

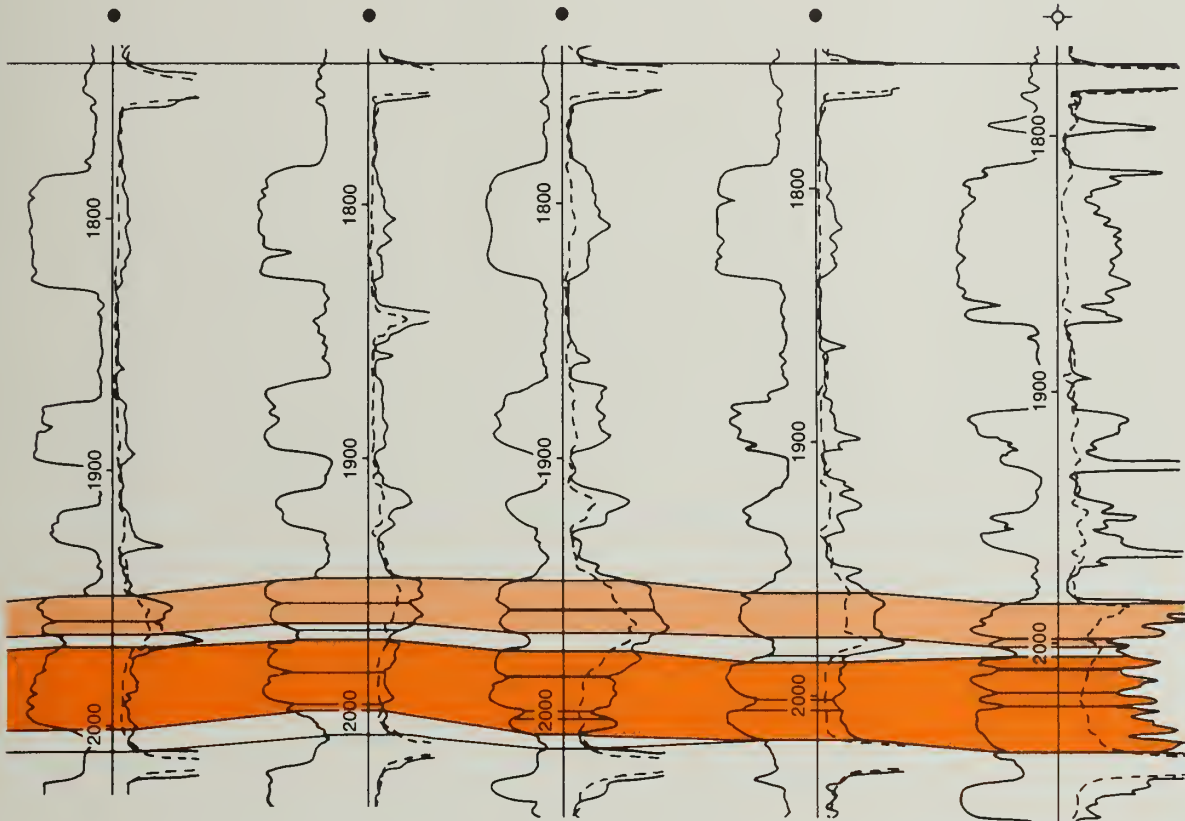
AUG. 05 1993

IP 139

S  
A. 65:  
IP 139  
C.2

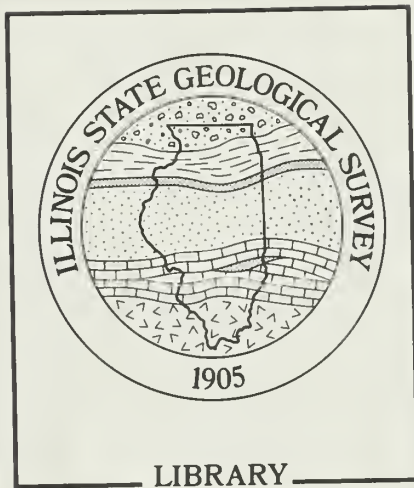
# Reservoir Characterization and Potential for Improved Oil Recovery within the Aux Vases Formation at Stewardson Field, Shelby County, Illinois

Richard J. Rice, Robert D. Cole, and Stephen T. Whitaker

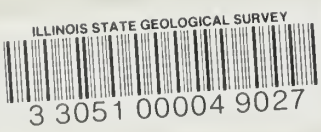


1993  
ILLINOIS PETROLEUM 139

Department of Energy and Natural Resources  
ILLINOIS STATE GEOLOGICAL SURVEY



LIBRARY



# Reservoir Characterization and Potential for Improved Oil Recovery within the Aux Vases Formation at Stewardson Field, Shelby County, Illinois

Richard J. Rice, Robert D. Cole, and Stephen T. Whitaker

ILLINOIS GEOLOGICAL  
SURVEY LIBRARY  
AUG. 05 1993

ILLINOIS PETROLEUM 139  
1993

ILLINOIS STATE GEOLOGICAL SURVEY  
Morris W. Leighton, Chief  
Natural Resources Building  
615 East Peabody Drive  
Champaign, Illinois 61820-6964

## **Disclaimer**

This report was prepared by scientists at the Illinois State Geological Survey (ISGS) for a project sponsored by the State of Illinois and the U. S. Department of Energy (USDOE). It presents reasonable interpretations of available scientific data. Any opinions, findings, conclusions, or recommendations expressed herein are those of the author(s) and do not necessarily reflect the views of the USDOE. Neither the ISGS, any member of the ISGS staff, the State of Illinois Department of Energy and Natural Resources, nor the USDOE assumes any liability with respect to the use of any information contained in this report, or for damages resulting from it.

*Printed by authority of the State of Illinois/1993/1200*



printed on recycled paper

# CONTENTS

|  |    |
|--|----|
| <b>ABSTRACT</b>  | 1  |
| <b>INTRODUCTION</b>                                      | 1  |
| Location and Geologic Setting                            | 1  |
| Discovery History  | 4  |
| Production History                                       | 4  |
| <b>RESERVOIR AND TRAP CHARACTERISTICS</b>                | 5  |
| General Stratigraphy                                     | 5  |
| Reservoir Geometry                                       | 5  |
| Structure  | 5  |
| Depositional intervals and environments of deposition    | 9  |
| Petrography and Diagenesis                               | 14 |
| Sandstone  | 14 |
| Limestone  | 17 |
| Clay   | 17 |
| Porosity and Permeability                                | 18 |
| Diagenetic Sequence                                      | 19 |
| Effects of Petrophysical Properties on Reservoir Quality | 20 |
| Trap Type  | 20 |
| <b>CLASSIFICATION AND IDENTIFICATION OF PLAY</b>         | 21 |
| <b>PRODUCTION CHARACTERISTICS</b>                        | 21 |
| Drilling and Completion Methods                          | 21 |
| Production Characteristics by Lease                      | 21 |
| Fluid Characteristics                                    | 23 |
| Volumetrics  | 24 |
| Original oil in place                                    | 24 |
| Remaining oil in place                                   | 26 |
| Development and Production Strategy                      | 26 |
| Improved recovery techniques                             | 26 |
| Enhanced recovery techniques                             | 26 |
| <b>CONCLUSIONS</b>                                       | 28 |
| <b>ACKNOWLEDGMENTS</b>                                   | 30 |
| <b>REFERENCES</b>  | 30 |
| <b>APPENDIXES</b>  | 32 |
| A Reservoir Fluids Analyses                              | 32 |
| B Gas Chromatograms of Saturated Hydrocarbons            | 34 |
| C Reservoir Summary                                      | 35 |

## FIGURES

|    |   |    |
|----|---|----|
| 1  | Regional map  | 2  |
| 2  | Location of wells at Stewardson Field   | 3  |
| 3  | Generalized stratigraphic column for the upper Valmeyeran and lower Chesterian Series in southern Illinois                          | 4  |
| 4  | Graph of annual oil production and water injection  | 5  |
| 5  | Type E-Log from Stewardson Field  | 6  |
| 6  | Structure map of the top of the Ste. Genevieve Formation  | 7  |
| 7  | Isopach map of the Aux Vases Formation reveals regional thinning north and northwest of the field                                   | 8  |
| 8  | North-south cross section along A–A' shows thinning in the upper Aux Vases Sandstone interval over the field                        | 10 |
| 9  | Northwest-southeast cross section along B–B' shows thinning of the upper sandstone interval of the Aux Vases northwest of the field | 10 |
| 10 | Isopach map of clean sandstones within the upper sandstone interval of the Aux Vases Formation                                      | 12 |
| 11 | Isopach map of clean sandstones within the lower interval of the Aux Vases Formation  | 13 |
| 12 | SEM photomicrograph of diagenetic clay minerals on quartz grains and intermediate calcite cement                                    | 19 |
| 13 | SEM photomicrograph of dissolved potassium feldspar with late stage hexagonal quartz overgrowths                                    | 19 |
| 14 | Diagram of diagenetic sequence for the Aux Vases reservoir at Stewardson Field  | 20 |
| 15 | Cumulative production by lease and initial production map   | 22 |
| 16 | Drill stem test data map  | 23 |
| 17 | Reservoir limit map   | 24 |
| 18 | Production decline curve for Stewardson Field   | 25 |

## TABLE

|   |   |    |
|---|---|----|
| 1 | Mineral analysis of the clay size particles | 18 |
|---|---|----|

## PLATES

|   |   |    |
|---|---|----|
| 1 | Photomicrograph of a sample from the Aux Vases Sandstone reservoir  | 15 |
| 2 | Photomicrograph of exceptionally well preserved echinoderm columnal   | 15 |
| 3 | Photomicrograph of several grains of feldspar in varying stages of dissolution  | 15 |
| 4 | Photomicrograph of <i>Archaeolithophyllum</i> sp., a red alga found in carbonate beds between the upper and lower sandstone intervals in Stewardson Field | 16 |
| 5 | Photomicrograph of miliolid foraminifera, an indicator of inner shelf environment   | 16 |

## **ABSTRACT**

Since its discovery in 1939, Stewardson Field has produced approximately 1,090,000 barrels of oil; a total of 950,000 barrels has come from sandstone reservoirs within the Aux Vases Formation. The formation is composed of sandstones, shales, and limestones of varying thicknesses. The producing facies at Stewardson Field are interpreted as shoreface sheet sandstones ranging in thickness from 9 to 24 feet. These sandstones are relatively homogeneous laterally, although there appear to be up to five distinct vertical intervals, of which only the upper two pay in the field. The sandstone facies are composed of fine grained, quartzose sand cemented with silica and various amounts of calcite. Clay content ranges from 0.4% to 5.2%. The porosity and permeability of the producing interval are relatively low for Aux Vases reservoirs; they average 13% and 36.5 md (millidarcies), respectively.

Stewardson Field is located on a subtle structural high that has about 20 feet of closure on the underlying Ste. Genevieve Formation. Isopach maps indicate that a very small paleotopographic high was at this locality during deposition of the Aux Vases. This high caused slightly less silt and clay to be incorporated within the sandstones deposited in Stewardson Field.

The calculated original oil in place for the Aux Vases is about 5,650,000 barrels. Remaining recoverable reserves are estimated at 83,800 barrels of oil for the field. Recovery efficiency from the Aux Vases reservoir averages 18% across the entire field, but it averages 42% in the part of the field that is on the paleotopographic high. This disparity is caused by the slightly higher content of fines and cements in the Aux Vases Sandstones in peripheral parts of the field.

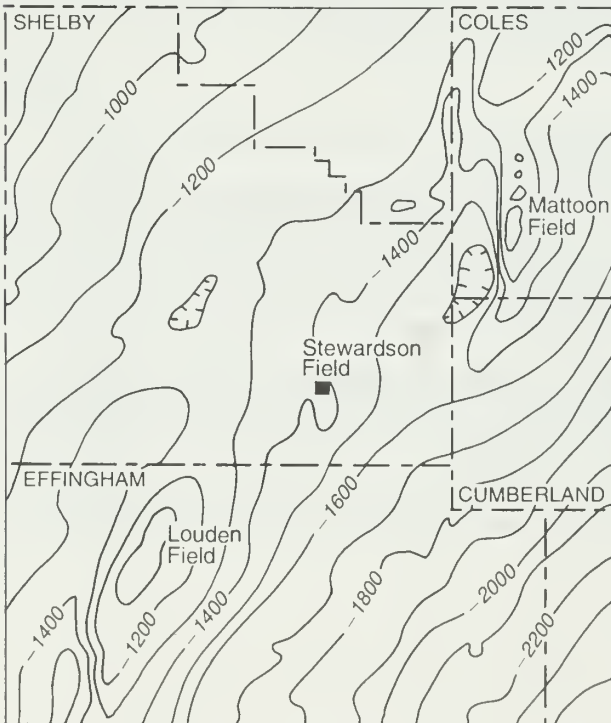
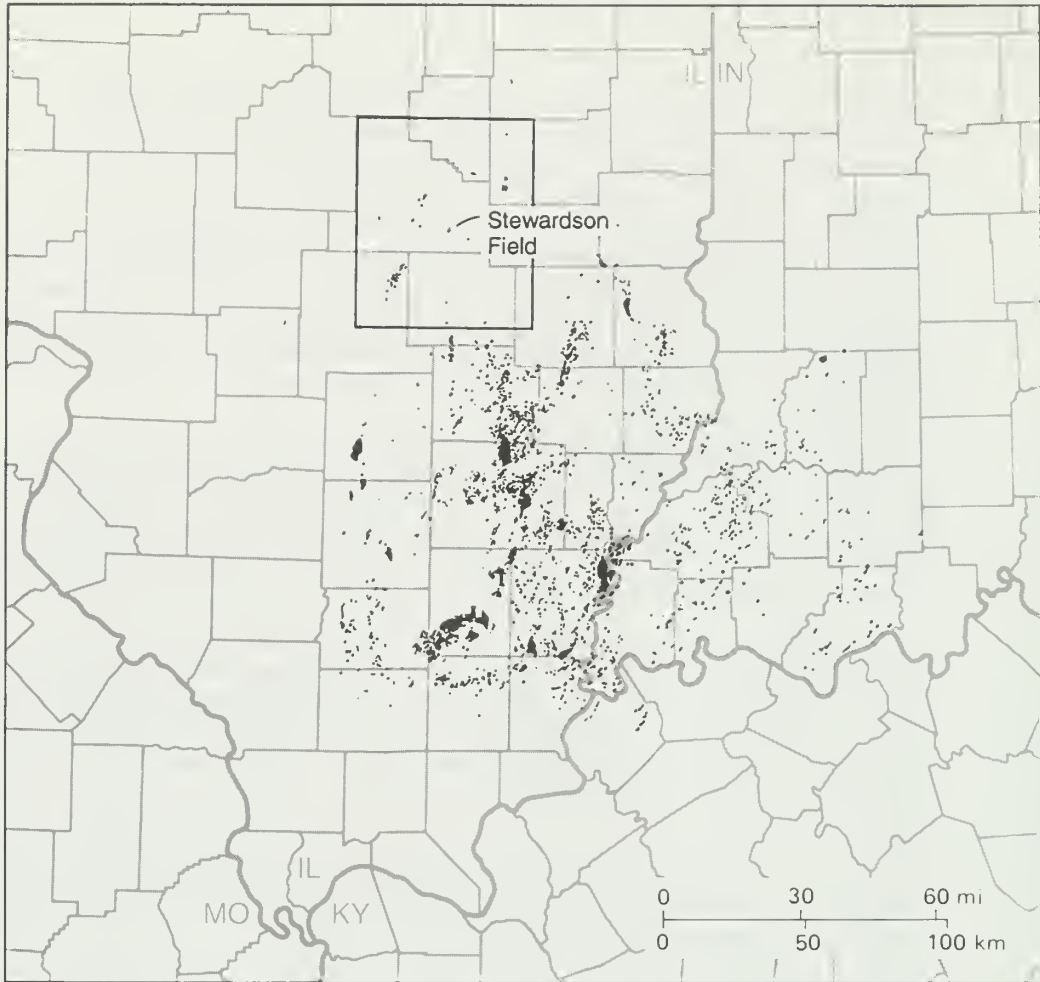
Additional hydrocarbons may be trapped in rocks of poor reservoir quality situated along the flanks of the field. The volume of these additional hydrocarbons is difficult to ascertain because of a lack of data. The low permeability encountered in the Aux Vases along the perimeter of the field indicates that economical recovery of these hydrocarbons is not feasible at the present. Enhanced recovery methods that should be considered for this particular reservoir include microbial enhanced oil recovery (MEOR) and immiscible carbon dioxide (CO<sub>2</sub>) injection.

## **INTRODUCTION**

### **Location and Geologic Setting**

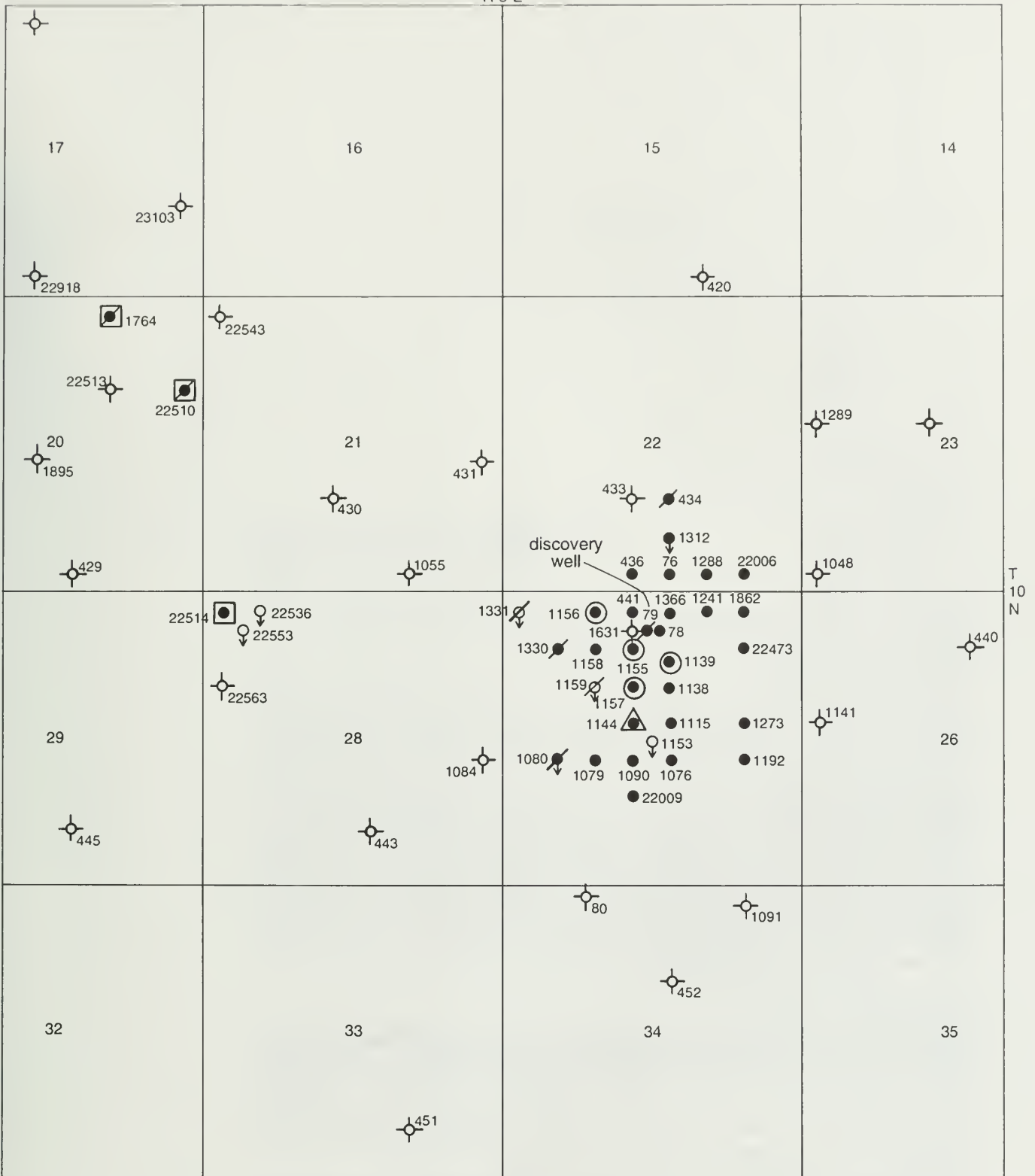
Stewardson Field is located in southeastern Shelby County (Secs. 22 and 27, T10N, R5E), 1/2 mile north of Stewardson, Illinois (fig. 1). The field is located in the north-central part of the Illinois Basin, approximately 35 miles (56 km) west of the La Salle Anticlinal Belt and midway between the Mattoon Anticline to the northeast and the Loudon Anticline to the southwest.

The purpose of this study was to identify the geologic parameters that affect recovery efficiency and to make recommendations that may improve recovery. To accomplish this purpose, it was necessary to (1) identify the reservoirs within the Aux Vases, (2) identify the environments of deposition for each reservoir, (3) identify the characteristics of each reservoir, (4) describe how the reservoir characteristics affect recovery efficiency, and (5) discuss methods that may improve the efficiency of recovery from reservoirs.



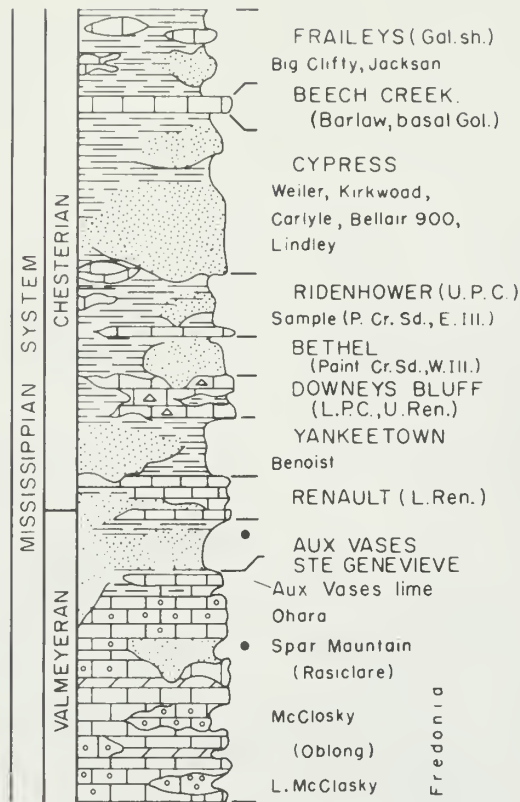
**Figure 1** Regional map above shows the location of Stewardson Field with respect to Aux Vases production within the Illinois Basin. The enlarged inset (left) shows Stewardson Field with respect to Ste. Genevieve structure.





**Figure 2** Location of wells at Stewardson Field, including abbreviated API numbers and producing formations.

- producing well
- (with downward arrow) injection well
- (with slash) abandoned well
- (with cross) dry/abandoned well
- (with downward arrow) producing well converted to injection well
- (with dot) Aux Vases production
- (with dot in circle) Aux Vases/Spar Mountain
- ▲ (in circle) Spar Mountain
- (with dot) Yankeetown (Benoist)



**Figure 3** Generalized stratigraphic column for the upper Valmeyeran and lower Chesterian Series in southern Illinois. Black dots indicate producing zones in Stewardson Field.

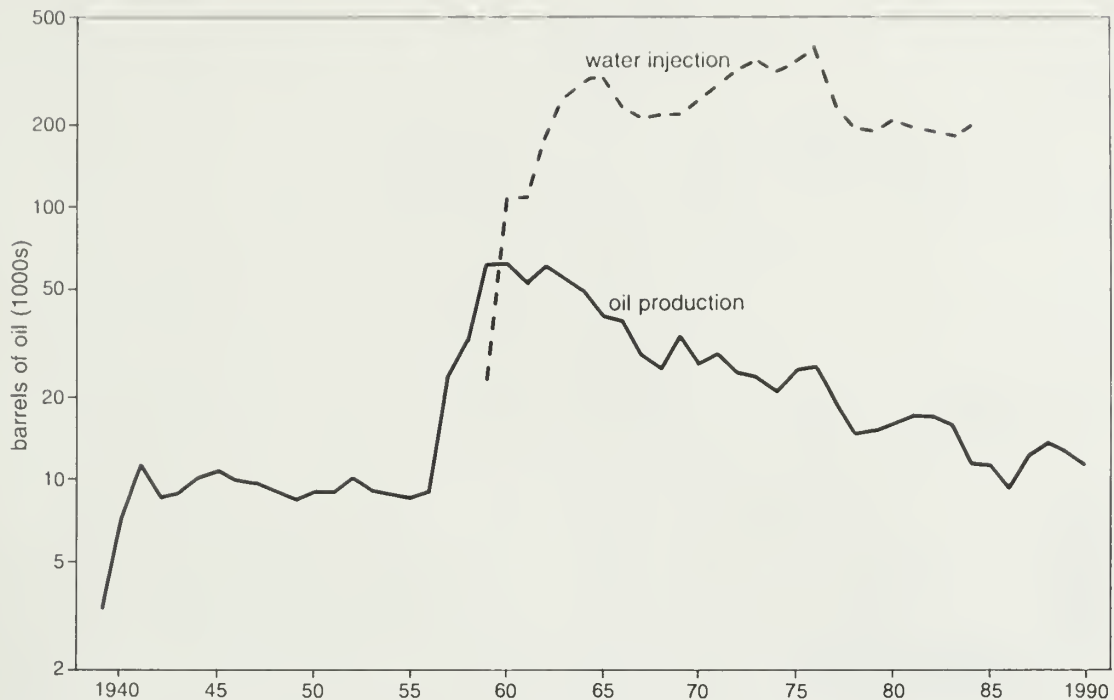
## Discovery History

The discovery well at Stewardson Field was spudded in December 1938 and completed in April 1939 (fig. 2). The J. A. Aylward No. 1 Wabash Railroad (well 79, 660 ft from north line [FNL], 2640 ft FWL, Sec. 27) was drilled to a total depth of 1,969 feet and completed in sandstones within the Aux Vases Formation at 1,938 feet (fig. 3). The initial production of this well was 28 barrels of oil per day (BOPD) and 3 barrels of water per day (BWPD). The reason for choosing the initial drill site is unknown. Production from sandstone of the Spar Mountain Member of the Ste. Genevieve Formation was added to the field in August 1958 when the Doran Oil No. 4 G. Chaffee (well 1144, SE SE NW, Sec. 27, fig. 2) was completed in the Aux Vases Formation and the Spar Mountain Member and yielded 35 BOPD and 12 BWPD. The operators estimated that 20 BOPD and 8 BWPD of the initial production were from the Spar Mountain (2,023 ft).

## Production History

Oil production from the Stewardson Field reached 1.09 million barrels of oil (MMBO). Most of the wells in the field were drilled between 1956 and 1959. Twenty-four wells have produced from the Aux Vases reservoir, four from commingled Aux Vases and Spar Mountain sandstones (fig. 2), and one from the Spar Mountain. Swab tests and initial production rates indicate that about 13% of the total hydrocarbon production is from the Spar Mountain.

The field was developed on 10-acre well spacing and comprises approximately 638 acres. According to Illinois State Geological Survey records, the Aux Vases is currently productive in 23 wells and the Spar Mountain in five wells; produced water is injected in two others. Daily oil production for the field ranges from 20 to 45 BOPD.



**Figure 4** Graph of annual oil production and water injection.

Secondary oil recovery via waterflood in the Aux Vases began in September 1959; a second waterflood was initiated in 1962. Figure 4 shows historical oil production and water injection data in the field. Estimated remaining recoverable reserves are 83,800 barrels of oil (BO).

## RESERVOIR AND TRAP CHARACTERISTICS

### General Stratigraphy

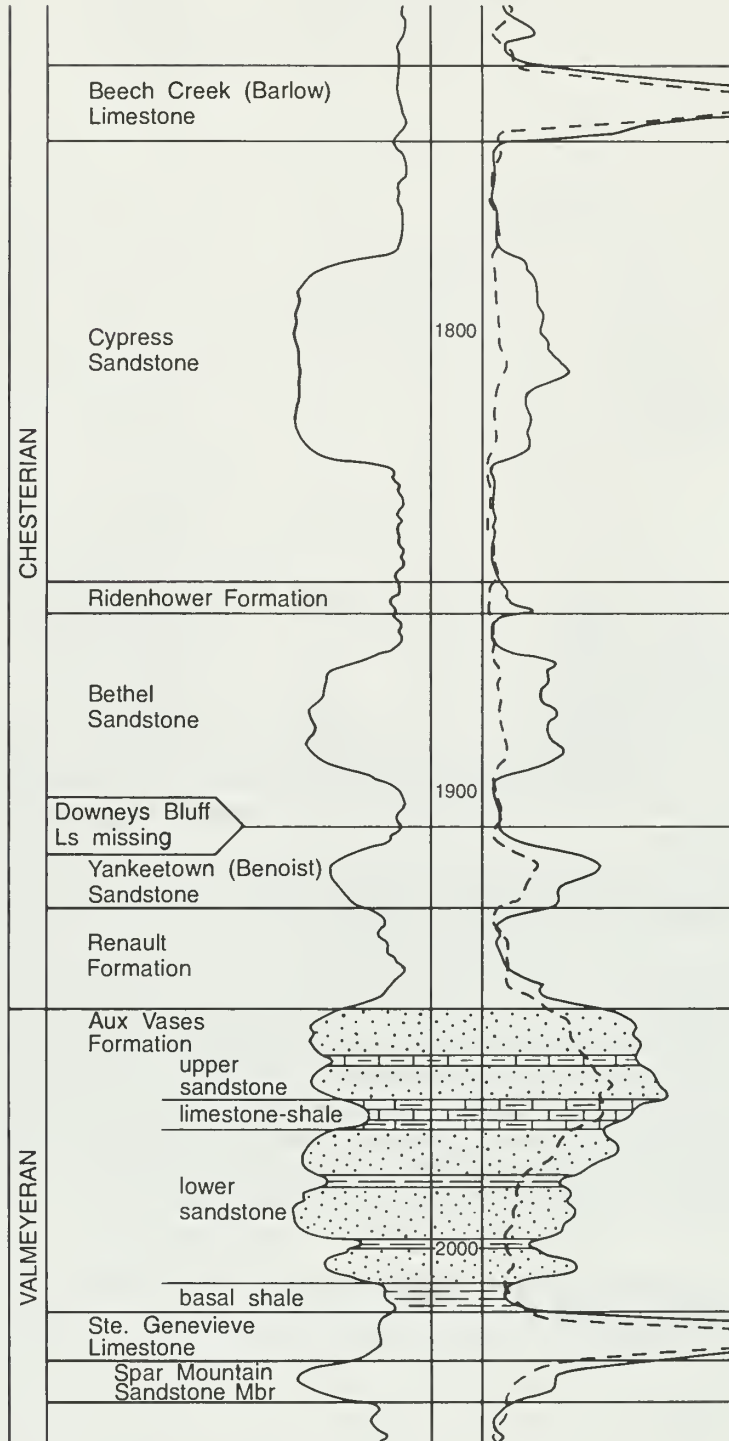
The Aux Vases Formation represents the first major influx of sand into the Illinois Basin during the Mississippian Period and marks the end of the carbonate-dominated deposition that prevailed in the basin during the previous 120 million years. The main progradational wedge of Aux Vases siliciclastics apparently was transported into the Illinois Basin from the west-northwest, as indicated by isopach maps and geologic mapping of outcrops (Willman et al. 1975, McKay 1980, Cole 1990). The formation grades from predominantly sandstone in the western part of Illinois to mixed sandstone, shale, and limestone in the eastern part of the state.

At Stewardson Field, the Aux Vases is predominantly sandstone interbedded with shale and some limestone (fig. 5). The Aux Vases directly overlies carbonates of the Ste. Genevieve Formation and underlies shale and carbonate of the Renault Formation.

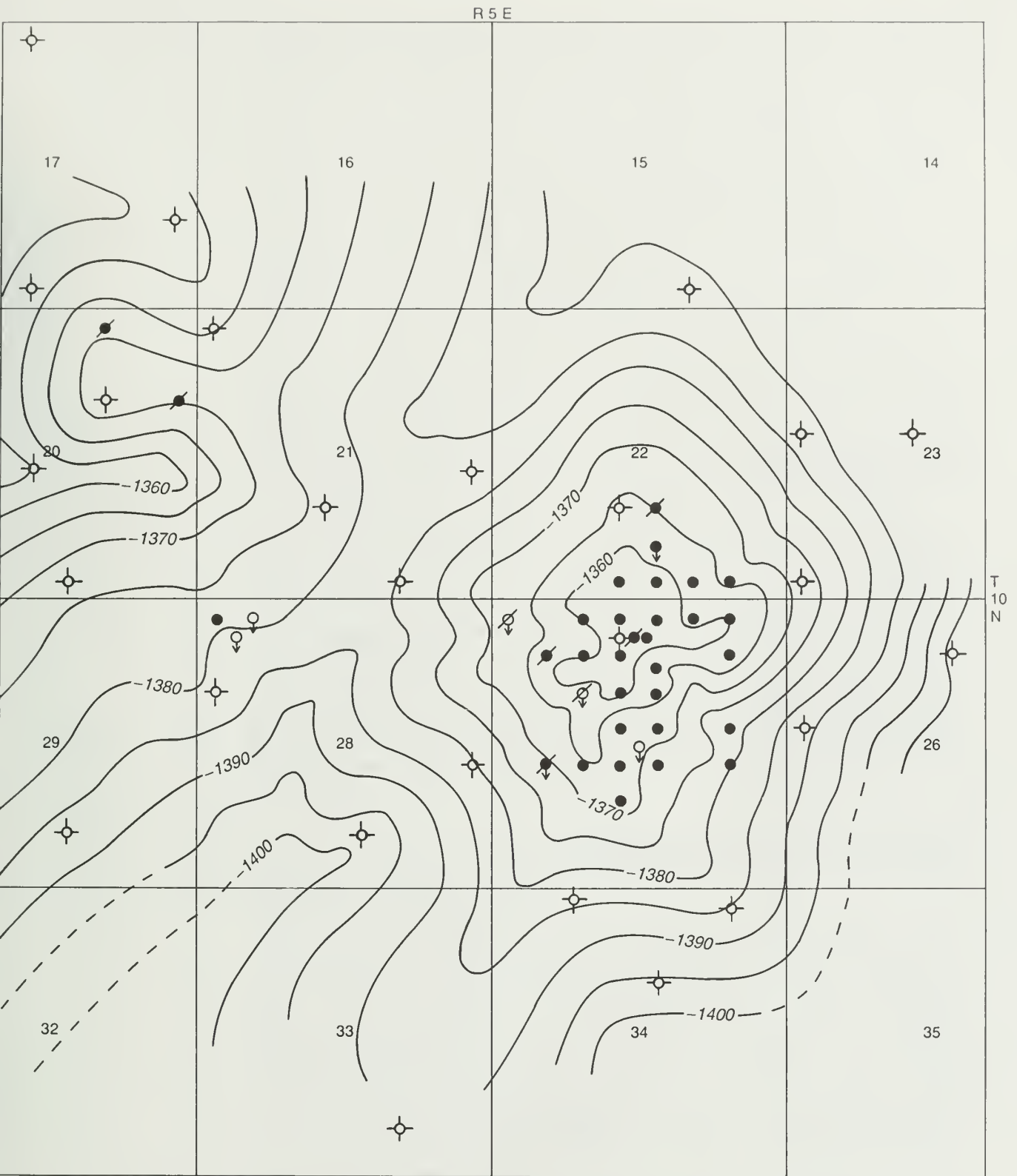
### Reservoir Geometry

**Structure** Stewardson Field occurs within a slightly elongate (1 mi long, 3/4 mi wide) dome on a southeastward-plunging structural nose. A structure map of the top of the Ste. Genevieve Formation (fig. 6) shows a closure of 20 feet. Regional dip is to the southeast.

Doran Oil  
 G. Chaffee No. 2  
 SW SW NE Sec. 27



**Figure 5** Type E-Log from Stewardson Field. The Aux Vases has been subdivided into four intervals: (1) upper sandstone, (2) limestone-shale, (3) lower sandstone, and (4) basal shale.



**Figure 6** Structure map of the top of the Ste. Genevieve Formation shows about 20 feet of closure at Stewardson Field. Contour interval is 5 feet.



**Figure 7** Isopach map of the Aux Vases Formation reveals regional thinning north and northwest of the field. Note the thickness of the Aux Vases along the southeastern portion of the field area and the relatively abrupt thinning within the field. Contour interval is 5 feet.

Two wells in the Stewardson Field, 1366 (NW NW NE, Sec. 27) and 1115 (SW SW NE, Sec. 27), were drilled into the Devonian Geneva Dolomite Member of the Grand Tower Formation. The top of the Geneva Dolomite Member in well 1366 is 39 feet higher than the top in well 1115 and the distance between the two wells is approximately 1/3 mile. In these same wells, however, the difference in elevation at the top of the Lingle Formation, which overlies the Grand Tower, is only 14 feet. This apparent thinning in the Devonian carbonates overlying the Geneva Dolomite indicates that a positive topographic or structural feature existed at Stewardson during Middle Devonian time. This feature may be the result of a reef in the Silurian-Devonian strata or tectonism. Absence of the pronounced structural closure generally associated with Silurian-Devonian reefs may be due to truncation of the reef in Early Devonian time during the period of erosion that marks the boundary between the Tippecanoe and Kaskaskia Sequences (Whitaker 1988).

A subtle topographic high at Stewardson may have also affected deposition of the Aux Vases Formation. This interpretation is based on the isopach map (fig. 7), which shows the thickness of the Aux Vases Formation decreasing over the area that generally coincides with the present structure at Stewardson Field (fig. 6). A relatively thick accumulation of sandstone that trends northeast-southwest across the south margin of the field (fig. 7) may be due to infilling of a slight paleotopographic low, or may represent a bar-like feature generated in a shoaling environment.

**Depositional intervals and environments of deposition** Correlations of wire-line log character indicate that the Aux Vases Formation at Stewardson Field can be subdivided into four intervals, each separated by shale or carbonate layers (fig. 5). Three to five sandstone beds occur within these intervals. The two uppermost sand bodies are referred to as the upper sandstone interval. Underlying this interval is a shale and limestone interval that ranges from 1.5 to 8 feet thick. The sandstones underlying this shale and limestone interval are collectively called the lower sandstone interval. Underlying the lower sandstone interval is the basal interval, which consists of intercalated shales and limestones. The upper interval contains the only sandstones in the Aux Vases Formation that produce hydrocarbons at Stewardson, although shows of oil have been reported in the lower sandstone interval in two wells.

Cross section A-A' (fig. 8) shows a general trend of thinner Aux Vases sandstones (9–14 ft thick) north of the field and slightly thicker sandstones (20–23 ft) to the south. Cross section B-B' also shows a thinning of the upper sandstone facies northwest of Stewardson Field (fig. 9).

The upper interval comprises two sandstone layers that are commonly separated by a thin, intermittent shale and carbonate layer (fig. 5). Although no permeability or pressure data are available to determine whether this thin shale interval is a barrier to fluid flow, production characteristics indicate that the interval behaves essentially as one reservoir. These two sandstones, therefore, were combined in our mapping and descriptions. Thickness maps of 50% clean sandstone were constructed for the upper and lower sandstone intervals within the Aux Vases Formation. Clean sandstones are defined in this report as those sandstones that have an SP (spontaneous potential) deflection of at least 50% of the total deflection between the cleanest sandstone on the log and the shale baseline. An isopach map of the clean sandstones within the upper interval of the Aux Vases (fig. 10) shows a relatively consistent distribution of sand across most of the mapped area. This sheet-sand geometry, in addition to petrographic evidences cited later, suggests that the environment of deposition for this interval was a subtidal shoreface.

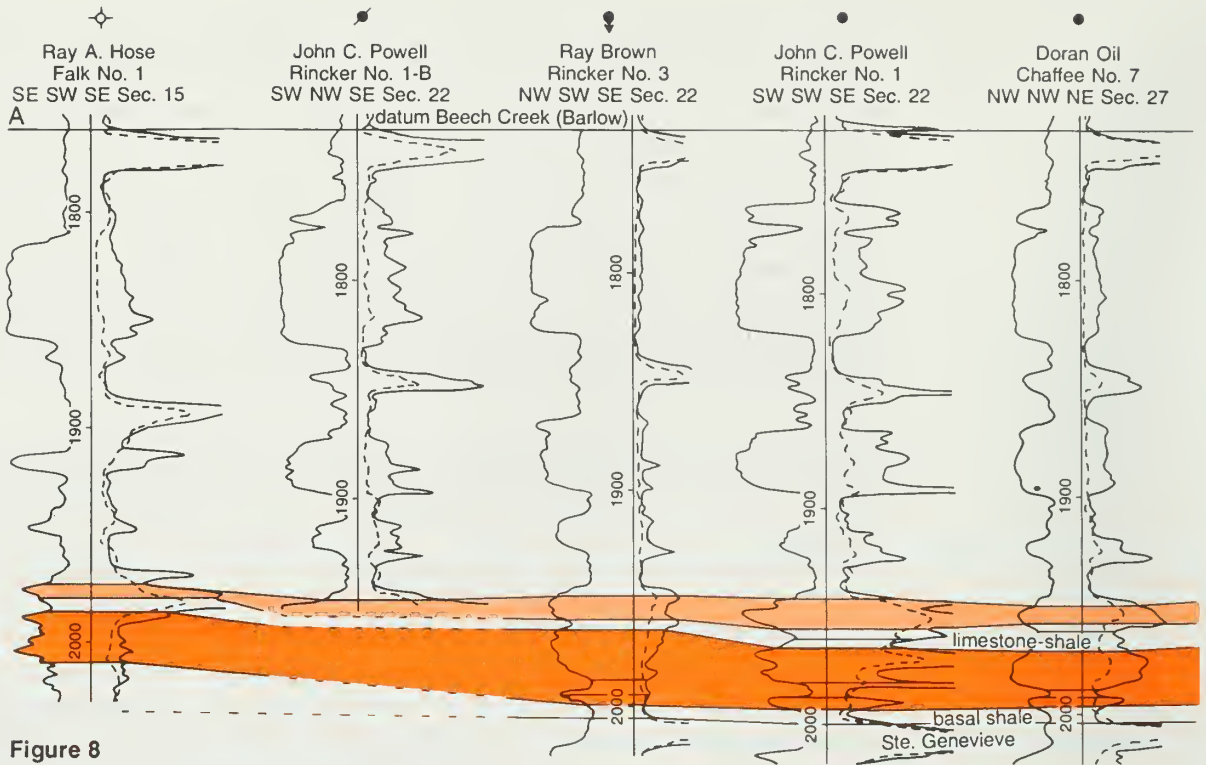


Figure 8

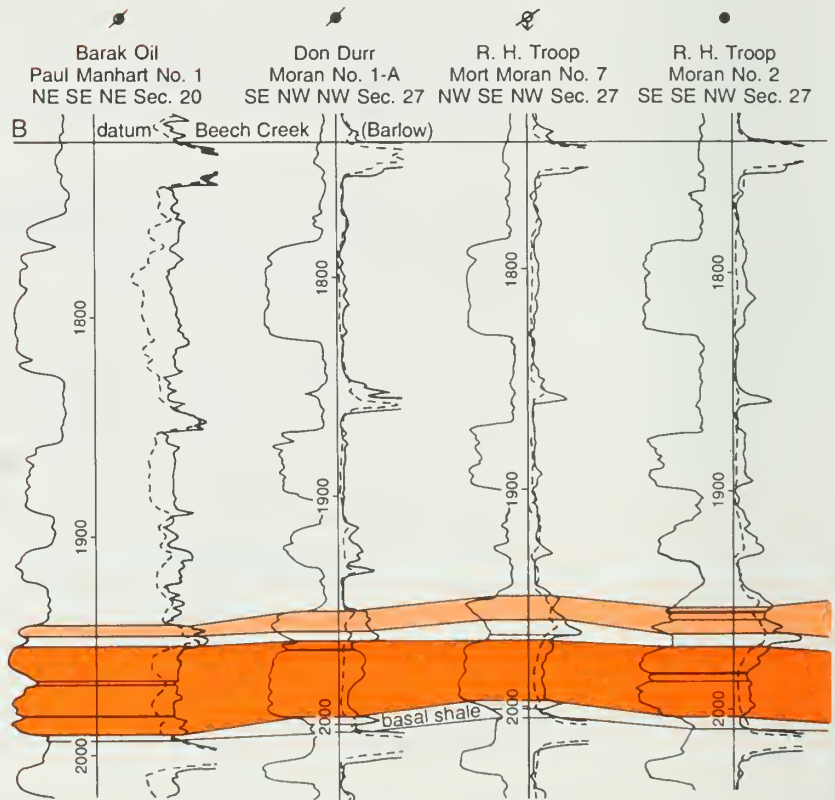
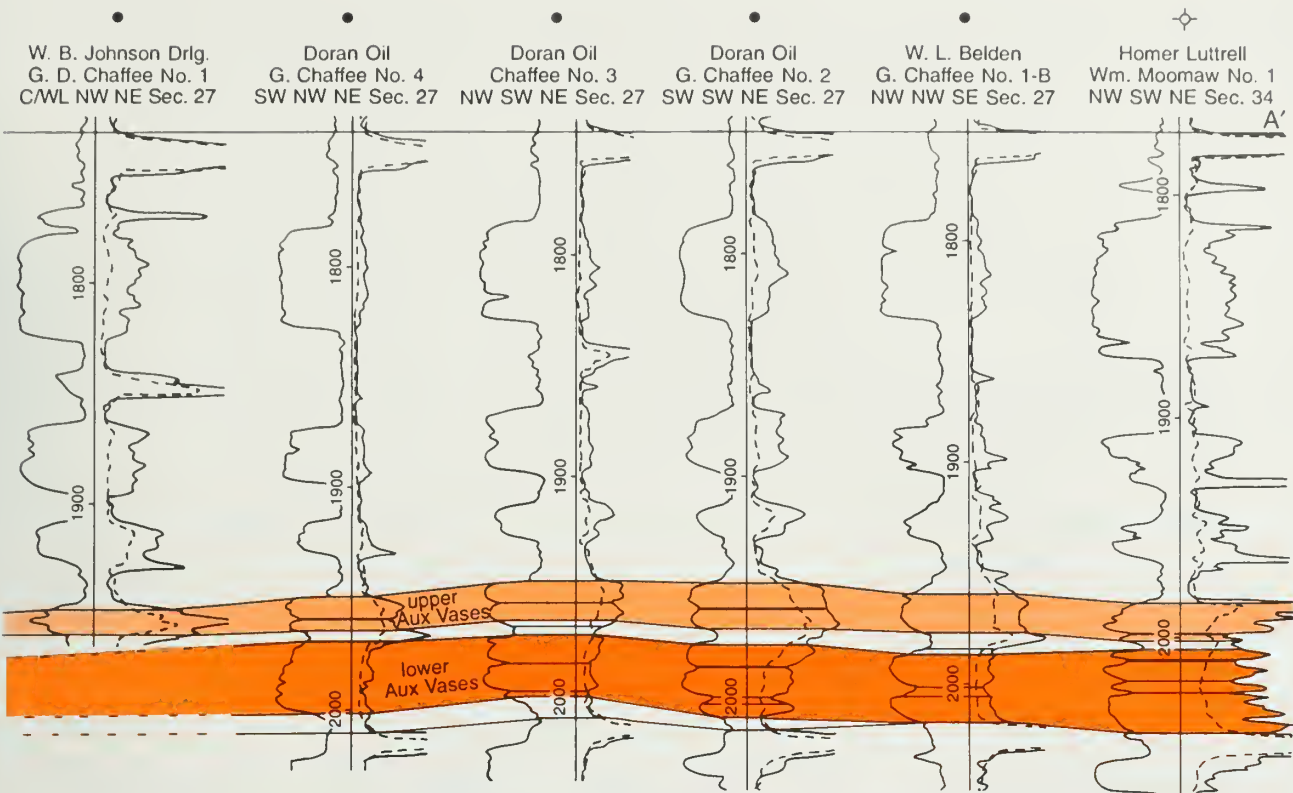
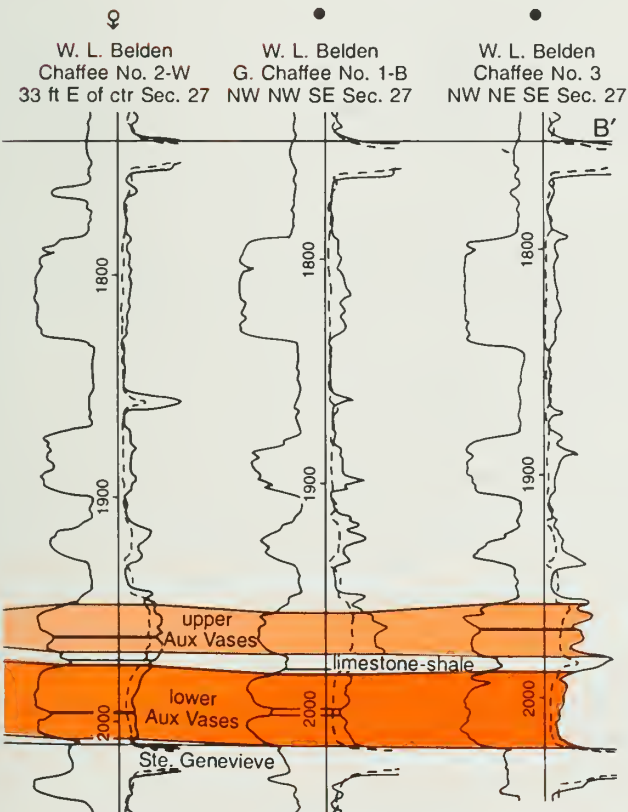


Figure 9

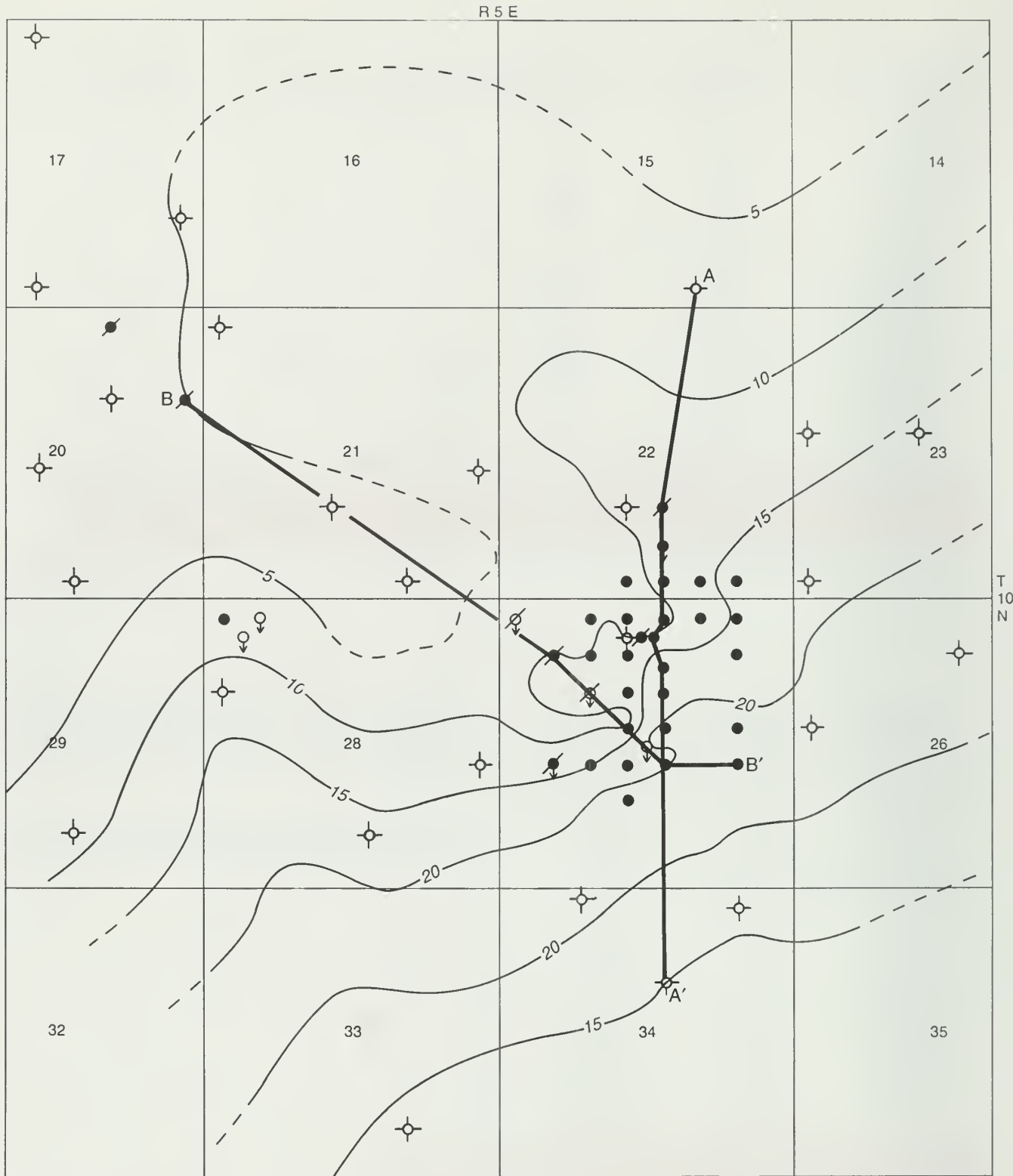




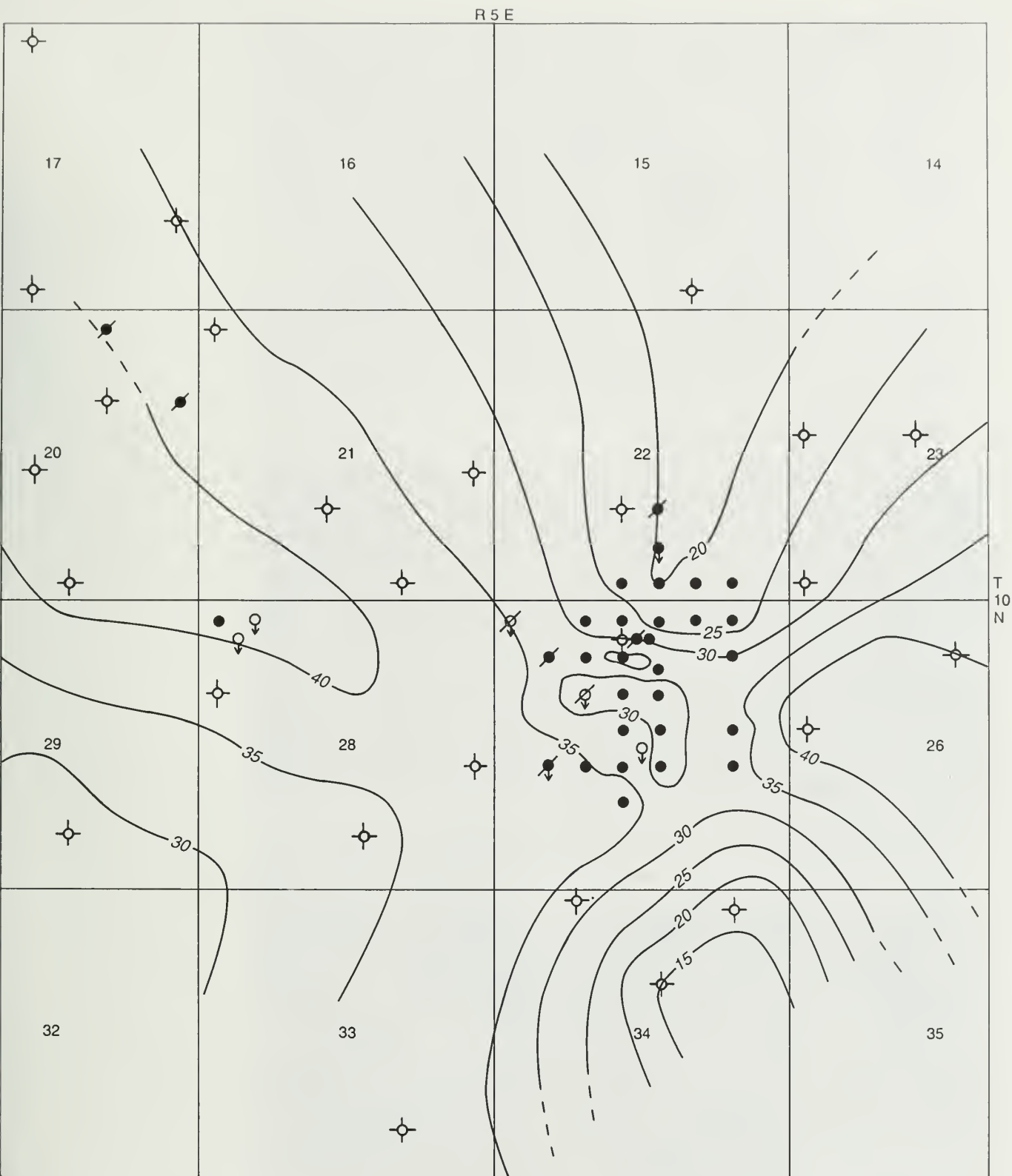
**Figure 8** North-south cross section along A-A' shows thinning in the upper Aux Vases Sandstone interval over the field. The lateral continuity of the upper sandstone interval is apparent. See figure 10 for location of cross sections.



**Figure 9** Northwest-southeast cross section along B-B' shows thinning of the upper sandstone interval of the Aux Vases northwest of the field.



**Figure 10** Isopach map of clean sandstones within the upper sandstone interval of the Aux Vases Formation at Stewardson Field shows a slight thinning over the field. The laterally extensive nature of the sandstone is indicative of a subtidal sheet sand. Contour interval is 5 feet.



**Figure 11** Isopach map of clean sandstones within the lower interval of the Aux Vases Formation at Stewardson Field shows a laterally extensive sheet-like distribution pattern similar to that in the upper interval. Contour interval is 5 feet.

The sheet-like distribution of sandstones within the lower interval is similar to that in the upper interval except that the lower interval sandstones are more extensive (figs. 8, 9, and 11). The thickness of sandstones within the lower interval in the field ranges from 20 to 35 feet. Shale beds are more common within the sandstones of the lower interval than they are in the upper interval, suggesting that a greater degree of vertical heterogeneity may exist within these lower sandstones than in their stratigraphically higher counterparts. The distribution and thickness of the lower sandstones, together with the presence of more numerous shale beds, indicate that the environment of deposition of the lower interval was also in the subtidal shoreface, but perhaps it was in slightly deeper water than the upper interval.

Although not productive at Stewardson, sandstones from the lower interval locally contain some oil, as indicated by core from well 1241 (NE NW NE, Sec. 27, fig. 2). In addition, a drill stem test taken from the lower interval sandstones in well 1155 (SE NE NW, Sec. 27, fig. 2) recovered 45 feet of slightly oil-cut mud. A drill stem test from well 1157 (Sec. 27, NE SE NW, fig. 2) recovered 32 feet of highly oil-cut mud from the upper and lower intervals combined.

### **Petrography and Diagenesis**

Although no whole cores were available from the field area, petrographic analyses of core biscuits and well cuttings were performed. Microscopic examinations included optical microscopy, scanning electron microscopy (SEM), energy dispersive X-ray (EDX) analyses, and X-ray diffraction (XRD) analyses. Correlations based on wireline log signatures were used to extrapolate lithofacies across the field.

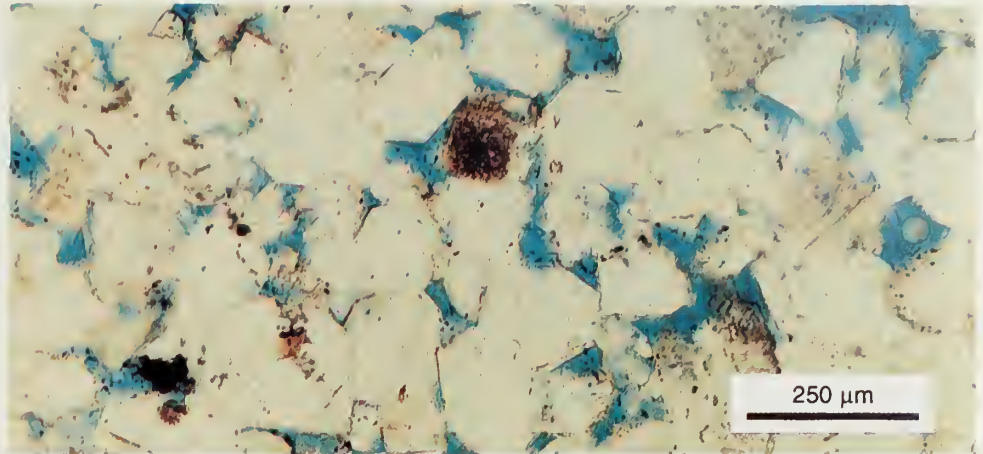
**Sandstone** Sandstones within the upper interval of the Aux Vases Formation at Stewardson are gray, fine grained, relatively well sorted, fossiliferous (mostly echinoderm fragments), and cemented by silica (quartz overgrowths) and calcite.

Sandstones in the lower interval also are cemented with calcite and silica and appear to be identical to sandstones in the upper interval. Despite the lithological and textural similarities, analysis of log characteristics indicates that the upper sandstones have higher resistivity readings than the lower sandstones even though SP (spontaneous potential) signatures are similar. This difference in resistivity may be due to the presence of hydrocarbons, more calcite cement in the upper sandstones, or more clay in the lower sandstones.

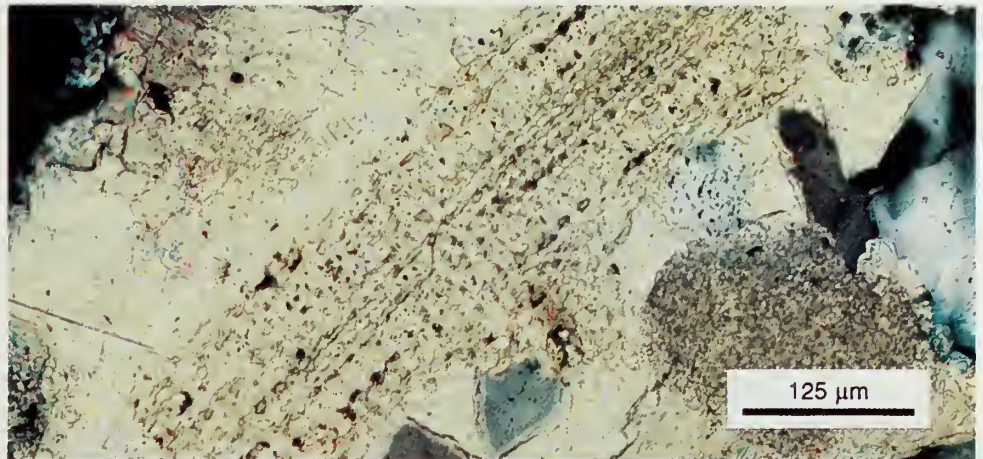
Petrographic analyses of thin sections show that all sandstones within the Aux Vases Formation at Stewardson Field have similar petrologies and are classified as quartz arenites or calcareous quartz arenites. These sandstones consist predominantly of fine grained quartz. They also contain minor plagioclase feldspar, very minor potassium feldspar, muscovite, and fragments of echinoderms, bryozoans, brachiopods, ooids, trilobites, and crinoid columnals. Clay is not a major constituent of the reservoir rock and typically comprises less than 3% of the total volume, as determined from samples collected near the crest of the paleostructure.

Quartz grains are subangular to subrounded, and at least some of this angularity is attributable to quartz overgrowths (plate 1). Feldspar grains are subrounded to angular, depending on the amount of dissolution that has affected them. The only plagioclase feldspars observed in the samples were sodium-rich. Potassium feldspars are rare and commonly display some degree of dissolution. The absence of other feldspars is due to the mineralogy of the source area or to the total dissolution of calcium-rich plagioclases and most of the potassium feldspars.

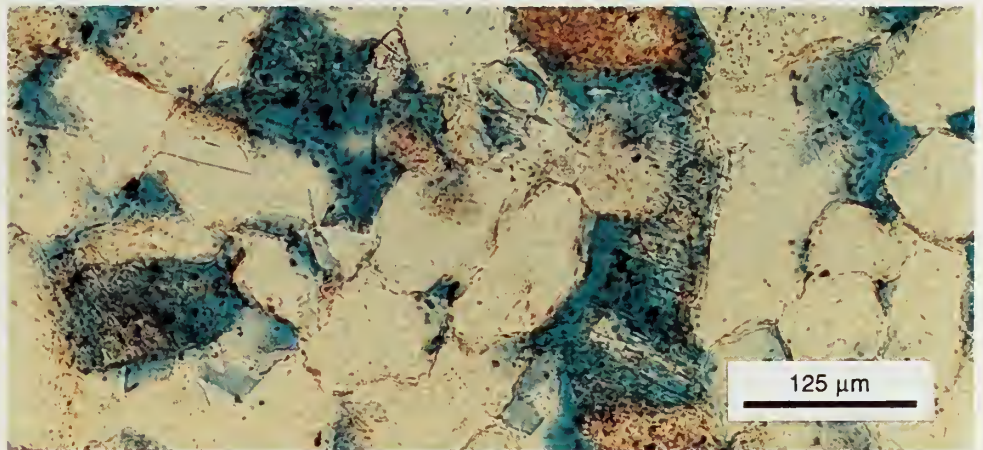
The abundance of fossil fragments within the sandstones appears to be dependent on the proximity of carbonate facies. All of the fossil fragments show varying degrees of abrasion, which is indicative of transport. Echinoderm fragments are the most



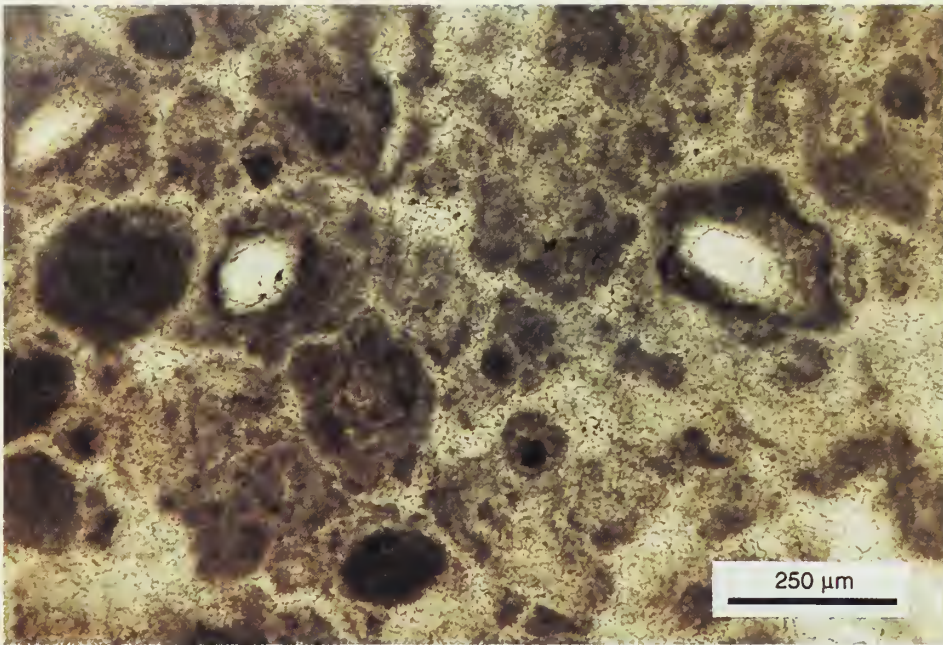
**Plate 1** Photomicrograph of Aux Vases Sandstone reservoir sample shows cementation of sandstone by well developed quartz overgrowths (straight euhedral edges). Porosity is highlighted in blue. The sample was taken at a depth of 1,960 to 1,965 feet from well 1076 (NW NW SE, Sec. 27).



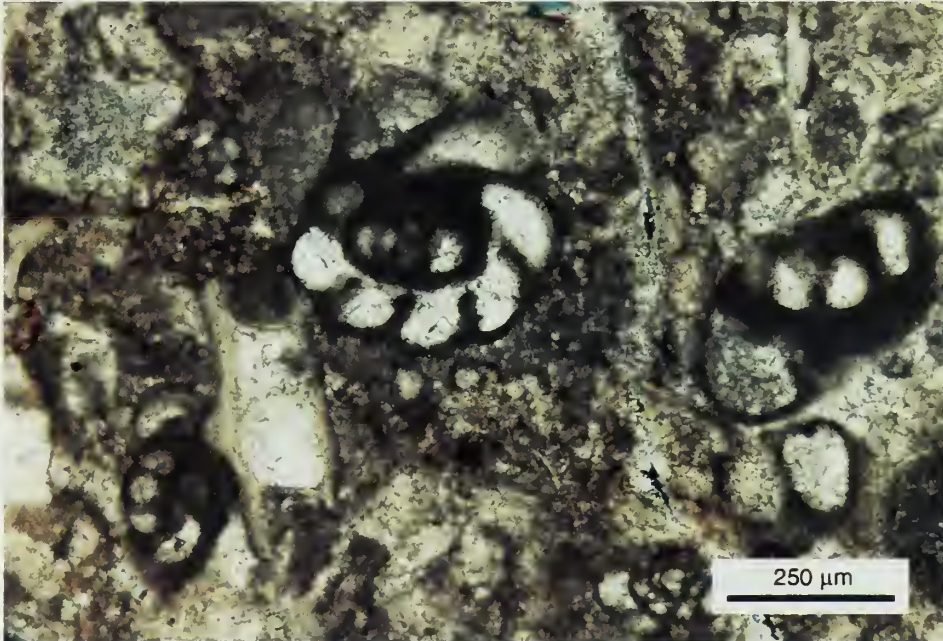
**Plate 2** Photomicrograph of exceptionally well preserved echinoderm columnar, cut lengthwise, showing syntaxial rim cement. The sample was taken at a depth of 1,955 to 1,960 feet from well 1862 (NW NE NE, Sec. 27).



**Plate 3** Photomicrograph showing several grains of feldspar in varying stages of dissolution. The sample was taken at a depth of 1,950 to 1,951 feet from well 78 (660 ft FNL, 150 ft FWL, Sec. 27).



**Plate 4** Photomicrograph of *Archaeolithophyllum* sp., a red alga found in carbonate beds between the upper and lower sandstone intervals in Stewardson Field. These algae are commonly found in shallow carbonate bank-forming areas. The sample was taken at a depth of 1,974 to 1,980 feet from well 1076 (NW NW SE, Sec. 27).



**Plate 5** Photomicrograph of miliolid foraminifera, an indicator of inner shelf environment. The sample was taken at a depth of 1,995 to 2,000 feet from well 1862 (NW NE NE, Sec. 27).

common faunal grains observed. Ooids, a minor component of the sandstones, could have been derived from the upper part of the Ste. Genevieve Formation or from a carbonate facies of the Aux Vases.

Silica, in the form of quartz overgrowths, is the dominant cement type. Calcite cement is also common and occurs both as syntaxial rims on echinoderm fragments (plate 2) and as interstitial, blocky, mosaic calcite. The degree of cementation, interpreted from log character, is apparently relatively similar throughout the field area, except that slightly more calcite cement may be present along the flanks of the structure. Lack of samples precluded verifying this estimation petrographically.

Dissolution of feldspar, and to a lesser degree calcite, provides a minor degree of secondary porosity within the Aux Vases Sandstones in the field (plate 3). This secondary porosity accounts for perhaps 2% to 3% of the total porosity observed in thin section. As previously mentioned, it is possible that entire feldspar grains have been dissolved.

**Limestone** The laterally extensive shale and carbonate interval that separates the lower and upper sandstones is 1.5 to 8 feet thick and grades laterally from a light gray to gray, algal mudstone-wackestone to a light gray grainstone. Allochems within the limestones include fragments of echinoderms, bryozoans, brachiopods, ooids, trilobites, crinoid columnals, peloids, and algae. One of the algae was tentatively identified as *Archaeolithophyllum* sp. (plate 4), a red alga commonly found as solitary or multiple crusts or as a foliate mass in shallow marine settings from the late Mississippian through Late Permian (Wray 1977). *Archaeolithophyllum* sp. can be found in mud-rich and mud-free environments, but it is primarily an encrusting alga, serving as a frame builder for reef and carbonate bank development (Wray 1964). In the Stewardson Field area, the algae appear to occur as masses or clumps rather than as encrusting forms. Rare algal biscuits, similar in shape to oncolites, may represent portions of an algal mat reworked during periods of relatively high energy. Samples from adjacent wells show that this same interval is a grainstone, suggesting that water depths may have been somewhat shallower in areas where the algae were present.

The intercalated limestone and shale interval at the base of the Aux Vases Formation (figs. 5, 8, and 9) is as much as 10 feet thick. The limestone lenses in this interval occur only at or near the top of the structure. Limestone from the basal interval was sampled in only one well (1862, NW NE NE, Sec. 27), and contained miliolid foraminiferans at a depth between 1,995 and 2,000 feet (plate 5). Miliolid foraminifera are commonly found in inner shelf environments (Bathurst 1975).

**Clay** Diagenetic clay minerals in the Aux Vases at Stewardson Field were identified by X-ray diffraction as illite, illite/smectite, chlorite, and mixed-layered chlorite. These clay minerals ranged from 0.4% to 5.2% (commonly less than 2%) of the total rock volume (table 1), and their presence may be due to diagenetic alteration of feldspars.

Scanning electron microscopy and energy dispersive X-ray analyses performed on samples from Stewardson Field revealed that small platelets of chlorite are present on some quartz grains (figs. 12, 13). Such chlorite coatings are known to inhibit the development of quartz overgrowths and thereby help to preserve primary porosity (Heald 1965, Pittman and Lumsden 1968, Pittman et al. 1990). Much of the chlorite in Aux Vases sandstones is a previously unrecognized mixed-layered variety that gives a distinctive signature on X-ray diffraction traces (Moore and Hughes 1991). This diagnostic signature is the result of interstratification of a material that is 7Å thick and similar to berthierine, kaolinite, odinite, or serpentine. The mixed-layered

**Table 1** Mineral analysis of the clay size particles from sandstone in the upper Aux Vases interval in the No. 1 G. D. Chaffee and the No. 8 Chaffee wells.

| depth (ft)                  | clay index | mineral analysis (%) |                 |           |          |        |            |             |         |          |
|-----------------------------|------------|----------------------|-----------------|-----------|----------|--------|------------|-------------|---------|----------|
|                             |            | illite               | illite/smectite | kaolinite | chlorite | quartz | K feldspar | plagioclase | calcite | dolomite |
| No. 1 G. D. Chaffee (00078) |            |                      |                 |           |          |        |            |             |         |          |
| -1946-47                    | 0.004      | 0.04                 | 0.03            | 0.00      | 0.32     | 67.87  | 2.80       | 2.08        | 26.87   | 0.00     |
| -1948-49                    | 0.024      | 0.83                 | 0.60            | 0.00      | 0.92     | 52.18  | 1.76       | 0.81        | 42.88   | 0.00     |
| -1950-51                    | 0.030      | 0.21                 | 0.15            | 0.00      | 2.66     | 88.13  | 2.57       | 1.78        | 4.50    | 0.00     |
| -1952-53                    | 0.022      | 0.39                 | 0.29            | 0.00      | 1.56     | 89.17  | 2.38       | 1.63        | 4.58    | 0.00     |
| -1954-55                    | 0.515      | 29.17                | 21.12           | 0.00      | 1.18     | 19.26  | 0.90       | 0.17        | 28.21   | 0.00     |
| -1960-61                    | 0.052      | 2.18                 | 1.58            | 0.00      | 1.43     | 64.88  | 3.08       | 2.63        | 24.21   | 0.00     |
| No. 8 Chaffee (01862)       |            |                      |                 |           |          |        |            |             |         |          |
| -1955-60                    | 0.027      | 1.17                 | 0.85            | 0.00      | 0.71     | 75.77  | 0.52       | 0.72        | 20.25   | tr       |
| -1960-65                    | 0.011      | 0.45                 | 0.32            | 0.00      | 0.37     | 81.06  | 1.19       | 0.81        | 15.81   | 0.00     |
| -1975-80                    | 0.026      | 1.06                 | 0.77            | 0.50      | 0.32     | 83.32  | 1.44       | 1.19        | 11.40   | tr       |
| -1980-85                    | 0.027      | 0.90                 | 0.65            | 0.42      | 0.78     | 85.93  | 1.70       | 3.38        | 6.24    | tr       |

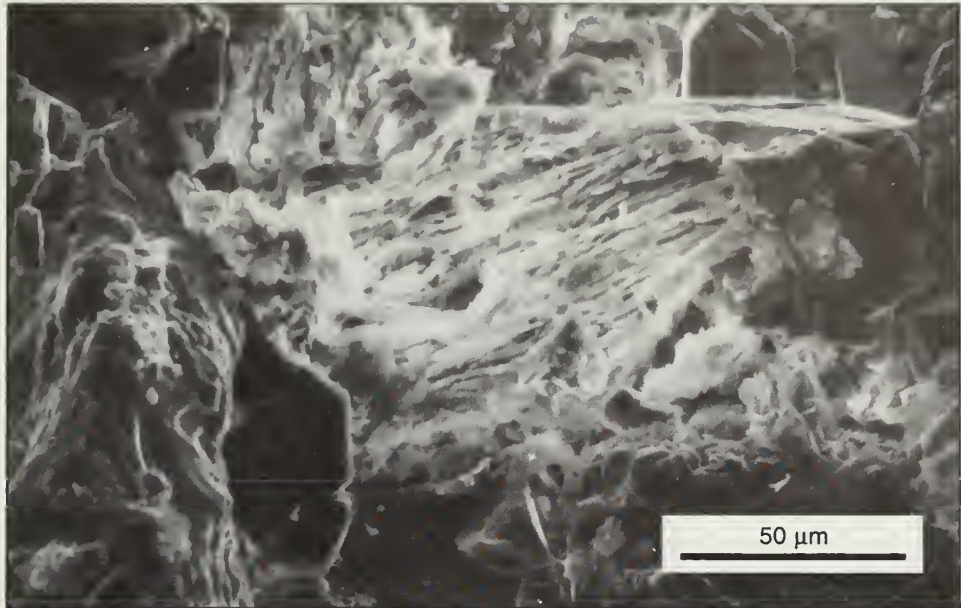
chlorite observed in this study may be more effective in preventing overgrowths, if it is present in sufficient quantities, than most other types of clay minerals. The fact that the amount of chlorite minerals at Stewardson is less than that found in other Aux Vases fields (Leetaru 1991; Huff, in press; Seyler, in preparation; Beaty and Fagan, in preparation) may be a primary reason the reservoir at Stewardson exhibits a higher degree of quartz overgrowths and thus, a lower porosity than is typical for the formation.

### Porosity and Permeability

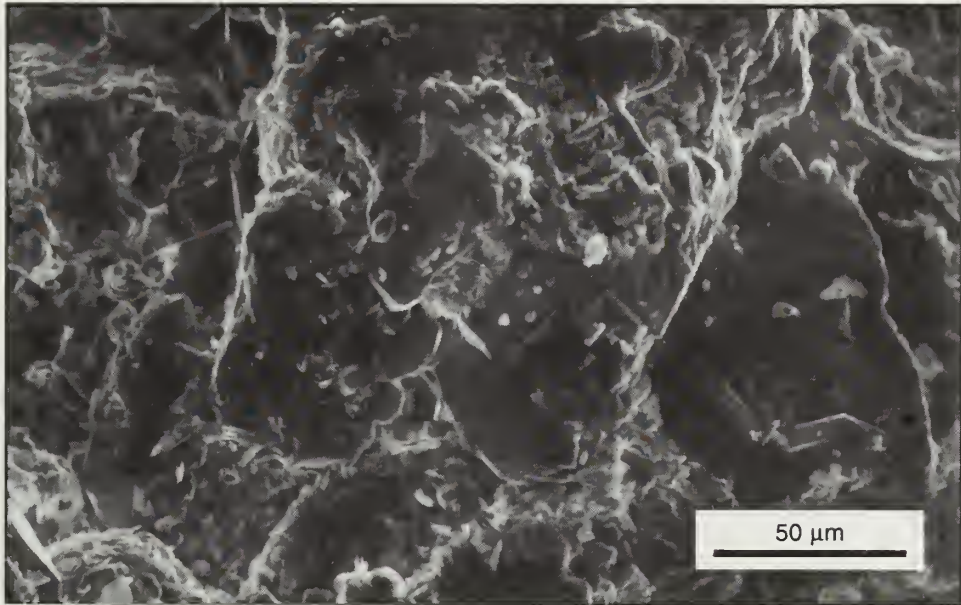
Early in the development of Stewardson Field, the Aux Vases was cored in eight wells near the crest of the structure, in the most productive part of the field (fig. 2). Commercial laboratory analyses of four of these cores showed that porosity ranged from 9.7% to 17.1% and averaged just 13%. Permeabilities in these same cores ranged from 2 md to 122 md and averaged 36.5 md. Little relationship between porosity and permeability is apparent. For example, wells 1273 (SW SE NE, Sec. 27) and 1138 (NW SW SW NE, Sec. 27) have average permeabilities of 43 md and 42 md and average porosities of 12.6% and 12.9%, respectively. Wells 1115 (SW SW NE, Sec. 27) and 1241 (NE NW NE, Sec. 27) have slightly higher porosities of 13% and 14.3%, respectively, but their permeabilities are only 33 md and 28 md, respectively.

Allochems transported to the flanks of the paleostructure by waves and tidal currents may account for the slightly greater amounts of calcite cement there. The presence of calcite in this region was determined by log interpretation. The presence of abundant quartz overgrowths, interstitial calcite cement, and minor diagenetic clays, as discussed in the petrography section, has partially occluded porosity and permeability. The apparent lack of relationship between porosity and permeability at Stewardson can probably be attributed to diagenetic overprinting.





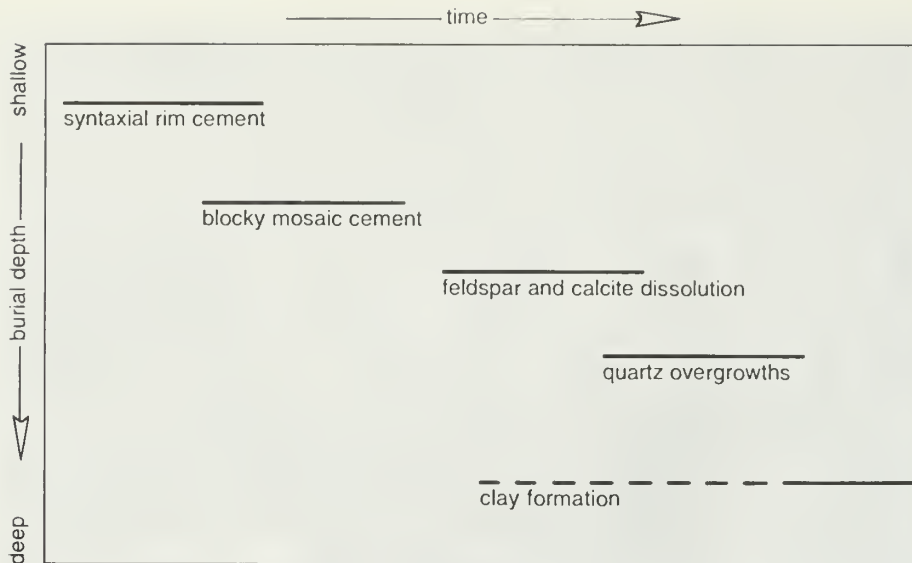
**Figure 12** SEM photomicrograph of diagenetic clay minerals on quartz grains and intermediate calcite cement. The sample was taken at a depth of 1,950 to 1,951 feet from well 78 (660 ft FNL, 150 ft FWL NE, Sec. 27).



**Figure 13** SEM photomicrograph of dissolved potassium feldspar with late stage hexagonal quartz overgrowths. The sample was taken at depth of 1,950 to 1,951 feet from well 78 (660 ft FNL, 150 ft FWL NE, Sec. 27).

### **Diagenetic Sequence**

On the basis of petrographic analyses, the following diagenetic sequence was developed for Stewardson field: (1) early cementation of calcite by syntaxial rim cement; (2) continuing calcite cementation with the precipitation of blocky, mosaic calcite; (3) dissolution of at least some of the calcite and plagioclase feldspars followed by some clay mineral formation; (4) silica cementation in the form of quartz



**Figure 14** Diagram of diagenetic sequence in the Aux Vases reservoir at Stewardson Field.

overgrowths; (5) continued formation of authigenic clay minerals (fig. 14). Patchy neomorphism of some calcite can also occur.

### Effects of Petrophysical Properties on Reservoir Quality

Log correlations and petrographic evidence indicate that the subtidal sheet sands of the Aux Vases originally deposited at Stewardson were evidently relatively homogeneous and contained little clay. Consequently, migrating fluids were perhaps able to flow more extensively through these sandstones than in the sandstones of more heterogeneous Aux Vases reservoirs farther south. The lack of clay minerals coating sand grains enabled cements, particularly silica, to develop more thoroughly at Stewardson (Pittman 1990) than in the more clay-rich Aux Vases reservoirs. Diagenetic alterations then occluded the porosity and permeability at Stewardson to a greater degree than in Aux Vases reservoirs farther south.

Portions of the upper sheet sands that were draped over the paleostructure at Stewardson are apparently slightly more permeable than those on the flanks of and off the structure, as indicated by production data and log characteristics. This slight permeability advantage may have been caused by hydrocarbons migrating into the pores of the upper sheet sands and displacing the brines responsible for the precipitation of silica cements and the formation of clay minerals. The slightly higher porosity and permeability values on the paleostructure may also be due to winnowing of fines during deposition.

### Trap Type

The homogeneous nature of the subtidal sheet sands in the Aux Vases at Stewardson precludes significant local stratigraphic entrapment of oil. Normally, sandstones such as these would require a structural closure to provide entrapment of hydrocarbons. The structural closure at Stewardson is probably not sufficient, however, to have enabled a significant accumulation of hydrocarbons. The pinchout of the upper interval sandstones within 2 miles to the northwest of the Stewardson structure is most likely a critical factor in this hydrocarbon accumulation. Thus, the trap type is structural-stratigraphic.

## CLASSIFICATION AND IDENTIFICATION OF PLAY

The Aux Vases shoreface play, as it is best classified, is primarily a stratigraphic trap where oil accumulations occur near the updip pinchout of sheet sands. Porosity and permeability may be too inferior to provide economical reserves unless some paleofeature enabled local preservation of adequate reservoir qualities.

## PRODUCTION CHARACTERISTICS

### Drilling and Completion Methods

With the exception of the discovery well at Stewardson Field, which may have been drilled with a cable-tool rig, all of the wells were drilled with rotary tools using freshwater-based drilling muds. During early development of the field in the 1940s, the standard completion practice was to complete the well open hole and artificially fracture the reservoir using 15 to 40 quarts of nitroglycerine. During later development of the field, from the mid-1950s to the present, the majority of the wells were cased through the producing zone and then shot with two to four perforations per foot. Following this procedure, a mud-cleanup acid (MCA) was used, followed by hydraulic fracturing.

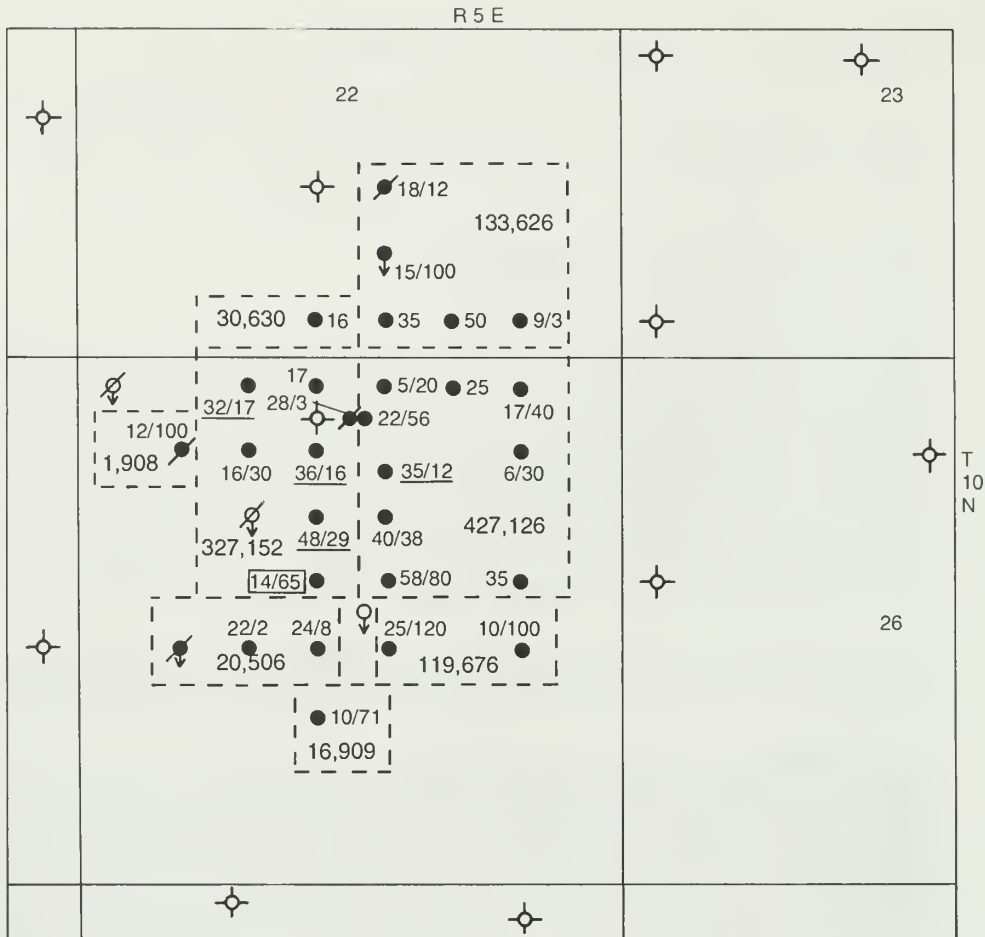
Oil did not flow from any wells at Stewardson Field during drill stem tests or production. Artificial lift was therefore necessary for all wells, and all associated gas was flared.

### Production Characteristics by Lease

Cumulative production data by lease (fig. 15) indicate that the Aux Vases is not as productive in the western half of section 27 as in the rest of the field. The wells in the SW1/4, Section 27 (Nos. 1079, 1080, 1090, and 22009, fig. 2), have a combined cumulative production of 37,415 BO. Well 22009 (SE NE SW, Sec. 27, fig. 15), still productive, produced 645 BO from June 1989 through June 1990. Well 1330 (SE NW NW, Sec. 27, fig. 15) produced only 1,908 BO before it was abandoned.

Commingling of Aux Vases and Spar Mountain production in the NW1/4, Section 27, precludes determining accurate production figures for each separate reservoir. Of the seven wells in this quarter section, three are commingled Aux Vases and Spar Mountain production, one is only Spar Mountain production, and the remaining three are only Aux Vases production. From the initial production data of these wells (fig. 15), an estimated 41% of the produced oil in the northwest quarter can be attributed to the Spar Mountain. In addition to the initial production data, swab tests were conducted on individual zones in two commingled wells in this quarter (wells 1155, SE NE NW, and 1157, NE SE NW, fig. 2). The tests produced a total of 5 BO and 2 BW per hour from the Spar Mountain and 4 BO and a slight show of water per hour from the Aux Vases. Producing zones in the third commingled well (1156, NW NE NW, Sec. 27, fig. 2) were not isolated during the swab test.

Figure 16 shows the results of the drill stem test of the Aux Vases Formation at Stewardson Field. The interval tested, length of test, recoveries, bottom hole pressure, and date of test are given. The results of the drill stem test for the combined upper and lower Aux Vases in well 1157 (NE SE NW, Sec. 27, fig. 16) lend support to an interpretation of reduced Aux Vases reservoir capacity in the NW1/4, Section 27. Fluid recovery was less in this well than in the other wells that had drill stem tests in the upper Aux Vases (i.e., well 1076, 330 ft FNL, 360 ft FWL SE, Sec. 27, and well 1141, SW SW NW, Sec. 26, fig. 16). The other drill stem test conducted in the NW1/4, Section 27 was of the lower Aux Vases in well 1155 (SE NE NW, Sec. 27).

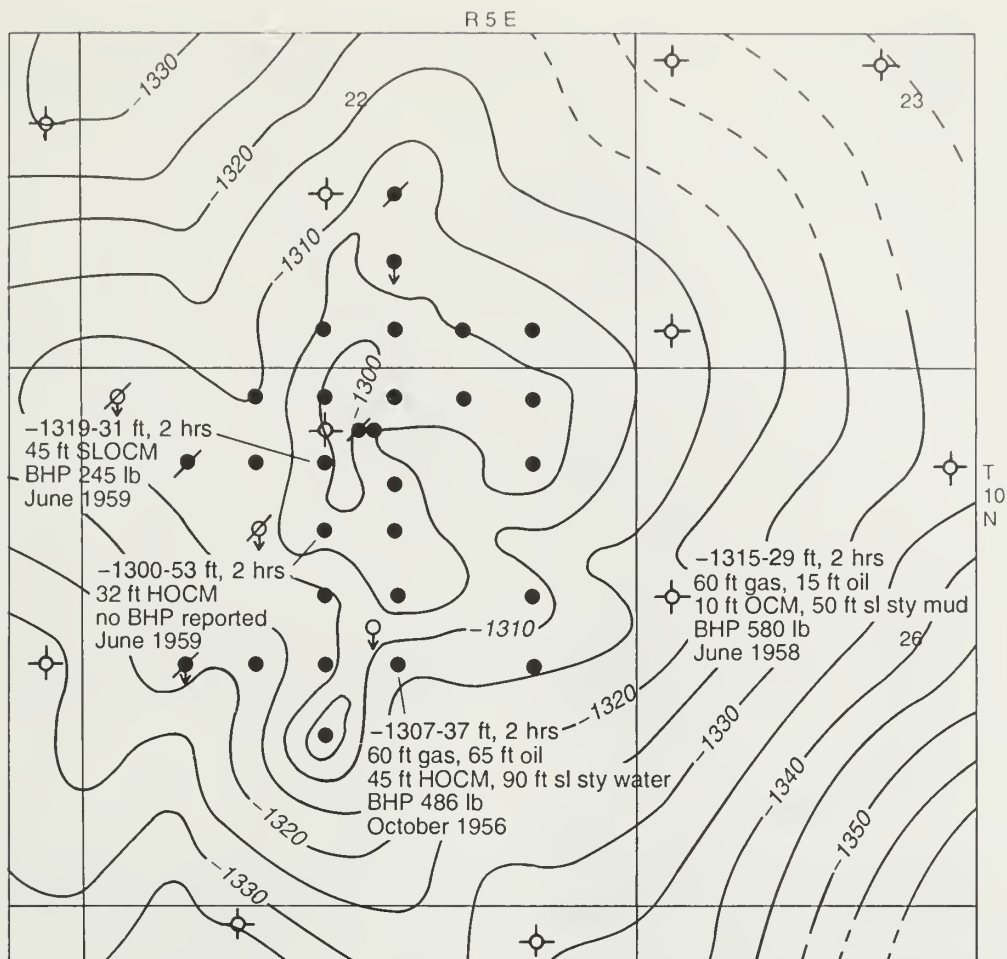


**Figure 15** Cumulative production by lease and initial production map. Note that much of the Aux Vases production has come from the leases that encompass the east-central portion of the field.

|              |                             |
|--------------|-----------------------------|
| 130,630 bbls | leased area with production |
| oil/water    | initial production (BOPD)   |
| 17/40        | Aux Vases                   |
| 35/12        | Aux Vases/Spar Mountain     |
| 14/65        | Spar Mountain               |

The oil–water contact is not readily apparent, but it was interpreted to be at or below –1,330 feet. The lowest perforated interval in the field is at –1,330 feet, and wells perforated to this depth did not produce appreciably more water than those wells perforated higher on the structure. In fact, wells with perforations at –1,329 feet produced less water than most wells that had slightly higher perforations. The higher water cut in the structurally higher wells was probably due to these particular wells having been drilled to the lower, water-wet sandstone facies and then plugged back. Apparently the operators of these wells could not prevent communication between these lower sandstones and the perforated intervals in the upper sandstones. This communication could be caused by poor cement jobs in the field or by inadequate stratigraphic seals separating the two sandstone intervals. Wells that did not penetrate the lower sandstones, and were completed open hole in the upper sandstone interval, had the lowest water cuts in the field.

Those wells on the periphery of the field and drilled off structure tested mainly water with some oil, even when the tested interval was structurally higher than –1,330 feet. Total fluid recoveries were fairly low in these wells. The results of these tests indicate that the reservoir quality in wells off the structure deteriorates sufficiently



**Figure 16** Drill stem test data map. — structure (ft) on top of Aux Vases Sandstone  
 The tests are indicative of a relatively low-permeability reservoir. Contour interval is 5 feet.

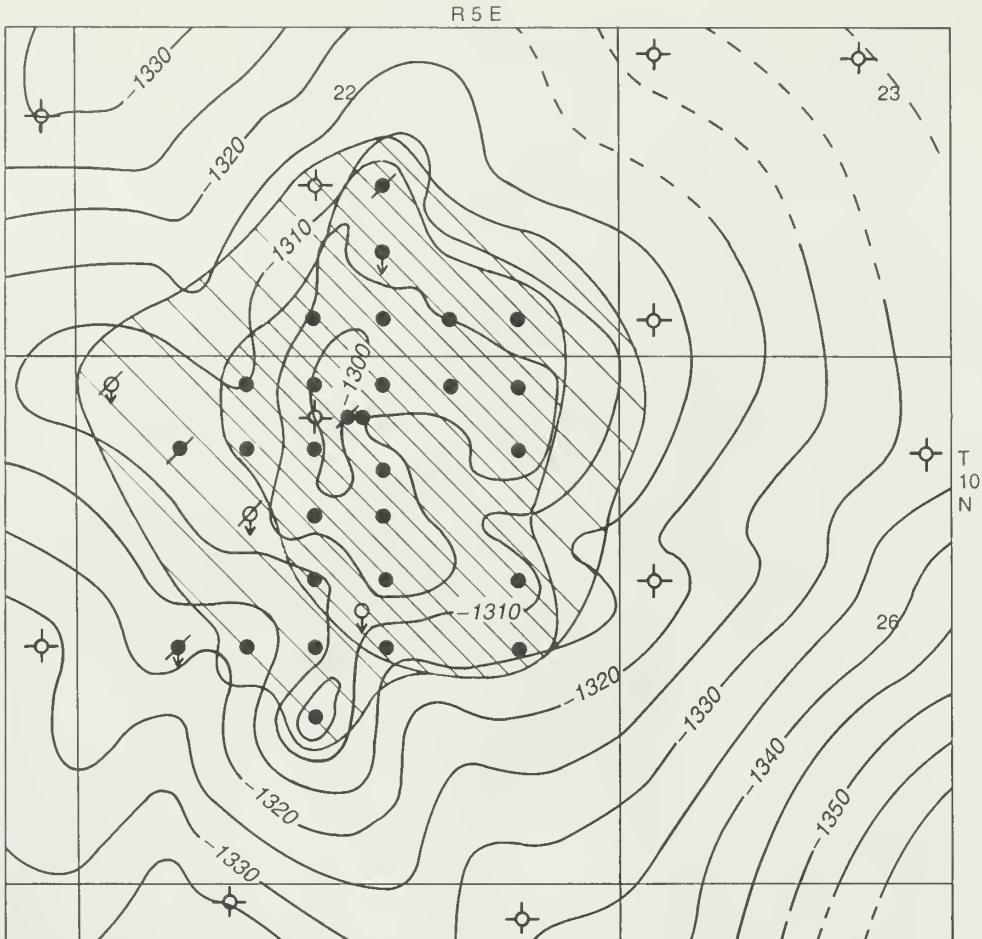
to prevent adequate hydrocarbon recoveries. Thus, the quality of the reservoir is more important than the oil-water contact in delineating the extent of the reservoir.

The extent of the effective reservoir at Stewardson is difficult to determine without more engineering data. Recoveries from wells indicate that the line of the effective reservoir extends around the field roughly in the area between the -1,310 and -1,320 contour lines (fig. 17). The area defined by this line is approximately 638 acres. The reservoir quality beyond this area is not adequate to allow economic hydrocarbon recovery using conventional methods.




### Fluid Characteristics

Samples of oil and brine from two wells, the Doran Oil No. 9 Chaffee and the Brown No. 2 Rincker (wells 1115, SW SW NE, Sec. 27, and 1366, NW NW NE, Sec. 27, respectively, fig. 2) were analyzed for this study. The data from these analyses are given in appendix A. The results of the analyses indicate that the oil is typical for Mississippian reservoirs in Illinois and that it exhibits relatively low resins and asphaltenes.

Although asphaltene content is relatively low at Stewardson, its presence is important when considering acidization of the well. Hydrochloric acid may encourage the



**Figure 17** Reservoir limit map. Both the extent of the effective reservoir and the limit of the "superior quality" reservoir with 42.7% recovery efficiency are shown. Contour interval is 5 feet.

 structure (ft) on top of Aux Vases Sandstone  
 limit of reservoir with 42.7% RE  
 limit of effective reservoir, 18% RE

formation of precipitates when in contact with asphaltenes, and thereby cause some clogging in pore throats.

## Volumetrics

**Original oil in place** Original oil in place (OOIP) was calculated using a standard volumetric equation:

$$\text{OOIP} = 7758 \times A \times h \times \phi \times (1 - S_w) \quad [1]$$

where 7758 = the conversion factor from acre-feet to barrels

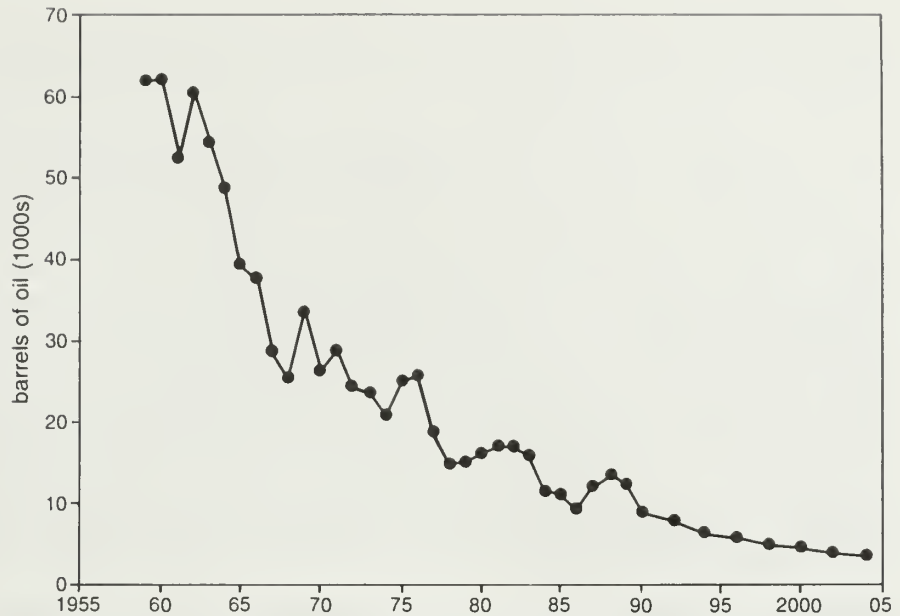
A = reservoir area in acres

h = average reservoir thickness in feet and is derived from the net sand isopach

$\phi$  = average reservoir porosity

$S_w$  = average water saturation

The reservoir oil volumes were then converted to surface volumes or STOOIP (stock-tank original oil in place) by dividing OOIP by the formation volume factor:



**Figure 18** Production decline curve for Stewardson Field.

$$\text{STOOIP} = \text{OOIP}/B_{oi} \quad [2]$$

where  $B_{oi}$  = formation volume factor under original reservoir conditions.

The standard industry value for  $B_{oi}$  in Aux Vases reservoirs is 1.15 (B. Podolsky, Podolsky Oil Co., personal communication, 1991).

The effective reservoir area for the Aux Vases was planimeted by using the sandstone thickness from the upper sandstone interval isopach. The following calculations show the best estimates for OOIP and STOOIP:

$$7,758 \times 9,067 \times 0.132 \times 0.70 = 6,499,581 \text{ BO (OOIP)}$$

$$6,499,581 + 1.15 = 5,651,809 \text{ BO (STOOIP)}$$

Production records from Stewardson Field include those wells that produce from the Spar Mountain Member of the Ste. Genevieve Formation. Consequently, the total production attributable to the Aux Vases had to be estimated by using initial production figures. The portion of the production that comes from Spar Mountain was estimated and subtracted from the total reported production. On this basis, the corrected cumulative production from the Aux Vases in Stewardson Field was estimated to be 948,300 BO.

Assuming present production methods are continued, estimating remaining recoverable reserves of the field by extrapolating the decline curve (fig. 18) renders 83,800 BO. This estimation is made on the assumption that the economic limit for production is about 10 BOPD for the field.

The recovery efficiency (RE) of Stewardson Field was calculated using the following equation:

$$\text{RE} = \frac{(\text{RRR} + \text{TPO})}{\text{STOOIP}} \quad [3]$$

where RRR = remaining recoverable reserves

TPO = total produced oil

Recovery efficiency was calculated at 18.3% for the entire effective Aux Vases reservoir (fig. 17). This relatively low number indicates that significant amounts of hydrocarbons may remain within the Aux Vases reservoir at Stewardson.

This study showed that the central portion of the field had recovered considerably more oil than peripheral areas of the field. This more productive area of the field was outlined (fig. 17), and its recovery efficiency was calculated using the same methods applied above. Calculations for this more productive area suggest that the central portion of the field has a recovery efficiency of 42.7%.

Two probable reasons for the higher recovery in the central part of the field are (1) slightly less interstitial calcite occurs in the central area than in the periphery of the field, and (2) the relative absence of a very fine grained fraction in the same area. This portion of the field was along the paleohigh that existed during deposition of the Aux Vases Formation (fig. 7). From log character and limited petrographic examinations, it is postulated that waves and tidal currents winnowed finer grained components (both carbonate and clastic) off the paleostructure during deposition, forming a well sorted deposit with better permeability and porosity characteristics than in other areas of the field.

**Remaining oil in place** The remaining oil in place, calculated by subtracting the total produced oil from the STOOIP, gives a total of 4,703,509 BO. The amount of remaining oil that is ultimately recoverable is dependent on the cost of the extraction method used and the price of oil.

## **Development and Production Strategy**

**Improved recovery techniques** As stated earlier, those wells that penetrated the sandstones within the lower interval of the Aux Vases, and were plugged back to the upper interval, produced more water than those that penetrated only the upper interval. Modern cementing techniques may prevent such communication problems and thereby prevent unnecessary water production from future holes drilled at Stewardson.

Although homogeneous sandstones generally are easily and effectively water-flooded, any waterflood operation must be coordinated across the entire reservoir to provide optimum recovery. Any injection wells placed near the higher quality reservoir will not drain any significant part of the inferior portion because the injected water tends to seek the path of least resistance (greatest permeability) and bypass those areas with lower permeability.

Additional drilling would be required to improve the drainage of the Aux Vases reservoir at Stewardson because of the variations in reservoir-quality sandstones. In particular, additional wells would need to be drilled into the lower quality sandstones, which have had poor recovery efficiencies. Higher well densities would be required to increase production. Modern hydrofracturing methods or horizontal drilling may enhance the recovery potential in these sandstones. If the area is oil saturated, as the authors believe, then the main factor preventing oil production in the inferior part of the reservoir is lack of permeability. Any method that can improve the permeability, or the amount of reservoir open to the borehole, has potential for recovering additional quantities of hydrocarbons.

**Enhanced recovery techniques** Enhanced oil recovery (EOR) methods utilizing thermal techniques, surfactant, polymer, CO<sub>2</sub>, microbial, or alkaline flooding may allow for even more effective recovery. Thermal methods (steam drive and soak) predominate in EOR projects in the United States, accounting for 80% of EOR production (Lake 1989). These methods are primarily used for heavy oil extraction in California. Thermal methods rely on several displacement mechanisms to recover



oil, but most important is the reduction of crude viscosity with increasing temperature. For heavy crudes (10°–20° API) thermal methods will produce a viscosity effectively within the flowing range. Thermal technology for viscosity reduction for lighter crude oils is not effective (Lake 1989), and therefore thermal methods are not nearly so applicable in Illinois. Waterflooding would be a more suitable method for the lighter crude oils found at Stewardson Field.

Polymer-augmented waterflooding can increase oil recovery in comparison with conventional waterflooding by improving volumetric sweep efficiency. Much of the incremental recovery by polymer flooding is the result of accelerated oil production before the economic limit of the field is reached. Polymer-augmented waterflooding, therefore, is applied most effectively in the early stages of a waterflood, while the mobile oil saturation is still high (Neil et al. 1983). Considering that the central portion of Stewardson Field has been subjected to two waterfloods since 1959, it would not appear to be a viable candidate for polymer flooding.

Alkaline flooding is best used in fields that contain viscous, naphthenic, low API gravity crude oil. Oil from Stewardson Field has a low viscosity and a high API gravity, indicating that this method would be inadvisable.

Surfactant flooding is one of several processes that use injection of surfactant solutions or dispersions into oil reservoirs to enhance crude oil recovery. The injected mixture (chemical slug) includes some or all of the following components: water, hydrocarbons, alcohols, polymers, and inorganic salts. The mechanisms for this method of oil removal include reduction of oil–water interfacial tension, oil solubilization, emulsification, and mobility enhancement (Hence 1976).

Several factors need to be considered in evaluating a reservoir for surfactant flooding. In general, desirable geologic characteristics include vertical and lateral uniformity of rock properties (homogeneity), high levels of porosity and permeability, and low clay content. A successful waterflood is a good indication of a reservoir's suitability for surfactant flooding, provided the residual oil saturation in the water-swept zone is high enough. Undesirable elements are fractures, a large gas cap or bottom water drive, unusually low residual oil saturations, and pay zones that are vertically stratified or laterally discontinuous (heterogeneity). Surfactant flooding is less attractive at lower permeabilities because increased retention of surfactant on clays requires larger amounts of chemicals, and individual injection and production rates of wells are reduced. Lower permeability limits of 20 md may be acceptable where oil saturation is high. Permeabilities range from 28 to 71 md at Stewardson Field and are within the acceptable limits. If the residual oil saturation in the swept zone is low, however, then feasibility of this type of EOR is poor.

Miscible flooding using CO<sub>2</sub> requires that oil viscosity be low enough that no channeling of carbon dioxide occurs and that certain miscibility pressures can be attained. At Stewardson Field pressure is currently less than 486 psi, nearly 400 psi less than that required for miscible CO<sub>2</sub> flooding. The desired pressure at Stewardson Field, calculated from a formula by Hence (1976), would be 870 psi.

Immiscible CO<sub>2</sub> flooding is another method that may have application at Stewardson. Thomas et al. (1990) demonstrated in a laboratory flood test of a core that cyclic CO<sub>2</sub> injection (the "huff and puff" method) may be beneficial to enhanced recovery under certain conditions. The laboratory tests indicated that residual oil from waterflood ( $S_{or}$ ) can be displaced in multiple cycles of CO<sub>2</sub> injection under immiscible conditions. The use of this technique is favorable when an initial reservoir gas cap saturation is well distributed. Thomas et al. (1990) also suggest that several mechanisms contribute to enhanced oil recovery. Foremost among these are oil

swelling, oil viscosity reduction, and altered relative permeability. Studies on these mechanisms are being conducted at the ISGS for Illinois reservoirs (Sim 1993). Thomas et al. (1990) also identified diffusion and phase behavior as important oil recovery mechanisms in subsequent field tests. One of their main conclusions was that gravity segregation allowed for deeper CO<sub>2</sub> penetration into the core, resulting in improved oil recovery. Stewardson would be a potential, but not ideal, candidate for this method.

Another method to consider is injection of gas, such as CO<sub>2</sub>, at the crest of the structure for pressure enhancement. Oil could be recovered along the peripheral wells as the expanding gas cap forced the oil off the structure. The cost of the infrastructure required for CO<sub>2</sub> injection may make this approach unattractive.

MEOR involves the use of microorganisms and their metabolic products to stimulate oil recovery. The microbes can accomplish this increased recovery by a combination of chemical and/or gas generation and by their tendency to plug off those pathways that have already been swept by previous waterflooding. The amount and type of metabolic products produced are dependent on (1) specific microbes already present in the reservoir, (2) any that may be introduced to the reservoir, (3) nutrient(s) provided for microbial growth, and (4) environmental conditions of the reservoir. According to Donaldson et al. (1989), metabolic products that may be generated from MEOR include gases such as carbon dioxide, hydrogen, and methane. Polymers occurring as polysaccharides or proteins can also be generated. In addition, surface-active compounds, which generally occur as polyanionic lipids, low molecular weight solvents (alcohols and ketones), and low molecular weight carboxylic acids, may also be byproducts of microbial activity. MEOR may be a feasible method to apply to the waterflooded part of Stewardson Field.

## CONCLUSIONS

Sandstones in the Aux Vases Formation at Stewardson Field exhibit less porosity and permeability than Aux Vases reservoirs studied by the ISGS in the more southern fields of the Illinois Basin, for example, in King (Leetaru 1991), Boyd (Leetaru, in preparation), Ziegler (Seyler, in preparation), Energy (Huff 1993), and Dale Consolidated (Beaty and Fagan, in preparation). The relatively poor reservoir quality of Stewardson Field has not translated, however, to equally poor recovery efficiency. Part of the answer to this incongruity is that the environment of deposition for the Aux Vases at Stewardson (subtidal shoreface sheet sands) differs from the environments interpreted for other Aux Vases fields (shallow marine bars from mixed clastic-carbonate environments).

Although the depositional conditions of the Aux Vases Formation at Stewardson caused some vertical compartmentalization, laterally the sandstones are relatively homogeneous. These characteristics are unlike the Aux Vases sandstones in southern Illinois where high degrees of lateral and vertical compartmentalization are caused by interfingering sandstone, shale, and limestone facies.

Observed differences in reservoir quality across Stewardson Field apparently are due to the significant diagenetic overprinting that has occluded pore throats and reduced permeability. This reduced permeability is most prevalent in the periphery of the field where slightly finer material may be present.

Clay contents of the reservoir sandstones at Stewardson are not as great as those of the Aux Vases reservoirs farther south. Clay coatings on the sand grains bind water and reduce the accuracy of resistivity measurements of formation fluids from wireline logs. Consequently, resistivity measurements from wireline logs at

Stewardson are more accurate than those commonly observed for the Aux Vases elsewhere in the basin. The lack of clays also means that clay-related production problems prevalent in many other Aux Vases reservoirs are not a major concern at Stewardson.

Some of the more important characteristics of the Aux Vases Formation at Stewardson are summarized below.

(1) A structural high was probably present at Stewardson Field prior to and during deposition of the Aux Vases Formation. This structure may have been due to either tectonism or compaction of sediments around a Silurian–Devonian reef. Evidence for this paleostructural high is the local thinning observed on several isopach maps, including one of the Aux Vases.

(2) The Aux Vases Formation at Stewardson Field is dominated by fine grained, quartzose sandstone containing minor feldspars and muscovite. Fossil fragments are common and some have provided nuclei for syntaxial calcite cement. Cements include silica (as quartz overgrowths), and calcite. The calcite occurs as syntaxial rim cement on echinoderms and as interstitial blocky, mosaic cement. These cements are locally more prevalent at Stewardson than in other Aux Vases fields to the south, possibly due to the paucity of clays in the formation. Where present in sufficient quantities, clays have been shown to inhibit the formation of cements.

(3) The productive upper sandstone interval is interpreted to be a sheet sand complex in a mixed siliciclastic–carbonate environment. The combination of fossil fragments, sandstone geometry, and preservation of algae immediately below this interval suggests that the depositional setting was probably subtidal shoreface. The nonproductive (water-saturated) lower sandstone interval is also interpreted to have been deposited as subtidal sheet sands.

(4) Well log data suggest that both the upper and lower sandstone intervals are laterally continuous across the field; however, discontinuous shale beds may preclude good vertical permeability.

(5) The STOOIP at Stewardson is calculated at 5,651,809 BO. Cumulative recovery from the Aux Vases through 1990 is 948,300 BO. The recovery efficiency for Aux Vases reservoir in the field as a whole is calculated at 18.3%. The portion of the field that was situated on the paleohigh during deposition of the Aux Vases, and consequently has slightly better reservoir quality, has a recovery efficiency of 42.7%. Remaining recoverable reserves, using present extraction methods, are calculated at 83,800 BO.

(6) Application of improved recovery techniques may extend production into the lower quality reservoir of the upper interval, if permeability of the relatively tight sandstones in this reservoir can be increased without entering the water leg. Reserve calculations indicate that reserves remain in the western and eastern periphery of the field. Lower reservoir quality in the western portion of the field, and the lower structural position and potential high water production in the southeastern portion of the field, would appear to make infill drilling in these areas uneconomical. The high recovery efficiency observed in the central part of the field suggests that the sandstones are relatively laterally homogeneous. If residual oil saturation is high enough, more production may be available by infill drilling and improved recovery techniques.

(7) Applications of enhanced recovery methods may be useful in the portion of the field with better reservoir quality. Permeability must be sufficient, however, to enable injection fluids to contact large volumes of the reservoir. Consequently, EOR

methods such as immiscible CO<sub>2</sub> injection or microbial activity may be the most cost-effective practices at this time. Studies on each proposed EOR method, however, would be required to determine their relative economic merits at Stewardson.

## ACKNOWLEDGMENTS

The authors are grateful to Richard H. Howard and Beverly Seyler for their helpful reviews of the manuscript, and to Donald F. Oltz for his support and consultation during this project. We also thank William Roach for his engineering consulting. Randall E. Hughes and Duane M. Moore provided X-ray analyses of the clay fraction. D. Scott Beatty provided technical assistance and sample preparation. Beverly Seyler performed SEM/EDX and cathodoluminescence analyses. Ilham Demir and R. Todd Black sampled the brines and oils from Stewardson Field and also provided the geochemical analyses of the brines. Gary L. Salmon provided analyses of the oils. We thank Bryan G. Huff for compiling production and waterflood data. The cooperation of Doran Production Company during this project is also appreciated.

This research was funded by the U. S. Department of Energy under grant DE-FG22-89BC14250 and the Illinois Department of Energy and Natural Resources under grant AE-45.

## REFERENCES

- Bathurst, R.G.C., 1975, Carbonate Sediments and Their Diagenesis: Elsevier Scientific Publishing Co., NY, 658 p.
- Beatty, D. S., and J. P. Fagan, in preparation, Characterization of the Mississippian Aux Vases Formation, Southwestern Dale Consolidated Field, Franklin, Hamilton, and Saline Counties, Illinois: Illinois State Geological Survey, Illinois Petroleum series.
- Cole, R. D., 1990, The stratigraphy, petrology, and depositional environments of the Mississippian Aux Vases Formation across the southern portion of the Illinois Basin: Ph.D. dissertation, Southern Illinois University, Carbondale, 260 p.
- Donaldson, E. C., G. V. Chilingarian, and T. F. Yen, 1989, Microbial Enhanced Oil Recovery: Elsevier Scientific Publishing Co., NY, 227 p.
- Grube, J. P., 1992, Reservoir Characterization and Improved Oil Recovery from Multiple Bar Sandstones, Cypress Formation, Tamaroa and Tamaroa South Fields, Perry County, Illinois: Illinois State Geological Survey, Illinois Petroleum 138, 49 p.
- Heald, M. T., 1965, Lithification of Sandstones in West Virginia: West Virginia Geological and Economic Survey, Bulletin 30, 28 p.
- Hence, H. J., (ed.), 1976, Enhanced Oil Recovery—An Analysis of the Potential for Enhanced Oil Recovery from Known Fields in the United States—1976 to 2000: National Petroleum Council, Washington, DC, p. 96, 107, and 114.
- Huff, B. G., 1993, Reservoir Characterization and Improved Oil Recovery of the Aux Vases (Mississippian) Formation at Energy Field, Williamson County, Illinois: Illinois State Geological Survey, Illinois Petroleum 141.
- Lake, L. W., 1989, Enhanced Oil Recovery: Prentice Hall, Englewood, NJ, 550 p.

- Leetaru, H. E., 1991, Reservoir Heterogeneity and Improved Oil Recovery of the Aux Vases (Mississippian) Formation at King Field, Jefferson County, Illinois: Illinois State Geological Survey, Illinois Petroleum 135, 51 p.
- Leetaru, H. E., in preparation, Reservoir Heterogeneity and Improved Oil Recovery of the Aux Vases (Mississippian) Formation at Boyd Field, Jefferson County, Illinois: Illinois State Geological Survey, Illinois Petroleum series.
- McKay, R. H., 1980, A depositional model for the Aux Vases Formation and Joppa Member of the Ste. Genevieve Formation (Mississippian) in southwestern Illinois and southeastern Missouri: Master's thesis, Southern Illinois University, Carbondale, 184 p.
- Moore, D. M., and R. E. Hughes, 1991, Varieties of chlorites and illites and porosity in Mississippian sandstone reservoirs in the Illinois Basin: American Association of Petroleum Geologists Bulletin, v. 75, no. 3, p. 639.
- Neil, J. D., H. L. Chang, and T. M. Geffen, 1983, Waterflooding and improved waterflooding, *in* Improved Oil Recovery: Interstate Oil Compact Commission, Oklahoma City, p. 1–67.
- Pittman, E. D., and D. N. Lumsden, 1968, Relation between chlorite coatings on quartz grains and porosity, Spiro Sand, Oklahoma: Journal of Sedimentary Petrology, Tulsa, v. 38, no. 2, p. 668–670.
- Pittman, E. D., R. E. Larese, and M. T. Heald, 1990, Clay coats: origin, characteristics, and relevance to preservation of porosity: Clay Minerals Society, 27th Meeting, Columbia, MO, Program and Abstracts, p. 102.
- Seyler, B. J., in preparation, Reservoir Characterization of the Aux Vases Formation (Mississippian) at Zeigler Field, Franklin County, Illinois: Illinois State Geological Survey, Illinois Petroleum series.
- Sim, S. K., 1993, Pressure-Volume-Temperature Correlations for Crude Oils from the Illinois Basin: Illinois State Geological Survey, Illinois Petroleum 140.
- Thomas, J., T. V. Berzins, T. G. Monger, and Z. Bassiouni, 1990, Light oil recovery from cyclic CO<sub>2</sub> injection: Influence of gravity segregation and remaining oil: Society of Petroleum Engineers, 65th Annual Technical Conference and Exhibition, Sept. 23-26, New Orleans, LA, p. 609–616.
- Whitaker, S. T., 1988, Silurian Pinnacle Reef Distribution in Illinois: Model for Hydrocarbon Exploration: Illinois State Geological Survey, Illinois Petroleum 130, 32 p.
- Whitaker, S. T., and A. K. Finley, 1992, Reservoir Heterogeneity and Potential for Improved Oil Recovery within the Cypress Formation at Bartelso Field, Clinton County, Illinois: Illinois State Geological Survey, Illinois Petroleum 137, 40 p.
- Willman, H. B., E. Atherton, T. C. Buschbach, C. Collinson, J. C. Frye, M. E. Hopkins, J. A. Lineback, J. A. Simon, 1975, Handbook of Illinois Stratigraphy: Illinois State Geological Survey, Bulletin 95, p. 142–144.
- Wray, J. L., 1977, Calcareous Algae: Elsevier Scientific Publishing Co. NY, p. 72 and 77.
- Wray, J. L., 1964, Archaeolithophyllum, an Abundant Calcareous Algae in Limestones of the Lansing Group (Pennsylvanian), Southeastern Kansas: Kansas Geological Survey Bulletin, v. 170, no.1, p. 1–13.

## APPENDIX A RESERVOIR FLUIDS ANALYSIS

**API Number** 121732247300  
**Operator** Doran Oil Properties  
**Well Name** Chaffee No. 9  
**Location** SW NE NE, Section 27, T10N, R5E  
**Producing Formation** Aux Vases  
**Perforations Depth** 1,953–1,957 ft  
**Surface Elevation** 646 ft (Kelly bushing)  
**Waterflooded** yes

### Brine Analysis

**Brine sample number** EOR-B2  
**Temperature (C)** 25°  
**Resistivity** 0.0705 ohm-m  
**Eh (mV)** -194  
**pH** 6.12

### Anion chemistry (mg/L)

|                               |        |                 |     |
|-------------------------------|--------|-----------------|-----|
| Br                            | 150    | I               | 3.5 |
| Cl                            | 68,000 | NH <sub>4</sub> | 27  |
| CO <sub>3</sub> <sup>*</sup>  | 0.1    | NO <sub>3</sub> | 0.2 |
| HCO <sub>3</sub> <sup>*</sup> | 88     | SO <sub>4</sub> | 3.5 |

*\*as CaCO<sub>3</sub>*

### Cation chemistry (mg/L)

|    |       |    |       |    |        |    |       |
|----|-------|----|-------|----|--------|----|-------|
| Al | 0.7   | Co | <0.07 | Mn | 0.71   | Si | 3.5   |
| As | <0.05 | Cr | 0.07  | Mo | <0.08  | Sr | 131   |
| B  | 2.82  | Cu | 0.05  | Na | 41,180 | Ti | <0.04 |
| Ba | 15.8  | Fe | 0.47  | Ni | <0.15  | V  | <0.07 |
| Be | <0.03 | K  | 122   | Pb | <0.4   | Zn | <0.02 |
| Ca | 3,540 | Li | 12.1  | Sb | 1.8    | Zr | <0.08 |
| Cd | <0.05 | Mg | 1,550 | Se | <0.7   |    |       |

### Oil Analysis

**Oil sample number** EOR- 02

#### *Sara analysis* (%)

|                        |       |
|------------------------|-------|
| saturated hydrocarbons | 64.27 |
| aromatic hydrocarbons  | 20.93 |
| resins                 | 9.35  |
| asphaltenes            | 5.45  |
| lost*                  | 12.6  |

\*highly volatile compounds and compounds adsorbed by chromatography column

#### *Selected hydrocarbon ratios*

|                                  |       |
|----------------------------------|-------|
| C <sub>17</sub> /C <sub>18</sub> | 1.084 |
| pristane/phytane                 | 1.620 |
| pristane/C <sub>17</sub>         | 1.160 |
| phytane/C <sub>18</sub>          | 1.733 |

## APPENDIX A *continued*

**API Number** 121730128800

**Operator** Ray Brown

**Well Name** Rincker No. 2

**Location** SE SW SE, Section 22, T10N, R5E

**Producing formation** Aux Vases

**Perforations Depth** 1,946–1,958 ft

**Surface Elevation** 641 ft (Kelly bushing)

**Waterflooded** yes

### Brine Analysis

**Brine sample number** EOR-B3

**Temperature (C)** 25°

**Resistivity** 0.0696 ohm-m

**Eh (mV)** -274

**pH** 6.43

#### Anion chemistry (mg/L)

|                               |        |                 |    |
|-------------------------------|--------|-----------------|----|
| Br                            | 180    | I               | NA |
| Cl                            | 65,892 | NH <sub>4</sub> | 24 |
| CO <sub>3</sub> <sup>*</sup>  | NA     | NO <sub>3</sub> | NA |
| HCO <sub>3</sub> <sup>*</sup> | NA     | SO <sub>4</sub> | NA |

<sup>\*</sup>as CaCO<sub>3</sub>

#### Cation chemistry (mg/L)

|    |       |    |       |    |        |    |       |
|----|-------|----|-------|----|--------|----|-------|
| Al | NA    | Co | <0.05 | Mn | 0.53   | Si | 2.66  |
| As | <0.5  | Cr | NA    | Mo | <0.08  | Sr | 144   |
| B  | 4.21  | Cu | NA    | Na | 38,440 | Ti | NA    |
| Ba | 0.75  | Fe | 1.34  | Ni | <0.15  | V  | NA    |
| Be | NA    | K  | 118   | Pb | <0.4   | Zn | <0.02 |
| Ca | 3,140 | Li | NA    | Sb | NA     | Zr | 0.08  |
| Cd | <0.05 | Mg | 1,350 | Se | NA     |    |       |

### Oil Analysis

**Oil sample number** EOR-03

#### *Sara analysis (%)*

saturated hydrocarbons 69.11

aromatic hydrocarbons 21.15

resins 9.04

asphaltenes 0.70

#### *Selected hydrocarbon ratios*

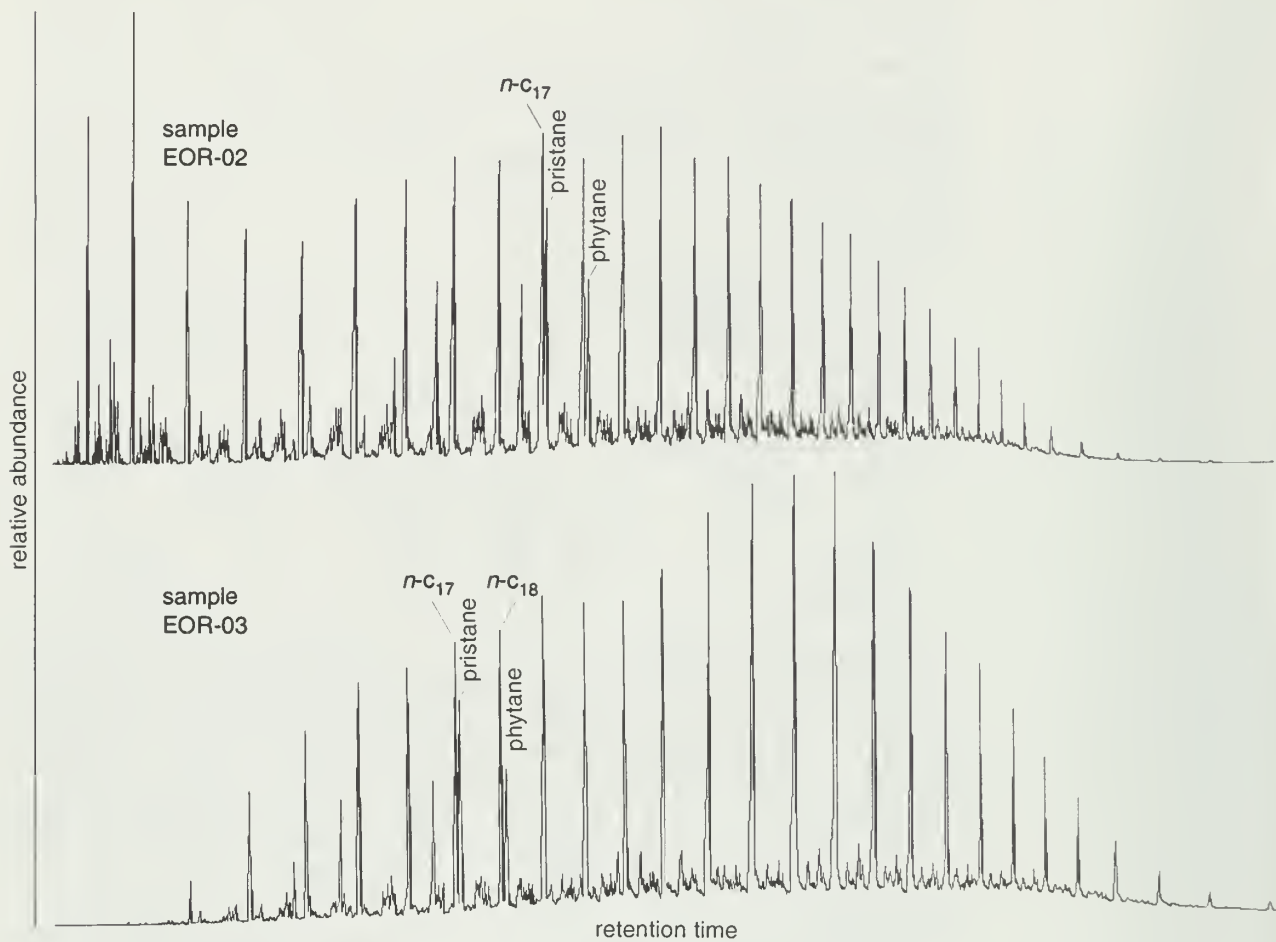
C<sub>17</sub>/C<sub>18</sub> 0.980

pristane/phytane 1.487

pristane/C<sub>17</sub> 1.307

phytane/C<sub>18</sub> 1.984

# APPENDIX B GAS CHROMATOGRAMS OF SATURATED HYDROCARBONS





## APPENDIX C RESERVOIR SUMMARY

**Field** Stewardson

**Location** Shelby County, Illinois; Sections 22 and 27, T10N, R5E

**Tectonic/Regional Setting** intracratonic basin

**Geologic Structure** anticline

**Trap Type** structural–stratigraphic

**Reservoir Drive** gas dissolution

**Original Reservoir Pressure** NA

### Reservoir Rocks

**Age** Mississippian (Valmeyeran/Chesterian)

**Stratigraphic unit** Aux Vases

**Lithology** calcareous quartz arenite

**Wetting characteristics** upper interval, oil-wet; lower interval, water-wet

**Depositional environments** upper interval, subtidal sheet sand complex; lower interval, subtidal sheet sand complex

**Productive facies** upper sandstone

**Petrophysics** ( $\phi$  and  $k$  from unstressed conventional core;  $S_w$  from log)

**Porosity type** intergranular and dissolution

|                           | Average | Range  | Cutoff |
|---------------------------|---------|--------|--------|
| $\phi$                    | 13%     | 10–17% | NA     |
| $k$ air (md)              | 36      | 5–122  | NA     |
| $k$ liquid                | NA      | NA     | NA     |
| $S_w$                     | 41%     | 36–46% | NA     |
| $S_{or}$                  | 28%     | 26–30% | NA     |
| $S_{gr}$                  | NA      | NA     | NA     |
| <b>Cementation factor</b> | NA      | NA     | NA     |

### Source Rocks

**Lithology and stratigraphic unit** New Albany Group

**Time of hydrocarbon maturation** Permo-Triassic

**Time of trap formation:** Valmeyeran/Chesterian

### Aux Vases Reservoir Dimensions

**Depth** 1940–2024 ft

**Areal dimensions** 638 acres

**Productive area** 290 acres

**Number of pay zones** 1

**Hydrocarbon column** unknown; probably 25 ft

**Initial fluid contacts** gas–oil, unknown; oil–water, unknown

**Average net sand thickness** upper interval, 14.5 ft; lower interval, 27.8 ft

**Average gross sand thickness** upper interval, 15.2 ft; lower interval, 30.2 ft

**Net/gross** upper, 14.5/15.2; lower, 27.8/30.2

**Initial reservoir temperature:** 85°F (estimated from logs)

**Fractured** natural, NA; artificial, nitroglycerin induced; hydraulic induced

### Wells

**Spacing** 10-acre primary; none secondary

**Pattern** normal primary with 5-spot injection program

**Total** 34 (24 producers, 0 water source, 0 observation, 0 suspended, 2 injections, 0 disposal, 6 abandoned, 2 dry holes)

## APPENDIX C *continued*

### Reservoir Fluid Properties

#### Hydrocarbons

*Type* oil and gas

*GOR* NA

*API gravity* 35.6° (current); 37.8° (Oct. 24, 1939)

*FVF* 1.10

*Viscosity* 6.8 cp. @ 77°F (current); 4.1 cp @ 100°F (Oct. 24, 1939)

*Bubble-point pressure* NA

#### Formation water

*Resistivity* 0.070 @ 77°F

*Total dissolved solids* 114,835 ppm

### Volumetrics (Aux Vases)

**In place** 5,651,809 BBLS STOOIP

**Cumulative production** 948,300 BO through 1990

#### Ultimate recovery

*Primary* 216,980 BO

*Secondary* 815,120 BO

*Tertiary* NA

**Recovery efficiency** Total 18.3% (better reservoir portion 42.7%)

### Typical Drilling/Completion/Production Practices

**Completions** open hole or cased

**Drilling fluid** freshwater mud

**Fracture treatment** 20–40 quarts of nitroglycerin or 1,500 to 30,000 pound water-sand combination

**Acidization** 100 to 1500 gal. of mud clean-up acid

#### Producing mechanism

*Primary* pump

*Secondary* pump (waterflood)



