water was from sandstones in the Aux Vases. Varied responses to waterflooding indicated that permeability barriers were present between sandstone bodies; at least three separate sandstone lenses had been identified within the main body of the field.

Waterflooding was used to boost primary production and to maintain reservoir pressure beginning in the Plumfield lease in 1965, approximately 2 years after the initial discovery, and later in the Bend lease after its discovery in 1973. Pressure maintenance became an increasingly more important element of reservoir management during the course of field development. When the sandstone bar on the Mack lease was discovered in 1987, water injection into the north and south offsetting wells was started immediately to maintain pressure in this separate reservoir.

GEOLOGIC SETTING

Stratigraphy

The Middle Mississippian Aux Vases Formation (Valmeyeran Series) represents the first major influx of siliciclastics into a predominantly carbonate basin during late Valmeyeran time. The Aux Vases marks the transition between the underlying Valmeyeran carbonates and the largely siliciclastic Chesterian units above (fig. 4).

The Ste. Genevieve Formation was the lowest marker horizon used for mapping in this study. This unit, composed of dense oolitic gray limestone and/or grainstone, lies immediately below the Aux Vases Formation. In most instances, depths to the top of the the Ste. Genevieve Limestone have been verified by examination of cores or core descriptions. Where these data were not available, the top of the Ste. Genevieve was determined on wireline logs at the abrupt transition from low resistivity sandstone in the Aux Vases to the highly resistive, dense limestone. Most wells at Zeigler Field penetrate only the uppermost portion of the Ste. Genevieve Limestone.

Identifying the depth of the top of the Ste. Genevieve was sufficient to determine the paleotopography on which the Aux Vases was deposited. The relatively few wells that penetrated the Ste. Genevieve limited, but did not prohibit, the determination of paleotopography of the top of the Ste Genevieve and its effects on Aux Vases sand deposition. For example, although it was not possible to determine whether the deposition of sandstone bodies in the Aux Vases was influenced by a carbonate bank in the underlying Ste. Genevieve Limestone (as was found in the Southwest Dale Consolidated Field; Beaty and Fagan, in prep.), it was possible to determine the variations in the depth of the top of the Ste. Genevieve Limestone.

The Renault Limestone overlying the Aux Vases was another mappable marker horizon used in the structural analysis. The transition between the underlying Valmeyeran and overlying Chesterian units occurs within the Renault Limestone (Swan 1963). The Renault Limestone was rarely cored, and most depth calculations for this unit were determined using spontaneous potential (SP) and resistivity log signatures. Because the lithology of the lower Renault varies from a dense, oolitic gray limestone to a calcareous marine shale, determining the Renault/Aux Vases contact (fig. 4) was difficult, especially where this transition is from a fossiliferous marine calcareous shale to an Aux Vases shale. In these cases, electric logs from offsetting wells with correlative horizons of dense limestone and shale horizons were used.

Additional overlying Chesterian markers include the Downeys Bluff Limestone and the Beech Creek Limestone (drillers' term, "Barlow limestone"). Because the drillers' terms (e.g., "Barlow" and others) are routinely used and are most familar to people in the petroleum industry, they were used in this paper. The Downeys Bluff Limestone, which lies approximately 70 feet above the Aux Vases, is a consistent basinwide

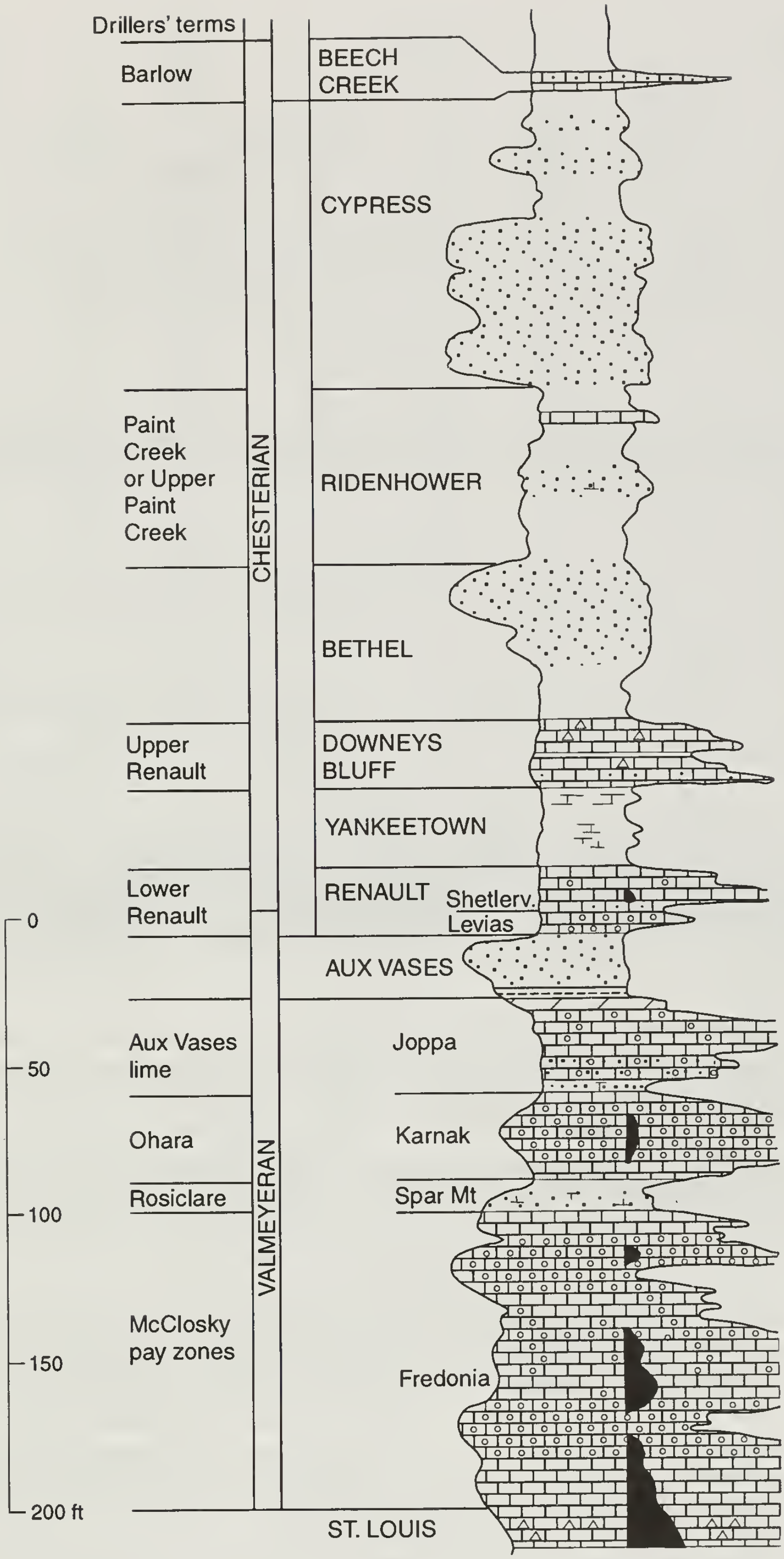


Figure 4 Generalized electric log shows vertical stratigraphic relationships. Common drillers' names are given on the left and formal stratigraphic nomenclature on the right. The log includes the transition from Middle Mississippian Valmeyeran carbonates to the predominantly siliciclastic Lower Chesterian units in southern Illinois (adapted from Swan 1963).

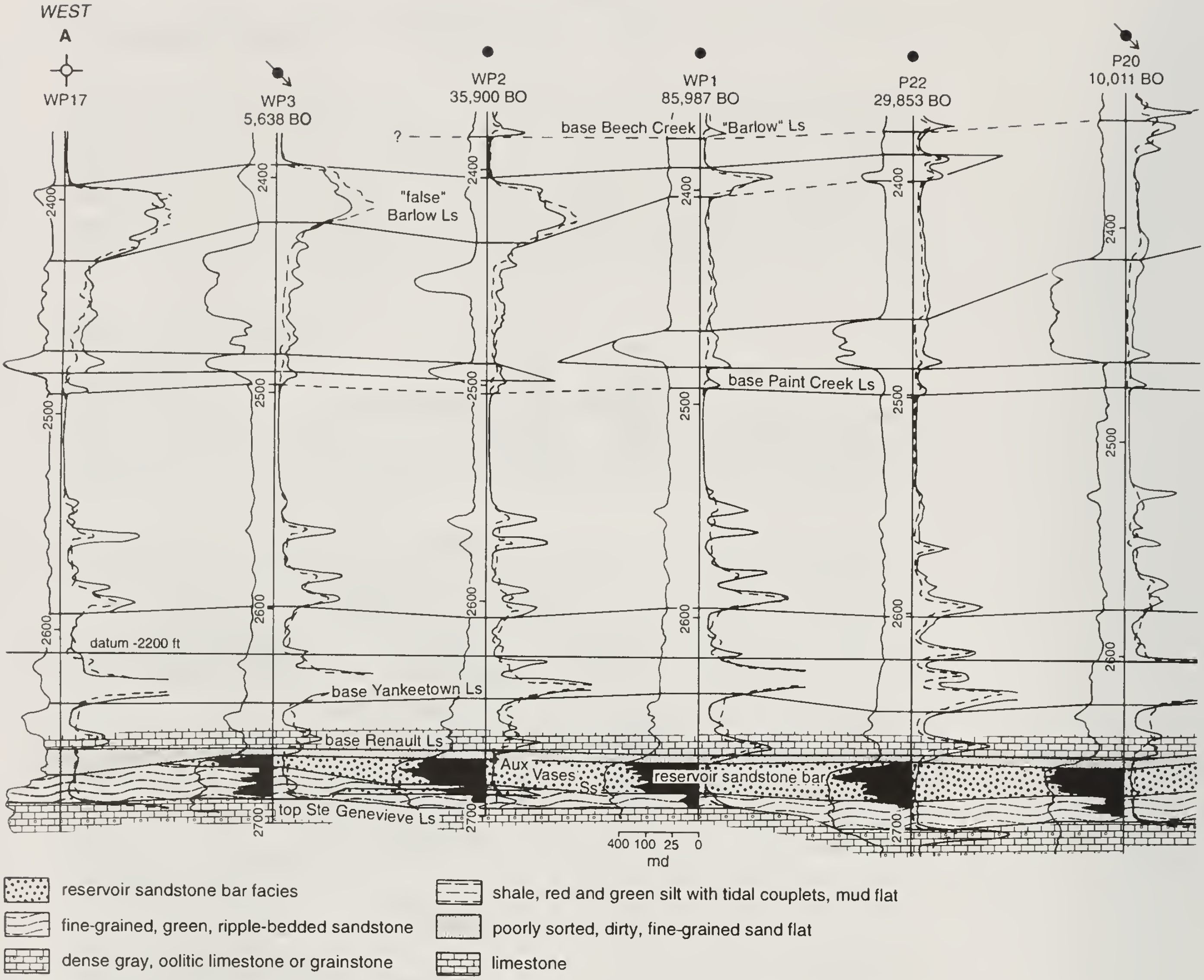
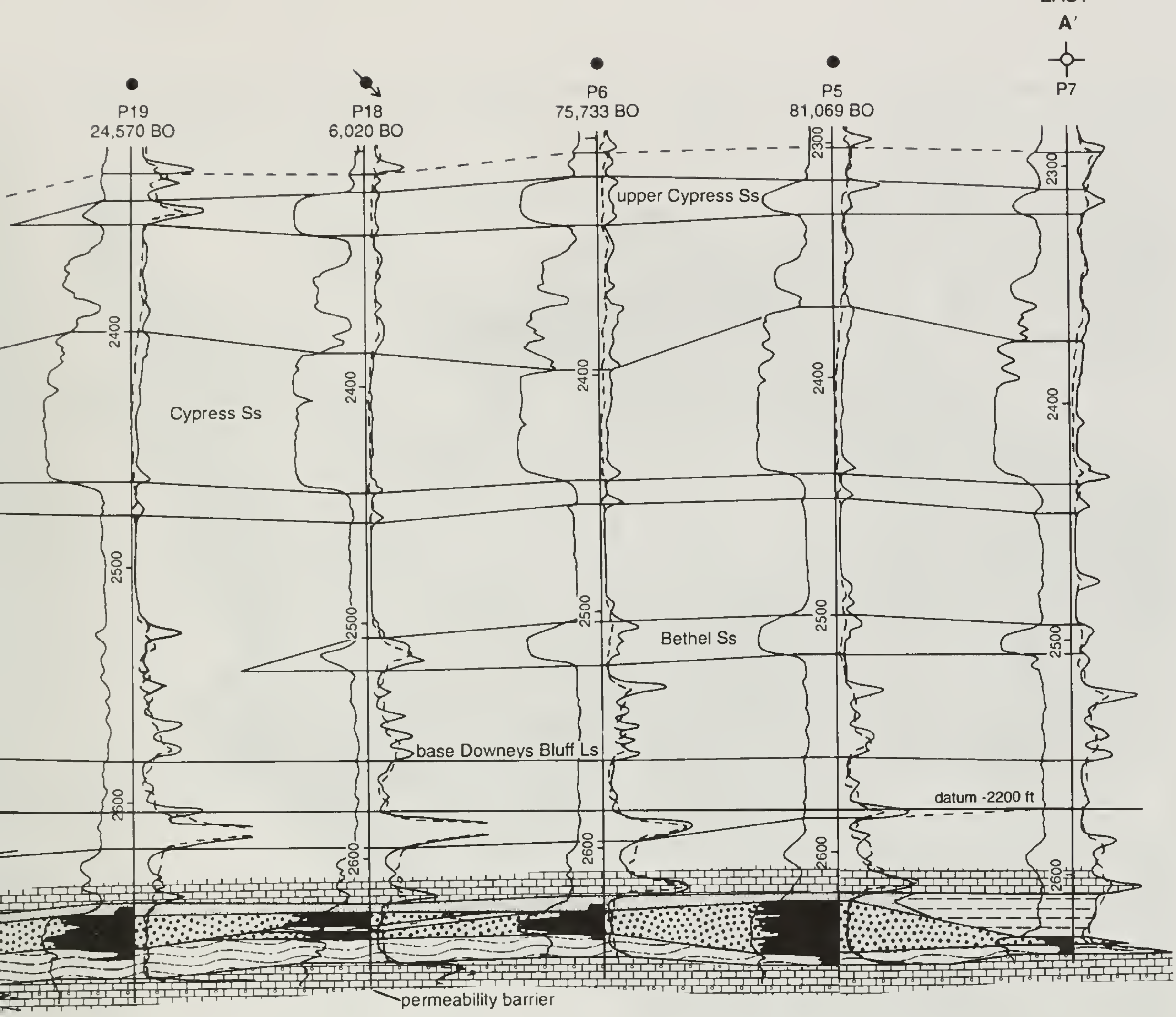


Figure 5 West–east, structural cross section (A–A′, fig. 3) of the northern part of Zeigler Field illustrates some of the correlation problems in the area. The wells are on 10-acre spacing, with distances between wells of approximately 660 feet. Permeability of the cored interval in the Aux Vases is graphed on the left side of the electric logs. Reservoir and several nonreservoir facies are indicated. Separate reservoir bars are located east and west of the permeability barrier at well no. 18.

marker horizon on electric logs. It generally contains three distinctive and highly resistant limestones separated by shales. Some logs from the Zeigler Field indicate more than three limestones; some indicate fewer than three. Siliciclastic units are sandwiched between thin limestone marker horizons in the lower Chester series. The most prominent siliciclastics are the Yankeetown Sandstone (drillers' term,"Benoist sandstone"), the Bethel Sandstone, the Ridenhower Sandstone ("Paint Creek sandstone"), and the Cypress Sandstone (fig. 4).

Lateral stratigraphic relationships Figure 5 illustrates the lateral stratigraphic relationship of these units and several of the correlation problems encountered. The Barlow limestone is the uppermost marker horizon mapped for this study. Although this unit ordinarily has one of the most consistent, widespread, and easily distinguishable electric log signatures in the Illinois Basin, it is difficult to map



in the Zeigler area. The difficulty is caused by local deposition of a lower, thicker limestone, known as the "false Barlow" (Cluff and Lasemi 1980), that underlies a very thin (in some cases, undetectable) "upper" Beech Creek Limestone ("Barlow limestone"). Examination of well cuttings from the study area shows that the "false Barlow" is made up of brown micritic limestone similar to that at Louden Field (Cluff and Lasemi 1980). The "false Barlow" at Louden Field is thought to be a channel-fill deposit. The "false Barlow" at Zeigler (fig. 5) could also be a channel-fill deposit.

A correlation problem can also occur within a locally thick (100 ft or more) salt-water aquifer in the Cypress through Bethel Sandstones. Where this aquifer occurs, it was not possible to distinguish between Cypress Sandstones and Paint Creek sandstones on electric logs (fig. 5). Therefore, correlation of these lower Chesterian units is difficult.

Regional Facies in the Aux Vases

During deposition of upper Valmeyeran and Chesterian units, the Illinois Basin was a shallow embayment open to deeper marine conditions in the region of the present Pascola Arch (Schwalb 1982). The depositional paleoslope was gentle, averaging less than 1/2 degree, and shallow marine depositional environments prevailed. No evidence of deep-water deposition or sedimentation below shelf-break conditions has been found in these units in Illinois (Seyler 1983). The Fairfield Basin was the axis of the Illinois embayment during deposition of these units, but the depocenter of

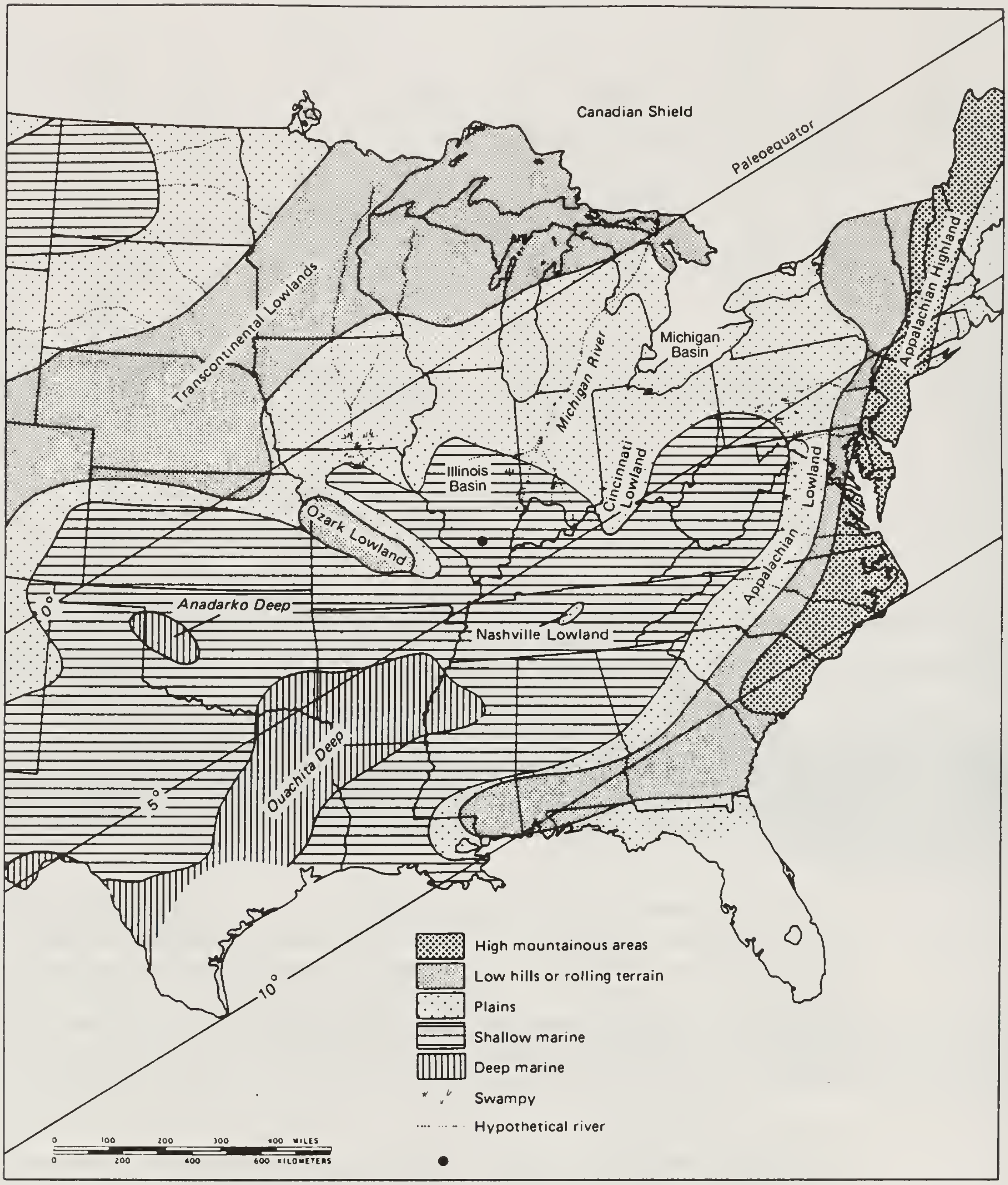


Figure 6 Paleogeographic map of eastern North America during late Valmeyeran time illustrates the approximate depositional setting of the Illinois Basin, the location of Zeigler Field, and the location of positive regions that may have been sources of sediment. The Canadian Shield and the Ozark Dome were both potential sources for Aux Vases siliciclastics (adapted from Treworgy 1985 and Craig and Varnes 1979).

the basin was located several hundred miles south of Illinois in the Ouachita Deep (fig. 6). By the end of middle Mississippian Valmeyeran time, active subsidence in the Michigan Basin had ceased (Craig and Varnes 1979), leaving an unimpeded fairway for sediment influx from the Canadian Shield into Illinois and farther south during Chesterian time and possibly earlier during uppermost Valmeyeran when the Aux Vases Formation was deposited.

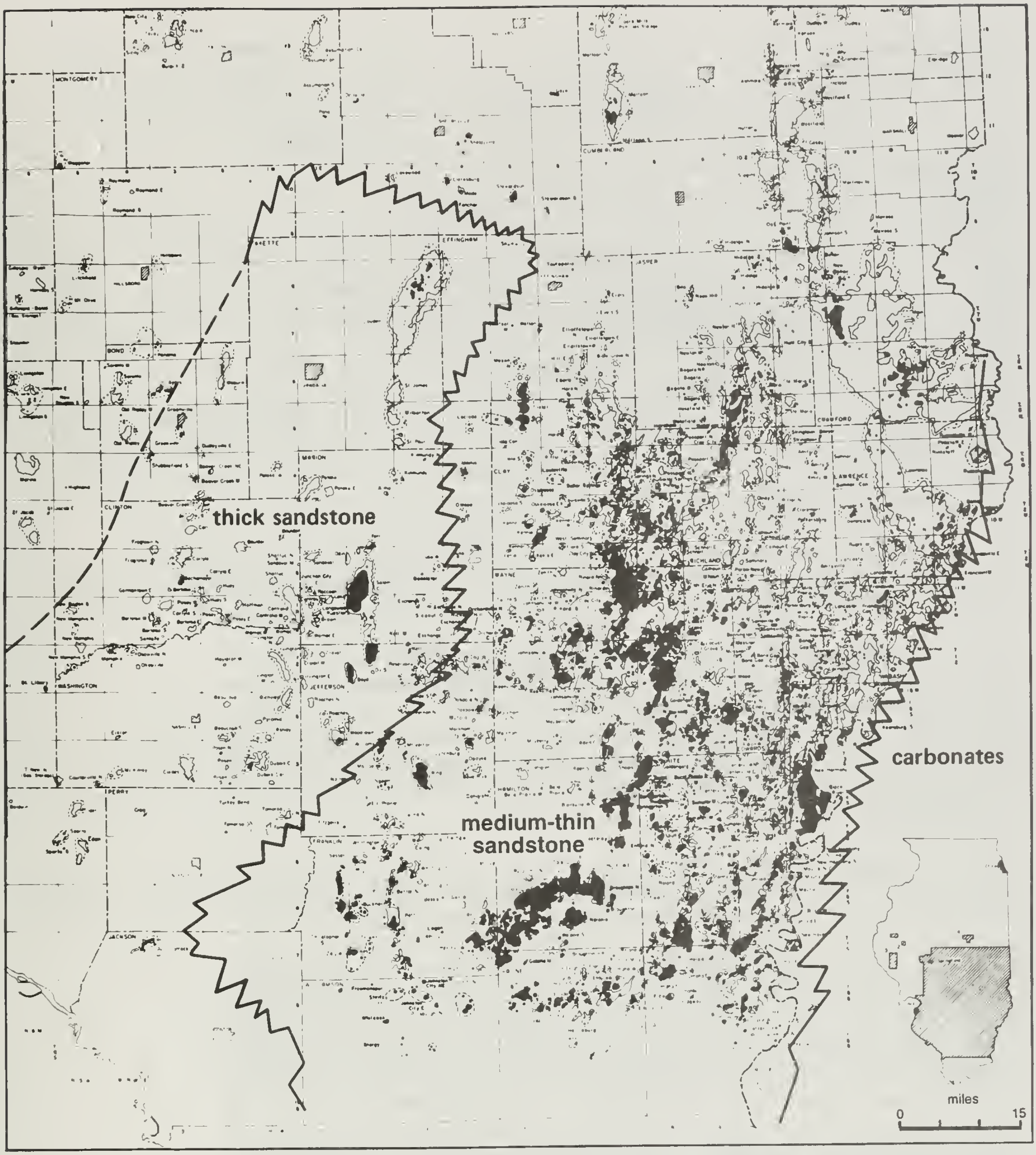


Figure 7 Distribution of broad facies belts in the Aux Vases in Illinois. Aux Vases oil fields are shaded in black (from Seyler 1986).

Three broad, regional facies belts and potential source areas have been identified across the state (fig. 7; Seyler 1986). Medium- to fine-grained sandstones on the west flank of the basin are the thickest, commonly 100 feet or greater. Aux Vases sandstone units in the most oil-productive part of the basin usually reach a maximum of 20 to 45 feet thick. They are very fine grained and may be interbedded with shale and siltstone or mixed with carbonate. Along the eastern margin of Illinois and into Indiana, the Aux Vases is more carbonate-rich, and sandstones in the formation

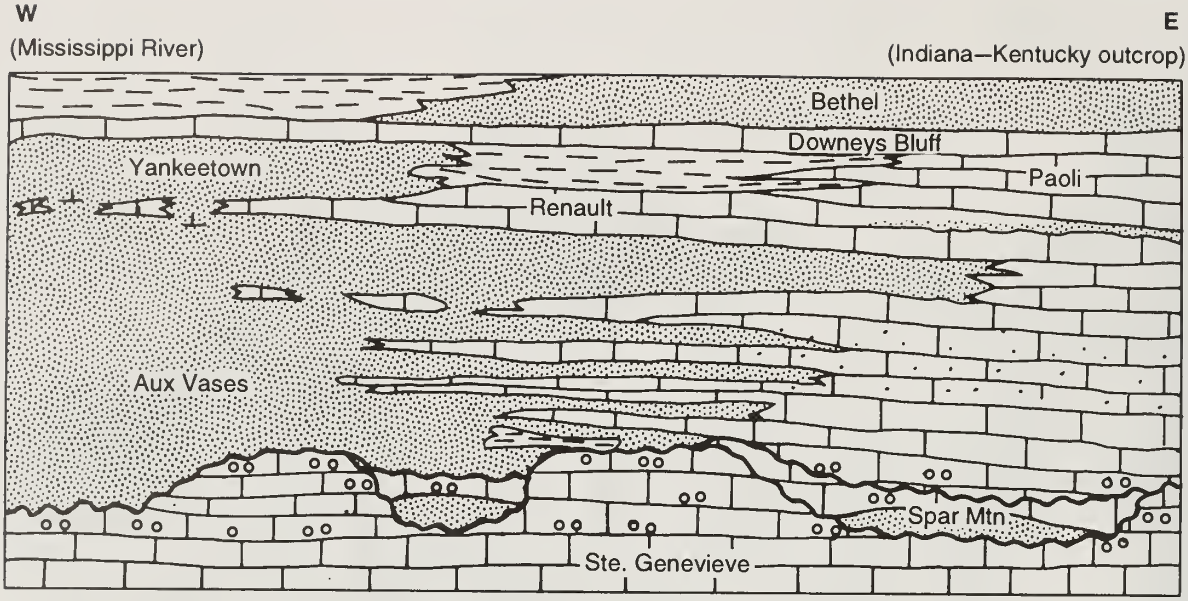


Figure 8 East–west cross-sectional view of regional facies changes in the Aux Vases Formation in Illinois. Sandstone thickness increases to the west, whereas carbonates become more prevalent to the east (adapted from Cluff and Lineback 1981).

become more isolated, finer grained, and thinner (fig. 8). The belt of thick sandstone on the northwest flank of the basin is interpreted to represent deltaic and coastal depositional environments. In the center of the basin, shallow marine environments are most common. Some siliciclastics were reworked by tidal processes into sand waves, which pinch out laterally to shale, impermeable silty sandstones, or dense carbonate grainstones. Fine-grained siliciclastic tidal-flat deposits are also common in the central part of the basin.

Thickest sandstone deposition took place in the west and northwest part of the basin, indicating that the source area for the clastics may have been either the Canadian Shield to the north, or the Transcontinental Arch or the Ozark Lowlands to the west (fig. 6). Thick, reservoir-quality Aux Vases sandstones in the proximal area in western Illinois represent widespread nearshore coastal and deltaic environments, but they are rarely oil-productive. Aux Vases production occurs where there is significant structural closure, which is presumably a necessary trapping mechanism in these thick sandstones that lack lateral facies changes (which form seals). With few exceptions, most Aux Vases petroleum production in the Illinois Basin is from central belt reservoirs (like Zeigler Field), which contain moderately thick (20–45 ft) sandstones deposited in a mixed siliciclastic-carbonate environment. Petroleum reservoirs become less common in eastern Illinois and Indiana, where the Aux Vases becomes more carbonate-rich, because sandstone bodies with good reservoir qualities are less common.

Structural Geology

Regional setting Zeigler Field is 3.5 miles north of one of the major tectonic features in southern Illinois, the Cottage Grove Fault System. The east-west-trending master fault system is composed of multiple high-angle faults with strong indications of oblique, right-lateral strike-slip movement (Nelson and Krausse 1981).The region of the study area is relatively downthrown. Subsidiary splinter faults are oriented obliquely to the trend of the fault and strike mainly northwest to southeast (fig. 2).

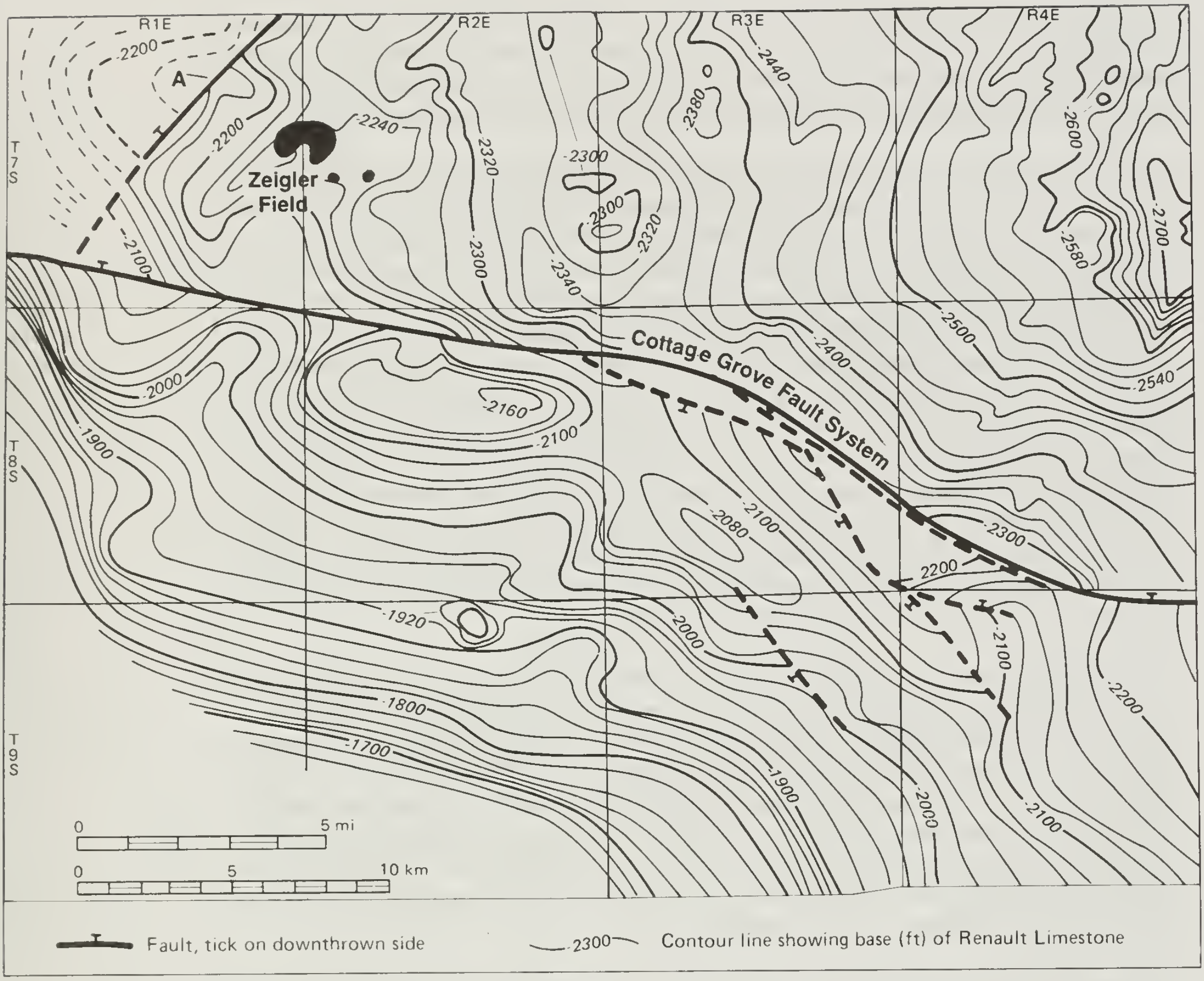


Figure 9 Structure contour map of base of the Renault Limestone in part of Franklin and Williamson Counties (adapted from Nelson and Krausse 1981).

Nelson and Krausse (1981) suggest these secondary faults formed as a response to maximum extensional stresses during right-lateral strike-slip movement along the Cottage Grove Fault System. Right-lateral strike-slip movement along the Cottage Grove Fault System occurred after middle Pennsylvanian and before Pleistocene time, but the lack of middle Pennsylvanian through Pleistocene units precludes pin-pointing the time of movement more closely.

A structure contour map of the base of the Renault Limestone (fig. 9) shows the master fault zone in nearly the same position as it is in Pennsylvanian coals (Nelson and Krausse 1981), although the Renault Limestone lies approximately 1,900 feet below the Pennsylvanian coals. In addition, Nelson and Krausse (1981) mapped a north-east-southwest-trending fault in the Renault Limestone about 4 miles west of Zeigler Field (fig. 9, fault A). This fault, which may intersect the Cottage Grove master fault, does not correspond to any known structure in Pennsylvanian units, suggesting that movement may have occurred before deposition of Pennsylvanian units or that the fault did not penetrate upward to the Pennsylvanian units (Nelson and Krausse 1981).

The presence of these faults indicates that the Aux Vases sandstone reservoirs at Zeigler have been subjected to regional stresses and localized tectonic activity likely to have caused natural fracturing. The wells at Zeigler Field were highly productive, but they were not hydraulically fractured, as is the normal practice for Aux Vases wells. Hydraulic fracturing apparently was not necessary at Zeigler because high permeability and a system of natural fractures provided adequate drainage.

The strain gauge measurements reported by Nelson (ISGS, pers. comm. 1993) gave maximum horizontal compressive stresses of S67°E in shale beds above coal seams in the vicinity of Zeigler Field. Modern regional stress fields become extremely important if hydraulic fracturing is used for well completions. Induced fractures will be aligned in a direction subparallel to these maximum horizontal compressive stresses and may be augmented by natural fractures oriented in this same direction. According to Beaty and Fagan (in prep.), the maximum horizontal compressive stress ($_H$) trends approximately east–west in the region surrounding Dale Consolidated Field, a field with Aux Vases reservoirs similar to those found in Zeigler Field. There are some indications that $_H$ may trend in west–northwest throughout the Zeigler Field study area (Nelson and Bauer 1987), paralleling the trend of the Cottage Grove Fault system. The impact of this phenomenon on the orientation of natural and human-induced fracture systems and the potential for creating channelized flow in Aux Vases reservoirs at Southwest Dale Consolidated Field is discussed in Udegbunam et al. (1993) and in Beaty and Fagan (in prep.).

At Southwest Dale Consolidated Field, hydraulic fracturing of Aux Vases reservoirs increased the size of natural fractures because they were both oriented in the same east–west direction (Udegbunam et al. 1993, Beaty and Fagan, in prep.). This enlargement led to an ineffective waterflood in the field because injected water was channeled through the enlarged fractures rather than spread throughout the reservoir. The lack of an effective sweep of the reservoir sandstone led to early water breakthrough and bypassing of mobile oil. Therefore, knowledge of the orientation of naturally occurring fractures is needed to avoid channelized fracturing, if a reservoir is hydraulically fractured prior to waterflooding.

Trap mechanism at Zeigler Zeigler Field is located on a structural plateau, as mapped on the top of the Ste. Genevieve Formation (fig. 10). A structural nose south of Zeigler Field and a depression northeast of the field (figs. 1, 10) have no apparent influence on the trapping or production of petroleum in this field.

No pronounced structural closure exists on any mappable Mississippian limestone horizon, and production is limited to porous and permeable parts of bar sandstones. Subsurface mapping at Zeigler indicates that stratigraphic encapsulation of reservoir-quality sandstones is the primary trapping mechanism. Zeigler is therefore classified as a stratigraphic trap. Many other Aux Vases fields in the Illinois Basin are combination traps where sandstone reservoir bodies are situated upon structural noses or within distinct anticlinal closure. Consequently, most exploration models for Aux Vases reservoirs have relied heavily on the drilling of positive structures. However, it is apparent from this and other Aux Vases studies (e.g., the Energy Field study of Huff 1993) that structural entrapment is only of secondary importance for some Aux Vases reservoirs.

Middle Mississippian faulting in the vicinity of Zeigler Several lines of evidence indicate that local faulting played a role in influencing deposition of Chesterian siliciclastics in the region. Because there is an abrupt change in the thickness of the Cypress Formation across the field, faulting may have occurred during Chesterian time at Zeigler Field. Cypress sandstones range from more than 100 feet thick on the east side of the field to less than 30 feet on the west side (fig. 5). The break in

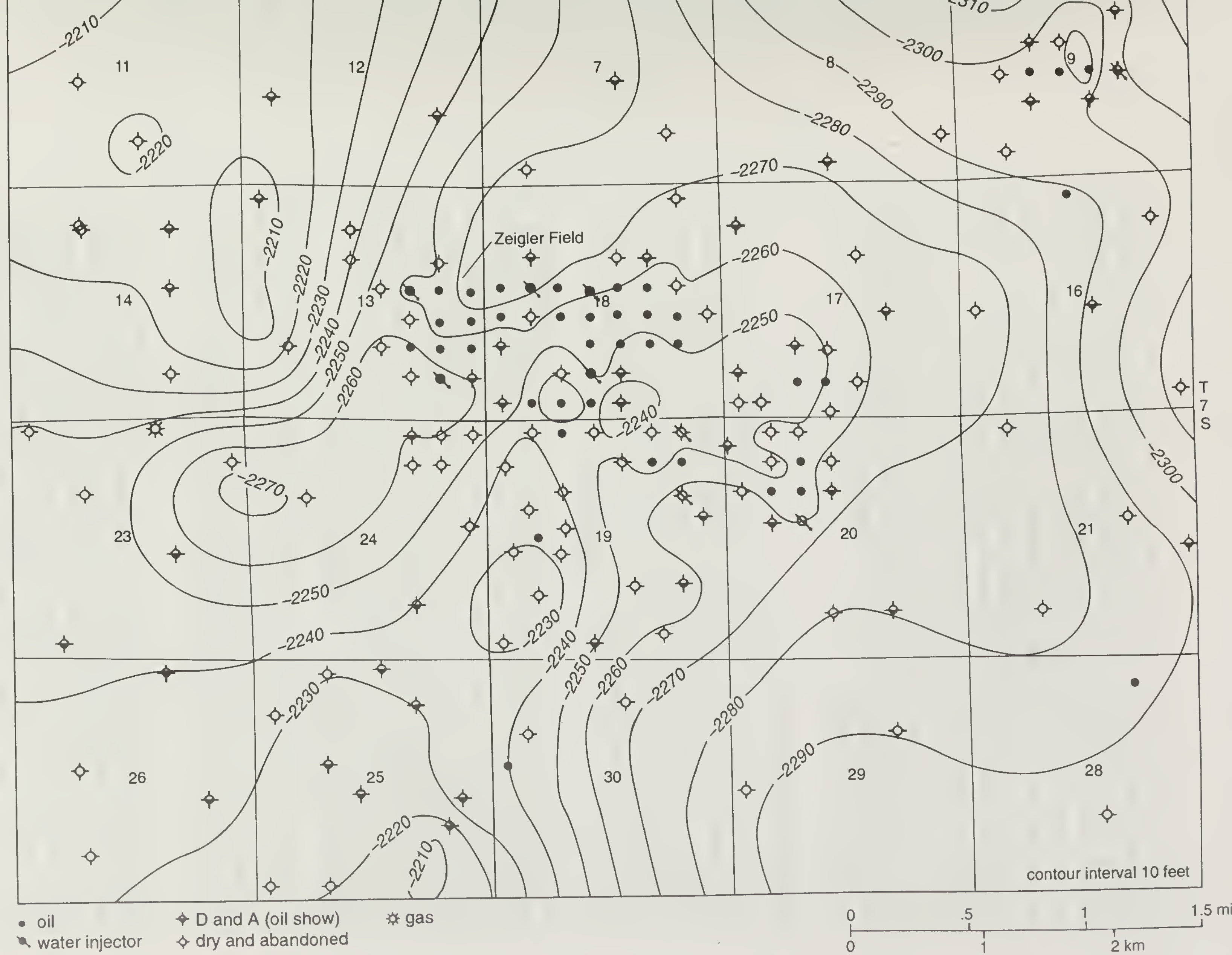


Figure 10 Structure on the top of the Ste. Genevieve Limestone shows a slight saddle but no structural closure at Zeigler Field.

Cypress sandstone thickness approximately coincides with a permeability barrier (fig. 5) that separates the east side from the west side of the field. A thick "false Barlow" (fig. 11) also coincides with this pressure break and the thinner Cypress sandstone. The fault mapped in the Renault Limestone by Nelson and Krausse (1981), near the west edge of Zeigler Field (fig. 9, fault A), is not present in younger Pennsylvanian units. Healed calcite-filled microfractures in the Ste. Genevieve Limestone below the Aux Vases and in the Renault Limestone above, as well as open fractures in Aux Vases sandstones, indicate several periods of fracturing prior to, during, or after major strike-slip movement along the Cottage Grove Fault System. This evidence indicates several possible episodes of faulting during the middle Mississippian in the region of the Cottage Grove Fault System. Multiple vertical fractures with parallel alignment and oil-staining in the Ste. Genevieve in many cores from Zeigler Field also indicate that a natural system of vertical fractures was the migration path for petroleum in this region.

FACIES CHARACTERISTICS

The Mack lease is typical of the Aux Vases reservoirs in Zeigler Field and other Aux Vases reservoirs throughout the region and was therefore used as a type model for Zeigler Field in this study. It is the most productive and most recently drilled reservoir in the field, and it provided much of the data for this study (fig. 3). Comparisons of core descriptions with porosity and permeability data, as well as electric log signatures of the Plumfield leases in the main body of the field, showed that these reservoirs exhibit a high degree of similarity to the reservoir in the Mack lease.

Data available for this study included a continuous core, 4 inches in diameter, taken from 2,605 to 2,627 feet subsurface in the Gallagher Drilling Company no. 2 Mack, a producing well on the Mack lease. Several large pieces of whole core and an excellent set of segmented core biscuits were also available for analysis from the Gallagher Drilling Company no. 1 Mack, currently the most productive well in Zeigler Field. Data from other wells in the Mack lease include a continuous core from 2,625 to 2,640 feet in the Gallagher Drilling Company no. 3 Mack, a water injection well; a continuous core from 2,611 to 2,637 feet in the Gallagher Drilling Company no. 5 Mack, a dry and abandoned well; and a continuous core from 2,602 to 2,633 feet in the Gallagher Drilling Company no. 6 Mack, a water injection well.

Since its discovery in 1987, the Mack lease has produced 133,000 barrels of oil from two producing wells and a negligible amount of water. The no. 1 Mack produced an average of 100 barrels of oil per day, and the no. 2 Mack produced an average of 50 barrels of oil per day. Neither well produced water during the first 5 years of production. Water breakthrough occurred in 1992.

Reservoir and nonreservoir facies in the Aux Vases and their lithologic and electric log characteristics are described beginning with the statigraphically lowest deposits. The Gallagher Drilling Company no. 2 Mack was used as the type well for describing Aux Vases sandstone reservoir facies in Zeigler Field (fig. 12). Some reservoir sealing and nonreservoir facies are not present in the Gallagher Drilling Company no. 2 Mack; therefore, the Gallagher Drilling Company no. 3 Mack (fig. 13), no. 6 Mack, and no. 2 Pelican wells were used as the type logs for many nonreservoir facies.

Ste. Genevieve Limestone: Nonreservoir Unit

The Ste. Genevieve Limestone (middle Mississippian Valmeyeran) directly underlies the Aux Vases Formation (fig. 4). The uppermost part of the Ste. Genevieve

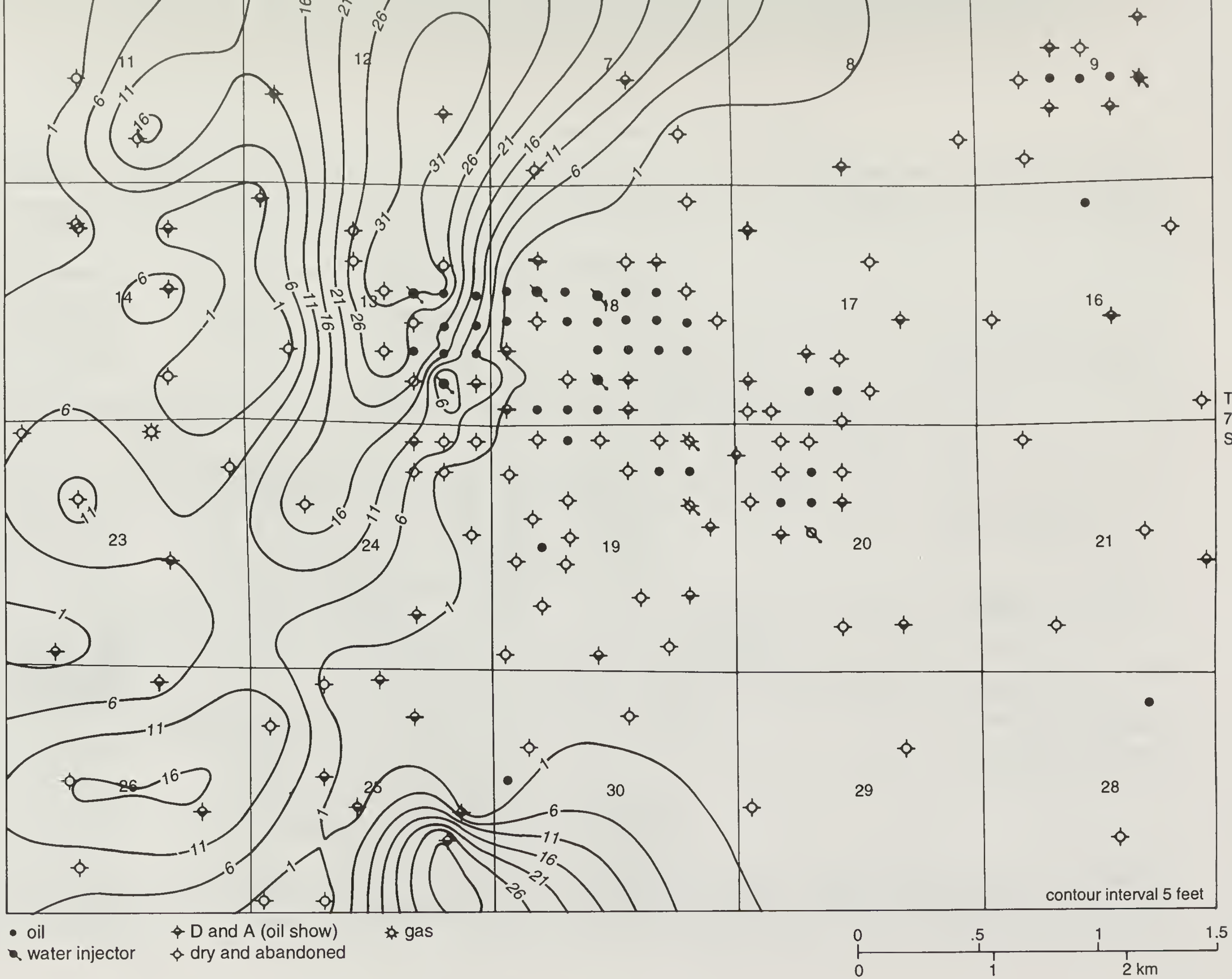
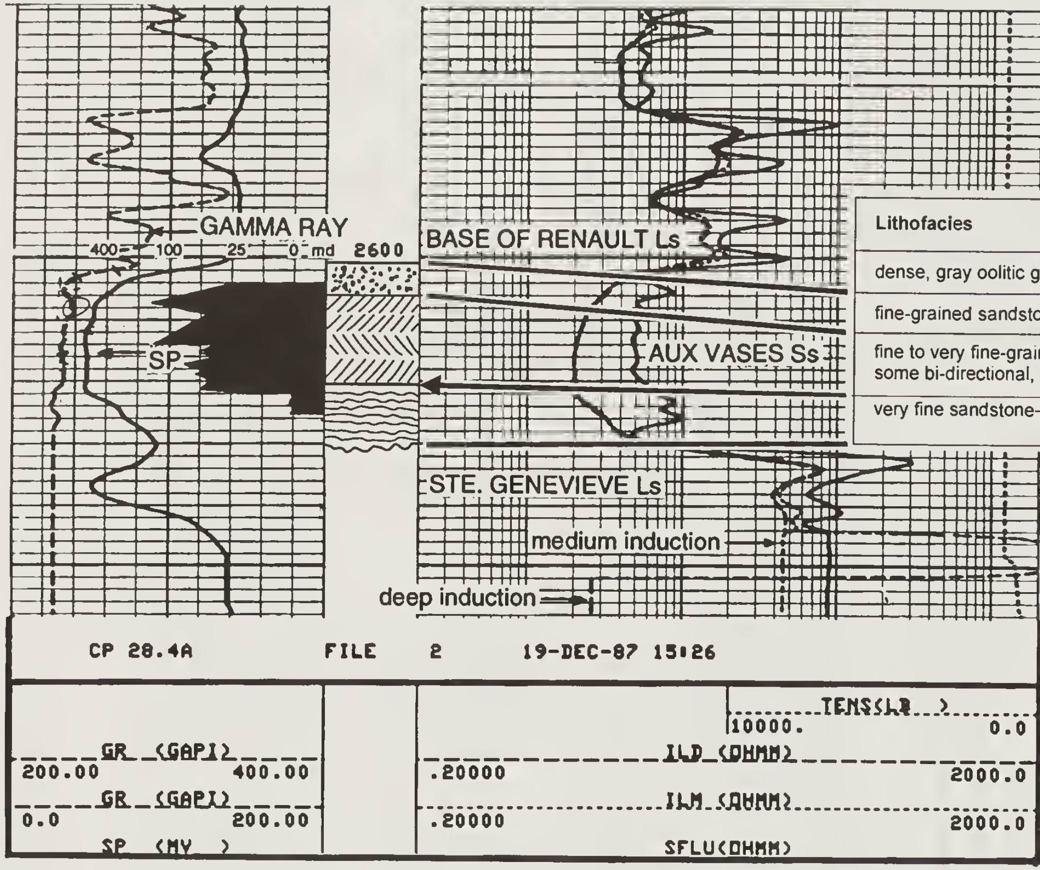
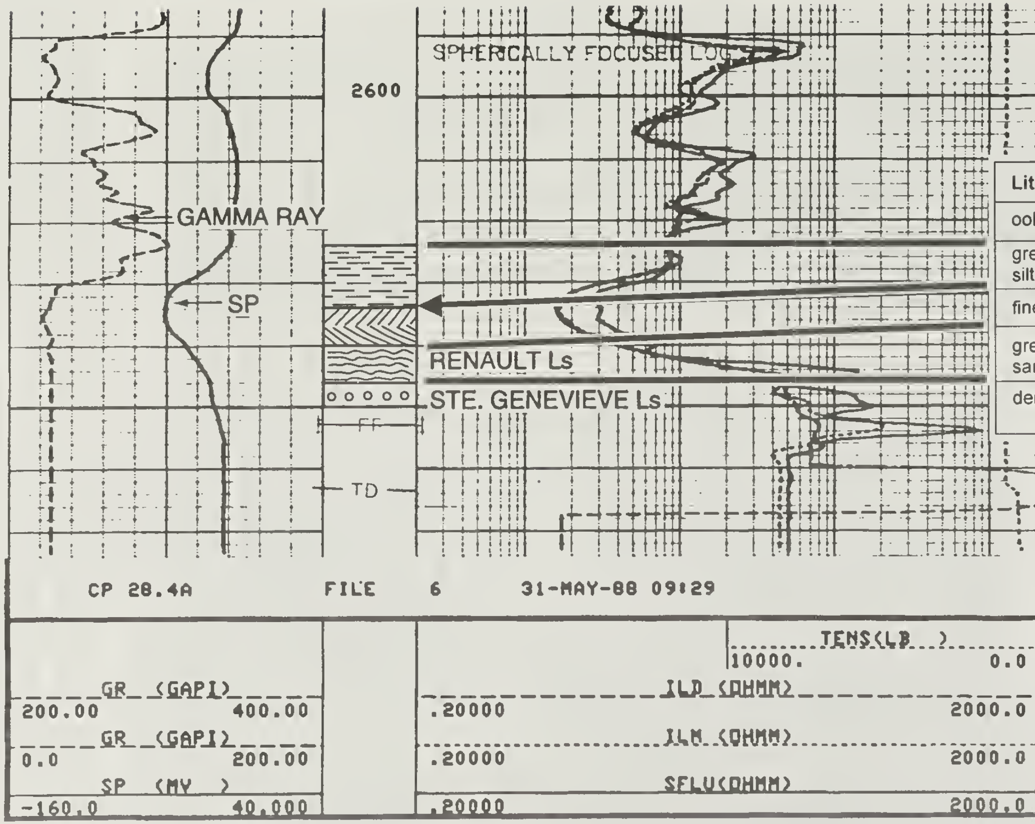


Figure 11 Isopach map of the "false Barlow" in the Zeigler Field region. The east side of this band of "false Barlow" coincides with the east side of the west bar of the Plumfield lease at Zeigler Field, suggesting some deeper structural control on sand deposition.



Lithofacies	Environments of Deposition
dense, gray oolitic grainstone	shallow marine oolite shoals
fine-grained sandstone, poorly sorted, nodules, oil-stained	intertidal sand flat
fine to very fine-grained sandstone, well-sorted, cross-bedded, some bi-directional, brown, oil-stained	subtidal sandbar
very fine sandstone–siltstone, ripple-bedded, green and tan	mixed flat shallow subtidal to intertidal

Figure 12 Typical log of a producing well in Zeigler Field from the Gallagher Drilling Company no. 2 Mack well. Core permeability is plotted in log scale along with the SP curve on the left side of the log. Permeability, measured at 1-foot intervals, illustrates a large degree of internal reservoir heterogeneity within the reservoir interval. Subtle variations in spontaneous potential and resistivity represent major facies changes and their transitions from reservoir to nonreservoir units (shown by arrow). In this instance, only the cross-bedded sandstone bar and sand-flat facies are oil-saturated, and only the sandstone bar facies has high porosity and permeability. The reservoir interval in this well has a resistivity of 2 ohm-meters, which is typical of all other producing wells in the field.



Lithofacies	Environments of Deposition
oolitic grainstone	shallow open marine, carbonate
green and red shale interlaminated with siltstone, tidal couplets, rootlets	tidal mud flat
fine-grained, cross-bedded sandstone	sandbar
green ripple-bedded very fine-grained sandstone and siltstone	mixed flat
dense, gray styolitic, oolitic, grainstone	shallow open marine, oolite shoals, carbonate platform

Figure 13 Log, core description, lithologies, and interpretation of environments of deposition from the Gallagher Drilling Company no. 3 Mack. Tidal mud-flat deposits are prominent in this injection well, but they are absent in the highly productive no. 1 and no. 2 Mack wells. An abbreviated thin cross-bedded sandbar unit is present in this well. Arrow points to the transition from the porous and permeable cross-bedded unit (sandbar environment) to the relatively nonporous and impermeable tidal-flat siltstone and shales.

Limestone in Zeigler Field is typically a dense, gray, styolitic, oolitic, vertically fractured, cross-bedded limestone or a dense, gray, bioclastic grainstone (fig. 14) that separates the Valmeyeran carbonates below from the Aux Vases siliciclastics above. The contact between the Ste. Genevieve Limestone and the overlying Aux Vases Formation is unconformable and abrupt. The contact is commonly overlain by a tightly cemented conglomerate that is a lag deposit.

The reservoir facies of the Aux Vases does not come into direct contact with the uppermost Ste. Genevieve Limestone at Zeigler Field. In most wells the Ste. Genevieve Limestone is overlain by the green, ripple-bedded sandstone facies of the Aux Vases. In some instances, however, other nonreservoir facies of the Aux Vases form an abrupt, unconformable contact with the underlying Ste. Genevieve.

The contact between the carbonates of the upper Ste. Genevieve Limestone and the sandstone of the lowermost Aux Vases can usually be determined using resistivity logs (fig. 12). Where carbonate-rich zones in the lower Aux Vases are present, however, they are not easily distinguishable from the Ste. Genevieve Limestone on electric logs.

Aux Vases Formation—Conglomerate Facies: Nonreservoir Unit

The conglomerate facies is composed of pebbles derived from ripped-up green siltstones, shales, fine-grained sandstone, phosphate rock, and carbonates in a gray micritic carbonate matrix (fig. 14). Clasts in the conglomerate are usually rounded and were lithified prior to being ripped up. Some clasts were derived from siliciclastic facies within the Aux Vases Formation. The conglomerate facies is usually found at the contact between the Ste. Genevieve Limestone and the Aux Vases Formation. This unit is thickest (about 1 ft) and contains the largest clasts when it occurs at the contact. Where present, it is 1 to 6 inches thick elsewhere in the section. Thinner conglomerate zones with green shale rip-up clasts have been observed in the lower, middle, and upper portions of the Aux Vases Formation in cores from dry and abandoned wells surrounding Zeigler Field. The conglomerate facies is thin and does not contrast with other units enough to have a distinctive signature in wireline or electric logs. Rocks from the conglomerate facies are tightly cemented and do not contain measurable porosity or permeability. Therefore, if extensive, the conglomerate facies could form a reservoir seal or contribute to compartmentalization in reservoirs by forming an impermeable bounding surface between reservoir sandstones.

Storm surge interpretation of environment of deposition The conglomerates are high-energy deposits. They probably represent storm surges where sediments were ripped up and later redeposited during the waning phases of the storm. Storm surges may be aligned with tidal currents, thereby adding to the erosional intensity of the surges. Erosion and sand migration downcurrent are greatest during the most intense storm surges (Reading 1978). Winnowed pebbles or storm lags may be formed in some areas, while other areas will show other erosional features and still other areas will be the sites for deposition of eroded sediments after the storm. Therefore, the features produced by storm surges will vary from place to place and may not be traceable from well to well.

Thick conglomerates near the contact of the Ste. Genevieve and Aux Vases Formations in many wells at Zeigler Field show that there was a major erosional storm event affecting a large area. Thinner conglomerates containing smaller clasts are not as extensive and represent lesser storm events.

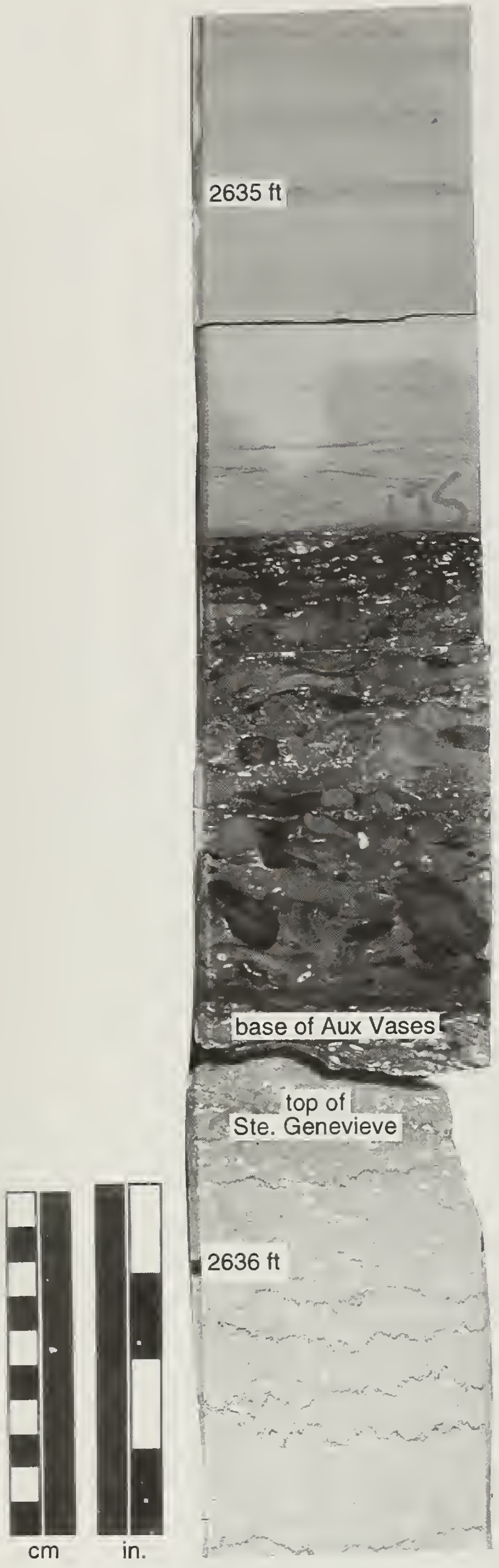


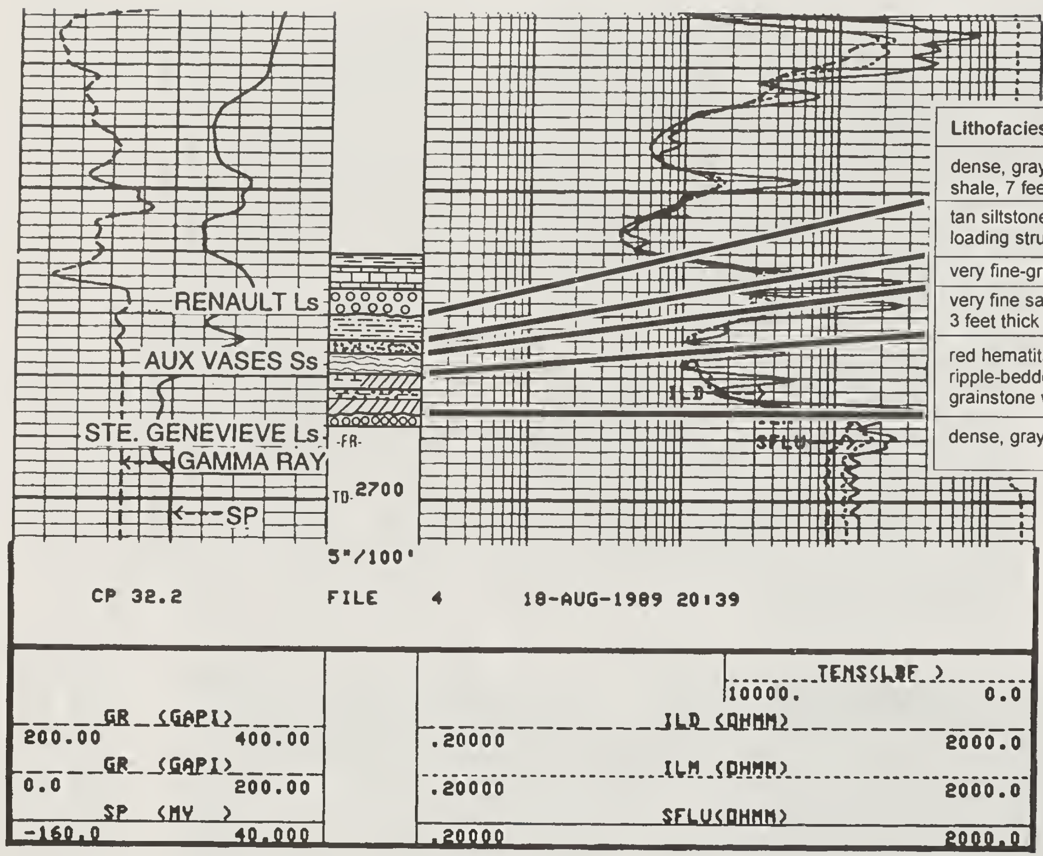
Figure 14 Dense, impermeable and nonporous, gray, styolitic, oolitic and crinoidal Ste. Genevieve Limestone directly underlies a conglomeratic bed and then the green, ripple-bedded facies of the Aux Vases in the Mack lease at Zeigler Field (sample from the Gallagher Drilling Company no. 6 Mack at 2,635–2,636 ft).

Aux Vases Formation—Cross-Bedded Hematitic Grainstone Facies: Nonreservoir Unit

Cross-bedded, hematite-rich grainstone has been found in outcrops and cores from the Gallagher Drilling Company no. 2 Pelican (fig. 15) and no. 1 Pelican wells, northern offsets of Zeigler Field. This grainstone, usually 1 to 3 feet thick, consists of coated bioclasts primarily from open, shallow marine carbonate environments; and it occurs above the contact with the Ste. Genevieve Limestone. It is generally associated with a green, ripple-bedded, mixed-flat sandstone. This facies is usually calcite-cemented and has no measurable porosity or permeability. In addition, it unconformably overlies the Ste. Genevieve Limestone in the no. 2 Pelican at Zeigler. No scouring into underlying siliciclastic or carbonate units has been observed in core or outcrop, but the lower contact is abrupt.

Tempestite or migrating channel interpretation of environment of deposition Extensive lateral deposits of migrating low- to high-angle, trough cross-bedding, hematite-coated carbonate grains and large rounded red shale and other clasts indicate that this facies represents migrating tidal channel deposits (Seyler 1986) or storm-generated tempestites. The great lateral extent of the trough cross-bedded grainstone indicates a single major episode of deposition. Incorporation of large rounded clasts and coated grains in the facies indicates high energy. The presence of hematite in the matrix and coating carbonate grains indicates a shallow oxidizing environment. A single high-energy event such as a storm carrying shallow marine carbonate grains from offshore onto intertidal deposits is a likely environment of deposition for this facies.

The cross-bedded hematitic grainstone facies is evidenced by an increase in resistivity in logs from the no. 2 Pelican well (fig. 15). Limestones in the Aux Vases are most easily recognized on electric logs when siliciclastic units separate them from the underlying Ste. Genevieve Limestone. For the no. 2 Pelican, because a tidal-channel grainstone directly overlies the Ste. Genevieve Limestone, the contact between the Aux Vases and the Ste. Genevieve cannot be identified from the electric log characteristics (fig. 15).



Lithofacies	Environments of Deposition
dense, gray oolitic grainstone, some interbedded green shale, 7 feet thick	shallow marine, oolite shoals
tan siltstone, green shale, ripple-bedded, soft sediment loading structures, rip-up clasts, 5 feet thick	intertidal tidal flat
very fine-grained sandstone, oil stained, one foot thick	intertidal sand flat
very fine sandstone–siltstone, ripple-bedded, green and tan, 3 feet thick	intertidal mud flat
red hematitic, cross-bedded bioclastic grainstone 2 feet thick, ripple-bedded sandstone 3 feet thick, red cross-bedded, grainstone with coated bioclasts, 2 feet thick	storm-generated, migrating tidal channels at contact
dense, gray, styolitic, oolitic grainstone	shallow open marine, oolite shaols

Figure 15 Description and interpretation of lithologies and sedimentary structures show tidal deposition of nonreservoir facies at Zeigler Field. Tidal-channel, tidal-flat, and mud-flat deposits observed in core correspond with electric log characteristics. These features are similar to those found in outcrop (fig. 30). Core is from the Gallagher Drilling Company no. 2 Pelican.

Aux Vases Formation—Green, Ripple-Bedded Sandstone Facies: Reservoir Seal

The green, ripple-bedded facies is commonly found in the lowermost Aux Vases at Zeigler. It also is common in the middle and upper portions of the Aux Vases in association with the green and red shale facies. In the lowermost Aux Vases, this facies has an abrupt, unconformable basal contact with the underlying Ste. Genevieve Limestone in many wells, but the contact can be transitional. This facies is between 3 and 16 feet thick and is composed of ripple-bedded and climbing ripple-bedded, extremely fine-grained, well-sorted sandstone, silt, and green shale (fig. 16). The amount of green shale varies; in some instances, the total amount is low (%) and confined to wispy flaser laminations that may drape ripples. As the amount of green shale increases, the thickness and frequency of continuous, wavy-bedded shale layers increases, forming wavy bedding. Localized carbonate-cemented zones containing fragments of fossils (brachiopods, bryozoans, and crinoids) characteristic of shallow-water, open-marine conditions may also be present in the green, ripple-bedded sandstone facies.

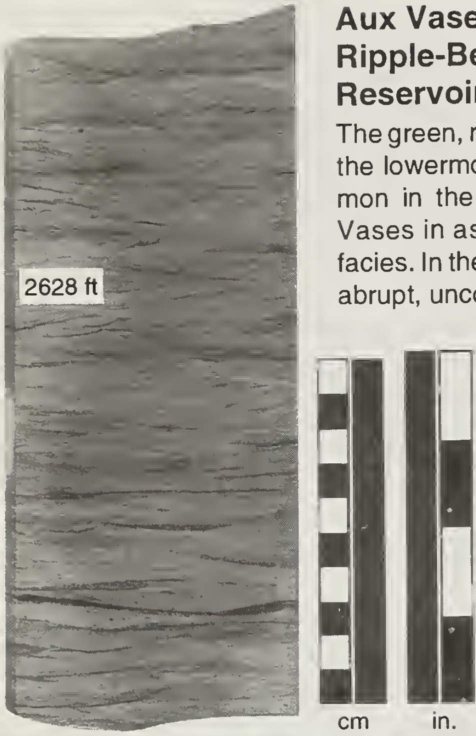
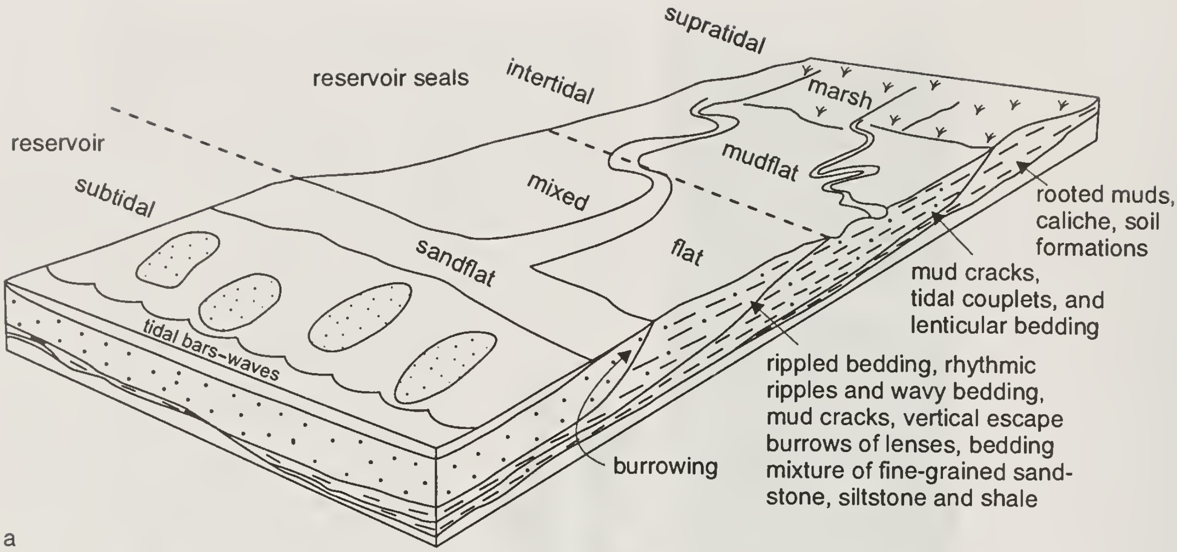


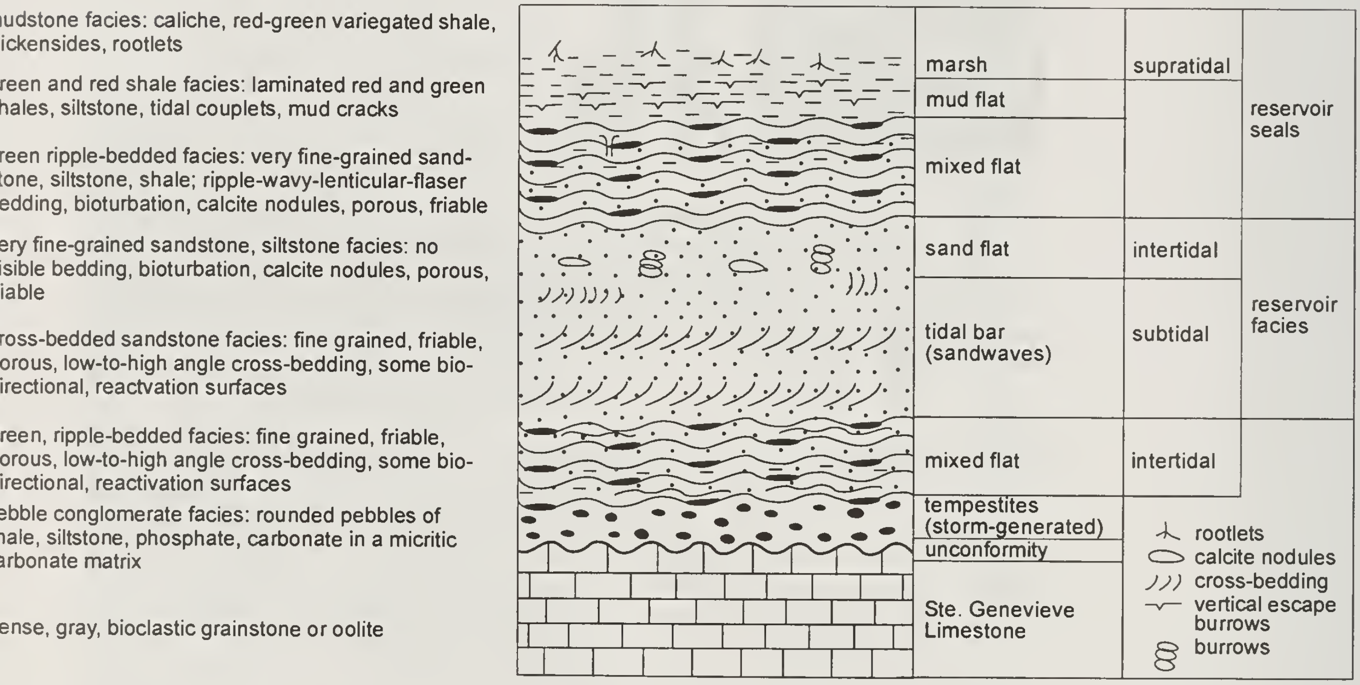
Figure 16 Ripple-laminated, extremely fine-grained, green sandstone and siltstone facies underlying the reservoir cross-bedded sandbar facies through much of Zeigler Field (sample from the Gallagher Drilling Company no. 2 Mack at 2,628 ft).

Tidal mixed-flat interpretation of environment of deposition Mud cracks found in some shale partings of this facies are diagnostic features that prove periods of subaerial exposure. The mud cracks occur most commonly in zones containing other evidence of intertidal deposition. The abundance of ripple, flaser, and wavy bedding and mud cracks indicates that the green, ripple-bedded sandstone facies was deposited by tidal processes in a shallow subtidal to intertidal environment by low- to moderate-energy regimes in a mixed-flat environment.

A model depicting the interpretation of deposition by tidal processes in subtidal-to-intertidal-to-supratidal zones for much of the Aux Vases Sandstone is shown in figure 17. A large (macro) tidal range typically produces broad tidal flats that become finer grained in a landward direction toward high-tide level and can be subdivided into sand-flat, mixed-flat, and mud-flat facies (fig. 17). The mixed-flat facies is a mixture of fine-grained sand and mud and is deposited by tidal currents in the intertidal zone. This facies forms a transition from the sand flat deposits at low-tide level and the mud flats at high tide. Transition from sand flats, through mixed flats, to mud flats and salt marshes is usually gradual, resulting from a decrease in tidal-current speeds in a landward direction (Dalrymple 1992).

Variations in the thickness of this facies in the lowermost Aux Vases across the field suggest that the green, ripple-bedded facies filled in areas that were topographically low (fig. 5). The green, ripple-bedded facies typically has a negligible amount of





igure 17 (a) Block diagram of tidal-flat, reservoir-sealing facies deposited in the intertidal zone in a macrotidal setting. The tidal flats ne in a landward direction toward the high-tide level, progressing gradually from sand flats to mixed flats and then to mud flats. Salt arshes may be deposited in the supratidal zone. The reservoir tidal sandbars or sand waves are deposited in the subtidal zone off-hore. (b) Vertical fining-upward sequence caused by prograding tidal flats in Zeigler Field.

permeability (0.1 md), and porosity is usually less than 3%, although it can be as high as 10%. Therefore, the green, ripple-bedded sandstone facies is not a reservoir-quality sandstone and may be a reservoir seal in some instances. Petrographic examination of the fine-grained sandstones showed sand grains tightly cemented by quartz overgrowths. The intergranular porosity was totally occluded by the addition of this silica cement.

The transition from the green, ripple-bedded sandstone into the overlying sandstone bar reservoir facies is usually abrupt, but it can be transitional. Electric logs show an increase in resistivity from the reservoir facies to the green, ripple-bedded facies, particularly in the focused log (fig. 12). These changes in electric log characteristics can be subtle if the contact is transitional. However, porosity and permeability increase markedly in the transition zone to the reservoir-quality, cross-bedded sandstone facies. Distinguishing the various sandstone facies in the Aux Vases by electric logs is important, especially when the cores are not available. Otherwise, reservoir volumes and reserves may be overestimated.

The lowest parts of the green, ripple-bedded sandstone facies may contain large amounts of calcite cement derived from Aux Vases limestones or from the underlying Ste. Genevieve Limestone. Nevertheless, resistivities are much higher in the Ste. Genevieve Limestone than they are in the green, ripple-bedded sandstone facies (fig. 12) unless a localized zone of carbonate cement occurs in the ripple-bedded sandstone.

Aux Vases Formation—Cross-Bedded Sandstone Facies: Primary Reservoir

The reservoir sandstone is composed of distinct bodies of fine-grained, friable, bidirectionally cross-bedded, brown, oil-stained sandstone overlying the green, ripple-bedded, silty sandstone facies. The sandstone bodies have a convex-upward geometry relative to the datum (fig. 18; B–B′ in fig. 3). They have been interpreted as sandstone bars. Porosity ranges between 20% and 28%, and permeability ranges between 50 and 800 md in the reservoir facies. The cross section of the sandstone reservoir in the Plumfield lease highlights the convex-upward geometry better than the similarly shaped sandstone reservoir in the Mack lease.

Low- to high-angle cross bedding is the most common sedimentary structure observed in cores of the reservoir sandstone bar facies (fig. 19). Locally, the facies shows bidirectional cross bedding. The cross bedding is composed of dark, oil-stained, coarser grained, porous laminae alternating with lighter colored, finer grained, less porous laminae. This alternation introduces a high degree of bedding-scale reservoir heterogeneity in sandstone bars. Because cross bedding is the dominant sedimentary structure, the alignment of alternating porous and nonporous laminae causes greater horizontal than vertical permeability measurements in the reservoir. The best reservoir qualities occur where the overall grain size is coarser than very fine-grained sandstone, and the coarser grained cross-laminae are much thicker than the finer grained laminae. Petrographic examination of samples from the sandstone bar facies showed that they have large amounts of intergranular porosity and sand grains loosely cemented by diagenetic clay mineral coatings. A few carbonate-cemented samples representing localized zones contain abundant fragments of fossils typical for a shallow open-marine environment.

Electric log characteristics of the sandstone bar facies include a large spontaneous potential (SP) deflection and extremely low resistivity (2 ohm m). These values are unusual for oil-producing zones, in general, but common for Aux Vases sandstone reservoirs (fig. 12). Such low resistivities usually indicate a porous zone filled with salt water. Here, however, they occur because of bound salt water trapped in the pore-lining clay minerals described later.

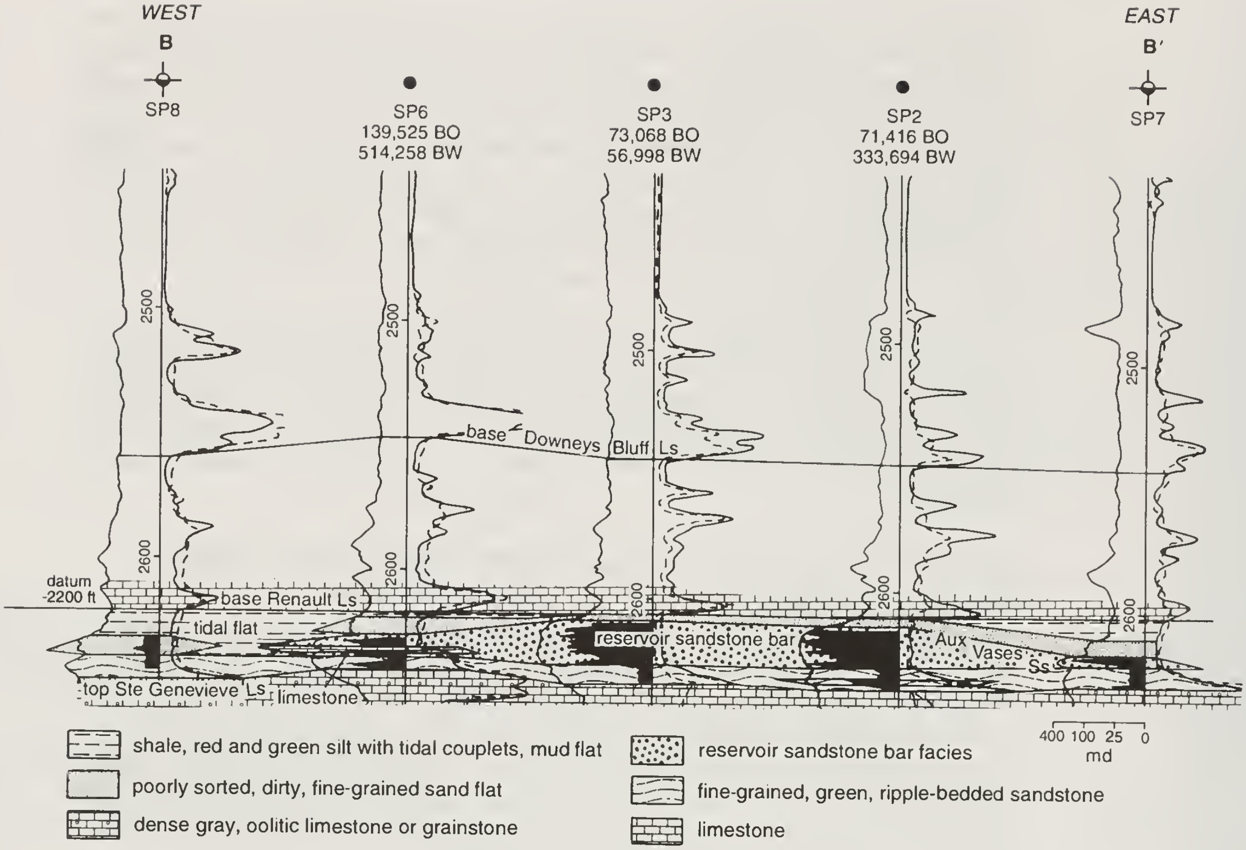


Figure 18 West–east cross section (B–B′ fig. 3) shows permeability, facies, and electric log relationships in the South Plumfield lease in the main body of Zeigler Field. The sandbar in this lease is separate from the one producing in the Mack lease to the south and thins to the east and west. The cross section illustrates effective recovery of petroleum by waterflood sweeping against bar edges. The best cumulative production (139,000 BO) was produced from the thinnest and least permeable zone in well no. 6 at the edge of the bar. The cross section also highlights the convex-upward, lenticular geometry of sandstone bars at Zeigler.

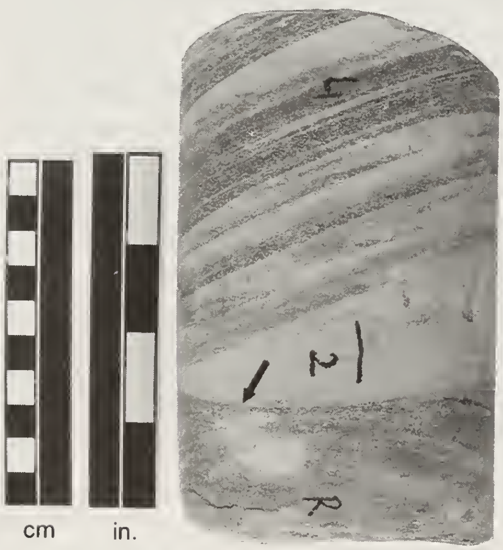


Figure 19 Close-up of bidirectional low- to high-angle cross bedding, the dominant sedimentary structure in the cross-bedded sandstone facies. A reactivation surface (arrow) separates low cross-bed strata from high-angle cross beds. Alternating light and dark laminae correspond to alternating finer grained, less porous, tan laminae and coarser grained, more porous, oil-stained, dark laminae (sample from the base of the reservoir sandstone interval in the Gallagher Drilling Company no. 1 Mack at a depth of 2,631 ft).

Tidal bundle interpretation of environment of deposition for reservoir facies

Figure 17 shows an interpretation of the cross-bedded, fine-grained sandstone reservoir facies as tidal sandbars or sand waves deposited in an open coastal environment offshore of the sand-flat portion of the tidal flat. Cluff and Lineback (1981) and Smith and Nelson (1996) have suggested an eolian sand dune origin for the cross-bedded facies. The close association of the cross-bedded reservoir facies with tidal-flat deposits and the presence of bidirectional cross bedding leads this author to the conclusion that this facies has a tidal origin. The accretionary cross bedding observed in outcrops can be attributed to tidal deposition in the sand-flat facies of the intertidal zone or in a tidal-bar facies of the subtidal zone (fig. 17).

The likely origin for the cross bedding in this facies is traction or current deposition (fig. 20; Nio and Yang 1991). Bidirectional dips indicate tidal origin.

It is possible that the cross-bedded reservoir facies are tidal bundle deposits. A tidal bundle sequence deposited by a successive series of dominant currents (fig. 21) is made up of large-scale, cross-bed bundles separated by thin mud drapes or erosional reactivation surfaces. Each bundle represents deposition during a single dominant current stage. Neap bundles are deposited during neap tides when the dominant currents are weak. Spring bundles are deposited during spring tides when the dominant currents are strong. Neap bundles are therefore thinner than spring bundles. The cross bedding shown in figure 18 could be a cross section through part of a tidal bundle. Erosional reactivation surfaces may separate set boundaries (figs. 19, 21).

Reactivation surfaces are erosional surfaces developed within cross-stratified sets. They are diagnostic of tidal deposition when they are produced during dominant and subordinate flows (Yang and Nio 1985). Reactivation surfaces are formed most frequently when ebb and flood tides are nearly symmetrical.

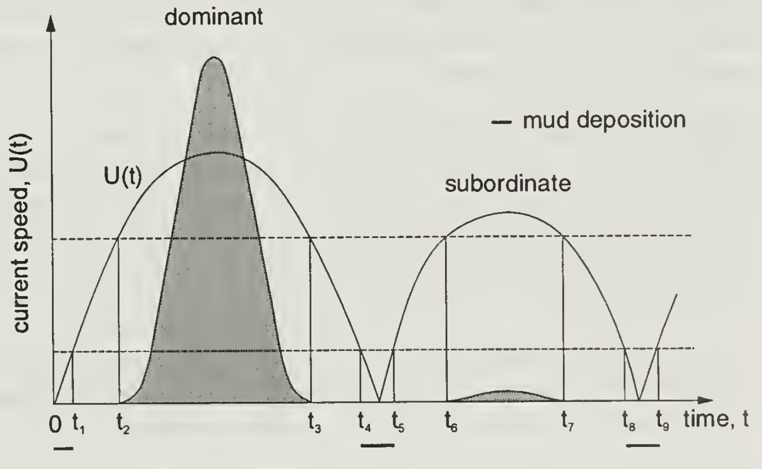


Figure 20 Model depicting deposition and transport of sand and mud during one strongly asymmetrical tidal cycle. In strongly asymmetrical tides, or where ebb and flood tidal channels do not coincide, the dominant current above the threshold velocity is responsible for most sand movement. The subordinate tidal current may be so weak that sand transport is negligible. Mud is deposited during the two slack-water periods (from Nio and Yang 1991).

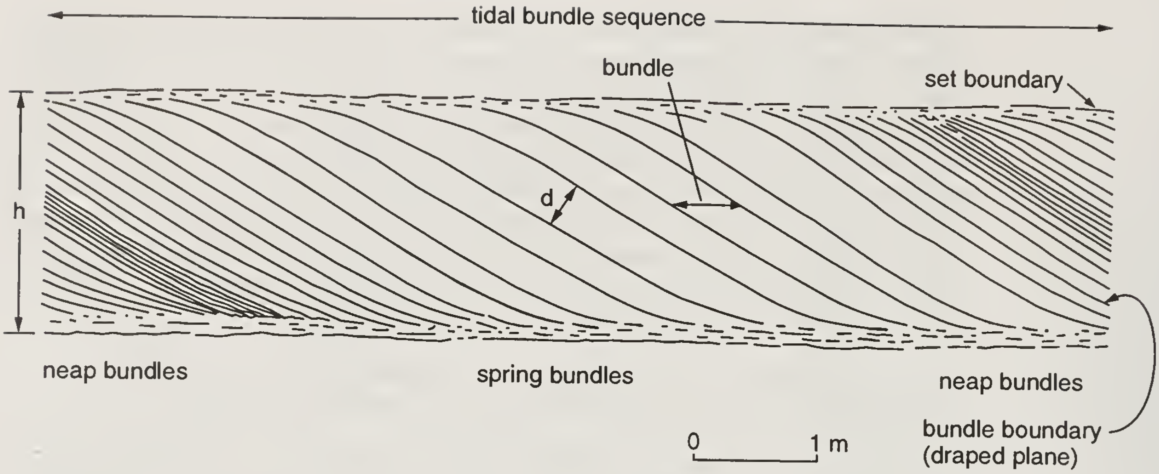


Figure 21 Possible origin of cross bedding in Aux Vases reservoir units formed as lunar-month tidal bundles on a megaripple. Bundle boundaries in low-energy settings are composed of finer grained sandy material with mud drapes. Unidirectional cross bedding is produced by asymmetrical tidal currents. Reactivation surfaces may also mark boundaries (after Yang and Nio 1985).

Aux Vases Formation—Fine Silty Sandstone Facies: Secondary Reservoir

The fine silty sandstone facies is composed of poorly sorted, extremely fine-grained sandstone with lower porosity (10–19%) and lower permeability (5–50 md) than the cross-bedded sandstone facies. This facies is a thin unit, usually 1 to 10 feet thick, commonly oil-stained, overlying the cross-bedded primary reservoir facies in many wells at Zeigler Field. Poor sorting in this sandstone may have been caused by bioturbation. Calcite nodules, probably formed by calcite cementation of burrows, can occur. In some wells, this facies is overlain by finer grained silts and shales. Thin-section analysis showed thick, highly birefringent, illite-rich coatings around most sand grains, and the clay-mineral content was greater than it was for the underlying cross-bedded facies. Halite was observed as a pore-filling mineral in SEM/EDX analyses of some samples.

Sand-flat interpretation of environment of deposition This unit is interpreted to be a sand flat deposited by tidal processes in close association with underlying tidal sand waves and overlying tidal mixed flats and mud flats. The change in sorting, presence of bioturbation and calcite nodules, and close association with other tidal deposits indicate deposition by tidal processes; but deposition occurred in an energy regime weaker than that for the underlying cross-bedded sandstone facies. The sand flat, which occupies the lowermost shoreward portion of the tidal flat, can extend from the lower intertidal zone into the upper subtidal zone (fig. 17). The sand-flat facies is the coarsest grained portion of the tidal flat and grades gradually to mixed-flat or mud-flat deposits in a fining-upward sequence at Zeigler (fig. 17b).

Although this facies has poorer reservoir qualities than the underlying cross-bedded sandstone facies, it is difficult to differentiate between the two facies on the basis of electric log characteristics (fig. 12) because both have low resistivities with overlying medium and deep induction curves. In addition, both are clean and porous enough to have similarly large SP deflections (fig. 12). An upward increase in the shallow spherically focused resistivity log occurs at the contact between the cross-bedded sandstone facies and the overlying silty, fine-grained sandstone facies, similar to that at the contact between the cross-bedded sandstone facies and the underlying green, ripple-bedded facies (fig. 12). This is one of the few electric log characteristics that may indicate a facies change because the decrease in the SP log (fig. 12) may be in response to the overlying Renault Limestone rather than an indication of finer grained siliciclastics.

Aux Vases Formation—Green and Red Siltstone and Shale Facies: Reservoir Seal

The green and red siltstone and shale facies is made up of nonporous, impermeable, green and red clay-sized siliciclastics and tan silt-sized siliciclastics. Intercalated thin, horizontal laminations of green and red shale and localized variegated shale constitute the dominant lithology in this facies. A fining-upward sequence is shown in cores and electric logs from the Gallagher Drilling Company no. 3 Mack and no. 6 Mack wells (figs. 13, 22, 23) where the fine-grained, silty sandstone facies is gradationally overlain by green and red siltstone and shale.

Tidal mud-flat interpretation of environment of deposition In this facies, mud cracks, tidal couplets, and possible rootlets are common sedimentary structures diagnostic of tidal mud-flat deposition. Tidal couplets are composed of alternating, horizontal laminations of green or red shale and tan siltstone (fig. 24). The upper parts of the tidal mud-flat units are the most shale-rich, and the lower parts usually contain more silt and extremely fine-grained sandstone (fig. 17a). Mud flats are the finest grained facies of a tidal flat and are deposited in the uppermost portion of the intertidal zone. The mud flat is at the top of the fining-upward sequence created by a prograding tidal flat (fig. 17b). Periods of subareal exposure associated with diurnal tidal cycles are evident in cores. In some instances, the mud flat is capped by mudstones containing rootlets, caliche, and paleosols formed in supratidal salt marshes (fig. 17a, b). The deposits of this facies are thickest at the edges of reservoir sandbars and were likely to form reservoir seals. At the centers of bars, where the cross-bedded sandstone reservoir facies is thickest (figs. 5, 22, 23), the green and red siltstone and shale facies may be absent, and the lower Renault Limestone is likely to form the upper reservoir seal.

An increase in resistivity and an increase in the SP deflection are the most observable changes in electric log characteristics in the transition from the reservoir-quality sand-wave and sand-flat units to the nonreservoir-quality, silt- and shale-dominated tidal mud-flat units (fig. 13). The lowermost parts of the tidal mud-flat units form a fining-upward sequence with sandstone dominating at the base and siltstone and shale dominating in the upper parts of the unit (figs. 13, 22). In the absence of a porosity log or core, it is only possible to observe that the changes in the resistivity and SP deflections are more subtle where the lower part of the tidal mud-flat unit is sandstone-rich rather than silt- or shale-rich (fig. 13).

The green color in this facies has been attributed to the presence of chlorite; however, other facies with equal or greater amounts of chlorite, as shown by XRD results, are not green. Thus, the color may have another cause (i.e., the presence of iron). Only a small amount of ferric iron is needed to impart a red color. The variegated red and green of tidal-flat sediments observed in the Aux Vases in this field are therefore attributed to small variations in the amount of ferric and ferrous iron. Because of the fine scale at which the color variations take place and the fact that they traverse bedding plane boundaries, they cannot be solely attributed to subaerial oxidation of red units versus unexposed green units. These color changes are probably the result of diagenetic alteration and/or depositional processes that resulted in exposure to oxygen for oxidized (ferric) versus nonoxidized (ferrous) iron.

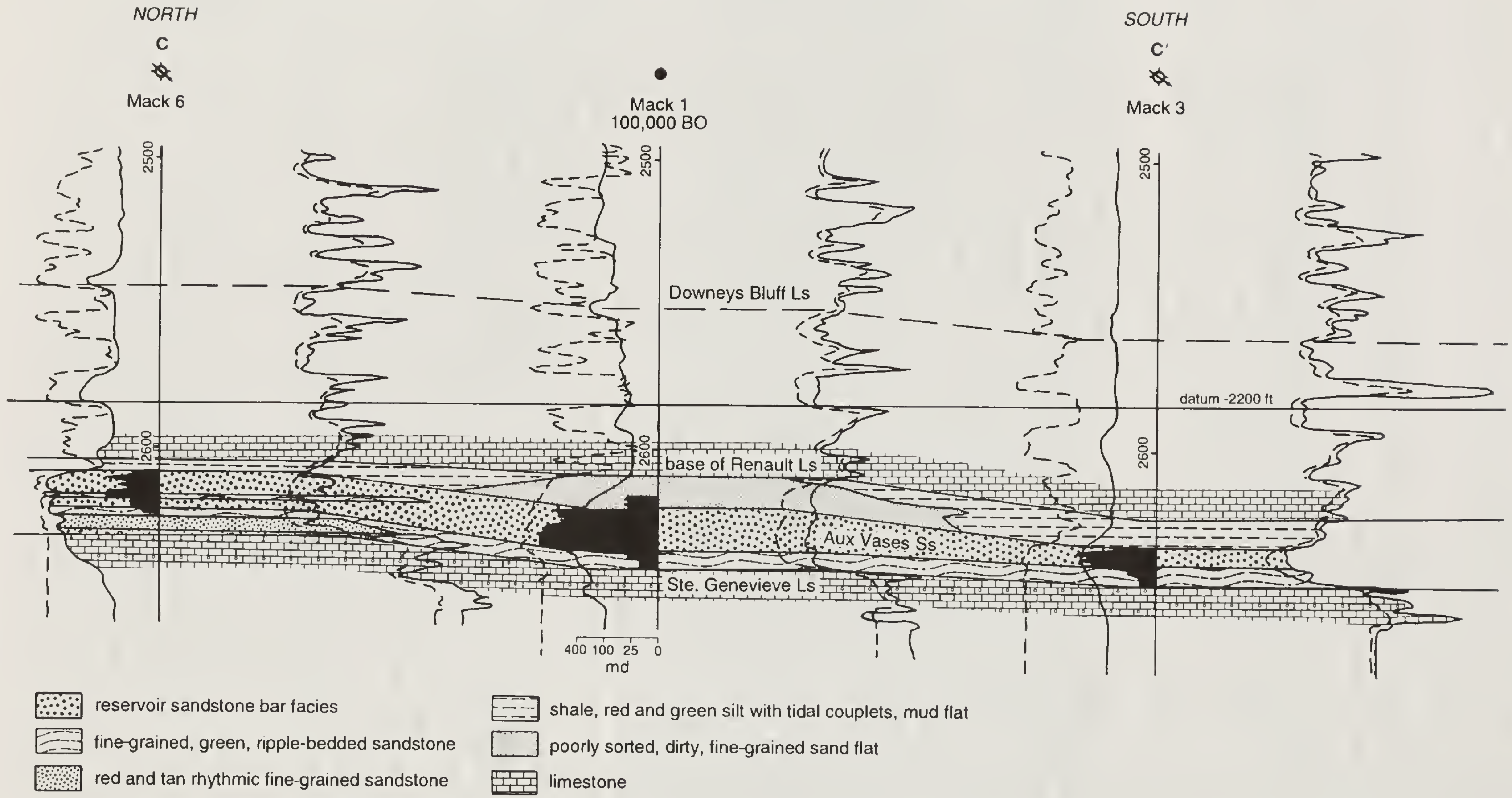


Figure 22 North–south structural cross section (C–C′ on fig. 3) of the Mack lease. The cross section uses spontaneous potential, gamma ray, and resistivity logs; core permeability is plotted on the left track. Core descriptions and interpretation of depositional facies are also shown. Permeability plots best illustrate changes from the primary cross-bedded reservoir facies to the secondary sand-flat reservoir facies. The change from excellent to fair reservoir quality is subtle and easily missed on electric logs.

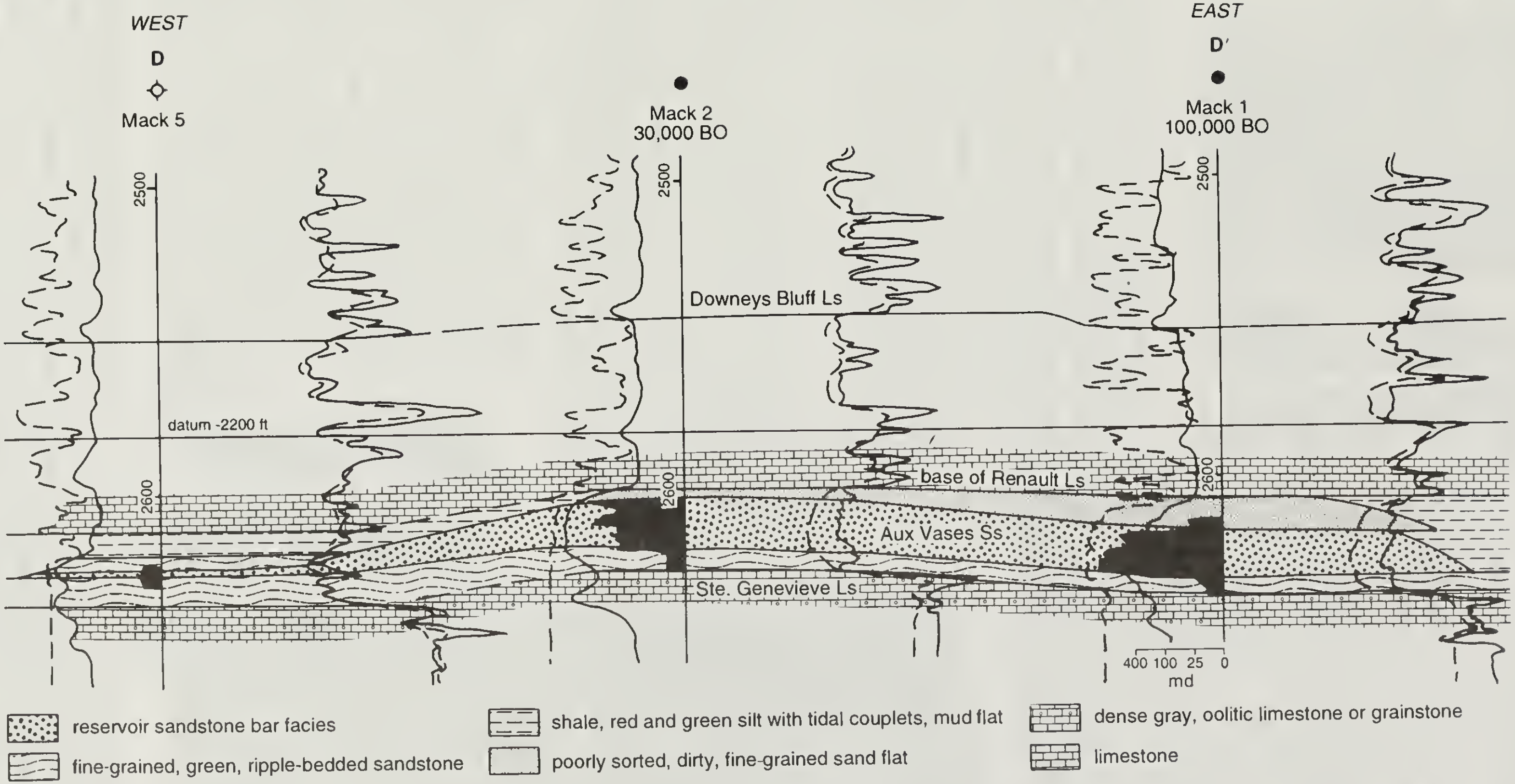


Figure 23 East–west structural cross section (D–D′ in fig. 3) of Mack lease shows abrupt thinning of sandstone bar in the westernmost Gallagher Drilling Company no. 5 Mack well.

Renault Limestone: Reservoir Seal

The lower Renault Limestone is the upper reservoir seal for many producing wells in Zeigler Field. The lower Renault Limestone is composed of nonporous and impermeable gray oolitic or bioclastic grainstone (fig. 25). A 1-foot-thick unit of wavy-bedded gray and green shale separates the upper and lower parts of the lower Renault. The lower part of the lower Renault is a gray or red oolitic limestone with styolites. In some wells, the grainstone is preceded by marine shale containing fossils indicative of an open, shallow marine environment.

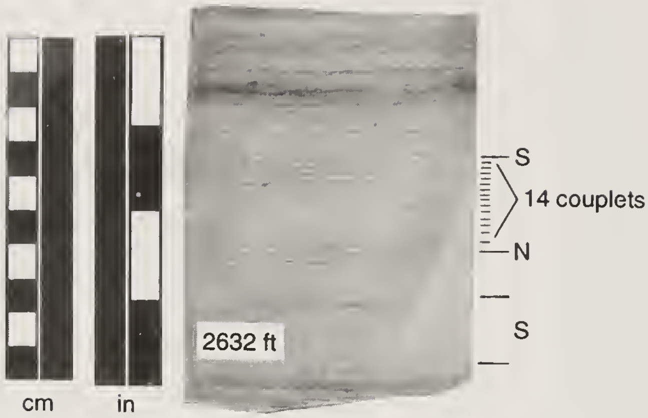


Figure 24 Tidal couplets diagnostic of deposition in a tidal flat overlying the sandbar in the Mack lease at Zeigler Field. Couplets (tick marks) are made up of alternating thinner laminae of mudstones and thicker laminae of fine-grained sandstone deposited by subordinate and dominant diurnal tidal currents. Gradual thickening and thinning of couplets at approximately 12 to 14 diurnal cycles (as shown) permits subdivision into semilunar neap-spring (N)(S) cycles (sample from the Gallagher Drilling Company no. 3 Mack, depth 2,632 ft).

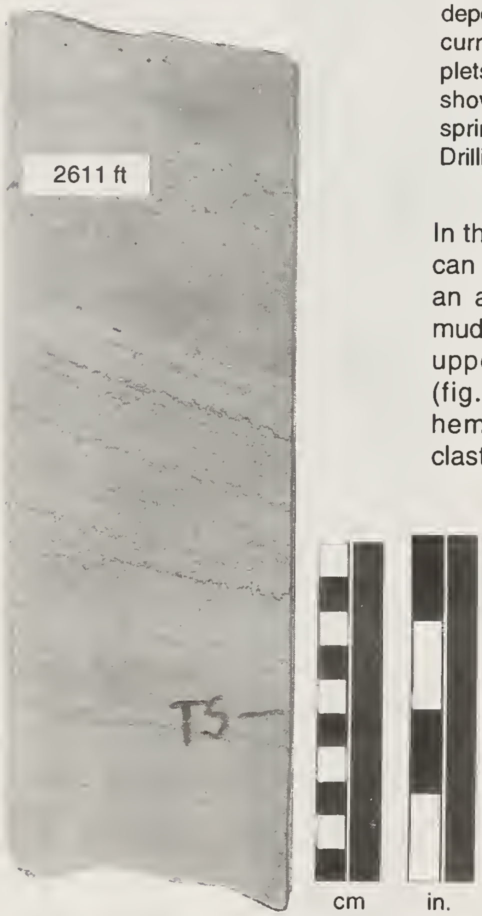


Figure 25 Dense, gray, oolitic limestone with styolites from the Renault Limestone. The layer sharply overlies tidal mud-flat sediments in the upper Aux Vases (sample from the Gallagher Drilling Company no. 5 Mack, depth 2,611 ft).

In the Gallagher Drilling Company no. 2 Pelican well, the lower Renault Limestone forms an abrupt, unconformable contact with tidal mud-flat deposits in the upper Aux Vases. The upper part of the lower Renault Limestone (fig. 15) is characterized by styolites and hematitic, oolitic grainstone with coated bioclasts, primarily echinoderm fragments.

Electric-log characteristics are usually distinctive because the limestone causes a large increase in the resistivity deflection. It is not possible, however, to distinguish the marine shale units at the base of the lower Renault from the shale-rich, tidal-flat units of the underlying Aux Vases. The SP and resistivity logs commonly reflect the thin, 1- to 2-foot-thick shale unit that separates the upper parts of the Renault Limestone (figs. 5, 17, 21, 22).

In the no. 5 Mack, the uppermost Aux Vases, consisting of 5 feet of red shale, is unconformably overlain by 4 feet of marine gray shale in the lowermost Renault Limestone, which is overlain by dense gray oolitic limestone. The change from red shale to gray shale shows a transition from red, tidal-flat sediments in the uppermost Aux Vases to gray, shallow-marine shales and finally to shallow-marine carbonates in the lower Renault after deposition of the reservoir sand body—evidence of a rise in sea level.

Evidence of Tidal Deposition in the Aux Vases in the Mack Lease

Many features observed in the cores from Zeigler Field and in outcrops indicate that tidal processes played a major role in depositing and shaping the sediments that became the reservoir and nonreservoir siliciclastic and carbonate units of the Aux Vases. Features that are considered diagnostic or strongly indicative of tidal deposition include tidal couplets, vertical escape burrows, herringbone cross bedding, bidirectional low-angle cross bedding, mud cracks, and flaser and wavy bedding (Blatt et al. 1980, Klein 1970). Figure 17a is a block diagram showing the relationship of facies within the tidal-flat setting beginning with the coarsest grained sand flat, which forms a gradual transition with the mixed-flat and mud-flat facies. A large macrotidal range is required for deposition of such broad tidal flats. When there is a lowering of sea level or the tidal flat progrades, a fining-upward vertical sequence such as that found in several cores in the Mack lease is produced (fig. 17b)

Tidal mud-flat or sand-flat deposits are found overlying all bar sandstones in Mack lease wells. Tidal mud-flat deposits are thicker and more fine grained in wells containing the thinnest sandstone bars, an indication that a tidal-flat environment followed sandbar deposition at Zeigler Field. Evidence also indicates that tidal-flat sediments separate sandstone bar units in the nos. 3 and 6 Mack wells. Mud cracks and possible rootlets are evidence of subaerial exposure. Their association with red and green variegated shale, silt, and extremely fine-grained sandstone indicates tidal-flat deposition. Tidal couplets (fig. 24), consisting of thinly laminated cyclic deposits that reflect deposition during ebb and flood tides, are strongly diagnostic of tidal-flat deposition (Kvale and Archer 1989). In each couplet, the finer grained, clay-sized fraction was deposited during the subordinate, lower energy portion of the flood-tide cycle. The coarser grained, silt-sized fraction was deposited during higher velocity portion of the flood-tide cycle. Tidal couplets are semidiurnal deposits, each representing 1 day of sedimentation, indicating rapid deposition for tidal deposits in the Aux Vases.

Semimonthly neap-spring cycles of approximately 12 tidal couplets were found in cores from the Mack lease (fig. 24). In these vertical sequences, the couplet thicknesses show a cyclical, gradual increase of the couplet thickness followed by a gradual decrease. Changes in couplet thicknesses are due to changes in height and velocity of tidal currents related to the semilunar cycle of spring neap tides. This cycle indicates deposition in an upper intertidal zone that was covered by tides during spring tidal periods. In subtidal to lower intertidal environments, each semimonthly sequence would ideally contain 20 to 28 couplets because tidal cover is present during all or most of the neap-spring cycle (Nio and Yang 1991). Two neap-spring cycles, representing approximately 1 month of deposition in an upper intertidal environment, are shown in figure 24.

Cyclicity within tidal couplets can be used to infer the amount of time involved in deposition of a tidal sequence (Archer and Kvale 1989). If the reservoir tidal sandbars were deposited under a similar regime, the timing for deposition and migration of reservoir sand bodies could be estimated. This information on the timing and migration is needed to identify modern analogs and may aid the development of a more predictive exploration model.

Vertical escape burrows (fig. 26), a sedimentary feature commonly associated with tidal-flat deposits, are found in the silty interval separating two cross-bedded, reservoir bar, sandstone intervals in the Gallagher Drilling Company no. 6 Mack (fig. 22). The rhythmic strata associated with the vertical escape burrows (fig. 26) show several 1- to 2-inch-thick cycles of thinly laminated, very fine sands and muds, a pattern of tidally deposited sediments described earlier. The burrows are sand-filled and contain curved, concave-upward, internal laminations indicating they were filled as their inhabitant burrowed upward. Vertical burrows are commonly formed by organisms that dwell in the substrate but filter food and water from the currents above. This type of organism is typical in higher energy tidal settings. Thus, the sedimentation style and the burrow morphology indicate that these cycles may be diurnal, as the coarser grained laminae were deposited during the dominant tidal phase and the thinner, finer grained laminae deposited by the subordinate current of the daily tidal cycle (Kvale and Archer 1989).

Lateral Relationships of Reservoir Facies

Figures 22 and 23 show lateral relationships between stratigraphy, structure, permeability, and lithofacies of the Mack lease. The north–south structural cross section of the lease (fig. 22) shows that the reservoir sandstone body thins and is less permeable and structurally lowest in the south in the Gallagher Drilling Company no. 3 Mack well. The thinner reservoir sandstone in the no. 3 Mack is much less permeable and porous than the thicker interval in the center of the bar at the Gallagher Drilling Company no. 1 Mack well. Although it is structurally higher, the sandstone at the north edge of the bar in the no. 6 Mack well is also much less porous and permeable than is the thicker sandstone in the no. 1 Mack well. A similar pinchout of the reservoir sandstone body is evident in the west–east cross section at the Gallagher Drilling Company no. 5 Mack well (fig. 23). Porosity and permeability (core analyses) in this thin sandstone layer, average 13% and 2 md, respectively, too low for a satisfactory reservoir. The sandstone body is also structurally lower. In the Gallagher Drilling Company no. 6 Mack well (fig. 22) to the north, the reservoir sandstone body splits into two zones, either as a result of the stacking of separate bars or the splitting of a single bar by a tongue of finer grained tidal-flat facies.

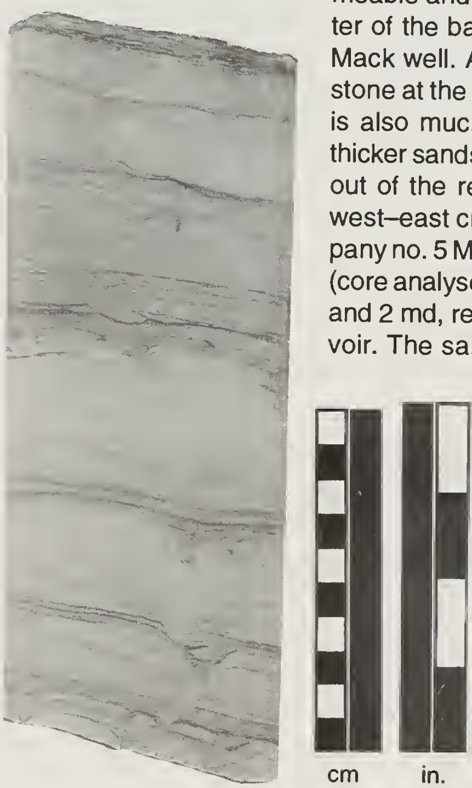
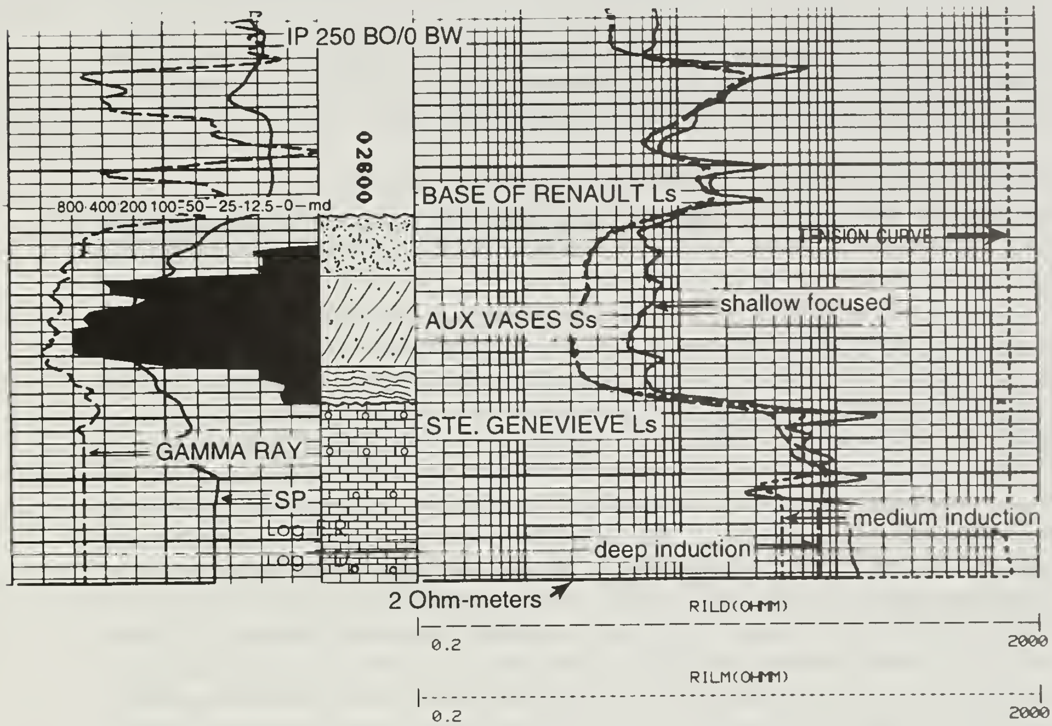


Figure 26 Vertical escape burrows are a common feature of some tidal sediments. In this sample, an organism burrowed through successive sediments deposited during several neap-spring semilunar tidal cycles (sample from the Gallagher Drilling Company no. 6 Mack, depth 2,629 ft).

The most abrupt thinning of the reservoir sandstone body occurs on the west side at the Gallagher Drilling Company no. 5 Mack well, a 660-foot offset of the Gallagher Drilling Company no. 2 Mack well (fig. 23). Thinning of the cross-bedded sandstone facies is more gradual to the north and south. The cross-bedded sandstone facies in these wells is much more porous and permeable than the cross-bedded sandstone facies in the west well. The top of the reservoir sandstone body in the Gallagher Drilling Company no. 2 Mack, the highest in the lease, is 3 feet higher than in the no. 1 Mack.

Both the reservoir and nonreservoir intervals in the Gallagher Drilling Company no. 1 and no. 2 Mack wells have similar lithofacies, sedimentary structures, and grain size variations, but the no. 1 Mack is twice as productive as the no. 2 Mack because the cross-bedded sandstone reservoir facies has more porosity and permeability. The cross-bedded sandstone facies in the no. 1 Mack is characterized by porosity as high as 28% and permeability as high as 750 md, compared with highs of 24% and 250 md in the no. 2. There is little difference, however, between the spontaneous potential, gamma ray, and resistivity logs of the two wells (figs. 12, 22, 23, 27). The superior qualities of the reservoir facies in the no. 1 Mack are not readily discernible in its electric log characteristics.



permeability graphed on left side; logarithmic scale ranges from 0-800 md

sand-flat facies: very fine grained, poorly sorted, clay-rich sandstone; oil-saturated, poor reservoir; permeability = 0-12 md, ϕ =15%

reservoir sandstone bar facies: oil-saturated, fine grained, well sorted, cross-bedded; excellent reservoir qualities; permeability = 150-800 md, ϕ = 23-28%

mud-flat facies (non-oil-saturated): extremely fine grained, green, ripple-bedded; permeability = .1 md, ϕ = .5-15%

limestone: dense gray, oolitic

Figure 27 Spontaneous potential, gamma ray, and long and short normal resistivity electric logs for the Gallagher Drilling Company Mack no. 1 well. The SP log deflection indicates a clean, well-developed sandstone interval in the Aux Vases, whereas the deep induction resistivity curve shows a very low resistivity of approximately 2 ohm-meters.

Comparing the lithologic characteristics of the no. 3 Mack, an injection well, with those of the no. 1 Mack located 660 feet (10-acre spacing) to the north (fig. 22) illustrates some of the rapid lateral changes that appear in the Aux Vases sandstone in Zeigler Field. The friable, cross-bedded reservoir facies in the no. 3 Mack is only 6 feet thick and lacks the more highly developed porosity and permeability found in the no. 1 or no. 2 Mack wells.

The no. 6 Mack contains two cross-bedded sandstone intervals (fig. 22). The upper interval is 7 feet thick and separated from the lower 3-foot-thick interval by 2 feet of silt and shale interpreted to be tidal-flat deposits. Both of these sandstones have only marginal porosity and permeability.

The cross-bedded facies in the no. 5 Mack is only 2 feet thick and, although brown and oil-stained, has the lowest porosity and permeability of any of the cross-bedded sandstone facies in the Mack lease. The porosity and permeability values are so low that this interval may act as a lateral seal in the reservoir rather than as a fluid conduit. Thus, although the cross-bedded reservoir facies has good porosity and permeability where it is thick, the porosity and permeability decreases markedly at the edges of the sandstone body where the sandstone thins.

Lateral Relationship of Reservoir Sealing Units

Nonreservoir facies in the Mack lease are typical of those found in other Aux Vases fields in the region, such as Dale Consolidated and Energy Fields (Huff 1993). Recognition of these facies is important because of their potential as reservoir seals and their association with the cross-bedded, tidal-bundle (primary) and sand-flat (secondary) reservoir facies. Their electric log characteristics are not always distinctive (fig. 22) because the transition from the cross-bedded, reservoir sandstone facies may be into a sandstone of the sand-flat facies or mixed-flat facies rather than into a shale-rich, tidal mud-flat facies. A porosity log would be necessary to distinguish between the highly porous and permeable cross-bedded sandstone facies and the nonporous and impermeable, fine-grained sandstone and siltstone in the tidal mixed-flat facies. The shale-rich part of the green and red siltstone and shale in the tidal mud-flat facies can be recognized on electric logs because the large amount of shale and siltstone is reflected by the gamma-ray and SP logs (fig. 22). In the Mack lease, porous and permeable reservoir sandstones are thin at the edges of the bar and overlain by approximately 9 feet of nonporous, impermeable, variegated red and green shale interbedded with siltstone interpreted as having been deposited in a tidal mud flat (figs. 22, 23). These tidal-flat sediments, which commonly fill the interval between the top of thin cross-bedded sandstone deposits and the base of the overlying Renault Limestone (figs. 22, 23), are thickest in the no. 3 Mack.

The siltstone and shale unit between 2,628 and 2,632 feet in the Gallagher Drilling Company no. 5 Mack well (fig. 22) corresponds to a similar unit in the Gallagher Drilling Company no. 6 Mack at 2,626 feet (fig. 22). Both units contain vertical escape burrows (fig. 26) and can be discerned on the SP and resistivity logs (figs. 22, 23). These units are tidal-flat deposits and are important because they may form permeability barriers within or between reservoir sand bodies.

The green, ripple-bedded sandstone facies at the base of the cross-bedded sandstone facies in the Mack lease forms a basal reservoir seal. This facies may have potential for forming seals at the top of sandbars as well as the potential for forming permeability barriers between stacked or shifted sandbars.

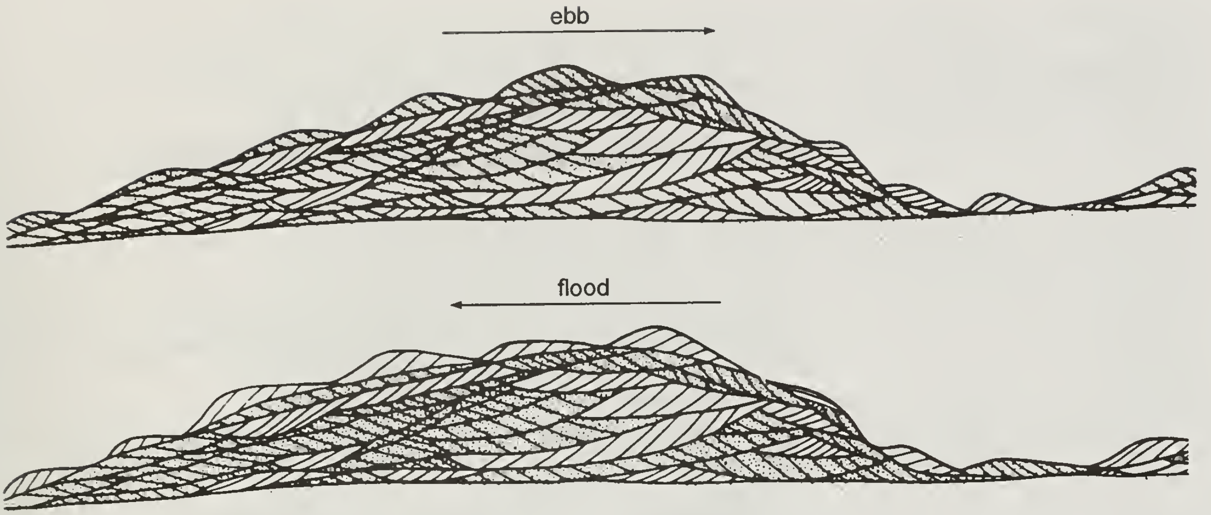


Figure 28 Ebb-flood tidal deposition of sand waves in the North Sea. Dominant and subordinate tidal currents depositing this sand were nearly symmetrical. Tidally deposited sand waves may be an analogy for deposition of cross-bedded reservoir sandstone (after Stride 1982 and Walker 1985).

REGIONAL SETTING FOR DEPOSITION OF SAND WAVE RESERVOIRS

Sand Waves: Possible Environment of Deposition

The term "sand wave," used in much of the literature devoted to shelf sandstones, refers to large sand bodies deposited by tidal processes. In other ISGS publications in this series, the term "sandbar" has been used to describe sand bodies deposited in the cross-bedded facies, and it is used in parts of this report.

Stride (1982) and Walker (1985) used box cores from the sand-wave complex in the North Sea to reconstruct internal sand-wave sedimentary structures that primarily consist of cross bedding produced by ebb and flood tidal currents (fig. 28). Cores of the cross-bedded, reservoir sandstone facies at Zeigler Field contain similar sedimentary structures. Therefore, sand-wave deposits in the North Sea may be a modern analog for deposition of the reservoir sandstone facies in the Aux Vases. Using box core data from the North Sea, Walker (1985) showed that sand waves are produced by superimposing cross-bedded megaripples. Internal structures within sand waves were predicted and classified by Allen (1980) using time velocity asymmetry as well as tidal current velocity and grain size as variables. In Allen's classification system, Class I sand waves contain large-scale, avalanche cross bedding with few reactivation surfaces (fig. 29). Class I and II sand waves in Allen's system are deposited when there is strong time-velocity asymmetry, the dominant tidal current is much stronger than the subordinate current, and flow strength exceeds the threshold velocity for sand movement throughout the tidal cycle. Class IV and V sand waves in Allen's system are at the other extreme: they are generated when there is increasing symmetry between ebb and flood components. Reactivation surfaces and bidirectional cross bedding are common in Class IV/V sand waves. The sand wave shown in figure 28 and the reservoir sandstone bodies from Zeigler Field exhibit many of the features found in the Class V category (e.g., thin bidirectional cross-bed sets). The bidirectional cross-bedded sandstone from Zeigler Field (fig. 19) could thus represent a sand-wave deposit.

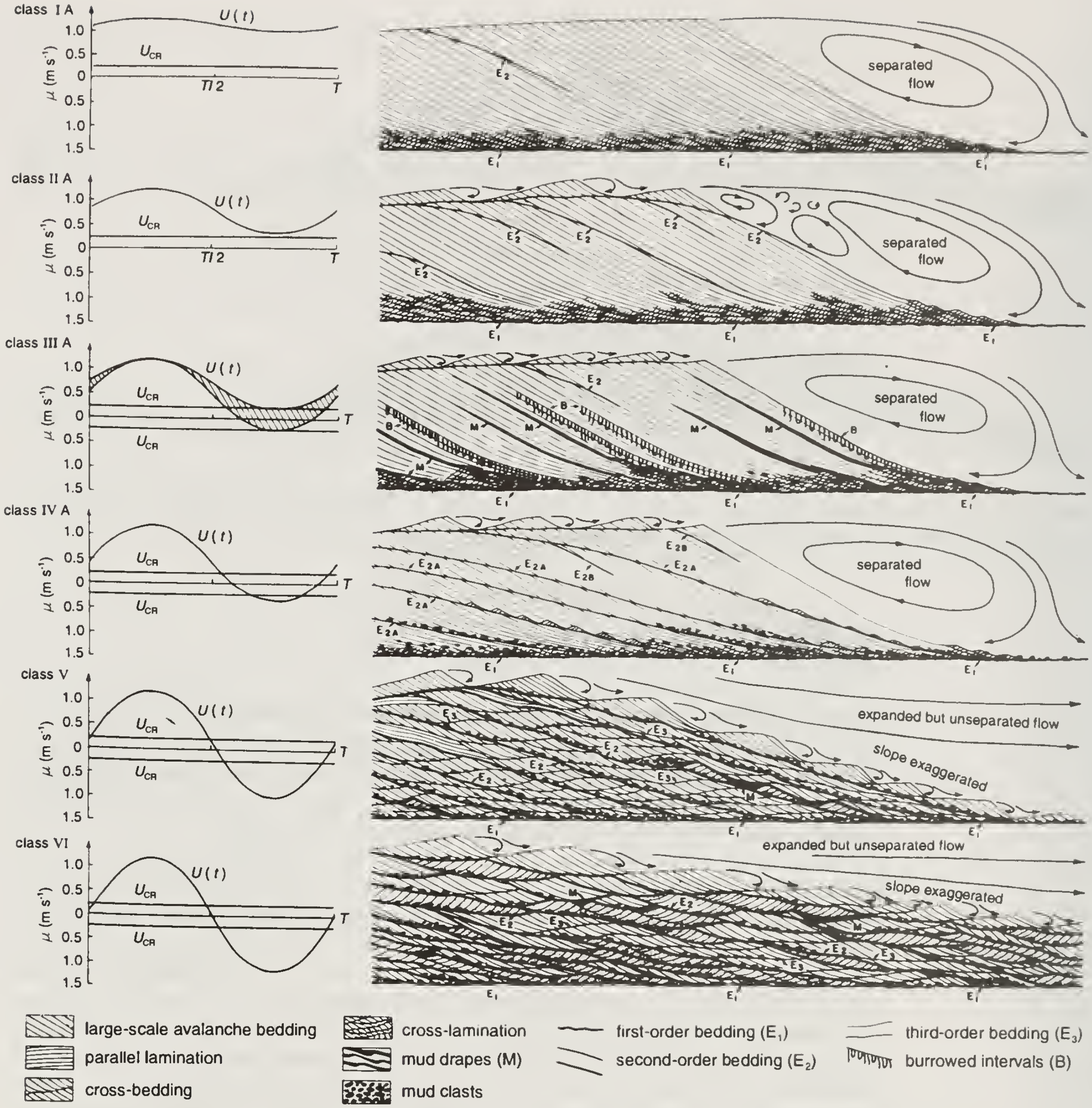


Figure 29 Sedimentary structures and bounding surfaces of Class I through VI sand waves. Class I waves are deposited by very strongly asymmetrical tidal cycles, producing unidirectional avalanche bedding with few bounding surfaces. Class VI sand waves are deposited by nearly symmetrical tidal currents exhibiting bidirectional cross bedding and numerous bounding surfaces (from Walker 1985).

The distinction between sand-wave categories is important because internal sedimentary structures can control heterogeneity and fluid flow in a reservoir. For example, reservoirs formed from Class I and II sand waves can be expected to be homogenous and have little compartmentalization. As a result, they will have greater sweep efficiency than reservoirs formed of Class IV and V sand waves. In Class IV and V sand-wave reservoirs, compartmentalization is expected to be significant because of the prevalence of bidirectional cross bedding, reactivation surfaces, and small- and large-scale erosional bounding surfaces that can create compartments (fig. 29).

In the modern North Sea examples of sand waves, the sand was originally transported during periods of major glacial activity when sea level was low (Walker 1985). The sediment was reworked later by tidal processes during periods of deglaciation when sea levels were higher. Glaciation has been suggested as a possible mechanism for causing cyclic, sea-level changes during deposition of Chesterian units (Treworgy 1985).

The reservoir facies at Zeigler, interpreted as sandbars (sand waves) deposited by tidal processes in subtidal to intertidal environments, contains some of the same features described by Walker (1985) as found in tidal sand bodies deposited on shelves in open shallow seas. Few examples of ancient sand bodies deposited by tidal processes in shelf/shallow marine environments have been described. Most ancient sandstones interpreted as having a tidal origin have been described as intertidal to very shallow subtidal deposits representing lagoonal sand flats or tidal channels.

The various Aux Vases units at Zeigler Field exhibit features from both of the open-marine shelf environments, as well as from tidally influenced nearshore environments. Evidence of a nearby shallow open-marine environment includes the presence of fossil fragments of animals that live in shallow, subtidal, open-marine environments and carbonate cement in the reservoir facies. In addition, the presence of Aux Vases limestones adjacent to the reservoir sandstone bodies and the close association of the Aux Vases with the underlying Ste. Genevieve and overlying Renault Limestones indicate shallow subtidal to open-marine environments of deposition. Nonreservoir units closely associated with the reservoir sandstone bar facies, however, contain features commonly found in sediments deposited in intertidal and shallow subtidal environments such as tidal couplets and mudcracks.

Similar reservoir sandstone bodies have been mapped at Southwest Dale Consolidated (Beaty and Fagan, in prep.), Energy (Huff 1993), and Oakdale Fields. Examinations of cores from reservoir units at Southwest Dale Consolidated, Energy, Oakdale, Storms, and Boyd Fields (fig. 1) show that cross bedding similar to that observed at Zeigler is the most common sedimentary structure in reservoir sandstones. Petrographic examinations of samples from these fields show that they have grain size, grain composition, cementation, and coating of framework grains by diagenetic clay minerals similar to those found at Zeigler Field.

Electric log characteristics of Aux Vases sandstone reservoirs in these fields also contain many similarities. The most prominent feature is low resistivity in the reservoir interval. The role played by diagenetic clay mineral grain coatings in producing low resistivities is discussed in a later section.

Comparison of sand waves with reservoir sand bodies The reservoir sand waves at Zeigler Field are part of an extensive complex, encompassing an area of approximately 10,000 km^2, in much of southern Illinois and parts of southwestern Indiana and Kentucky. Modern shelf sand-wave complexes of similar magnitude include the Georges Bank Atlantic Shelf off Massachusetts and the sand-wave complex off the coast of Holland (Walker 1985).

The sandstone bodies in the Aux Vases are thinner (typically less than 6 m [~18 ft]) and smaller than those found in modern shelf complexes, where average sand thicknesses are between 7 and 15 m (~21 and 45 ft) (Walker 1985). Bedforms are very large in modern shelf complexes but are unmeasurable in many ancient examples. Given the wide area in which Aux Vases reservoirs have similar sedimentary structures, it is possible that the Aux Vases reservoirs at Zeigler Field are part of a large shelf sand-wave complex. If this is the case, then the periodicity, height, length, width, and spacing of the sand waves may be predictable and useful as an exploration tool.

Reservoir sandstone bodies at Zeigler are relatively small, typically about 0.5 mile long, 0.25 mile wide, and an average of 15 feet thick. The size, shape, and distribution of reservoir sandstone bars across the southern part of the Illinois Basin indicate that an analysis of their periodicity may be a useful exploration strategy. Periodicity has been suggested as an exploration tool by Huff (1993) and Off (1963). Spacing and interrelationship of sandstone bars within Zeigler Field and in the surrounding vicinity may help to locate other undiscovered reservoirs. Orient Field, the nearest Aux-Vases-producing bar sandstone reservoir, is also a stratigraphic trap of approximately the same size as the bars on the Mack and Bend leases (fig. 3). Structurally, Orient Field is lower than Zeigler Field (fig. 10). The region between these two fields has received little exploration attention, and several additional sandstone bar reservoirs might be found there.

Relative timing of reservoir sand-body deposition Some sandstone bodies (sand waves) at Zeigler are shingled, partially overlapping one another (figs. 5, 22, 23), and separated by tidal-flat deposits that may have formed between episodes of marine regression following deposition of offshore marine sandbars. At least four phases of sandbar deposition occurred at Zeigler. Evidence for these multiple phases include the three overlapping and/or narrowly connected bars located in the main body of the field and roughly coinciding with the limits of the Plumfield, West Plumfield, and South Plumfield leases. In addition, there are two isolated sandbars in the Mack and Bend leases (fig. 3). These sandstone bars cannot be correlated with one another in stratigraphic cross sections and vary in depth from marker beds, indicating that they were deposited at slightly different times. Lithologic slice maps, produced by inputting lithologic data from core descriptions into the stratigraphic modeling program SGM (Stratamodel), illustrate the relative timing of deposition of these sandbars following the formation of the unconformity surface at the top of the Ste. Genevieve Limestone and the base of the Aux Vases. The erosional contact at the top of the Ste. Genevieve was used as a relative time marker for the field. The lithologic slice maps for the field show the following relative sequence of sandbar deposition: (1) the Plumfield lease, (2) the west Plumfield lease, (3) the south Plumfield lease, and (4) the Mack lease.

There are varying degrees of overlap and communication between these bars. For example, the reservoir sandstone bar in the West Plumfield lease partially overlies the sandbar in the Plumfield lease. The Gallagher Drilling Company no. 18 Plumfield well, however, has two thin sandstones separated by a 2-foot shaley interval (fig. 5). Pressure tests prove there is no communication of fluid between these two sandbars. The Plumfield sandbar, in turn, is partially overlain by the South Plumfield sandbar, which was most likely deposited after the Plumfield and West Plumfield sandbars. Limited communication occurs between the West Plumfield and South Plumfield bars. The South Plumfield bar is stratigraphically higher than the other two sandbars. The structure of the top of the sandstone bar in the Mack lease is higher than those in any of the Plumfield leases. Because there is no structural closure on any of the limestone marker horizons, this sandbar was probably the last to be deposited in Zeigler Field.

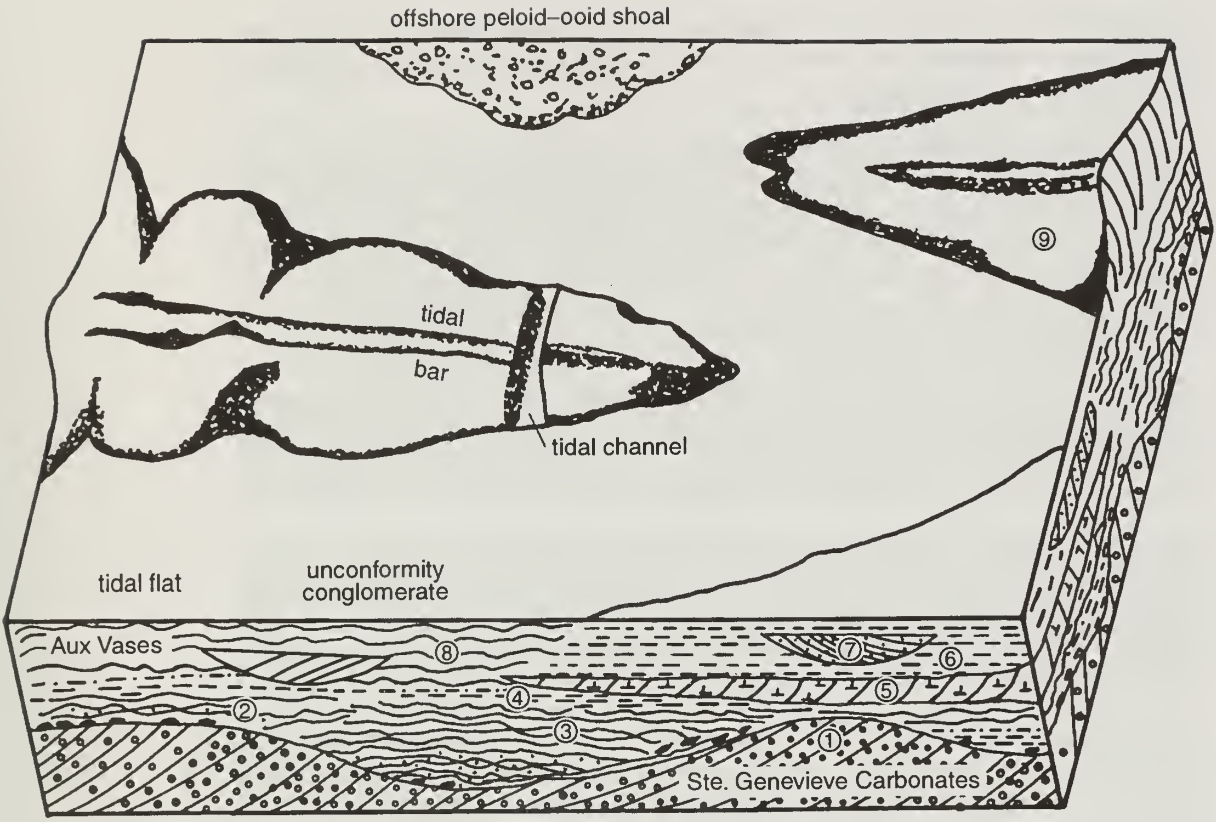


Figure 30 Schematic depicting environments of deposition of cross-bedded reservoir facies and associated non-reservoir facies in the Aux Vases at Zeigler Field and in outcrop. Numbers represent different facies of deposition and are discussed in the text.

Environments of Deposition: Zeigler-Based Model

Although many of the best Aux Vases reservoirs in the central facies belt (fig. 7) exhibit somewhat similar reservoir characteristics, they vary at the local level. All these reservoirs are composed of loosely cemented, friable sandstone that is distinctly different from other producing horizons in the Illinois Basin. Local variations among the sandstone reservoirs of the Aux Vases include the proximity of limestone units, amount of carbonate in reservoir units, thickness of the sandstone bodies, and proximity of shale units.

Zeigler Field is a typical Aux Vases reservoir deposited in a shallow-marine environment in the central part of the basin. The reservoir facies consists of moderately thick, tidally dominated, possibly offshore, shallow-marine, cross-bedded sand bodies. Carbonate framework grains including micritized pellets, ooids, and fragments of echinoderms, bryozoans, brachiopods, and other marine fossils are incorporated into the predominantly siliciclastic Aux Vases reservoir sands; and rapid lateral facies changes from siliciclastics to carbonate grainstone units indicate a high degree of marine carbonate influence. Some of the fine- to very fine-grained, cross-bedded reservoir sandstones were deposited less than 10 feet above the lithified ooid and bioclastic shoals in the underlying Ste. Genevieve Limestone (fig. 30). Additionally, bioclastic grainstones are common in the lower part of the Aux Vases Formation adjacent to or beneath reservoir sandstone bodies. These Aux Vases limestones probably formed contemporaneously with the reservoir sand bodies as pelloidal and oolite shoals in shallow, open-marine environments located near, but marineward, of the sandbars (Seyler 1984).

Carbonate and siliciclastic deposits are generally mutually exclusive because the influx of siliciclastics usually prevents the clear-water environment needed by most carbonate-producing organisms (Friedman and Sanders 1978). In the setting of the Aux Vases, however, the two contrasting environments existed very close to one another. Whenever the siliciclastic influx diminished or was diverted away, conditions conducive to carbonate formation and accumulation prevailed in the area. These conditions produced a mixed carbonate-siliciclastic environment.

Rapid shifts between siliciclastic and carbonate deposition probably were controlled by siliciclastic input and water depth that, together, regulated accumulation of carbonate and siliciclastic sediments, including the reservoir sand bodies. Both lithologies were apparently deposited and shaped by tidal processes.

Cores from Zeigler, Oakdale, Dale Consolidated, and outcrops near Anna, Illinois, were interpreted to develop a depositional model (fig. 30). This model shows a typical Aux Vases sandstone reservoir consisting of regressive, offshore-marine, tidal sandbar complexes that unconformably overlie upward-shoaling oolite sequences of the Ste. Genevieve Formation (Seyler 1986).

The succession of events shown in the model is as follows (fig. 30): (1)The Ste. Genevieve Limestone formed an oolitic or grainstone carbonate platform on which Aux Vases siliciclastics and carbonates were unconformably deposited. Paleorelief on the Ste. Genevieve had some influence on the deposition of overlying Aux Vases sediments. (2)The contact between the Ste. Genevieve and Aux Vases Formations is generally marked by a conglomerate lag. Other storm-generated lags may be present in the Aux Vases. (3) Extremely fine-grained, green, ripple-bedded sandstone with mud cracks interpreted as mixed-flat deposits filled depressions in the underlying Ste. Genevieve. In many instances, this facies forms the base on which the reservoir sandstone bars were deposited. (4) Red and green variegated shale interpreted as tidal mud-flat deposits may also overlie the Ste. Genevieve or be interbedded with the green, ripple-bedded mixed-flat facies. (5) Red hematitic trough cross-bedded grainstone, observed in some cores and outcrops, was interpreted as a shifting tidal channel or storm deposit. This facies may erode or cut into tidal sand-flat, tidal mixed-flat, or tidal mud-flat deposits. (6) Tidal mud-flat deposits consistof tidal couplets of red and green shale and siltstone; some deposits contain rootlets—an indication of long-term subareal exposure. (7) Very fine-grained sandstone with bidirectional trough cross bedding, observed in cores and interpreted as tidal channels, may cut into tidal-flat deposits. (8) Extremely fine-grained, green, ripple-bedded sandstone, siltstone, and shale with mud cracks were interpreted to be tidal mixed-flat deposits. (9) Fine-grained, cross-bedded, friable sandstone with excellent porosity was probably tidally deposited; it forms the reservoir sandbar facies. Pelloid and ooid shoals identified in some areas were deposited contemporaneously with the sandstone bars and are depicted in the schematic diagram (fig. 30) (Seyler 1984).

The relationships between the tidal-flat and storm deposits and the reservoir sandstone bodies is important because these units form relatively impermeable, nonporous seals encasing the sandstone reservoir bodies or they may form permeability barriers if interbedded within reservoir sandstone bodies.

Comparison of Facies at Zeigler Field with Aux Vases Outcrops

The nearest outcrop of the Aux Vases is approximately 30 miles south of Zeigler Field in a roadcut on U.S. Route 51 adjacent to the Anna Quarry, approximately 0.5 mile north of the intersection with Illinois Route 146. This outcrop (fig. 31), as well as a shallow core from Cobden (obtained 5 miles north of Anna on U.S. Rte. 51), exhibit many of the features seen in nonreservoir units in both producing and dry and abandoned wells surrounding Zeigler Field.

No high-porosity, high-permeability, cross-bedded, friable sandstone has been found in this or any other Aux Vases outcrop. Many core samples of the Aux Vases, warehoused at the ISGS and protected from weathering since the 1940s, have disintegrated into individual sand grains. This disintegration indicates that any outcrop of rocks similar to the reservoir facies of the Aux Vases would be rapidly weathered and disintegrate shortly after exposure to weathering.

The most prominent feature in the U.S. Route 51 outcrop is the red, hematitic, low-angle trough cross-bedded, shingled grainstone interpreted by Seyler (1986) as a shifting tidal channel deposit (fig. 31). Cole (1990) assigned this unit to the uppermost Joppa Member of the Ste. Genevieve Limestone, but Seyler (1986) placed it in the Aux Vases Formation. A dense, gray, fossiliferous grainstone that occurs approximately 7 feet below the hematitic, cross-bedded grainstone at the U.S. Route 51 outcrop is interpreted to be the top of the Ste. Genevieve Limestone. A red, hematitic, grainstone with low-angle trough cross bedding similar to that of the unit in the outcrop is present in core from the Gallagher Drilling Company no. 2 Pelican well in the

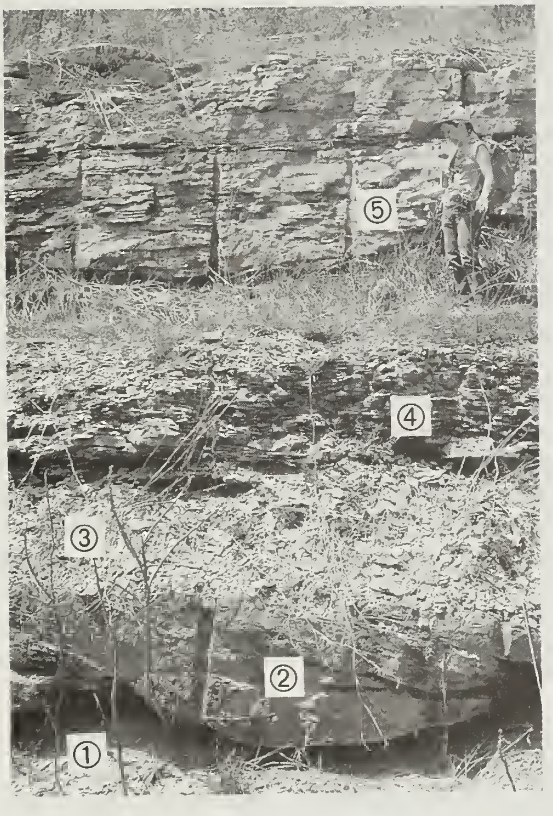


Figure 31 Photograph of Aux Vases outcrop on U.S. Route 51 adjacent to the Anna Quarry. This outcrop most closely resembles units observed in cores from within Zeigler Field and in dry and abandoned test holes near the field. The sharp, underlying contact with the dense, gray, oolitic Ste. Genevieve Limestone can be seen in the ditch cut along the highway. Aux Vases units from the base upwards are as follows: (1) red and green shale; (2) red hematitic, cross-bedded, carbonate grainstone with some quartz sand grains, deposited by a migrating tidal channel; (3) ripple-bedded, silty, red and green shale are tidal mud-flat deposits; (4) fine- to very fine-grained, ripple-bedded sandstone with mud cracks and green shale drapes deposited on a tidal sand flat; and (5) fine-grained sandstone with low-angle trough cross-stratification and some burrowing. These units were deposited by tidal processes similar to those identified from Zeigler Field cores.

overlying the dense, gray, oolitic Ste. Genevieve Limestone. The hematitic, cross-bedded grainstone therefore continues to be assigned to the Aux Vases.

Red and green variegated shale underlies the red hematitic, cross-bedded grainstone at the U.S. Route 51 outcrop. These shale beds, which may represent tidal mud-flat deposits, are underlain by a dense, oolitic grainstone very similar to the upper Ste. Genevieve Limestone at Zeigler. Red and green shale interbedded with tan, ripple-bedded siltstone overlies the red hematitic, cross-bedded grainstone. Extremely fine-grained, ripple-bedded sandstone with mud cracks and green shale drapes appears to be equivalent to the extremely fine-grained, green, ripple-bedded mixed-flat facies that underlies the reservoir sandstone bar facies at Zeigler. The top of the U.S. Route 51 outcrop is composed of a fine-grained sandstone with low-angle trough cross bedding and minor burrowing similar to that found capping some of the reservoir sandstone bars at Zeigler and in the interbar areas adjacent to the field. This unit, in both the outcrop and in cores in and adjacent to Zeigler Field, exhibits features diagnostic of tidal deposition. The major difference is that the high-quality reservoir facies is absent from the outcrop.

Similar lithologies, sedimentary structures, and facies have been observed in Aux Vases units in the no. 3 Mack and no. 2 Pelican wells from Zeigler Field and at the U.S. Route 51 outcrop near Anna. Although high-quality reservoir sandstone units occur sporadically and they are not present at the U.S. Route 51 outcrop, evidence for the deposition of Aux Vases units by tidal processes is obvious at all locations. Rocks with features typical of tidal mud-flat, tidal mixed-flat, and tidal-channel deposits are among the most common units.

PETROGRAPHY AND DIAGENESIS

Diagenesis played a major role in the formation and enhancement of porosity and permeability in Aux Vases sandstones. Petrographic analyses of the reservoir facies rocks at Zeigler Field concentrated on samples from the Mack lease because cores were available from these wells. A broader, in-depth discussion of diagenetic alteration in sandstone reservoirs in the Aux Vases and Cypress Formations will be provided in Seyler et al. (in prep.).

Petrographic Methods

Analyses performed included light microscopy, XRD, cathodoluminescence, and SEM/EDX. Used together, these techniques provide a comprehensive petrographic analysis of the Aux Vases and determination of its diagenetic history.

Thin sections were vacuum-impregnated at room temperature with epoxy stained blue with Keystone A dye to highlight porosity and dissolution features. They were stained with potassium ferricyanide and alizarin red to highlight the carbonate phases.

XRD analyses provided data on mineralogical composition and relative percentages of various mineralogical occurrences in selected samples. The results of these analyses are presented in appendix A.

Cathodoluminescence was employed to determine the original shape and size of quartz grains, highlight feldspar grains, and estimate the relative abundance of feldspar. These features can be distinguished using cathodoluminescence because grains luminesce in response to variations in the amounts of luminescent minerals or impurities. These variations commonly result in easily observable differences in color, intensity, and hue of grains.

SEM/EDX analyses were used to determine the size, shape, distribution, and geometry of pores as well as the morphology and distribution of pore-lining minerals in three dimensions and the elemental compositions of minerals.

Critical-point drying and freeze drying were the SEM/EDX sample preparation techniques used to preserve original clay-mineral morphology and prevent collapse, which commonly occurs during routine air-drying, particularly for hydrated clay mineral surfaces. The release of surface tension on hydrated clay-mineral surfaces commonly results in varying degrees of morphological change involving shape, size, geometry, and structure of hydrated minerals. The more hydrated a mineral, the greater the degree of morphological change that will occur as a result of air-drying. The technique, described in detail in Seyler et al. (in prep.), can be used only on fresh, "preserved core" samples; it was used in Zeigler Field when a fresh core from the Gallagher Drilling Company no. 1 Alex became available.

Results of Petrographic Analyses

Framework grain composition of reservoir sandstone Siliciclastic framework grains in Aux Vases reservoir-facies sandstones of the Mack lease at Zeigler Field include, in descending order of relative abundance, undulose quartz, nonundulose quartz, polycrystalline quartz, K-feldspar (orthoclase and microcline), plagioclase feldspar, chert, and trace amounts of opaques and heavy minerals. Carbonate framework grains include micritized pelloids, ooids, and fragments of echinoderms, bryozoan, and brachiopods. XRD analyses of samples from the cross-bedded sandstone reservoir facies show a compositional range of 81% to 92% quartz, 0.5% to 1.6% potassium feldspar, 3.9% to 6.6% plagioclase feldspar, and 4.4% to 7.7% total feldspar. Calcite content ranged from 0.2% to 6.4%; clay-mineral content ranged from 0.7% to 5.2%; and four samples contained trace amounts of dolomite. Of the 13 samples from the reservoir sandstone bar facies in the Gallagher Drilling Company no. 1 and no. 2 Mack wells analyzed by XRD, 12 contained between 5.2% and 7.7% total feldspar and were classified as subarkoses. The remaining sample contained 4.4% total feldspar and is a quartz arenite. The average sandstone bar sample in Zeigler Field is a subarkose with a minor amount of calcite in the form of framework grains or patchy calcite cement and 2.5% diagenetic clay minerals coating grains and lining pores.

Paragenetic Sequence

The observed paragenetic sequence of diagenetic events that controlled the formation, preservation, and destruction of porosity and permeability following deposition of the reservoir sandstone bar facies at Zeigler Field is diagramed in figure 32. The paragenetic sequence indicates the relative timing of diagenetic events from early to late. Early events include minor compaction, incipient silica cementation at some grain contacts, and pervasive calcite cementation at shallow burial depths and low temperatures. Much secondary enhancement of porosity and permeability occurred during the middle stages of diagenetic alteration at deeper burial depths and higher temperatures.

The two recognized phases of burial diagenesis responsible for porosity and permeability alteration in the Aux Vases sandstone reservoir facies are a shallow and an intermediate burial phase (Seyler et al., in prep.). No evidence indicates that reservoir sandstones in the Aux Vases ever reached deep burial depths greater than

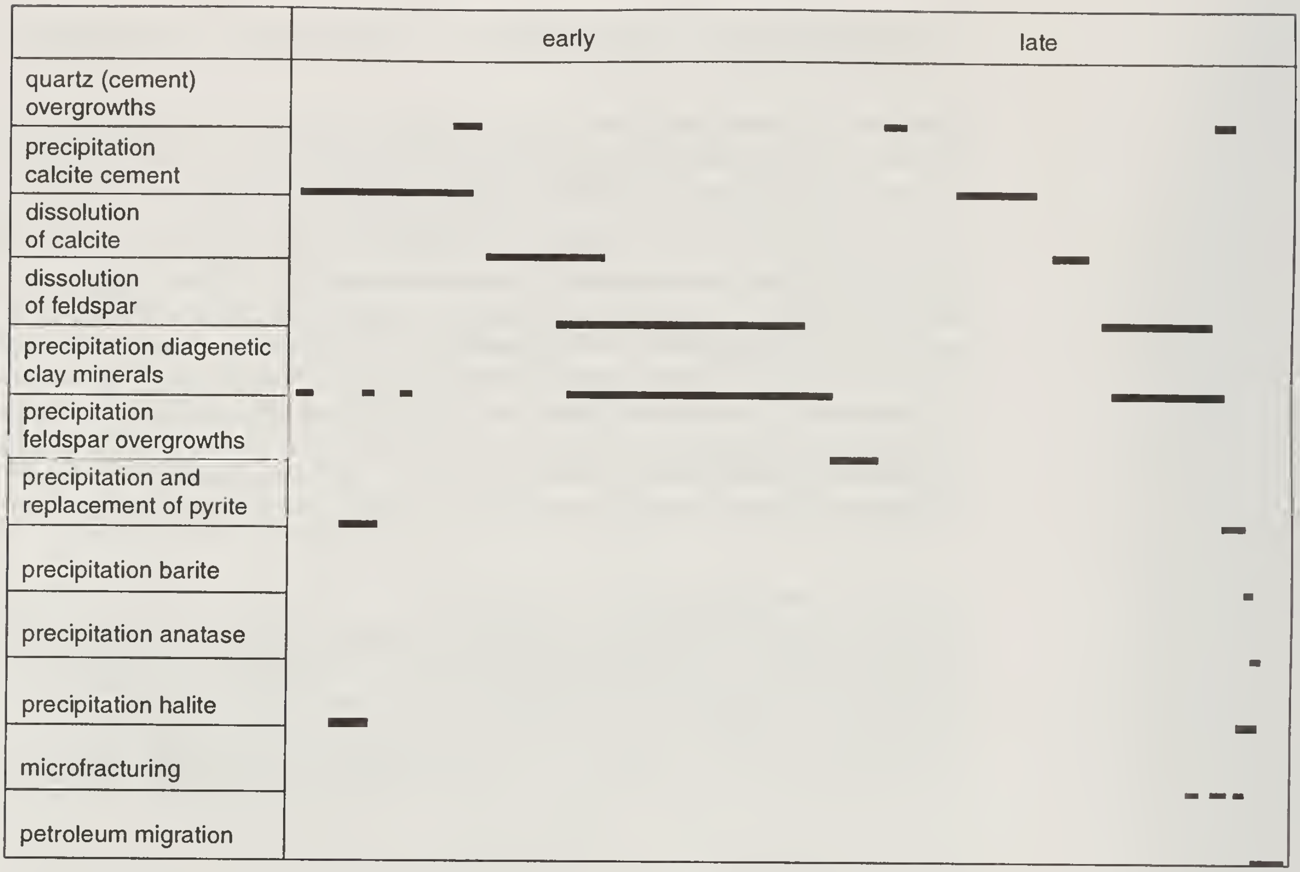


Figure 32 Paragenetic sequence chart shows early- through late-stage diagenetic events in the cross-bedded reservoir sandstone bar facies at Zeigler. Petrographic analyses of Aux Vases reservoir samples show that, although diagenetic alterations have been extensive, these units have been subjected to only shallow and intermediate burial diagenesis as defined by Surdam et al. (1989).

5,000 feet. The fact that burial depths remained relatively shallow is a key factor in the preservation of porosity and permeability.

Early Diagenetic Events

Early diagenetic events in the reservoir facies at Zeigler Field, with the exception of early calcite cementation, are relatively minor and have effectively preserved much primary porosity. Silica cementation was minor during early burial stages and took place only at some grain contacts (fig. 33, plate 1a). There is no trace of diagenetic clay minerals on any of the broken point contacts, as would be expected if the entire grain was coated with clay at the time of silica cementation. The fact that silica cementation occurs only at points along some grain-to-grain contacts shows that this was a minor event. This evidence indicates that little compaction occurred and that calcite cement or some other pore-filling cement supported the framework grains and was later removed by dissolution. Cathodoluminescence analyses revealed that minor quartz overgrowths developed prior to precipitation of diagenetic clay mineral grain coatings (plate 1a).

SEM/EDX and cathodoluminescence analyses performed on the same sample area confirmed that the color, intensity, and hue of feldspar luminescence vary with composition (plate 1a). Polished thin sections and their corresponding heels (the parts sawed off during thin section preparation) were prepared for two-dimensional elemental distribution image analysis. Cathodoluminescence and SEM/EDX analyses of the same sample area showed as much as 13% detrital Na-feldspar and K-feldspar in localized areas. Na-feldspar luminesces brown, yellow, or red, whereas K-feldspar luminesces bright blue.

The SEM/EDX analyses showed that virtually all grain surfaces and pores are coated with diagenetic clay minerals. In reservoir sandstones at Zeigler, later stage quartz overgrowths occur as minute (usually 10 μm) crystals that have precipitated on quartz grains with thin or incomplete coatings of diagenetic clay minerals. This observation indicates that these quartz overgrowths were precipitated after diagenetic clay-mineral precipitation. These later stage quartz overgrowths are rare and do not significantly reduce porosity or permeability.

Early calcite cement There is little primary calcite cement remaining in samples of the cross-bedded sandstone reservoir facies at Zeigler Field. Small amounts of primary calcite were found, however, in some samples of the cross-bedded sandstone facies in the no. 6 and no. 3 Mack wells (see fig. 31).These samples are from the outer fringes of the sandstone bar in the Mack lease, where porosity and permeability are low because much of the original early-stage primary calcium carbonate cement remains. The sample in plate 1b (also from the cross-bedded facies) shows carbonate framework grains, primarily echinoderm fragments stained red, with syntaxial rim cement and pore-filling cement stained purple.

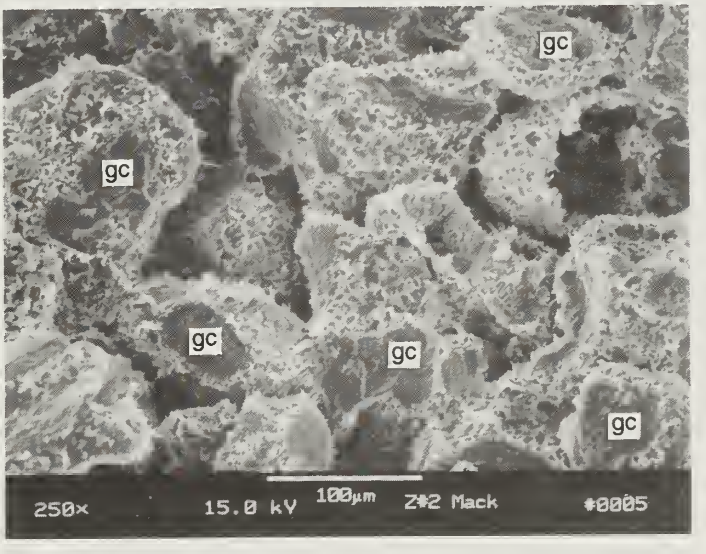


Figure 33 SEM photomicrograph of typical Aux Vases reservoir sandstone shows framework grains coated with diagenetic clay minerals (Gallagher Drilling Company no. 2 Mack, depth 2,619.5 ft). Beneath the clay minerals, the grains are also cemented by small amounts of silica cement at grain contacts. Some grain contacts (gc), split during sample preparation, can be seen as flat dark surfaces uncoated by diagenetic clay minerals. Silica cementation at the grain contacts occurred prior to precipitation of diagenetic clay-mineral coatings and probably was caused by slight pressure solution. The sample was air-dried and coated with carbon.

Seawater in near-surface marine environments is nearly saturated with dissolved calcium carbonate. This $CaCO_3$-charged water could infiltrate the bar facies following deposition, leading to the development of calcium carbonate cement during early diagenesis at shallow burial depths or possibly immediately following deposition. In addition, other areas located at the outer fringes of the sandbar contain cross-bedded, calcareous sandstone with primary calcite cement completely filling intergranular pores (plate 1d). If the calcium carbonate cement were removed, these cross-bedded, calcareous sandstones would be similar to the alternating porous, coarser grained and nonporous, finer grained laminae that make up the cross-bedded sandstone bar facies (plate 1c).

The suggestion that early, pervasive calcite cement filled much of the primary porosity in the bar facies is confirmed by the following factors: (1) the presence in thin sections of pores so large that numerous areas contain grains that do not contact other grains and appear to be floating and unsupported, and (2) some instances where even the clay rims between grains do not touch. In contrast, the grains in the fine sandstones in the green, ripple-bedded facies underlying the reservoir facies have undergone extensive silica cementation and are tightly cemented by quartz overgrowths. Quartz overgrowth development was inhibited in the reservoir facies by the coatings of diagenetic clay minerals around virtually every sand grain.

For these reasons, it is suggested that the reservoir-quality, cross-bedded sandstone facies at Zeigler contained large amounts of early-stage calcium carbonate cement, some of which nucleated around shallow marine fossil fragments in a mixed siliciclastic-carbonate environment. Later diagenetic events dissolved varying amounts of this primary calcite cement. At Zeigler Field, dissolution of calcite cement was nearly complete, particularly in the center of the sandstone bars and resulted in the development of large amounts of secondary porosity and enhanced permeability.

Intermediate stage: porosity enhancement Dissolution of feldspar is an intermediate-stage event that has enhanced porosity and permeability. The presence of organic acids could lower Eh and pH conditions, resulting in greater dissolution of feldspars than would ordinarily be expected at the relatively shallow burial depths, cool temperatures, and normally pressurized conditions to which these rock units have been subjected. Where feldspar grain dissolution is complete, enlarged oversized pores are left behind. Effective permeability and porosity can be increased significantly when complete or nearly complete dissolution of feldspar grains occurs. Incomplete dissolution of feldspar grains creates microporosity, which contributes very little to the effective porosity of the reservoir.

Plagioclase feldspars are the most common rock-forming aluminosilicate mineral (Deer et al. 1966). Their composition ranges between sodium-rich (albite) to calcium-rich (anorthite). Crystal twins, with division of lamellae into Na-rich and Ca-rich regions, are common. Although only minor amounts of calcium-rich plagioclase feldspars have been found in low-permeability and low-porosity units at Zeigler, they may have been originally present in larger quantities but completely dissolved in those zones with good porosity and permeability. Calcium-rich plagioclase, the least stable of the feldspars (Jackson 1970), is the most susceptible to dissolution. Although it is no longer present in most Aux Vases sandstone reservoirs, many of the enlarged grain-shaped pores in reservoir sandstones were probably formed by dissolution of Ca-plagioclase feldspar grains. This is why Ca-plagioclase is very rare in these rocks, but more stable K-feldspar and sodium feldspar grains are still present in the reservoir. A substantial amount of microporosity has been developed within individual twinned plagioclase grains as a result of preferential dissolution of the calcium-rich lamellae; whereas those composed of the sodium-rich feldspar remain. The importance of this type of secondary enhancement of porosity depends upon the amount of detrital calcium-rich plagioclase deposited. It may account for as much as 5% of the porosity but more commonly is responsible for 1% to 2%. K-feldspars are intermediate in stability and commonly found in a partially dissolved or degraded state (fig. 34). Most K-feldspar grains are highly altered, whereas the more stable Na-feldspar grains exhibit less alteration.

Remnant clay-mineral coatings are all that remain of many dissolved feldspar grains and indicate that some diagenetic clay mineral coatings were present before dissolution of feldspars. However, dissolution of feldspars almost certainly provided the Al, Si, and lesser amounts of cations such as Mg, Fe, and K needed for the precipitation of the diagenetic clay-mineral suite found in the reservoir.

Embayed quartz grains are diagnostic of an intermediate stage of quartz dissolution and are evidence of incomplete coating of some sand grains by diagenetic clay minerals at the time of silica dissolution. Dissolution of silica, although minor, is a distinct diagenetic event separate from other events involving the precipitation of minerals. Any conditions conducive to the dissolution of silica were also likely conducive to the dissolution of carbonate. This intermediate-stage event added a small amount of porosity and permeability to the reservoir facies.

Diagenetic clay mineral grain coatings The precipitation of diagenetic clay mineral coatings on virtually all sand grains is another major intermediate stage diagenetic event that contributed to preserving porosity and permeability in sandstone bar reservoirs at Zeigler and in many other Aux Vases fields. Although it may initially appear that precipitation of diagenetic clay mineral coatings on sand grains would occlude porosity and permeability by filling pores, their presence is responsible for preserving intergranular porosity developed after dissolution of early-stage calcite cement. Diagenetic clay mineral coatings apparently prevented nucleation of silica overgrowths on sand grains in the reservoir sandstone facies. In other facies, silica cement overgrowths completely occlude porosity where the overgrowths are extensive.

It is important to consider the presence of these clay-mineral coatings when designing drilling, completion, and recovery programs because drilling and treatment fluids will come into contact and react more with the diagenetic clay minerals, the major pore-lining minerals, than with the relatively inert underlying quartz and feldspar framework grains. Identification of specific clay-mineral types is necessary because they will react differently depending on the composition of drilling and recovery fluids. For example, smectite will swell when exposed to fresh water and may clog pore throats. Clay minerals in the Aux Vases have been shown to be sensitive to water less saline than formation water (Haggerty and Seyler 1997). Chlorite, another pore-lining mineral in the Aux Vases, is susceptible to leaching by hydrochloric acid, which may lead to the precipitation of iron-hydroxide gels in pores (Simon and Anderson 1990).

Aux Vases sandstone reservoirs may appear to be water-saturated on electric logs because some of the pore-lining clay minerals are hydrated varieties (fig. 35a). The effects of clay minerals on resistivity logs are discussed in a later section. Some of the complexities involved with identification of diagenetic clay minerals at Zeigler and other Aux Vases fields are discussed below.

Diagenetic clay mineral identification The diagenetic clay minerals in Aux Vases reservoirs could not be identified solely by SEM/EDX or XRD techniques.

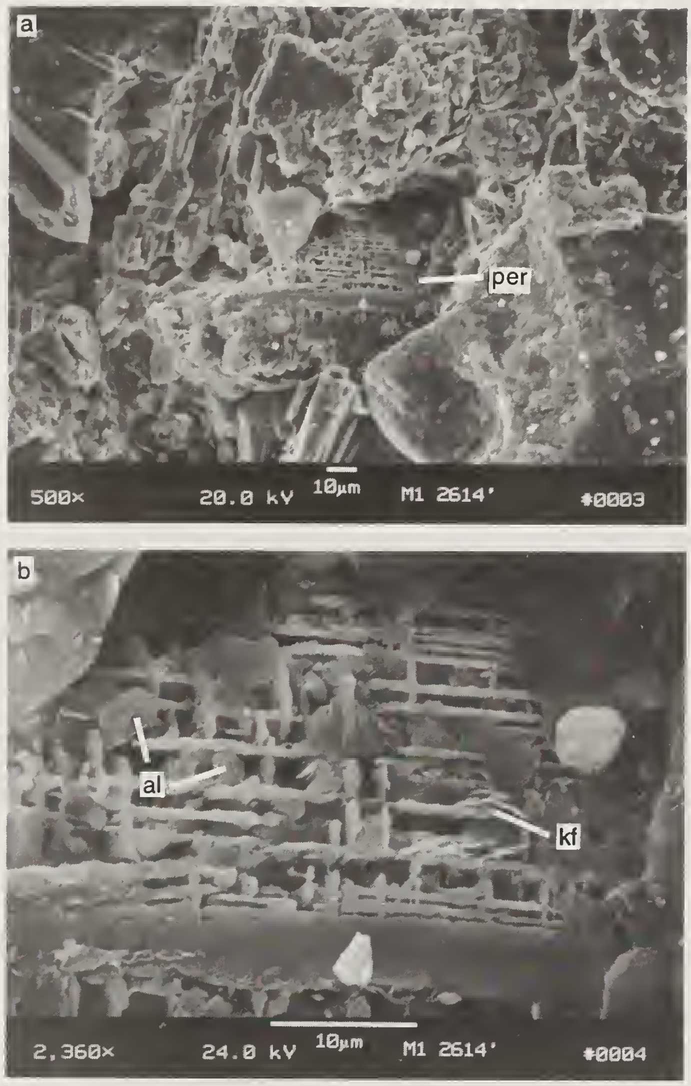


Figure 34 SEM photomicrographs of an Aux Vases sample from tidal sand-flat facies containing relatively poor reservoir qualities (Gallagher Drilling Company no. 1 Mack, depth 2,614 ft). (b) Close-up of partially dissolved perthite grain shown in (a). Vertical permeability is 3.2 md; horizontal permeability is 15.5 md; and porosity is 20.7%, in contrast to the 25.24% average porosity in the cross-bedded sandstone reservoir facies in the Mack lease. In the center of (a) is a partially dissolved perthitic feldspar grain (per), where the least stable laths have been dissolved, leaving remnants of K-feldspar. Brighter checkerboard laths are partially dissolved K-feldspar (Kf) with serrated edges. Euhedral crystals precipitated between laths are albite overgrowths (al). Identification of albite and K-feldspar was made by EDX analysis.

Both XRD and SEM/EDX analyses were necessary to show that grain-coating clay minerals in the cross-bedded sandstone reservoir facies are composed of a closely intergrown mixture of aluminum- or magnesium-rich chlorite, illite, and mixed-layered illite/smectite. Figure 35b illustrates that the morphology of typical intergrown pore-lining clay minerals, when air-dried or critical-point-dried, consists of

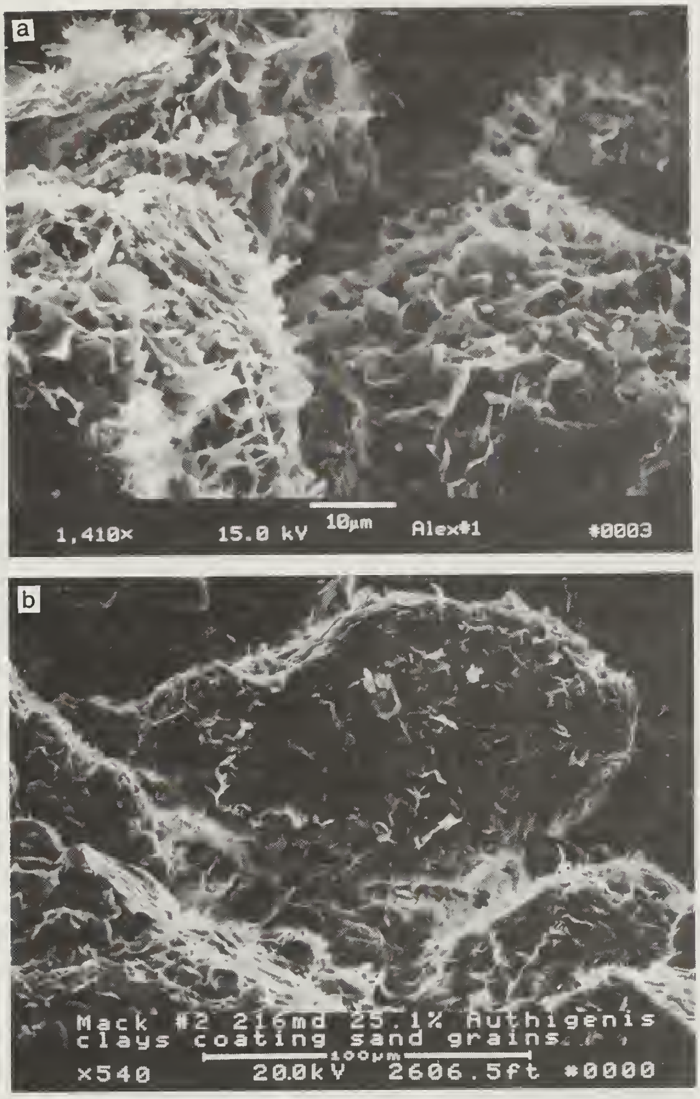


Figure 35 (a) SEM photomicrograph of a sample prepared by critical-point drying and then coated with Au/Pd (Gallagher Drilling Company no. 2 Alex, depth 2,631 ft). Framework grains are coated and pores are bridged by typical, intergrown diagenetic clay minerals. (b) SEM photomicrograph of an air-dried sample coated with Au/Pd (Gallagher Drilling Company no. 2 Mack, depth 2,606.5 ft). There is little apparent morphological difference between samples prepared using critical-point-drying and air-drying.

flakes with slightly crenulated surfaces. The flakes are prevalent in nearly all air-dried and critical-point-dried Aux Vases reservoir sandstone samples studied to date, including those from Zeigler, Oakdale, Dale Consolidated, Energy, Boyd, King, and Storms Consolidated Fields. A discussion of the differences in diagenetic clay minerals and their importance in reservoir sandstones in the Aux Vases and Cypress Formations can be found in Seyler et al. (in prep.).

Semiquantitative (EDX) elemental analyses of these clay minerals usually indicate the presence of a trace to as much as 0.5% K (potassium). This amount is too great for chlorite and an order of magnitude too small for illite, but it is reasonable for some mixed-layered illite/smectites. There are varying amounts of Mg (magnesium) and

Fe (iron), in addition to Al (aluminum) and Si (silica). The XRD analyses showed that the chlorite is an aluminum-rich variety. This evidence indicates that, although discrete phases of illite, mixed-layered illite/smectite, and chlorite are identified in XRD analyses, they occur as a closely intergrown mixture of crystallites too small for specific clay-mineral identification.

Effects of critical-point and air-drying on clay minerals A comparison of critical-point and air-dried samples of the reservoir-quality, cross-bedded sandstone facies was undertaken because air-drying of reservoir cores under ordinary storage conditions may cause deterioration of grain-coating and pore-lining diagenetic clay minerals (particularly illite), and discrete clay-mineral phases were not identified in XRD analyses. This experiment was performed to test the hypothesis that discrete illite had been present in the reservoirs but had become unrecognizable in air-dried samples because of deterioration. A fresh core sample from the Gallagher Drilling Company no. 1 Alex well (depth, 2,631 ft) was immediately placed in petroleum and brine from the offsetting Gallagher Drilling Company no. 2p Alex well. Part of the sample was critical-point-dried (fig. 35a); another part was air-dried (fig. 35b). No discrete illite was found in either sample, confirming that the illite was not rendered unrecognizable by air drying but was part of a closely intergrown mixture of clay minerals.

Late Stage Diagenetic Events

Some late-stage diagenetic events served to occlude porosity and permeability in varying degrees; however, others had the opposite effect. Minor amounts of late-stage, iron-rich carbonate cement and late-stage quartz and albite overgrowths were observed during SEM/EDX and thin-section analyses, but the amount of porosity occlusion they caused was negligible. Trace amounts of secondary halite, pyrite, barite, and clay minerals were also observed.

Figure 36 shows euhedral triclinic laths of albite overgrowths containing Na, Al, and Si. Much albite (Na-feldspar) in the Aux Vases occurs as detrital framework grains. The euhedral crystal faces shown in figure 36 indicate that this albite is not detrital but precipitated in situ as an overgrowth. Relict laths of undissolved plagioclase (probably Na-rich) appear to have served as seed crystals for the albite overgrowths.

Precipitation of late-stage ferroan calcite cement, product of a minor diagenetic event at Zeigler, occluded only a negligible amount of porosity. The latest stage of iron-rich calcium carbonate precipitation formed extremely minute (20 μm or less) euhedral crystals on top of diagenetic clay minerals in pores.

Late-stage calcite usually contains more iron than that found in fossil fragments and primary cements. Staining thin sections with potassium-ferricyanide and alizarine red can thus be used sometimes to distinguish between early and late phases of calcium carbonate precipitation because the later-formed cement stains a blue to purple color, whereas the primary calcite cement stains red (plate 1b). In general, little calcium carbonate is present in the reservoir-quality, cross-bedded sandstone facies at Zeigler.

In some samples with poor porosity and permeability from the sand-flat facies, halite fills pores and forms linings and bridges. Halite was not found in samples from the cross-bedded sandstone tidal-wave facies with good reservoir qualities. Figure 37 is an SEM photomicrograph of halite crystals on which diagenetic clay minerals have precipitated, proof that some diagenetic clay mineral precipitation occurred after halite precipitation. Because halite dissolves during thin-section preparation, thin sections cannot be used to observe the presence of halite as a pore-filling cement.

Precipitation of titanium oxide in the form of euhedral anatase crystals is another rare, very late-stage diagenetic event that occurred in some reservoir sandstones. These crystals are usually small (15–30 µm) and euhedral, and they constitute a minor component of pore linings and pore fillings. The fact that crystals most commonly precipitated on top of diagenetic clay minerals indicates that anatase was one of the last mineral phases to precipitate. Only rarely did diagenetic clay minerals precipitate on top of the anatase crystals.

Barite and barium-rich celestite precipitated during another minor, very late-stage diagenetic event. Crystals were identified in samples from the Gallagher Drilling Company no. 2 Alex well. These rare minerals are some of the few sulfur-bearing minerals found in the Aux Vases. Minute pyrite octahedrons are the only other sulfur-bearing minerals found in the Aux Vases at Zeigler and are more rare than either barite or barium-rich celestite.

Diagenetic alteration ceased after migration of petroleum into the reservoir sandstone bodies. Petroleum migration is therefore the last diagenetic event.

Microfractures

Vertical microfractures filled with sparry calcite cement are present in the dense Renault Limestone above and the dense Ste. Genevieve Limestone below the reservoir sandbar facies at Zeigler (plate 1e). Oil-stained vertical fractures and microfractures are common in the dense Ste. Genevieve Limestone. Open microfractures, some of which are filled with residual oil, are also found in the cross-bedded sandstone reservoir facies (plate 2c) at Zeigler. Because the grains in this sandstone are so weakly bonded, it is not always possible to discern whether microfractures in the

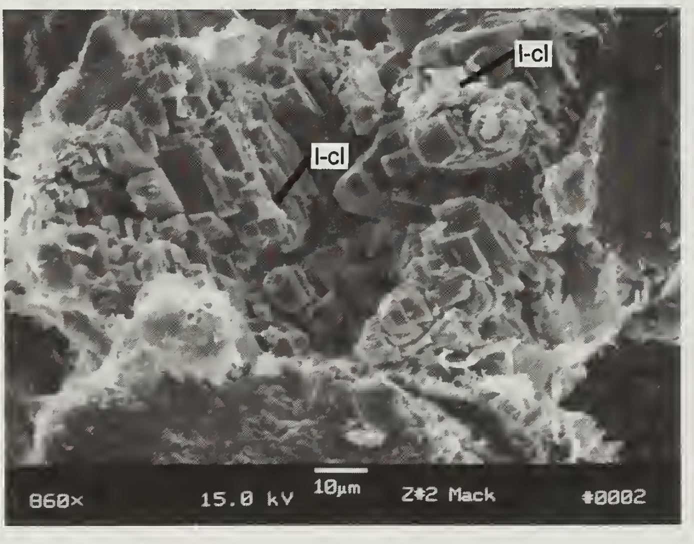


Figure 36 SEM photomicrograph of late-stage, euhedral albite overgrowths (Gallagher Drilling Company no. 2 Mack, depth 2,606.5 ft). The original feldspar framework grain was coated with diagenetic clay minerals. The feldspar grain was then partially dissolved and albite overgrowths precipitated on remnant laths. A small amount of diagenetic clay mineral precipitation followed precipitation of albite overgrowths (I-cl).

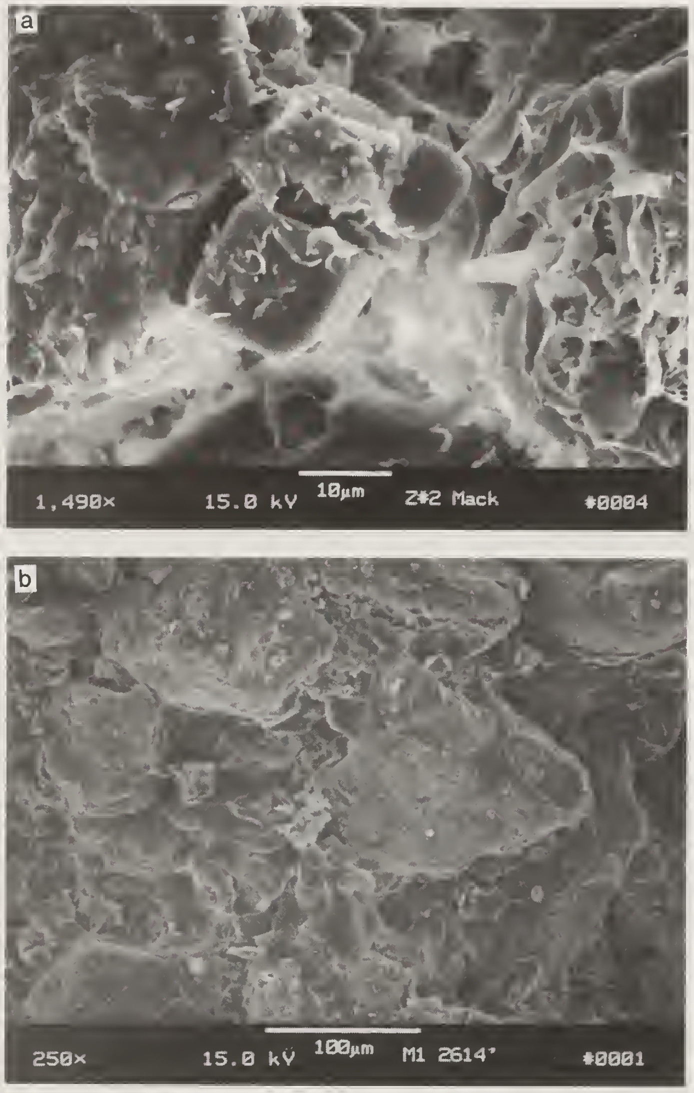


Figure 37 (a) SEM photomicrograph of halite (NaCl) crystals in the reservoir sandstone interval of the Aux Vases (Gallagher Drilling Company no. 2 Mack, depth 2,606.5 ft) shows diagenetic clay minerals precipitated on top of the halite crystals, evidence that the salt crystals precipitated before the clay minerals. This presence of very late-stage, diagenetic clay minerals indicates several stages of diagenetic clay-mineral precipitation, most of which preceded halite and some that followed salt crystal formation. Halite as a pore-filling cement was not observed in thin sections because this highly soluble mineral would have been dissolved during thin section preparation. (b) Pore-filling halite from the upper sand-flat facies in the Gallagher Drilling Company no. 1 Mack (depth 2,614 ft). Vertical permeability is 3.2 md, horizontal permeability is 15.5 md, and porosity is 20.7%. It is apparent that this halite precipitated after sediment deposition and is not a recent precipitation product because the halite is a widespread, pore-filling cement in this sample; it is intermixed with diagenetic clay minerals; and it lacks the small cubic crystals associated with recent evaporation of brine.

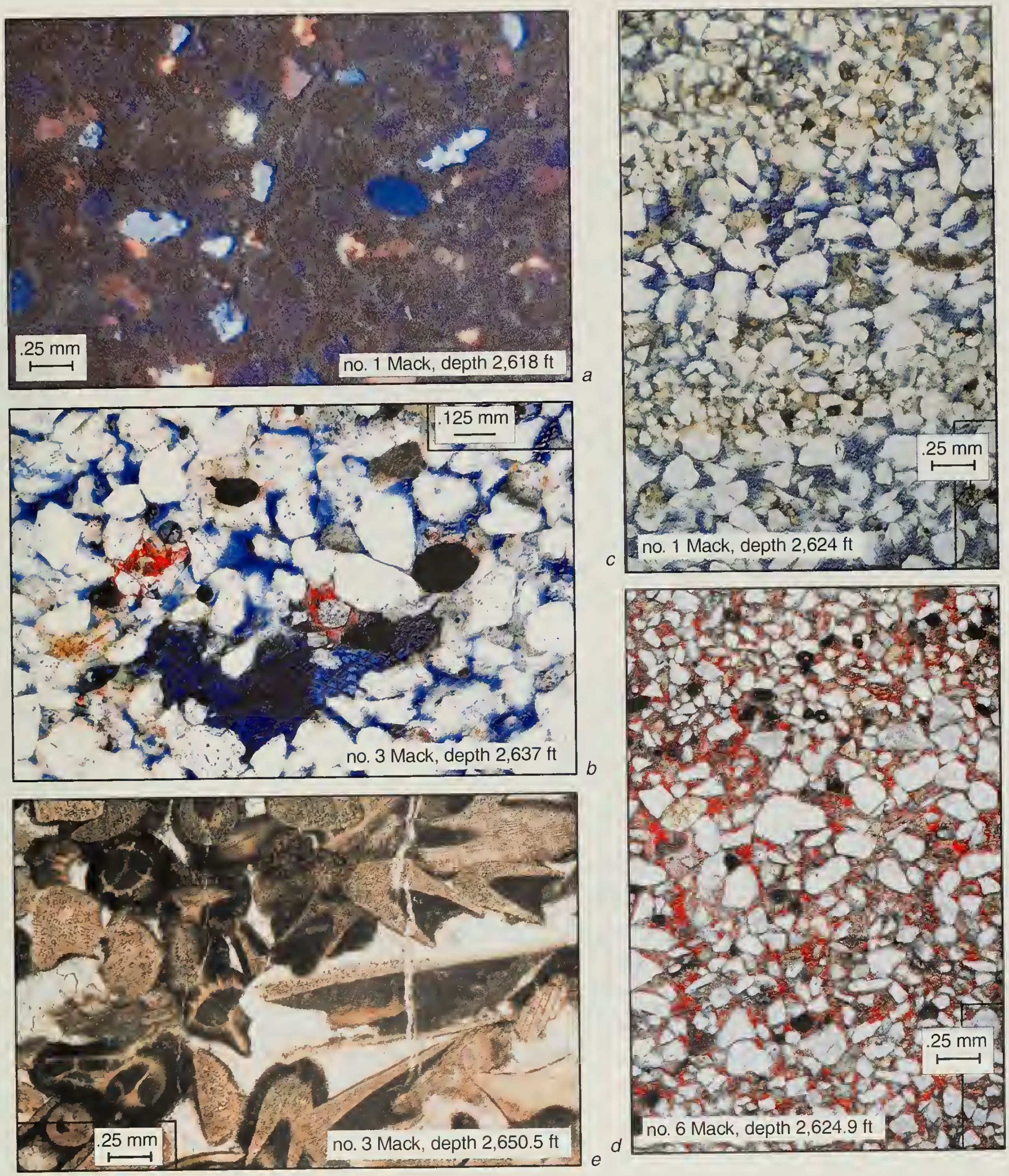


Plate 1 Thin-section photomicrographs. (*a*) Reservoir sandstone analyzed using cathodoluminesence shows early-stage, poorly developed quartz overgrowths and an abundance of feldspar grains, k-feldspar (bright blue), and Na-feldspar (bright yellow, red, and dull brown). Epoxy filling pores is a dull gray. (*b*) Remnant primary calcite cement (stained red) on the outer fringes of an isolated sandbar. Original calcite grains and early calcite cement are stained bright red. Some patchy blue-violet-stained calcite cement is located near the primary calcite stained red, possibly having nucleated on the primary calcite. The violet-stained calcite was precipitated at a later and deeper burial phase than was the primary red-stained calcite cement. (*c*) Porous, cross-laminated reservoir sample shows highly developed porosity, particularly in the coarser laminae. This porosity may be partly caused by dissolution of early-stage, infill calcite cement. (*d*) Calcite-cemented sample of the cross-laminated sandstone facies with early-stage calcite (red stain) cement completely surrounding framework grains. The photomicrographs in C and D illustrate the extremes of calcite cementation possible in the cross-bedded sandstone facies in the Aux Vases. (*e*) Vertical microfracture veins filled with clear, sparry calcite cement in a bioclastic grainstone in the Ste. Genevieve Limestone underlying the Aux Vases sandstone reservoir at Zeigler Field.

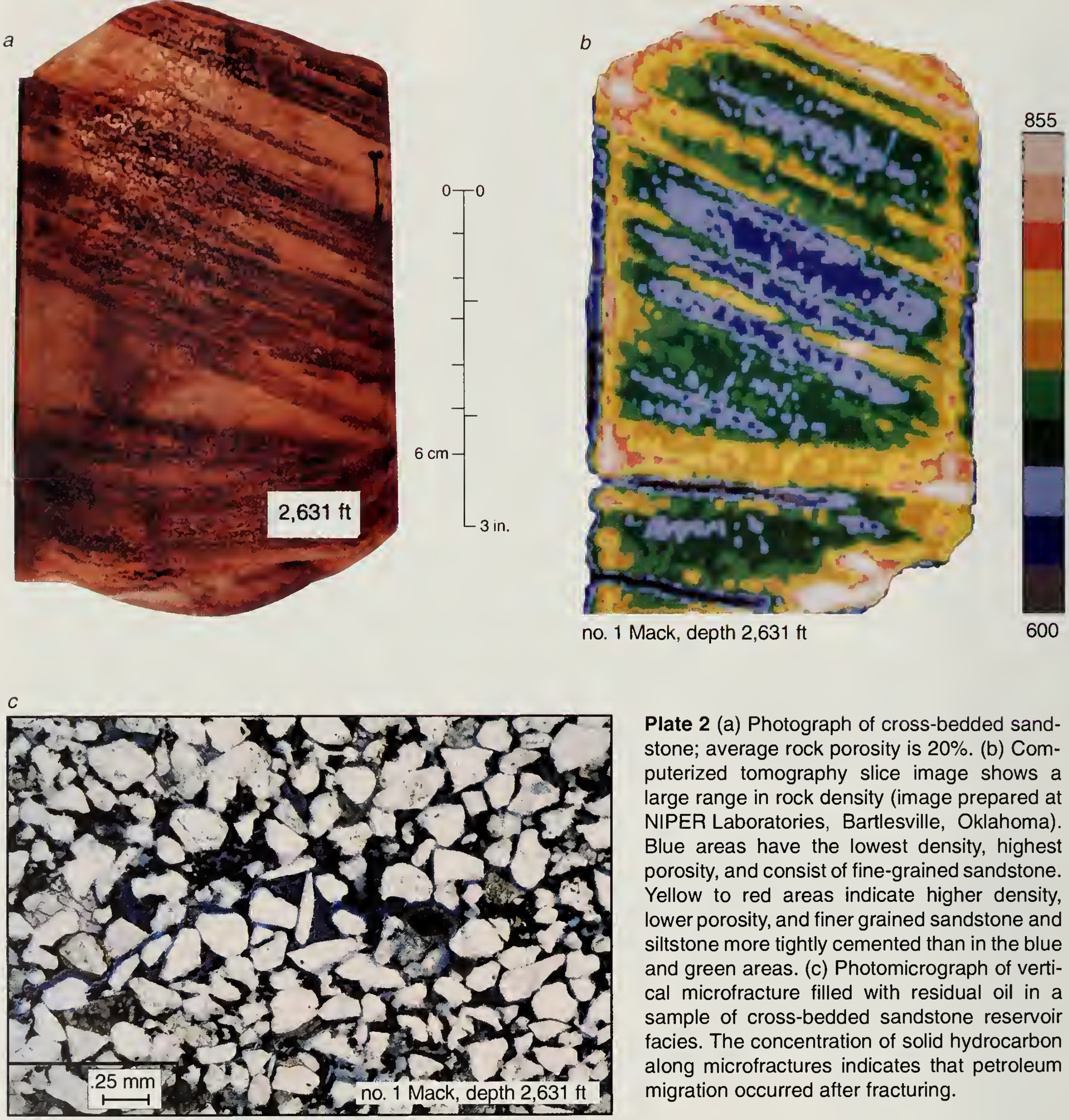


Plate 2 (a) Photograph of cross-bedded sandstone; average rock porosity is 20%. (b) Computerized tomography slice image shows a large range in rock density (image prepared at NIPER Laboratories, Bartlesville, Oklahoma). Blue areas have the lowest density, highest porosity, and consist of fine-grained sandstone. Yellow to red areas indicate higher density, lower porosity, and finer grained sandstone and siltstone more tightly cemented than in the blue and green areas. (c) Photomicrograph of vertical microfracture filled with residual oil in a sample of cross-bedded sandstone reservoir facies. The concentration of solid hydrocarbon along microfractures indicates that petroleum migration occurred after fracturing.

reservoir were formed in response to regional stress, localized faulting, or the sandstone splitting apart with the release of pressure when the core is pulled to the surface. The presence of residual oil in some microfractures, and healed microfractures in vertically adjacent limestones, as well as the proximity of a major fault system and several minor splinter faults, all indicate that open micro- and macrofracturing may have played a major role in channelizing permeability at Zeigler.

Water Saturation and the Effects of Diagenetic Clay Minerals

Diagenetic clay minerals are the cause of many of the problems encountered in exploring for and producing from Aux Vases sandstone reservoirs. The reservoir sandstone is friable because only diagenetic clay minerals and minimal silica cement at grain contacts weakly bind the sand grains together. The loosely cemented sand grains are easily disintegrated during drilling, thereby allowing the grains to pass through the cuttings separator without retention. Thus, cuttings of the reservoir sandstone are not always available for evaluation. In addition, the abundant clay-mineral coatings cause low resistivities to be recorded on electric logs, which leads to erroneously high water saturation (S_w) values when the Archie equation is used (Dewan 1983). Every producing interval in the Aux Vases at Zeigler Field has a deep induction resistivity of approximately 2 ohm-meters and has only produced water under waterflood operations. The Gallagher Drilling Company no. 1 Mack is a good example. The values used in the Archie equation (below) no. 1 Mack are as follows:

$$S_w = \sqrt[n]{\frac{aR_w}{\phi^m R_t}}$$

R_t = 2 ohm-meters (resistivity of formation)
ø = 25% (porosity)
R_w = 0.0525 based on direct measurement of brine from the no. 1 Alex well at 25° C and then converted to 35° C (resistivity of formation water)
m = 2 (cementation factor)
n = 2 (saturation exponent)
a = constant determined empirically, generally between 0.6 and 1.0 (set at 1.0 for this example)
S_w = water saturation

For this example, the calculated S_w is 64%. No water was produced, however, with the first 100,000 barrels of oil from the reservoir—a fact confirming that the calculated reservoir water saturation, based on the formation resistivity, is much too high.

Most of the high-quality, oil-saturated, reservoir sandstones in the Aux Vases appear, on the basis of the Archie equation, to be water-saturated, nonproductive zones. Consequently, estimated petroleum reserves in Aux Vases reservoirs have a greater degree of uncertainty than is usually acceptable. In an effort to obtain more accurate S_w calculations for purposes of reserve estimates, m and n were measured (by Alan Byrnes, formerly of GeoCore, currently with the Kansas Geological Survey) in four core plugs from the Gallagher Drilling Company no. 2 Mack well at depth of 2,608.8 feet (m = 1.94, n = 1.95), 2,609.2 feet (m = 1.98, n=1.76), 2,610.0 feet (m = 1.96, n = 2.15), and 2,615 feet (m = 1.98, n = 2.15). These values closely approximate the value of 2, which is traditionally used for sandstone reservoirs in the Archie Equation (Dewan 1983). All variables used in the equation above, with the exception of R_t, were measured directly from rock or fluid. Therefore, the resistivity log-derived value of 2 ohm-meters for R_t is unrealistically low because of the presence of bound (unproduceable) water (lining pores and within the micropores of pore-lining diagenetic clay minerals) that provides a very low resistance electrical path through Aux Vases reservoir sandstones (Seyler 1986). This highly conductive, irreducible (clay mineral bound) water affects both the medium and deep focus resistivity readings (fig. 27).

Another method for calculating water saturation is by direct measurement with conventional core analysis. Water saturations measured by conventional methods on core plugs, however, are typically also misleadingly high because most wells are drilled with water-based muds that infiltrate permeable zones. Drilling with an oil-based mud would yield more accurate water saturations, but this was not done in Zeigler Field (Anderson 1975). Thus, these formation evaluation techniques have some inherent problems and should be used with caution.

For these reasons, it is important to use alternative methods for calculating irreducible water saturation in these reservoirs and ensure more accurate determination of fluid saturations. An alternate method uses capillary pressure to indirectly measure water saturation. Air capillary pressure curves for four core plugs from the no. 2 Mack well are shown in figure 38. Water saturations calculated using these curves ranged from 28% to 41%. Direct measurement of irreducible water saturation from core plugs is also possible and was a second method used for the same four plugs. Each plug was cleaned of oil and restored by injecting brine until 100% of the pore space was filled with brine. Then, oil was injected until brine no longer flowed from the core plug. The difference in weight between the 100% brine-saturated condition and the oil-and-brine-saturated condition provides the irreducible brine saturation. The irreducible brine saturation or water saturation for the same four core plugs, when measured using this method, ranged from 24% to 37%. Both

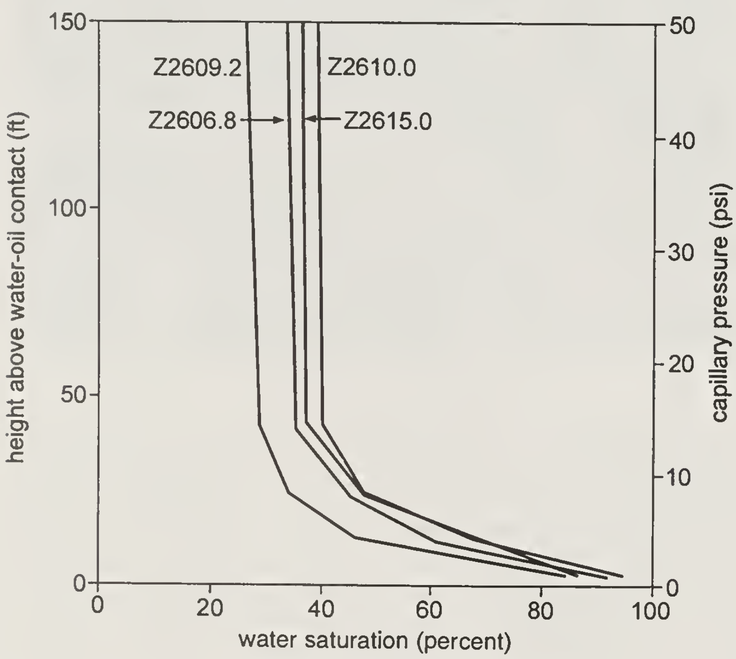


Figure 38 Capillary pressure curves from four core plugs in the no. 2 Mack well. Connate water saturation values ranging from 27% to 42% are derived from these curves. These values are much more realistic than the 65% calculated using log-derived values and the Archie Equation.

capillary pressure and irreducible brine measurements appear to provide water-saturation values more in keeping with saturation estimates made using material balance calculations (see Sim et al. 1994).

Computer Tomography (CAT Scan)

Reservoir heterogeneity on a macro- and microscale was visually highlighted and confirmed by computerized tomography (CAT scan) experiments. At the Laboratories of the National Institute for Petroleum and Energy Research, this imaging tech- nique was performed on a 6-inch-long section of core from a depth of 2,633 feet in the Gallagher Drilling Company no. 1 Mack well. It contains typical bidirectional, cross-bedded, porous, coarser grained laminae alternating with less porous, finer grained laminae. The most permeable zones, which correspond with the darker laminae, are coarser grained, stained with solid hydrocarbons, and more porous than the light tan, finer grained, less porous, and less permeable laminae (plate 2b). Minipermeameter measurements show that this sample has relatively poor reservoir qualities, with permeability ranging from 4.6 to 65.7 md, because of its overall finer grain size than the typical high-quality, cross-bedded sandstone reservoir facies of the Aux Vases. The sedimentary structures and relative grain-size relationships shown here, however, are similar to those observed in all available cores of cross-bedded sandstones in the Aux Vases.

Plates 2a and b shows both a photograph of the core and the corresponding CAT-scan image. The CAT-scan measurements, related to density and atomic number, are represented by a color scale. The denser zones of the core (reds and yellows) would be less porous than the gray, blue, and green parts of the CAT-scan, if mineralogical composition is relatively uniform. The variability shown by the CAT scan indicates that even the best reservoir facies may have a large amount of heterogeneity in porosity and permeability on a small scale. Thus, local rates of fluid flow (permeability) will be preferentially greater in a horizontal direction, parallel to the strike of the cross beds, than in a vertical direction. The horizontal permeability of the samples from the Gallagher Drilling Company no. 1 Mack is generally greater than the vertical permeability. Because the widths of the cross-bed sets are small, however, in comparison with the dimensions of individual reservoir sandstone bodies, these directional effects on permeability may be small.

RESERVOIR ENGINEERING

Reservoir Fluids

Brines Three brine samples from Zeigler Field were analyzed. Two of the samples are from the older Plumfield lease. Since 1965, wells have been waterflooded with brines drawn from both Pennsylvanian and Cypress Sandstones (some 1,200 and 200 ft above the Aux Vases, respectively) and later with produced Aux Vases brines. Because the brines drawn from Pennsylvanian sandstones and Mississippian Cypress sandstones contain fewer total dissolved solids than do the brines in the Aux Vases, it is presumed that they have diluted the Aux Vases brine samples from these wells. Therefore, it is thought that the R_w measured on undiluted brines from the Gallagher Drilling Company no. 1 Alex well are more representative of the original brine in Zeigler Field. Complete results of brine analyses for the no. 1 Alex are shown in appendix B and summarized below.

Total dissolved solids measured in the sample from the no. 1 Alex are 137,331 ppm. The major components are 82,000 ppm Cl (the most abundant anion) and 45,950 ppm Na, 6,020 ppm Ca, and 1,900 ppm Mg (the most abundant cations). The pH of

6.24 (appendix B) is more acidic than most brines analyzed to date. Total dissolved solid concentration is also greater than most brines sampled to date. The measured R_w of 0.061 ohm-meters is well within the range of 0.058 to 0.070 ohm-meters of other Aux Vases brines in the region (Demir 1995).

It is important to ensure compatibility of brines with reservoir fluids when planning waterflood programs. Although there is no indication that problems have occurred at Zeigler Field, precipitation of solids may occur when brines are brought to the surface. There is enough Ca and SO_4, at 6,020 and 490 ppm, respectively, for precipitation of gypsum to occur, and the amount of Fe, 17.2 ppm, is large enough for significant iron-oxide precipitation. If brines have been allowed to oxidize, filtering is necessary before reinjection, even into the same horizon. Oxidation of iron is a problem commonly encountered when using brines produced from the subsurface for reinjection. It is necessary to treat and filter these brines as a safeguard against potentially adverse reactions between the injection fluids, the in situ reservoir fluids, and the clay minerals lining the reservoir pores.

Oils Gas chromatograph analyses of oils from three wells are shown in appendix C. The API gravity of the oil from the Gallagher Drilling Company no. 1 Alex is 38°. Viscosity is 4.4 cp at 95°F and atmospheric pressure. Bubble-point pressure is 504 psi. Pressure-volume-temperature relations of crude oil from the Gallagher Drilling Company no. 1 Alex were reported in Sim (1993). The pristane/phytane ratios of 1.5 are indicative of oils sourced from the Devonian New Albany Shale (appendix C).

Production

Production at Zeigler Field is solely from the cross-bedded sandstone bar (wave) and the fine-grained sandstone, sand-flat facies of the Aux Vases. To date, the field has produced approximately 2.1 million barrels of oil from two separate bars and three other bars that partially overlap but have minimal fluid communication. The cumulative production per well is extremely variable, ranging from a high of 203,774 barrels of oil from the Gallagher Drilling Company no. 1 Plumfield to a low of 646 barrels of oil produced from the Gallagher Drilling Company no. 10 West Plumfield, a marginal well that was converted to an injector. The average cumulative production per well at Zeigler is 65,540 barrels of oil. Production history for the Plumfield leases, which make up the main body of Zeigler Field, is shown in figure 39. The field was discovered in 1963 and has had a maximum of 27 producing wells. Although production had started to decline in 1965, water injection reversed this trend in1966. Production was maintained or increased through 1969 by converting strategic producing wells to water injectors (fig. 39). Appendix D summarizes the reservoir data.

Production for each well varies with the thickness, permeability, and porosity of the reservoir sandstone facies, proximity of injection wells, fracture systems, and duration of waterflood. There are a total of 40 oil wells in Zeigler Field. Two in the Mack lease still produce oil. All 16 wells in the West Plumfield bar have been plugged. Two wells in the Plumfield bar still produce oil and 12 have been plugged. All five wells in the South Plumfield bar have been plugged, as have the three wells in the Bend bar. The Gallagher Drilling Company no. 1 Alex well is a marginal producer in Sec. 19, T7S, R2E, in a sandstone bar with poor reservoir qualities. The Gallagher Drilling Company no. 1 Ruzich well in Sec. 17, T7S, R2E, is another marginal producer in a poorly developed bar. The West Plumfield bar, the largest and most productive, has yielded a total of 842,084 stock tank barrels of oil. The Plumfield bar is the second largest with 824,372 stock tank barrels of oil produced to date. The South Plumfield bar has produced 296,091 barrels of oil. The cumulative production of 133,000 barrels at the

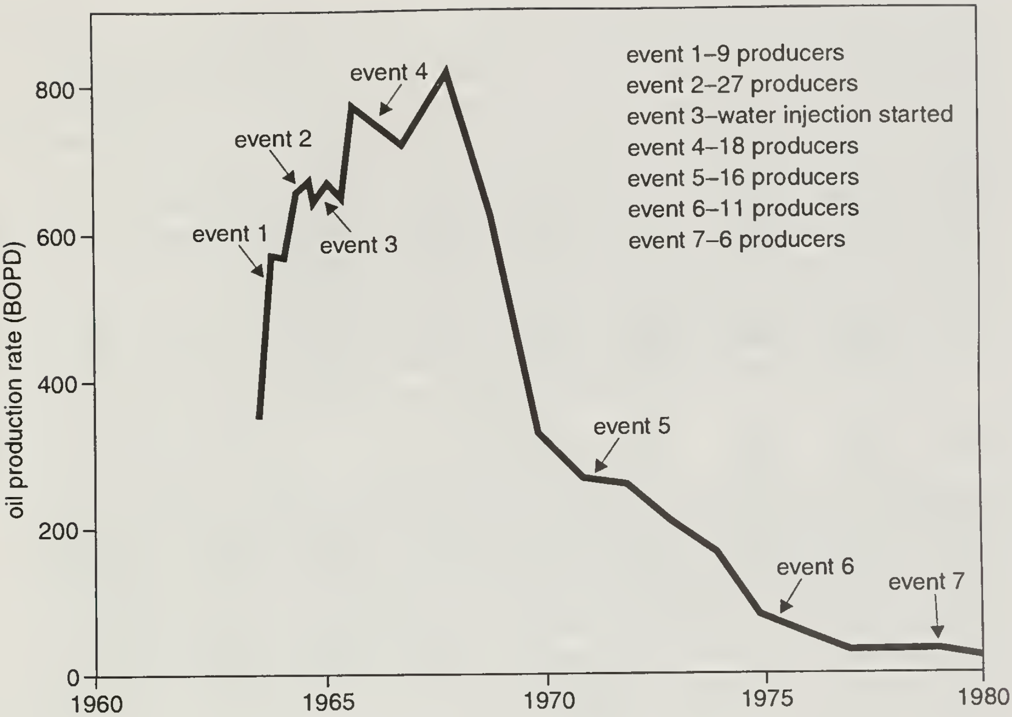


Figure 39 Production history of Plumfield leases, encompassing the main body of Zeigler Field. Major events affecting production are highlighted (from Sim et al. 1994).

Mack bar is the lowest, but the Mack is also the youngest producing unit in the field and it has the highest potential for future production.

Pressure Surveillance

Pressure surveillance is used to monitor changes in reservoir characteristics through time and may be used initially to aid in defining the size and boundaries of a reservoir. Comprehensive pressure surveillance, an under-utilized tool in the Illinois Basin, was a key element in reservoir management at Zeigler Field. Pressure surveys revealed a large pressure differential between the east and west parts of the main area of Zeigler Field and confirmed the existence of two different sandbars separated by a permeability barrier (fig. 40). This relationship was not obvious from a study of electric logs and other geologic data.

The isopach map of sandstone thickness in the Aux Vases (fig. 3) was constructed using a high deflection of the SP curve as the criterion for clean, reservoir-quality sandstone. It closely approximates the actual thickness of the reservoir sandstone bar facies. The only indication of the permeability barrier on this map, however, is a constriction of the isopach to a width of two well spacings (approx. 1,320 ft) between the Plumfield no. 18 and no. 19 wells at the 5-foot contour interval. Structural and stratigraphic cross sections (fig. 5) also do not readily indicate the presence of two distinctly separate sandbars. Electric logs (fig. 5) in the no. 18 Plumfield well indicate only a minor shaly sandstone break between two thin, more permeable sandstone bodies. Therefore, data from pressure surveys significantly aided in making the geologic interpretation of two separate and slightly overlapping sandstone bars.

The fact that these two bars are totally separate has greatly influenced petroleum movement and recovery. For example, results from the initial waterflood design

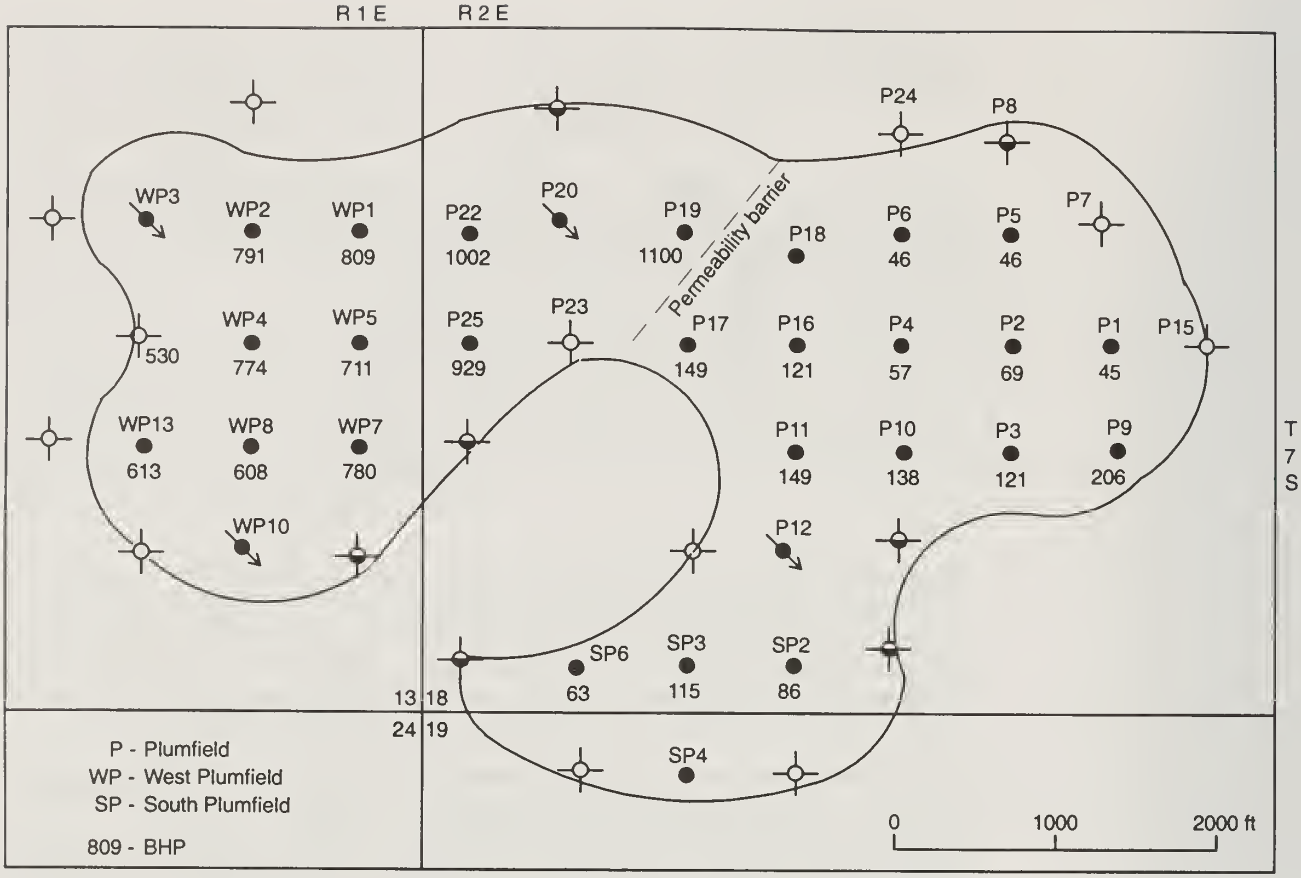


Figure 40 Pressure survey of Zeigler Field in 1966. The large differences in pressures between the west and east sides of the field occur at the indicated permeability barrier and demonstrate the lack of communication between the West Plumfield and Plumfield bars, even where they overlap (from Sim et al. 1994).

showed that there was no fluid movement between the West Plumfield bar and the Plumfield bar (fig. 3). Effective redesign of the waterflood was possible when pressure data revealed the location of the permeability barrier. This example demonstrates the value of acquiring pressure data as a relatively inexpensive means of monitoring reservoir behavior.

Pressure surveys and surveillance of fluid production showed that another, less effective, permeability barrier exists between the Plumfield and South Plumfield sandstone bars (figs. 3, 40). Production data and response to water injection (figs. 40, 41c) show that there is little north–south fluid flow between these two reservoirs on either side of the no. 12 Plumfield well. The pressure surveys showed a pressure differential (fig. 40) separating the Plumfield bar from the South Plumfield bar. Isopach maps of the reservoir facies show that fluid communication between these two sandstone bodies is limited to a narrowly constricted pathway of approximately one well spacing at the no. 12 Plumfield.

Production data show that there was no response in the production of wells to the north for several years after inception of water injection in the Plumfield no. 12. Thus reservoir communication is likely to be more limited to the north than to the south and southwest. As with the permeability and communication barrier separating the West Plumfield and Plumfield bars, electric logs and core descriptions did not indicate the presence of a permeability barrier. The pressure differential between these two bars was reduced through time, thereby indicating a minor amount of communication between the Plumfield and South Plumfield bars. The permeability of the injector well is consistently in the 200-md range throughout the reservoir sandstone bar zone, but permeabilities in the sandbar zone in offsetting wells to the north and south vary from 50 to 600 md. Because both north and south offsets display approximately equal variations in permeability, the preferential effects of waterflooding directed to the southeast cannot be explained solely by variations in permeability. One possible explanation for the fluid communication barrier is the presence of an overlapping of sandstone bars or a silty zone separating the Plumfield and South Plumfield sandstone bars. Another possible influence on porosity and permeability previously discussed is a fault separating the two parts of the field.

Waterflood Results: The Bar Edge Effect

At Ziegler Field, wells with the highest cumulative oil production are generally located at the edges of sandstone bars and not necessarily associated with wells penetrating the thickest, cleanest, most porous and permeable sandstone (fig. 41a, b). This edge production is the result of very effective waterfloods, which pushed oil to the periphery of individual sandstone bars toward the last available well before stratigraphic pinch-out of sandstone bars. A contoured map of the cumulative oil production for wells in Zeigler Field (fig. 41a) helps to illustrate this phenomenon (see also fig. 18).

Comparison of the contoured map of initial production data (fig. 41b) with the cumulative production map (fig. 41a) demonstrates that, with few exceptions, the wells with the largest initial production rates do not necessarily have the largest cumulative production. There is a good correlation between large initial production rates and large isocapacities (compare figs. 41b and c). The isocapacity map in figure 41c contours the cumulative permeability of the reservoir-quality, cross-bedded sandstone bar facies in each well and illustrates the rapid pinch-out of permeability at the edges of sandstone bars. The Gallagher Drilling Company no. 1 Mack well has the largest capacity in Zeigler Field. Other wells with very large capacities are the Gallagher Drilling Company no. 5 and no. 3 Plumfield wells in the Plumfield sandstone bar. The Gallagher Drilling Company no. 3 South Plumfield and no. 2 South Plumfield wells have the largest capacities in the South Plumfield bar, while the Gallagher Drilling Company no. 19 and no. 20 Plumfield wells have the largest capacities in the West Plumfield sandstone bar. In only one of these cases, the no. 1 Mack well, has the well with the greatest capacity in a sandstone bar produced the most oil. These maps highlight the effectiveness of the waterflood program in this field and demonstrate the importance of strategic conversion of producing wells to injectors in order to drain the reservoir effectively.

Figure 18 shows the relationship between reservoir sandstone thickness, permeability, and production (also see figs. 40, 41, 42). The Gallagher Drilling Company no. 6 South Plumfield well at the western extremity of the South Plumfield bar has produced 139,525 barrels of oil from just 3 feet of sandstone with permeability of 73 md or less, whereas the offsetting well (no. 3 South Plumfield) produced 73,068 barrels of oil from 15 feet of sandstone with more than 250 md of permeability. The South Plumfield no. 6 also produced much more water than the other two wells in the bar (no. 3 South Plumfield and no. 2 South Plumfield), although both had better reservoir-quality sandstone (fig. 18). This pattern shows that the waterflood injection at the no. 12 Plumfield moved reservoir fluids to the west edge of the sandbar where the sandstone was thin and encased in impermeable tidal-flat and shallow-marine sediments that sealed the reservoir.

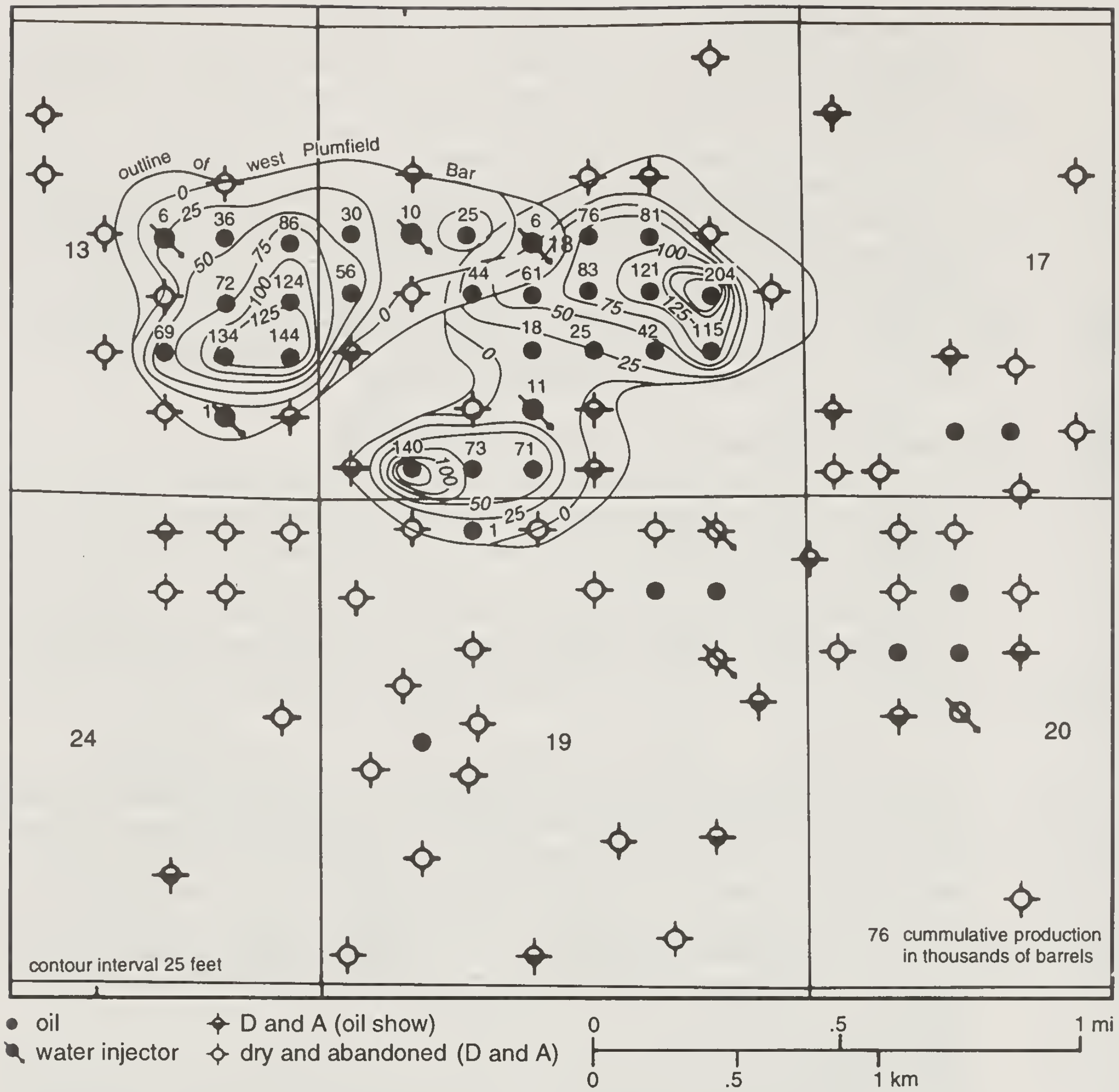


Figure 41 (a) Isopach of cumulative production at Zeigler Field. Waterflooding has pushed oil to wells at the edge of sandbars so that most of the oil has been produced from wells with the thinnest and least permeable reservoir sandstone. Comparison of the three maps that make up figure 41 (a , b, and c) with the isopach of the reservoir sandstone thickness map (fig. 3) shows the effective draining and fluid movement resulting from waterflooding in this field.

See pages 65 and 66 for the following:
(b) isopach of initial production,
(c) isocapacity map constructed by contouring permeability times thickness (k [md] x h [ft]) values of the sandstone bar reservoir facies in each well.

Monitoring the quantities of injected and produced fluids, in addition to surveillance of the pressure in each well in the field, shows that fluid preferentially flows in an east to west direction in these reservoirs. The bar in the South Plumfield lease shown in figure18 is one of several examples where east and west offsetting wells responded more quickly than north or south offsetting wells did to waterflood. Production decline curves (fig. 43) for these wells show a delayed response to waterflooding relative to their direciton from the injection well. The Gallagher Drilling Company no. 12 Plumfield was converted to a salt-water injection well in February 1965; there are no

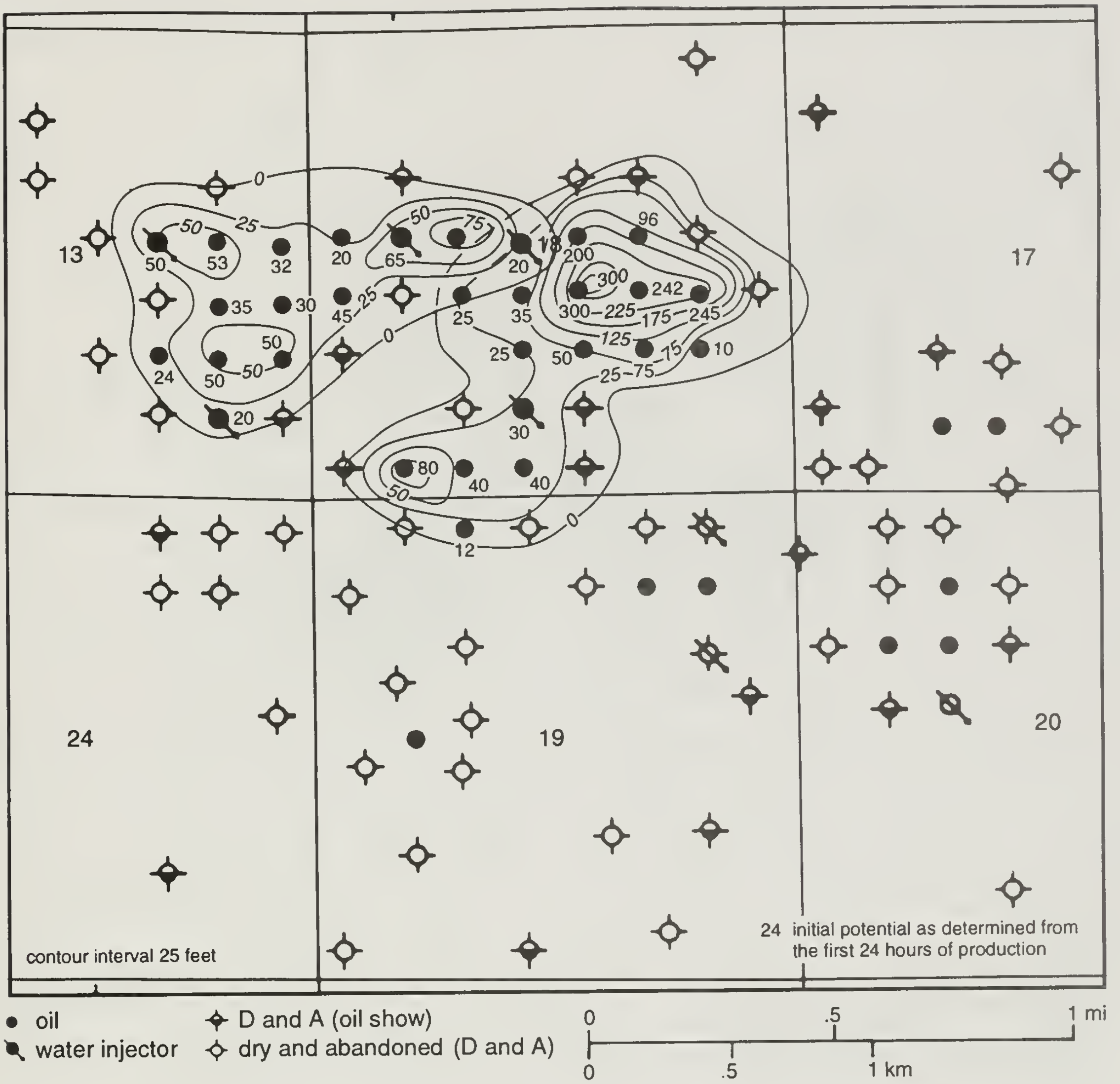


Figure 41 (b) Isopach of initial production. Waterflooding has pushed oil to wells at the edge of sandbars so that most of the oil has been produced from wells with the thinnest and least permeable reservoir sandstone. Comparison of the three maps that make up figure 41 (a, b, and c) with the isopach of the reservoir sandstone thickness map (fig. 3) shows the effective draining and fluid movement resulting from waterflooding in this field.

See pages 64 and 66 for the following:

(a) Isopach of cumulative production at Zeigler Field,

(c) isocapacity map constructed by contouring permeability times thickness (k [md] x h [ft]) values of the sandstone bar reservoir facies in each well.

direct east or west offsets to the no. 12 Plumfield. The Gallagher Drilling Company no. 2 South Plumfield, a southward offset (660 ft), is the closest well to the no. 12 Plumfield. The Gallagher Drilling Company no. 3 South Plumfield well, offsetting the no. 12 Plumfield 933 feet to the southwest, is the next closest and the no. 6 South Plumfield is a 1475-foot southwest offset (fig. 40). The three wells responded almost simultaneously to the start of waterflooding in 1966. Production curves for the wells (fig. 43) show a much greater increase in production as a response to the waterflood at the west edge of the bar (no. 6 South Plumfield) in comparison with the southern offset well (no. 2 South Plumfield). (Well locations appear in figures 40 and 18.)

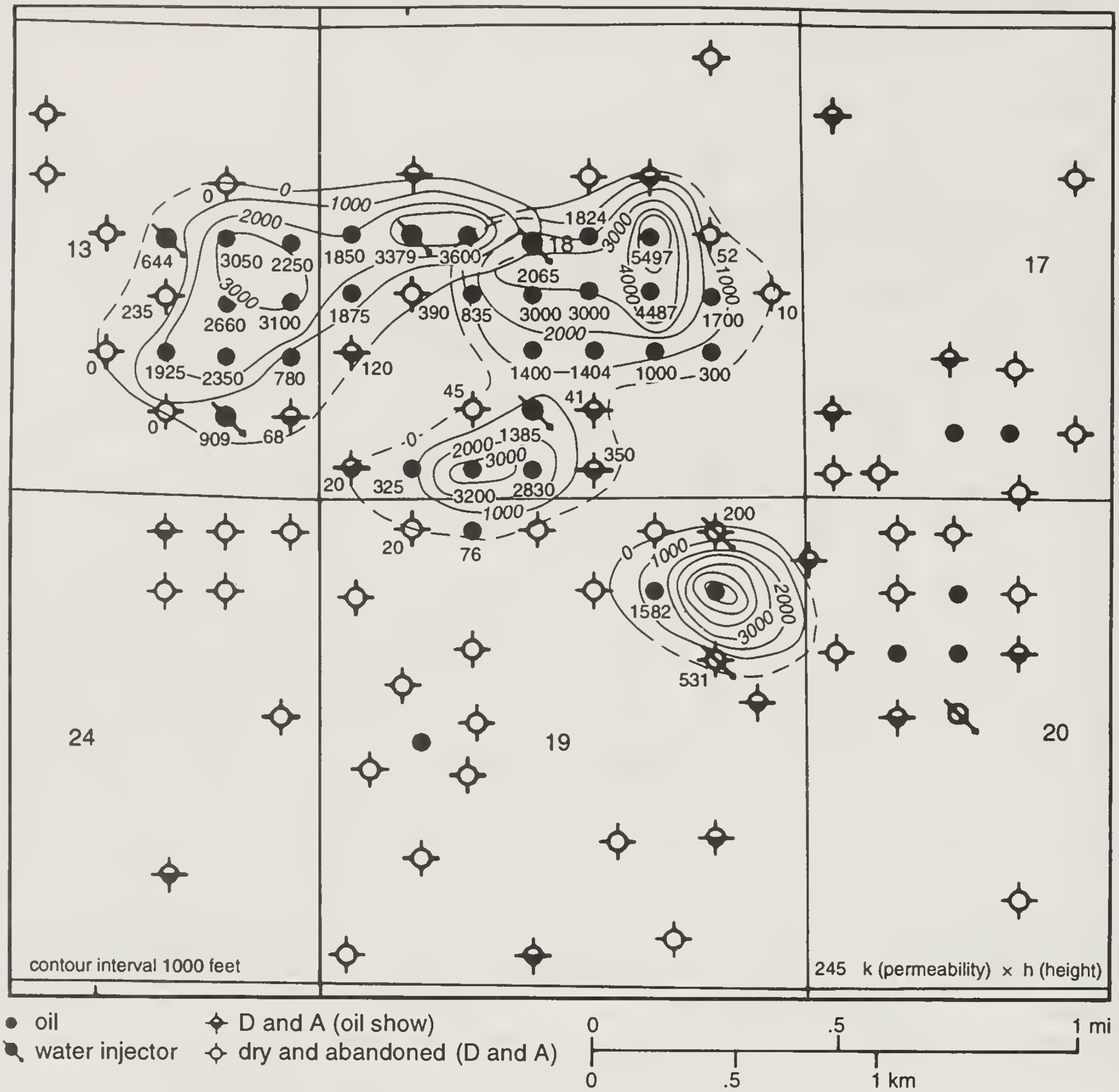


Figure 41 (c) Isocapacity map constructed by contouring permeability times thickness (k [md] x h [ft]) values of the sandstone bar reservoir facies in each well. Waterflooding has pushed oil to wells located at the edge of sandbars so that most of the oil has been produced from wells with the thinnest and least permeable reservoir sandstone. Comparison of the three maps that make up figure 41 (a, b, and c) with the isopach of the reservoir sandstone thickness map (fig. 3) shows the effective draining and fluid movement resulting from waterflooding in this field.

See pages 64 and 65 for the following:
(a) Isopach of cumulative production at Zeigler Field,
(b) isopach of initial production.

Production peaks for the three wells show a slight delay from east to west: the no. 2 South Plumfield had peak production in 1966, the no. 3 South Plumfield in January 1967, and the no. 6 South Plumfield in January 1968. Water production was established during January 1967 for the no. 2 South Plumfield, June 1967 for the no. 3 South Plumfield, and June 1967 for the no. 6 Plumfield. Fluid movement toward the west edge of the bar was much more rapid than fluid movement to the south. The no. 2 South Plumfield well became watered out, but the no. 3 and no. 6 South Plumfield wells had high cumulative productions because of an effective sweep and pressure maintenance through waterflood injection in the no. 12 Plumfield well.

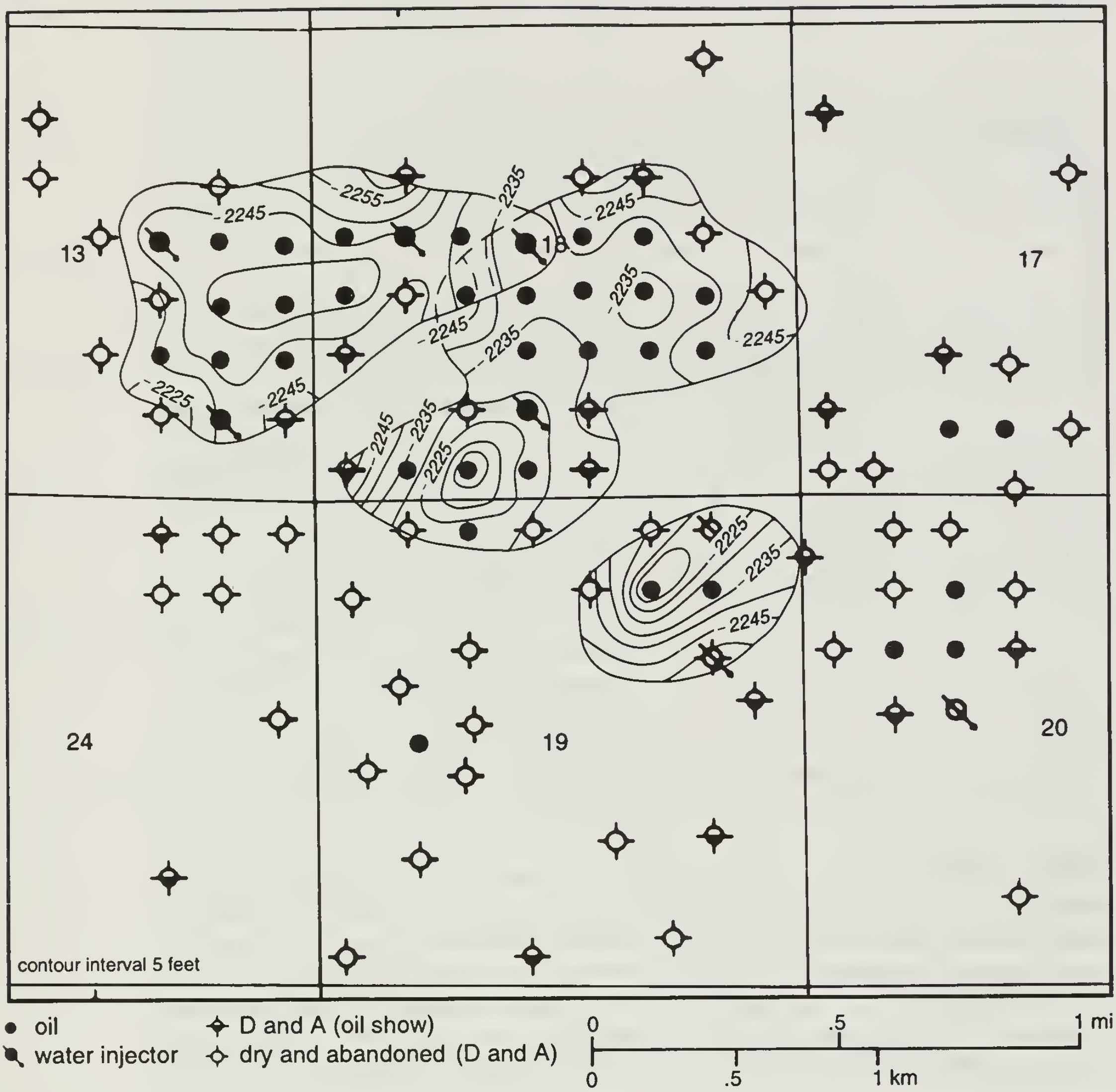


Figure 42 Structure map of the top of the cross-bedded sandstone reservoir facies.

The sweep of oil was predominantly from east to west rather than from north to south. The well to the south of the no. 3 Plumfield (no. 4 Plumfield) and the well to the north of the no. 12 Plumfield (no. 11 Plumfield) were unaffected by this waterflood.

Structural elevation of the bar top has not played a role in the edge wells producing more than the central wells because the thickest part of the sandbars coincides with the structurally highest areas (fig. 42). Preferential east–west flow has also been documented in Aux Vases reservoirs in Dale Consolidated Field. Beaty and Fagan (in prep.) attributed the east–west flow at Dale to channeling caused by vertical or near-vertical natural fractures oriented parallel to subparallel to the maximum horizontal compressive stresses. The more rapid east–west flow of fluids documented in Zeigler Field indicates that a similar system of vertical fractures may exist at this field. The orientation of natural fractures is an important factor to consider when designing reservoir management programs.

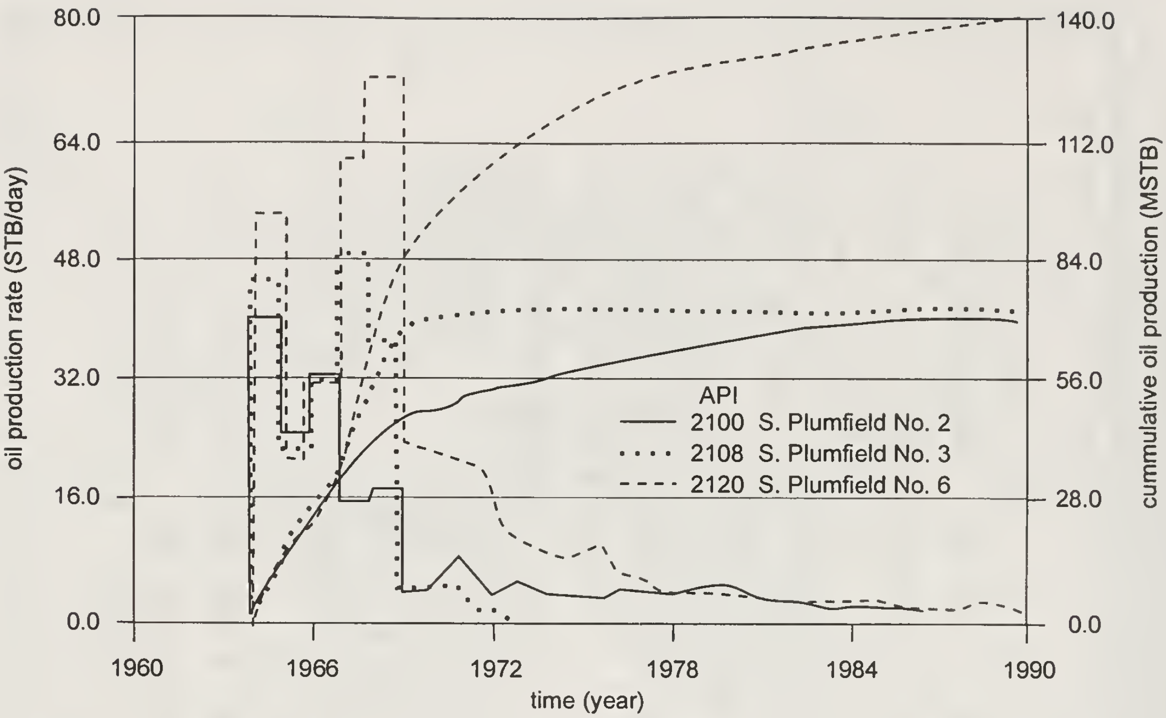


Figure 43 Production decline curves of the producing wells shown in cross section B–B′ (fig. 18).

Drive Mechanism

Solution gas was the drive mechanism at Zeigler for the first 6 months of production. Initial pressure in the field was 1,250 psi, which diminished to 100 psi in the Plumfield reservoir after the first year of production. The pressure dropped rapidly in this reservoir, mainly because of the large volume of fluid removed and the limited volume of the reservoir. The other sandstone bars, placed on pressure maintenance before appreciable depletion, yielded greater recovery efficiencies than the main Plumfield bar.

Volumetrics

Volumetrics were calculated using the following equation. The original oil in place (OOIP) is given by:

$$OOIP = 7758\phi AhS_o$$

Where OOIP = original oil in place

ϕ = average porosity in the bar: 21%

Ah = volume in acre-feet (will vary depending on volume of sandstone bar)

S_o = average oil saturation: 60%, 65%, and 70% (see table 1)

7758 = conversion factor of acre-feet to barrels

$$STOOIP = 7758\frac{\phi AhS_o}{B_o}$$

Where $STOOIP$ = stock tank original oil in place

B_o = formation volume factor: 1.068

Estimates of the STOOIP were made for all of the sandstone reservoirs. Other data for the STOOIP determination are shown in the appendix D.

The West Plumfield sandstone bar is the largest reservoir in Zeigler Field. The Plumfield and South Plumfield sandstone bars were combined for volumetric calculations because they overlapped and had some communication. The sandstone bar in the Mack lease is one of the smallest in the field and totally isolated from the other bars. Nonreservoir sandstones that commonly showed 10% or greater porosity, but had permeabilities less than 20 md, were not included in calculations of reservoir volumes.

Because there is no oil/water contact in any of the sandstone bar reservoirs at Zeigler, the total pore volume of each of the bars was calculated to determine OOIP, STOOIP, and recovery efficiencies. The volume of each bar was determined by the planimeter method from the isopach maps of the reservoir sandstone bars (fig. 3).

Recovery efficiencies for the West Plumfield and the combined Plumfield and South Plumfield sandstone bars were exceptionally large in comparison with the other Aux Vases fields studied. Recovery efficiency for the West Plumfield bar was 49%, and the combined Plumfield and South Plumfield bars produced 56% of the STOOIP. This is an estimate because several variables, such as porosity, oil saturation, and reservoir volume, can vary depending upon the method used for measurement and how they are averaged; for example, oil saturation can be measured by several methods. A range of average values (59–74%) has been calculated using different methods. Therefore, oil saturation values of 60%, 65%, and 70% were used to calculate reserves in table 1. Variations in calculated reservoir volumes (acre/ft) are caused by different interpretations of the thickness of reservoir-quality units, different contouring, and different methods of measurement. The reservoir volume estimates used in this study are conservative because porous, low- permeability sandstones were considered to be of nonreservoir quality and were not included in reservoir volume calculations.

Table 1 Recovery efficiency calculations for three different scenarios of average reservoir oil saturations and porosity.

Bar	Acre/ft	STOOIP	Produced BO	Remaining BO	RE %
porosity = 21%, S_o = 60%					
W. Plum.	1876	1,707,045	842,084	874,961	49
Plum/S.P.	2182	1,997,118	1,120,463	876,655	56
Mack	625	572,043	133,000	439,043	23
porosity = 21%, S_o = 65%					
W. Plum.	1876	1,860,133	842,084	1,018,049	45
Plum/S.P.	2182	2,163,544	1,120,463	1,104,308	51
Mack	625	619,713	133,000	486,713	21
porosity = 23%, S_o = 70%					
W. Plum.	1876	2,194,003	842,084	1,351,919	38
Plum/S.P.	2182	2,551,734	1,120,463	1,431,410	44
Mack	625	730,944	133,000	597,944	18

Acre/ft = unit of volume; STOOIP = stock tank original oil in place; BO = barrels of oil; S_o = oil saturation; and RE = recovery efficiency.

These large recovery efficiencies for Zeigler Field are largely attributed to the early inception of a pressure maintenance program implemented by converting producing wells to salt-water injection wells or plugging them as soon as they reached their economic limit. In this way, the field was started on waterflood shortly after field development was complete. The first waterflood was started in 1965, before pressure in the West Plumfield and South Plumfield bars was depleted below the bubble point. Data from careful monitoring of the pressure response of the wells was extensively used in designing an effective, efficient waterflood program at Zeigler Field. Knowledge of the locations of permeability barriers acquired from the pressure monitoring program permitted effective selection of new injection well locations.

Recovery efficiencies in the reservoir sandstone bars at Zeigler Field are significantly higher than those found in similar Aux Vases reservoirs at Energy, Dale Consolidated, and Oakdale Fields, where efficiencies of 21%, 30%, and 15%, respectively, were calculated (Oltz 1993). The lower recovery efficiencies at these fields are attributed to the less effective pressure maintenance and waterflood programs used at these fields.

The current recovery efficiency of the Mack lease is approximately 23%, much less than that of the other sandstone bars in the field; but it is a much newer waterflood unit and may have many years of good production remaining.

Because the porosity has been averaged, it does not necessarily account for variations across the field. The volumetrics of Zeigler Field are discussed in Sim et al. (1994). Their reservoir simulation techniques, which incorporated massive amount of data available for Zeigler Field, achieved an excellent history match.

CONCLUSIONS

Aux Vases reservoirs at Zeigler Field are sandstone bars deposited in a mixed carbonate-siliciclastic, shallow-marine environment. A strong tidal influence is evident throughout the Aux Vases interval at Zeigler Field. In the main body of the field, deposition of intertidal, tidal-flat, and interbar sediments was important in forming effective reservoir seals and permeability barriers within sandstone bars.

Original porosity and permeability of the sandstone bars were affected by later diagenetic events. Some of the most important of these diagenetic events were the precipitation of diagenetic clay-mineral coatings around all sand grains. Precipitation of clay minerals caused weak cementation at grain contacts, dissolution of early calcite cement, and dissolution of feldspar grains. Dissolution of these early calcite cements enhanced porosity and permeability. Partial dissolution of feldspar grains provided the elements necessary for precipitation of diagenetic clay minerals. Reservoir sandstones are friable because sand grains are weakly cemented by clay minerals. Diagenetic clay minerals severely restricted precipitation of quartz cement, thereby preserving excellent porosity and permeability. Salt water trapped in the micropores of diagenetic clay minerals that coat virtually every grain in Aux Vases sandstone reservoirs causes a low resistivity to electric current. Therefore, the Archie equation cannot provide accurate water saturations for use in reserve calculations and oil saturations are not indicated by high resistivities.

The sandstone bars in the Mack and Bend leases are isolated and sealed. The sandstone bars in the Plumfield lease have varying degrees of separation and isolation. The sandstone bar in the West Plumfield lease partially overlaps the sandstone bar in the Plumfield lease. The lack of fluid communication between the reservoir compartments formed by these two bars has been confirmed by production data and pressure surveys. The sandstone bar in the Plumfield lease and the sandstone bar in the South Plumfield lease are, however, narrowly connected. Pressure surveys and production data show minor fluid communication between these sandstone bars. Each bar at Zeigler Field is encased in impermeable rocks of the tidal-flat and interbar facies. The recognition of reservoir-bounding facies is an important reservoir management tool. There was no original oil/water contact in any of the sandstone bars.

Monitoring pressure and production behavior during field production provided the information necessary for efficient reservoir management strategies. Analysis of this data led to effective well placement for field development and waterflooding. Permeability barriers within the field were identified and compensated for by suitable placement of injection wells. Early pressure maintenance was achieved through the conversion of strategically located, marginal producers to salt-water injection wells. These tactics led to excellent recovery efficiencies, which average 48% in the Plumfield lease. Recovery efficiencies in similar Aux Vases reservoirs at Energy, Dale Consolidated and Oakdale Fields were much less (21%, 30%, and 15%, respectively) because of less effective recovery programs.

The original oil in place for the Plumfield and Mack leases in Zeigler Field is calculated to be approximately 4.28 million barrels STOOIP, nearly 2.1 million barrels of STOOIP has been produced by primary and secondary waterflood techniques. The combined Plumfield and South Plumfield bars had the best recovery efficiency at 51%, and the recovery efficiency in the West Plumfield bar was 45%. Although pressure was depleted below the bubble point before injection of waterflood brines in the Plumfield bar, recovery efficiency was greater for the combined Plumfield and South Plumfield bars than for the West Plumfield bar because of better sweep efficiency, longer period of waterflooding, and more effective placement of injection wells. Most remaining oil in place is located in the West Plumfield bar; however, additional secondary and tertiary techniques may not be cost effective because injection wells were plugged.

Effective sweeping of petroleum against impermeable, nonreservoir units that encased the sandstone bars helped to produce these higher efficiencies and added to the economically feasible duration of waterfloods in the field. As a result, it is common for wells at the edges of sandstone bars to have the highest cumulative petroleum production, although they may be stratigraphically lower, thinner, and have considerably less porosity and permeability than the thick bar sandstones.

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PENDIX A X-Ray Diffraction Mineralogy: Core Plug Analyses

l .	Well no.	Depth (ft)	Facies	XRD % I	% I/S	% C	% Q	% Kf	% Pf	% Cc	% D	k and ϕ kmd	ϕ%
4	Mack #1	2613.0	Tidal-flat ss	3.3	1.4	1.1	87.5	1.6	3.2	1.9	tr	2.4	19.0
		2621.0	Offshore bar ss	0.9	0.6	0.9	89.6	1.4	5.0	1.7	tr	131.0	23.8
		2627.0	Offshore bar ss	0.4	0.2	1.1	92.7	0.8	4.6	0.2	0.0	750.0	25.3
		2632.0	Offshore bar ss	0.7	0.7	1.4	90.3	1.4	3.9	1.6	0.0	62.0	21.9
		2633.0	Tidal-flat silt	0.2	0.1	1.2	86.4	1.4	3.4	7.4	0.0	11.9	20.4
0	Mack #2	2605.5	Tidal-flat ss	0.9	0.4	0.2	75.0	1.3	3.9	18.3	0.0	24.9	14.4
		2606.5	Offshore bar ss	2.3	1.6	1.3	81.9	1.6	4.8	6.4	tr	216.0	25.1
		2608.5	Offshore bar ss	1.2	0.5	0.8	88.3	1.0	4.2	4.0	0.0	49.0	22.1
		2610.5	Offshore bar ss	0.8	0.5	0.7	87.6	0.9	4.8	4.7	0.0	64.0	22.1
		2611.5	Offshore bar ss	1.2	0.6	1.3	86.9	0.9	5.7	3.4	0.0	124.0	24.1
		2612.5	Offshore bar ss	1.2	0.5	0.9	86.7	0.6	5.0	5.1	0.0	152.0	25.5
		2614.5	Offshore bar ss	0.8	0.4	1.3	86.9	1.1	6.6	2.8	tr	35.6	23.6
		2617.5	Offshore bar ss	0.7	0.4	2.2	88.4	0.9	4.4	3.0	tr	89.5	24.5
		2618.5	Offshore bar ss	0.6	0.3	2.1	88.2	0.5	3.9	4.4	0.0	47.8	24.8
		2620.5	Offshore bar ss	0.2	0.2	0.6	90.9	0.7	4.4	3.0	0.0	47.8	23.5
		2621.5	Offshore bar ss	0.2	0.0	0.5	91.0	0.7	4.7	2.9	0.0	56.0	23.8
		2623.7	Tidal-flat silt	0.7	0.6	1.4	85.7	0.4	1.9	9.4	tr	0.1	8.8
		2623.8	Tidal-flat silt	0.8	0.6	1.6	91.1	1.2	3.8	0.9	0.0	0.1	12.0
		2625.5	Tidal-flat silt	0.6	0.6	1.2	88.5	0.8	5.6	2.7	0.0	0.1	17.0
		2629.0	Tidal-flat silt	0.5	0.6	1.6	83.6	0.8	3.9	8.9	0.0	0.1	11.7
3	Mack #3	2634.5	Tidal-flat ss	0.8	0.6	2.7	89.1	1.4	5.1	0.3	tr	2.5	17.5
		2636.5	Offshore bar ss	0.3	0.5	0.8	91.5	0.7	3.4	2.7	0.0	145.0	25.2
		2639.0	Offshore bar ss	0.6	0.2	0.9	90.6	0.9	3.5	3.3	0.0	35.6	23.0
		2640.5	Offshore bar ss	0.4	0.3	0.9	90.6	0.9	3.4	3.5	tr	89.5	23.6
		2642.5	Tidal-flat silt	0.1	0.2	0.5	88.3	1.4	4.2	4.9	0.6	11.9	21.0
		2645.5	Tidal-flat silt	0.9	1.2	1.5	90.3	0.4	4.1	1.6	0.0	0.1	14.9
		2646.5	Tidal-flat silt	0.7	0.6	1.2	88.7	0.4	3.7	4.8	0.0		
		2647.1	Ste.Gen. ls	1.3	1.2	0.7	8.3	0.0	0.0	88.5	tr		
		2648.9	Ste.Gen. ls	0.0	0.0	0.0	0.0	0.0	0.0	100.0	0.0		
		2650.5	Ste.Gen. ls	tr	tr	tr	0.0	0.0	0.0	99.6	tr		
68	Mack #5	2611.8	Renault ls	0.8	1.0	0.2	0.0	0.0	0.0	98.0	0.0		
		2618.0	Tidal flat shale	39.0	19.1	1.6	37.4	0.7	2.3	tr	0.0		
		2623.4	Tidal flat silt	2.3	1.4	1.4	84.5	2.3	8.0	tr	tr	0.1	17.6
		2624.7	Offshore bar ss	0.2	0.1	0.2	88.9	0.4	2.5	7.8	tr	2.2	16.7
		2626.0	Offshore bar ss	0.1	0.1	0.1	93.0	0.8	2.6	3.4	0.0	2.1	11.8
		2627.5	Offshore bar ss	0.6	0.4	0.5	81.5	0.4	2.3	14.3	tr	2.2	14.1
		2631.0	Tidal-flat silt	4.0	2.1	3.0	79.4	1.8	4.3	4.5	0.7		
		2633.0	Tidal-flat silt	1.4	1.1	2.3	84.6	1.0	2.8	6.2	0.5		
		2634.0	Tidal-flat silt	1.0	0.7	0.8	88.2	1.4	5.8	2.2	0.0		
		2635.0	Tidal-flat silt	0.8	0.6	2.3	87.2	0.7	3.2	5.3	0.0		
69	Mack #6	2615.7	Offshore bar ss	2.0	1.4	1.6	83.8	1.6	9.6	0.0	0.0	7.1	17.8
		2617.0	Tidal-flat silt	1.1	1.3	1.1	92.0	0.4	3.5	0.3	0.4	35.0	18.7
		2619.8	Offshore bar ss	1.1	0.7	0.9	85.1	6.0	4.8	0.6	0.7	7.6	17.8
		2621.0	Offshore bar ss	0.5	0.3	1.9	91.0	1.2	3.1	1.7	0.3	1.4	18.9
		2624.9	Tidal-flat silt	0.9	1.1	1.1	64.4	1.3	2.6	28.2	0.4	10.9	19.5
		2628.0	Tidal-channel ss	0.6	0.7	2.8	81.4	0.9	3.5	9.8	0.2	2.4	17.0
		2631.0	Tidal-channel ss	1.2	0.9	2.7	87.5	1.2	5.8	0.7	tr		
		2633.8	Tidal-channel ss	0.6	0.5	2.0	86.8	0.0	4.4	5.6	0.0		
		2635.5		0.3	0.3	1.3	87.1	1.1	3.8	6.1	0.0		
		2635.5		1.7	1.4	1.6	43.6	0.4	2.4	47.6	1.5		
		2636.0		tr	tr	tr	0.0	0.0	0.0	99.6	0.3		

te; I/S, mixed layered illite/smectite; C, chlorite; Q, quartz; Kf, potassium feldspar; Pf, plagioclase feldspar; Cc, calcium carbonate; D, dolomite
meability (k) in millidarcies (md); and porosity percent (ϕ%); ss = sandstone, ls = limestone.

APPENDIX B Aux Vases Reservoir Fluid Analysis: Zeigler Field, Franklin County, Illinois

API Number 1205523877
Operator Gallagher Drilling Company
Well name Alex no. 1
Location 2675 ft N line, 1130 ft W line, NW, Sec. 19, T7S, R2E
Perforations depth 2629 ft sample depth Aux Vases
Surface elevation 394 KB
Waterflooded contamination unlikely, new well in new bar

Brine Analysis
Brine sample number EOR-B59
Resistivity 0.061 OHM-M @25^{o} C
EH -111 mV
pH 6.24
Total dissolved solids 137331 mg/L

Anion Chemistry (Mg/l)

Cl.... 82,000
Br........ .190
I............ 10
SO_4....... 490
NO_3.......... 0.29
CO_3......... 0.03
HCO_3....120
NH_4........ 35

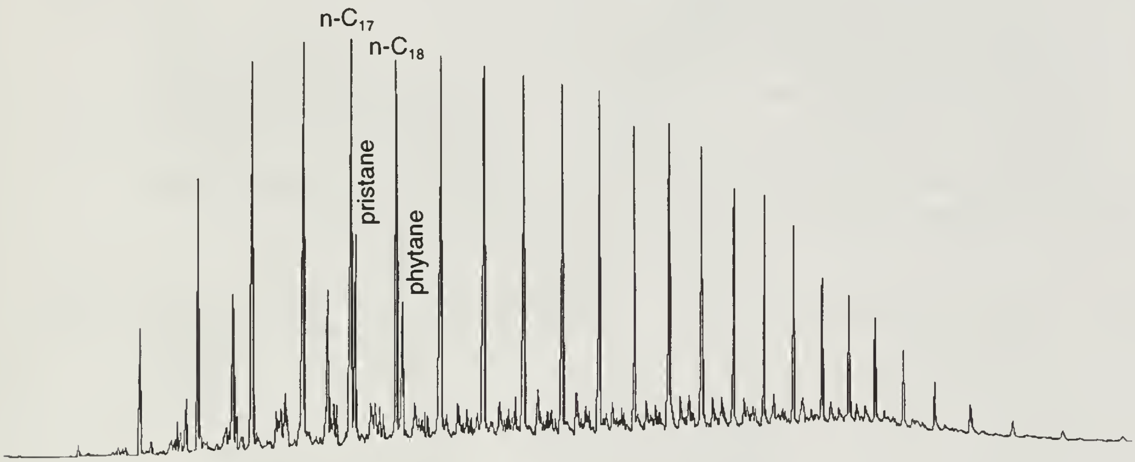
Cation Chemistry (Mg/l)

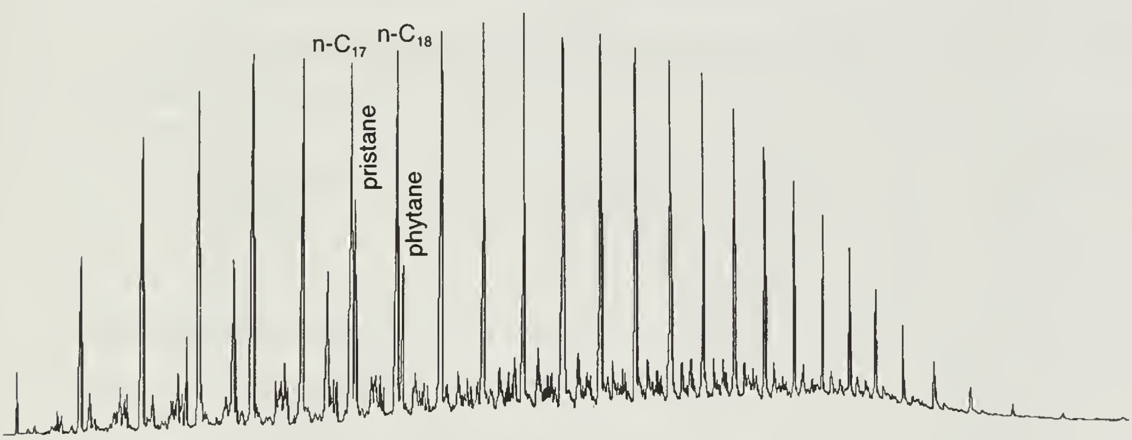
Na.....445,950
Ca......... 6020
Mg......... 1900
K.............196
Sr...........381
Al...............0.20
Si.............. 3.40
Mn............. 1.04
Fe............ 17.2
B............... 2.19
Pb............ <0.4
Ti............. <0.05
V.............. <0.08
Co........... <0.07
Ni............. <0.15
Cu............ <0.05
Zn.............<0.49
Zr............. <0.08
Cd............ <0.05
Ba.............. 0.44
Be........... <0.003
Cr............ <0.0
As............ <0.50
Se........... <0.80
Mo............<0.08
Li.............. 10.6

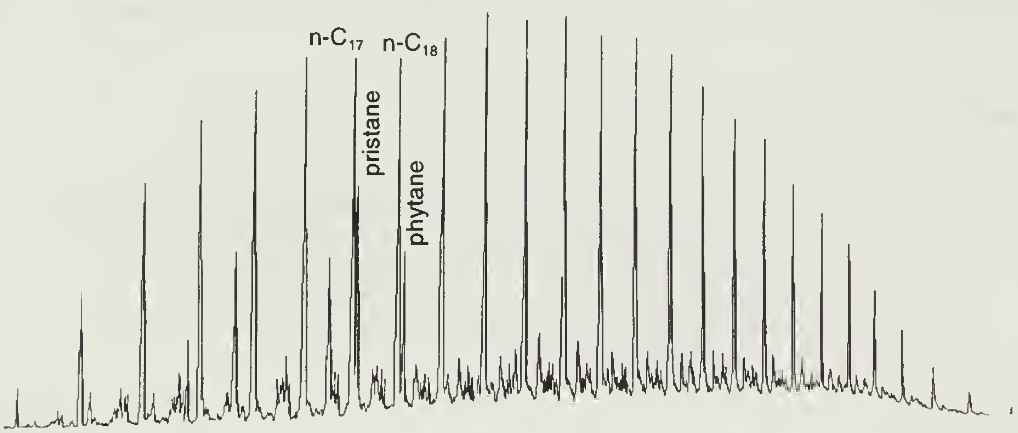
APPENDIX C Gas Chromatographs

Sample*	Well no.	Depth (ft)	Organic geochemical parameters		
			pr/nC_{17}	ph/n-C_{18}	pr/ph
EOR-4	#2 Mack	2,603–2,621	0.51	0.36	1.5
EOR-29	#9 Zeigler Coal and Coke	2,623–2,629	0.61	0.4	1.48
EOR-30	#1 Zeigler-Plumfield	2,611–2,640	0.64	0.43	1.5

*EOR-4, NE Sec. 19 T7S, R2E; EOR-29, SW NE SE Sec. 18, T7S, R2E; EOR-30, NW NE SE Sec. 18, T7S, R2E.







APPENDIX D Reservoir Summary

Field Zeigler
Location Franklin County, Illinois; Sec. 13, T7S, R1E; Secs. 18, 19, and 20, T7S, R2E
Tectonic/Regional Paleosetting intracratonic basin
Geologic Structure none
Trap Type stratigraphic
Reservoir Drive solution gas drive
Original Reservoir Pressure approximately 1,100 psi

Reservoir Rocks

Age Middle Mississippian Upper Valmeyeran
Stratigraphic unit Aux Vases Formation
Lithology quartz arenite-subarkose
Wetting characteristics Water-wetting
Depositional environment offshore tidal marine bar complex in mixed siliciclastic-carbonate environment
Productive facies marine sandstone bar facies
Petrophysics ϕ and k from unstressed conventional core; S_w from core analyses
Porosity type ϕ total = 21%: primary ?%; secondary ?%

	Average	Range	Cutoff
ϕ field average	21.0	19.0–28.0	
k air (md) - field average	125	0.1-800	50
k liquid (md)			
S_w - field average (%)	40		60
S_o - field average (%)	60		40
S_{gr}	NA	NA	NA
Cementation factor	1.97	NA	NA

Source Rocks

Lithology and stratigraphic unit shale; New Albany Group (Devonian)
Time of hydrocarbon maturation Permo-Triassic
Time of trap formation Upper Valmeyeran (stratigraphic)

Aux Vases Reservoir Dimensions

Depth top of sandstone 2,600 to 2,700 ft (absolute); -2215 to -2264 ft (subsea)
Areal dimensions 1,250 acres
Productive area approximately 600 acres
Number of Aux Vases pay zones 1
Hydrocarbon column 5–25 ft
Initial fluid contacts Oil/Water: none measured in field; none present in any producing sandstone bars
Ave. net sand thickness 14 ft in W. Plumfield bar; 15 ft in Plumfield and S. Plumfield bars
Ave. gross sand thickness 15 ft
Initial Reservoir Temperature 100°F estimated from logs
Fractured Natural fractures present; some wells shot with 10-60 quarts of nitroglycerin

Wells

Spacing 10 acre
Pattern injection program utilizing peripheral and converting poor producers
Total 37

12 producers and 3 injectors in W. Plumfield; 9 producers and 2 injectors in Plumfield bar during early development, 3 producers; 2 injectors and 2 producers in S. Plumfield during early phase of development; many producers were converted to injector wells during later phases of development in the Plumfield leases; 2 producers and 2 injectors in Mack bar from initial production to present; cannot distinguish between primary and secondary recovery because waterfloods were started early to maintain pressure

Reservoir Fluid Properties

Hydrocarbons

Type oil

GOR NA

API gravity 38°

FVF 1.068

Viscosity 4.4 cp @ 95°F

Bubble point pressure 504 psig

Formation water

Resistivity 0.061 ohm-m @ 77°F

Total dissolved solids 137,331 PPM

Volumetrics

Total production 2,095,547 stock tank barrels of oil (1990)

Bar/Producing unit	W. Plumfield	Plumfield/S. Plum.	Mack
Volume (acre-ft)	1876	2182	625
In-Place (STOOIP; ϕ=21.0%)	1,717,045	1,997,118	572,043
Cumulative Production (STBO)	842,084	1,120,463	133,000
Remaining Oil in Place (STBO)	874,961	876,655	439,043
Recovery Efficiency (%)			
Primary and Secondary	46.12	56.1	23.25 (to date)
Tertiary	NA	NA	NA

Typical Drilling/Completion/Production Practices

Completions open hole or cased

Drilling fluid Fresh-water mud

Completion

Unit	*Fracture treatment*	*Acidization*
W.Plumfield	0–50 quarts nitroglycerin	none
Plumfield/S. Plumfield	0–60 quarts nitroglycerin	none
Mack	none	none

Producing mechanism Primary: pump; secondary: pump

Typical Well Production to date

Average daily IP

Unit	*Fluids produced per day*	*Water/oil*
W. Plumfield	276.0 BOPD; 0.5 BWPD	0.002
Plumfield	173.0 BOPD; <1.0 BWPD	0.006
S. Plumfield	96.0 BOPD; 4.0 BWPD	0.042
Mack	69.5 BOPD; 24.0 BWPD	0.345

Cumulative production to 11/91 (average barrels of oil—primary and/or secondary)

Unit	*No. of wells*	*Average production*
W.Plumfield	12	72,874 bbl/well
Plumfield	13	60,910 bbl/well
S. Plumfield	3	94,669 bbl/well
Mack	2	66,500 bbl/well

Illinois State Geological Survey
Natural Resources Building
615 East Peabody Drive
Champaign, IL 61820-6964

Address Correction Requested