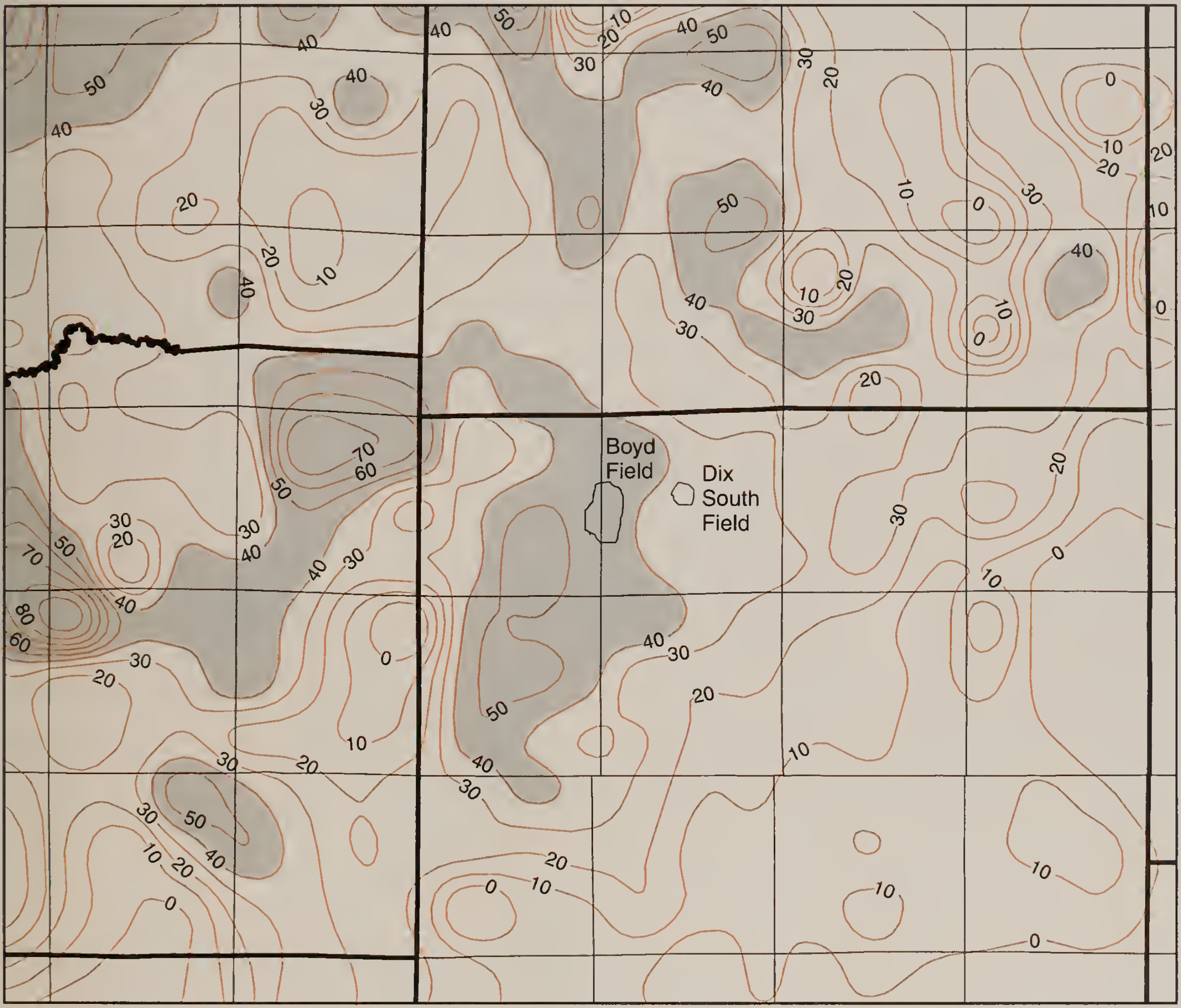
IP 159

# Benoist Sandstone Reservoirs in South-Central Illinois

Hannes E. Leetaru and Kristin Mize



**Illinois Petroleum 159 2003**

Rod R. Blagojevich, Governor

Illinois Department of Natural Resources
Joel Brunsvold, Director

ILLINOIS STATE GEOLOGICAL SURVEY
William W. Shilts, Chief

## Disclaimer

*Cover: Isolith map of the Benoist Sandstone showing the location of Boyd Field and Dix South Field.*

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## Abstract

Boyd and Dix South Fields, located in Jefferson County, Illinois, exemplify the challenges of exploiting and recovering additional oil from Mississippian Benoist sandstone (Yankeetown Sandstone) reservoirs in the Illinois Basin.

The Benoist sandstone in both fields was deposited in a fluvial-deltaic coastal plain as a relatively continuous 40- to 60-foot-thick unit. The reservoir is a subarkose sandstone with a median porosity of 17.5% and a median permeability of 150 millidarcies (md). Three-dimensional modeling shows the reservoir to be stratified into layers of high and low permeability, which may cause premature lateral water breakthroughs during water flooding. Brine underlying oil in the reservoir supplies a partial water drive.

Boyd Field illustrates the problem of trying to recover additional oil from a mature oil field. Boyd Field, located on an anticline with about 27 feet of structural closure, has produced more than 15 million barrels of oil, principally from the Benoist sandstone. The Benoist reservoir at Boyd Field is characterized by abundant vertical fractures that form pathways for water movement. This vertical water movement and previous management practices, such as maximizing flow rates in a vertically fractured reservoir, have resulted in early water coning, which can be a major problem that interferes with oil production. In the 1990s, the Benoist reservoir at Boyd Field was extended south where a separate low-relief structure also produced some oil.

Dix South Field, a small Benoist field, illustrates the difficulty of producing oil from low-relief anticlinal structures. The Benoist sandstone in Dix South Field is similar to the main Boyd Field depositionally and petrologically, but Dix South Field has less than 10 feet of structural relief. Two wells in the field have produced slightly more than 13,000 barrels of oil from the Benoist reservoir sandstone, but the early coning of water and the production of large amounts of water have plagued the field. Therefore, Dix South Field never produced enough oil to be profitable.

Because Illinois has been heavily explored, new Benoist discoveries likely will be on low-relief structures similar to those at Dix South Field and the Boyd Field southern extension. These new discoveries will be uneconomical unless the problem of early water coning can be overcome.

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## Introduction

Since the 1930s, the lower Chesterian (Mississippian) Benoist sandstone has been a significant oil reservoir in southern Illinois. The Benoist is the informal name used by the oil industry in the Illinois Basin for the Yankeetown Sandstone (Willman et al. 1975). There continue to be new, successful infield development wells and outposts to existing fields in this formation.

The two fields, Boyd and Dix South Fields, selected for this detailed reservoir characterization study are located in northwestern Jefferson County, Illinois (fig. 1). At Boyd Field, the original operator, Superior Oil, acquired core from 37 wells drilled in an area of slightly more than 1 square mile. The company measured the permeability and porosity from 1,064 samples from the Benoist reservoir. This abundance of detailed core analyses, which form the basis of our reservoir investigation, is rarely available from a single oil field in Illinois. Most of the 15 million barrels of oil produced at Boyd Field came from the Benoist sandstone. Dix South Field, a much smaller oil field, exemplifies the problems of developing an oil field with low structural relief. Both fields also have produced oil from the

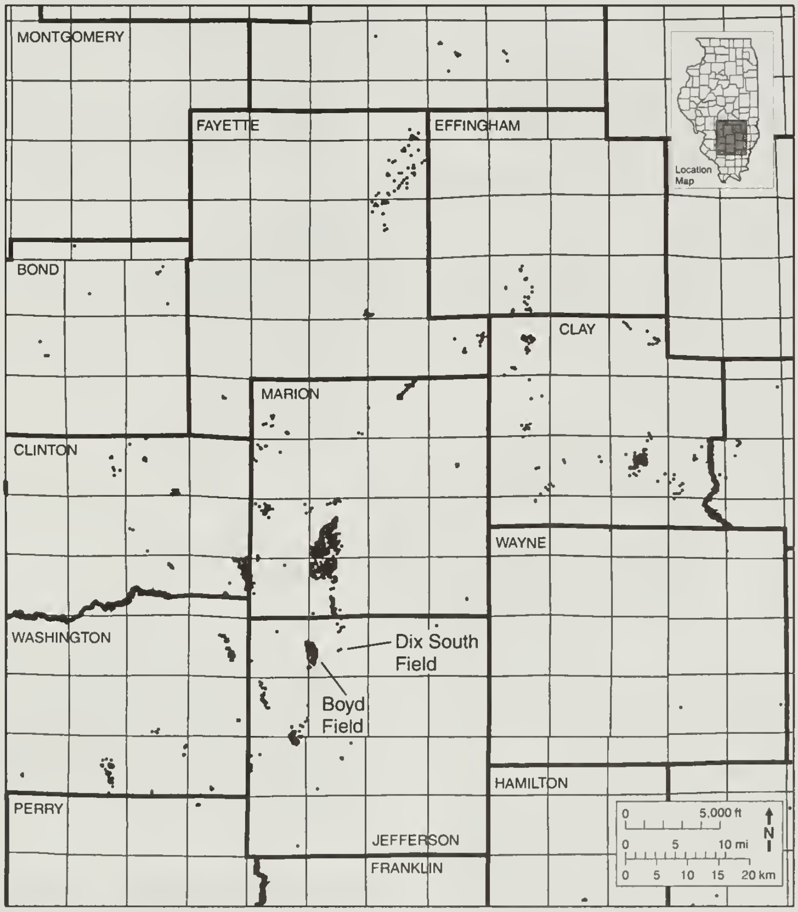


**Figure 1** Regional map showing Benoist producing wells and the locations of Boyd and Dix South Fields.

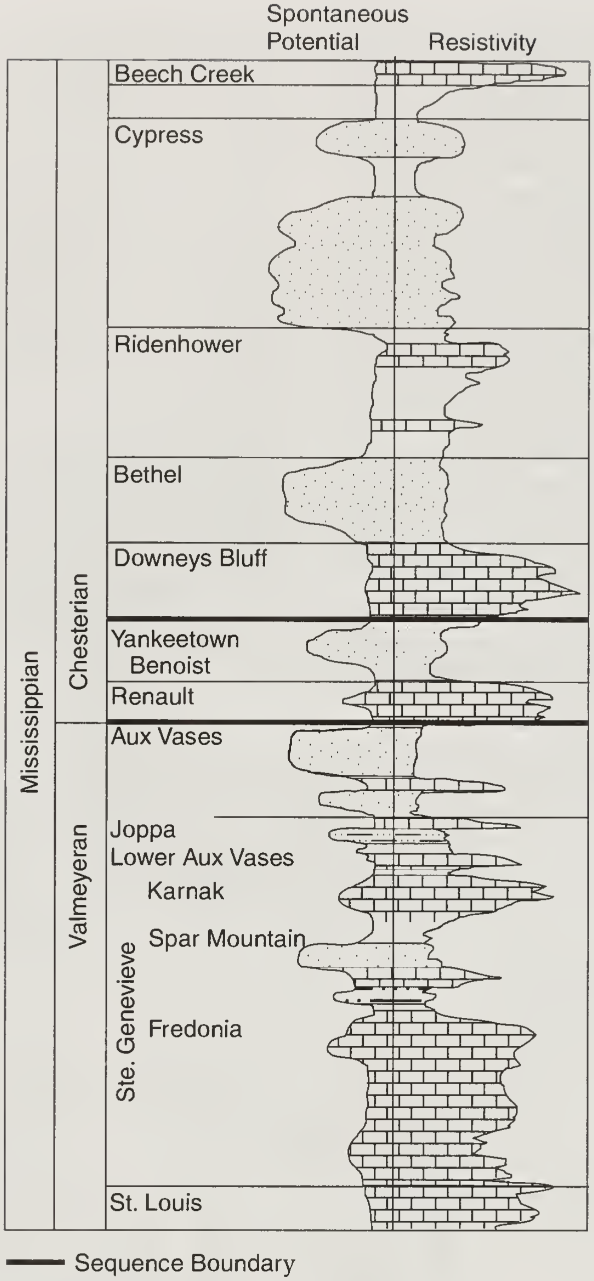


**Figure 2** Stratigraphic column of Mississippian rocks from the Beech Creek Limestone to the St. Louis Limestone for southern Illinois.

Mississippian Renault and Aux Vases Formations and Ordovician Trenton (Galena) Limestone.

This paper is the first detailed reservoir characterization study published for a Benoist sandstone oil field. The Benoist, as illustrated by Boyd and Dix South Fields, has unique problems that have not been observed in the overlying Mississippian Cypress or underlying Aux Vases Sandstone reservoirs. This report focuses on oil production in the Benoist Sandstone and its relationship with facies architecture, reservoir characteristics, and previous reservoir management techniques.

## Regional Geologic Setting

The Benoist sandstone (Yankeetown Sandstone, lower Chesterian Series, Mississsippian System) (fig. 2) is bounded at its top by an unconformity that marks a significant stratigraphic boundary (Leetaru 2000, Nelson et al. 2002). This unconformity surface has been observed along both the outcrop belt and in subsurface cores. There does not appear to be any significant regional unconformity between the Benoist and the underlying Renault Limestone. Across Illinois, the Renault Limestone is a cross-bedded oolitic limestone that ranges in thickness from a few feet to more than 30 feet.

In southern Illinois, the Benoist is commonly overlain by the Downeys Bluff Limestone, a 3- to 15-foot-thick limestone that is characterized by abundant reddish (hematite-stained) crinoidal fragments (Swann 1963). In the area surrounding Boyd and Dix South Fields, the wireline signature of the Downeys Bluff is difficult to correlate because the limestone facies is not present everywhere. The top of the Benoist is commonly characterized by red beds (Swann 1963). In addition, Nelson et al. (2002) identified horizons that resemble paleosols in the uppermost Benoist interval in both core and outcrops along the western margin of the basin.

On wireline logs, the Benoist generally appears to be a relatively massive sandstone, but it may contain localized thin (1- to 3-foot), shale-rich layers that are characterized by a slight negative inflection on spontaneous potential (SP) wireline logs. These shale-rich layers are laterally continuous over small areas and, where present, can separate the Benoist reservoir into an upper and lower unit.

An area of more than 1,300 square miles surrounding the two fields was mapped for this study (fig. 3). Boyd and Dix South Fields occur 10 miles northeast of the bifurcation of the Du Quoin Monocline in Jefferson County, Illinois (fig. 4), in a relatively flat structural area approximately 5 miles from the west branch and 3 miles from the east branch of the Du Quoin Monocline (Nelson 1995).

The regional Benoist sandstone isolith map (fig. 5) shows that the sandstone thins to the southeast,

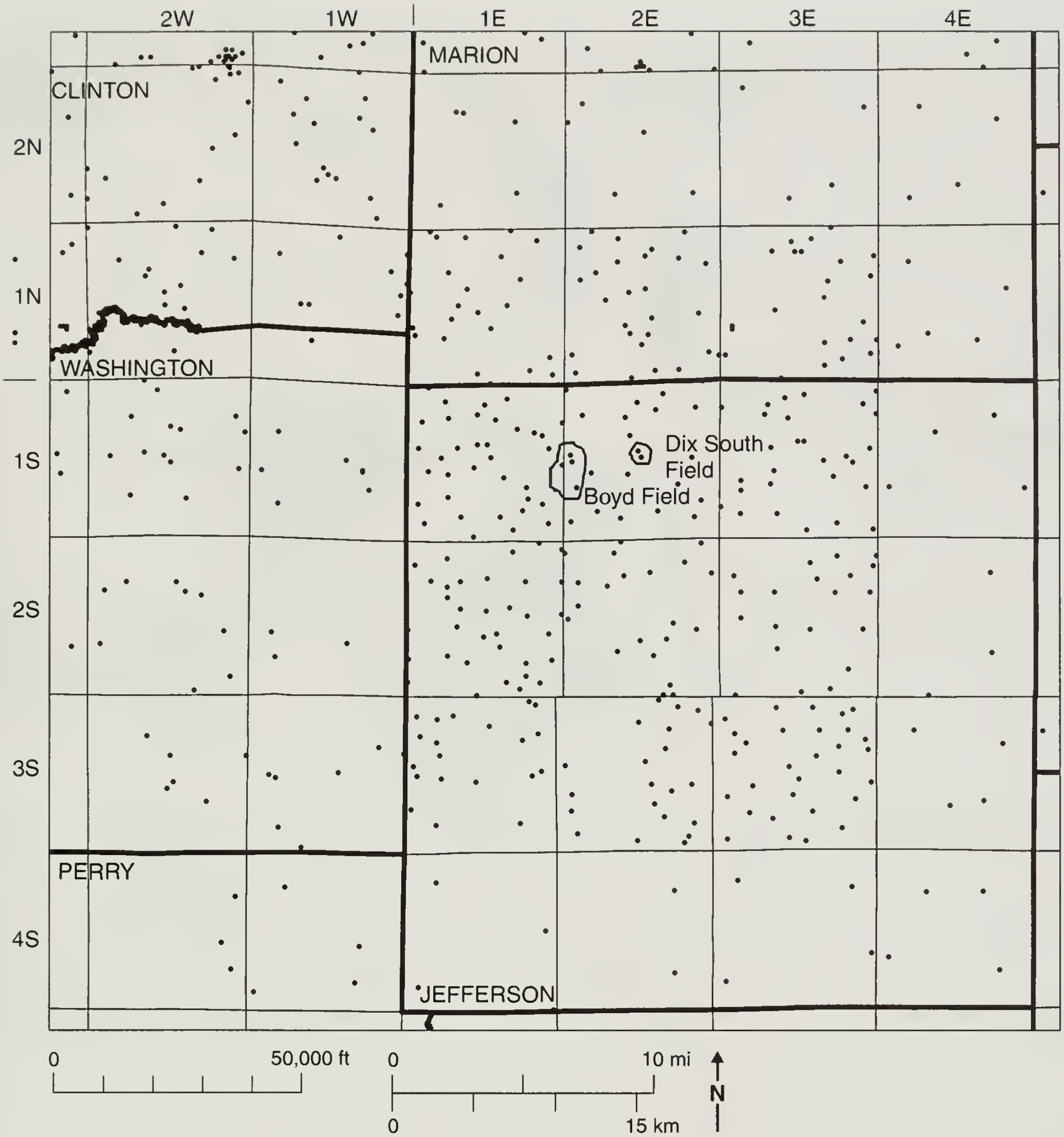


**Figure 3** Map showing locations of wireline logs used in subsurface mapping of the regional structure and sandstone isolith.

and the sandstone body orientation changes from a predominantly north or northwest trend to a northeast to southwest trend at the southern edge of the sandstone facies. The Benoist is interpreted to be a deltaic system with the north-to northwest-trending sandstone bodies deposited in a channel system. The northeast-trending sandstone bodies are interpreted to have been deposited as part of a strandline at the delta's edge. The Benoist sandstone has extensive lateral continuity in the area surrounding Boyd and Dix South Fields (fig. 5). Superior Oil Company workers noticed a drop in initial reservoir pressure as each of the Benoist fields in the surrounding area was discovered in the 1930s and 1940s (Campbell and Rickman Consultants 1954). The company interpreted these successive drops in reservoir pressure as strong evidence that the Benoist sandstone was laterally continuous across the area.

# Boyd Field

## Methodology

The wireline logs for all 115 wells drilled in the field were examined and correlated (fig. 6), but only 35 were digitized and used in the three-dimensional model because of the need for quality data and penetration through the entire Benoist section. In addition, 1,064 permeability and porosity measurements were taken from cores

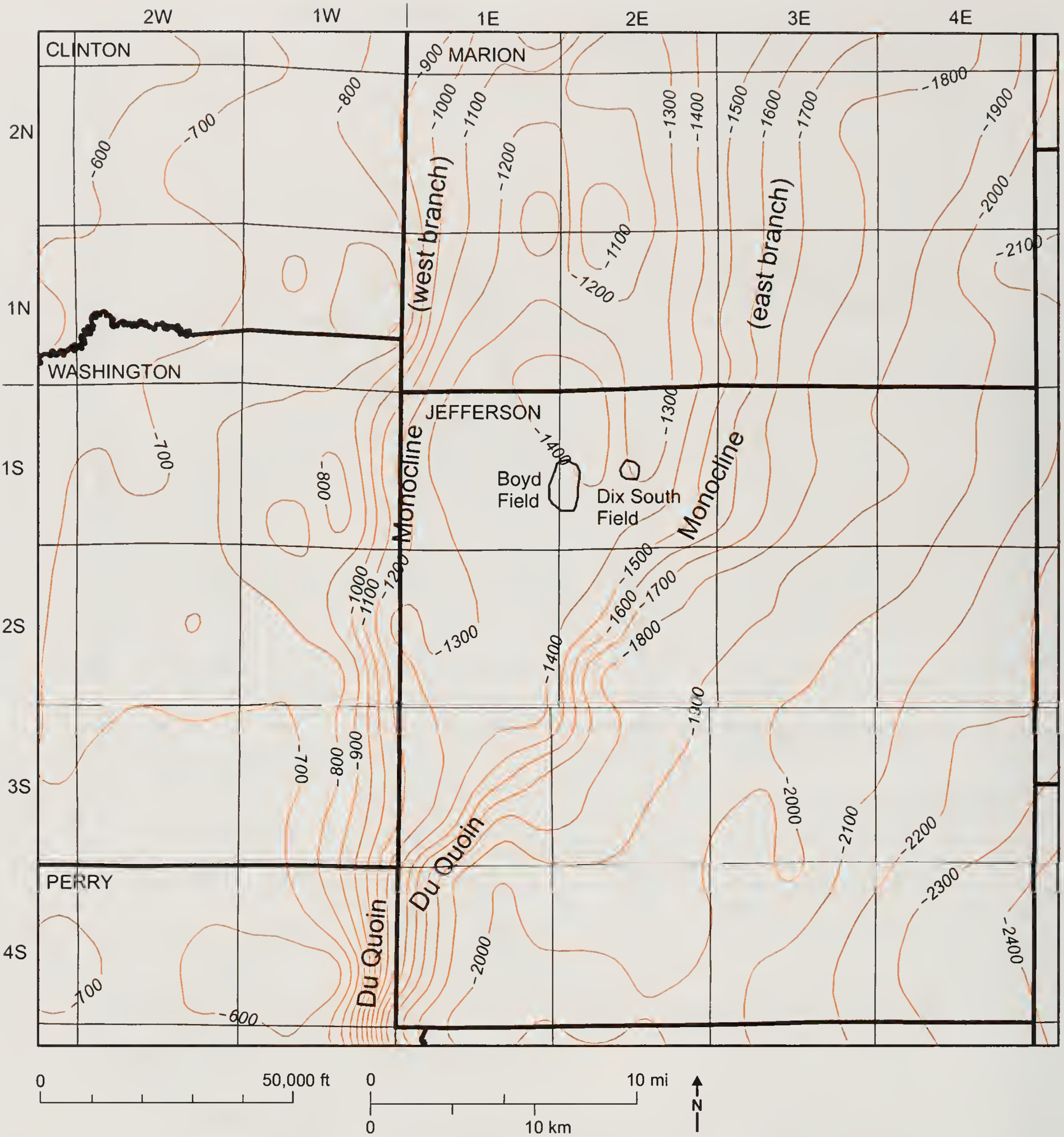


**Figure 4** Regional structure contour map of the top of the Beech Creek Limestone in south-central Illinois. The Du Quoin Monocline bifurcates into westerly and easterly branches in northeast Perry County. Contour interval is 100 feet.

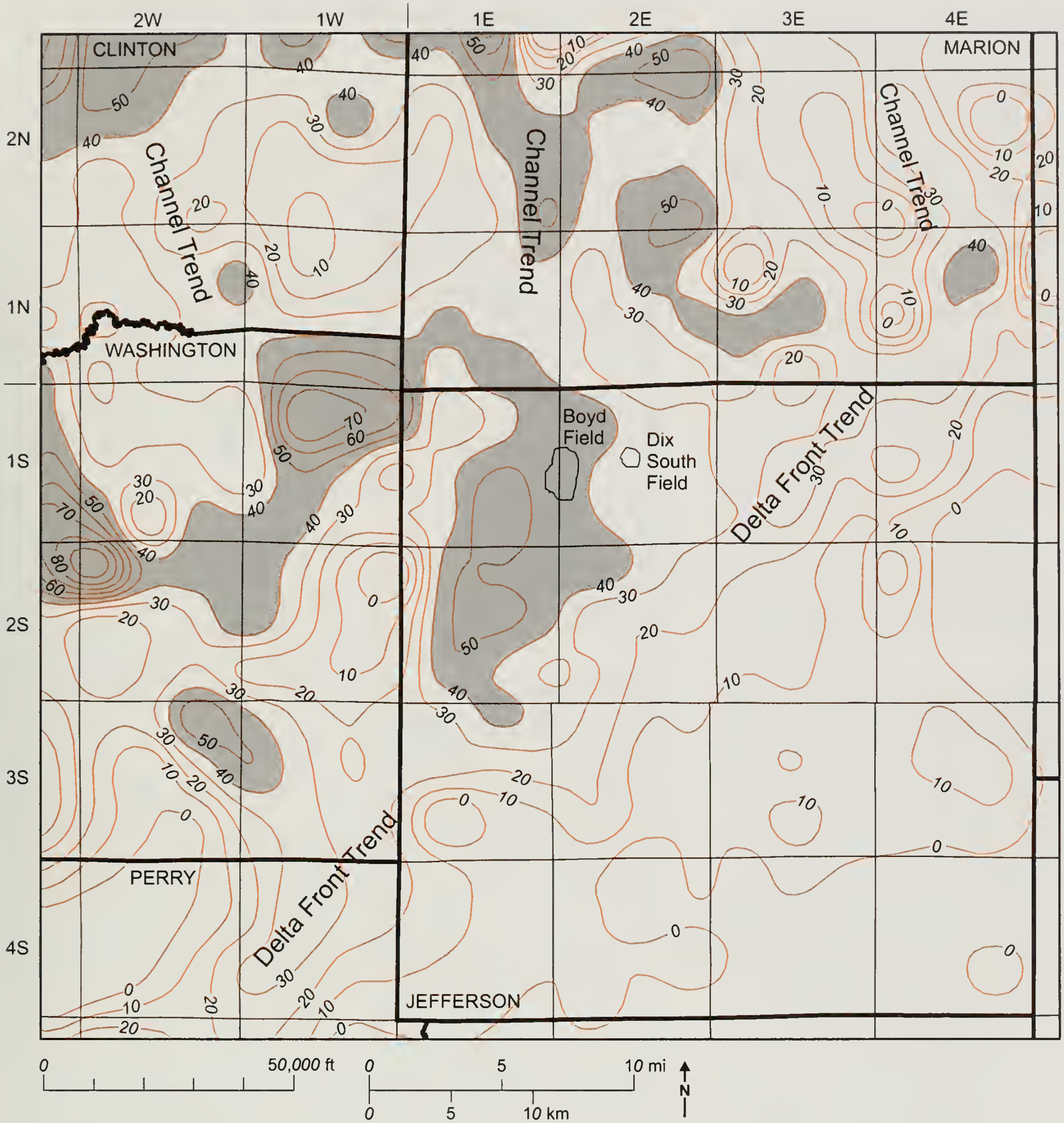


**Figure 5** Isolith map of the Benoist sandstone. The channels are interpreted to be sourced from the north and northwest. The delta front strandline trend occurs at the southeast margin of the sandstone deposition. Contour interval is 10 feet.

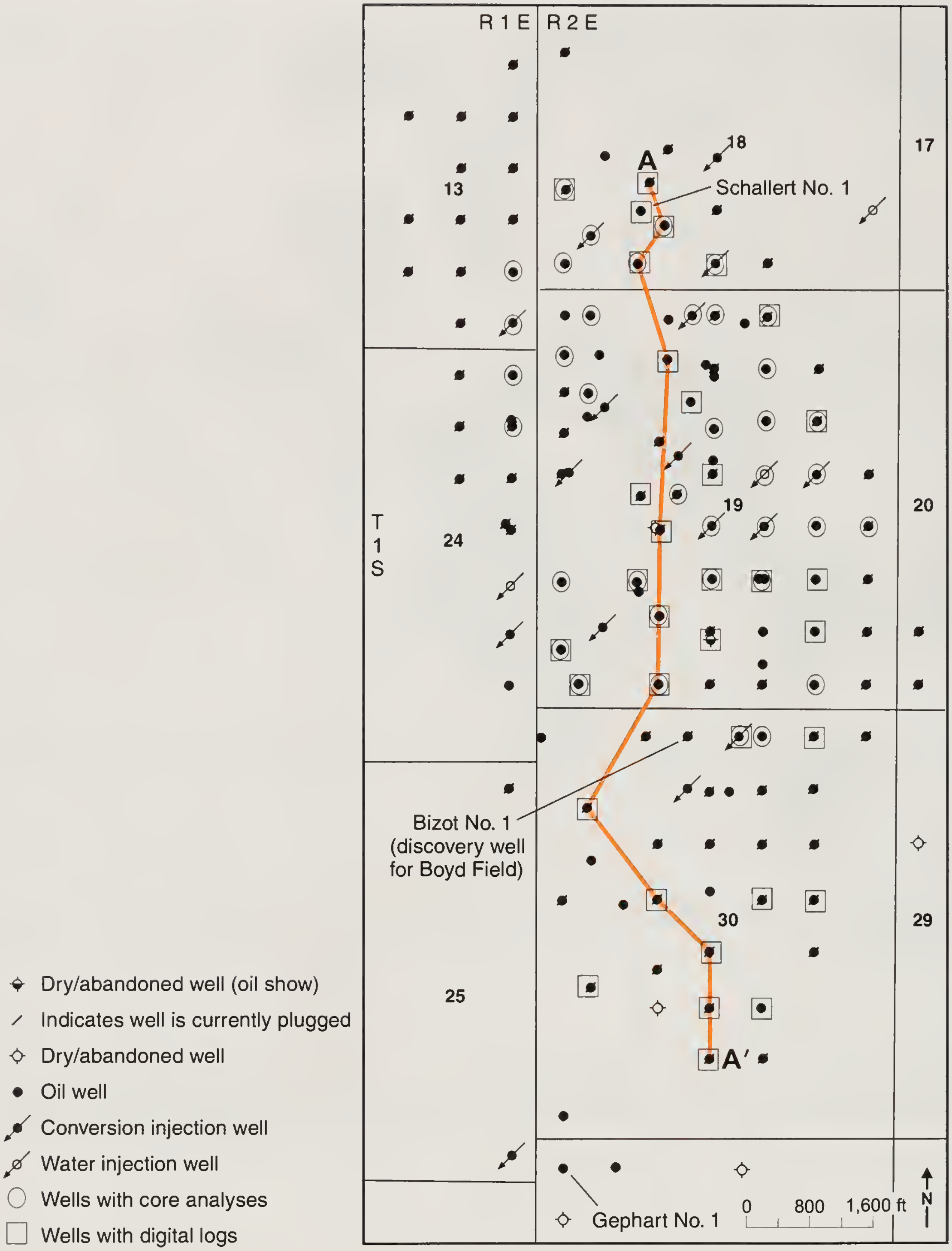


**Figure 6** Base map of the Boyd Field area. The locations of all wells referred to in this report and cross section A–A′ are annotated.

from 37 wells, mostly concentrated near the middle of Boyd Field (fig. 6). These data and additional reservoir engineering and production data were integrated into the reservoir characterization model. The normalization of wireline logs, contouring, and volume modeling were performed with Landmark Graphics Corporation's Petroworks™, Stratworks™, Z-MAP Plus™, and Stratamodel™ software.

Descriptions of sedimentary facies of the Benoist were based primarily on one continuous core from the Superior Oil Company Schallert No. 1 Well (fig. 6). Only biscuit-sized samples were available for the other Benoist cored wells. Those samples were too small to be used for facies analysis.

## Oil Production

Boyd Field was discovered in 1944 by the Cameron Oil Company Bizot No. 1 Well (fig. 6). The majority of the 15 million barrels of oil production in Boyd Field has come from the Benoist, but oil also has been produced from the Mississippian Renault and Aux Vases Formations and the Ordovician Trenton (Galena) Limestone. There have been only 12 completions in the Renault, and none produced significant amounts of oil. The average permeability of the Renault is 46 md. In contrast, the Aux Vases is an important secondary target within the field (Leetaru 1993); the average permeability of the Aux Vases is 240 md, and the average initial production of Aux Vases wells is 100 barrels of oil per day. Production from most Aux Vases wells was commingled with Benoist oil; therefore, the cumulative production from the Aux Vases is not known. Trenton producing wells have average initial production values of 30 barrels of oil per day, and individual wells can ultimately produce about 20,000 barrels of oil.

## Structure and Trapping Style

Boyd Field is 1.25 miles wide and 2.5 miles long and has up to 27 feet of structural closure (fig. 7). The anticlinal closure is observed in multiple horizons from the Ordovician to the younger Mississippian strata. The complexity of the top of the Benoist structure is influenced by structural and stratigraphic factors. For example, the structurally low Area A (fig. 7) directly overlies a shale-rich Aux Vases Sandstone body. Both the east and west sides of this structural low are underlain by thicker and more massive Aux Vases Sandstone bodies. Differential compaction of the shale-rich Aux Vases relative to the adjoining sand-rich Aux Vases areas may have caused the overlying Benoist to sink, forming this structural low. Because of this apparent differential compaction, the Benoist sandstone in Area A has a relatively thin oil column.

The reservoir sandstone underlying and adjacent to the entire producing area of the field varies in thickness from 10 to 35 feet, and the brine in it provides a water drive to the Benoist sandstone. The effective original oil-water contact (subsea) was at –1,542 feet; the top of the transition zone was at –1,530 feet. The subsea depth of the Benoist oil-water contact varied by less than 2 feet in all of the wells.

## Reservoir Characterization

**Depositional Facies** Two depositional facies were observed in the 50-foot core from the Superior Oil Company Schallert No. 1 Well (figs. 6 and 8). The reservoir sandstone is the laminated sandstone facies; the flaser- to lenticular-bedded depositional facies has large amounts of shale that make it a poor reservoir sandstone.

**Laminated Sandstone Facies** The laminated sandstone facies, which is common in the upper Benoist, consists of low-angle, cross-bedded to horizontally laminated sandstone. Alternating layers of finer and coarser sandstone define the laminations. The upper 5 feet of the core from the Shallert No. 1 Well contains 1- to 2-inch-diameter, calcite-cemented nodules in a sandstone with laminae of grayish shale or silt (fig. 9). The density and distribution of these laminae in the Schallert No. 1 Well suggest that the laminae probably could impede vertical fluid flow.

**Shale Facies** In approximately one-third of the wells (fig. 10), a thin, 1- to 2-foot shale or shale-rich interval occurs approximately 10 feet below the top of the Benoist. This shale-rich layer, characterized by a slight decrease in the SP curve values (fig. 10), appears to be discontinuous, but, in local areas of the field, the layer apparently separates the uppermost Benoist sandstone from the rest of the reservoir. In addition, a 5-foot shaley interval locally separates the lower 20 feet of the Benoist from the upper reservoir.

**Flaser- to Lenticular-bedded Sandstone Facies** The flaser- to lenticular-bedded sandstone in the lower part of the Benoist interval in the Schallert No. 1 Well is indicated on wireline logs by a rightward deflection of the SP curve, suggesting sandstone containing large amounts of shale. The facies, which is characterized by its greenish color, grades from flaser-bedded (fig. 11a) at the top to lenticular and wavy-bedded toward the bottom (fig. 11b). Bioturbation, which is common in this facies, was not observed in the upper laminated sandstone facies.

**Environment of Deposition** The flaser, wavy, and lenticular bedding found in the lower part of the Benoist sandstone in the Schallert No. 1 Well is characteristically formed in tidal flat settings (Nio and Yang 1991). The progression from flaser to lenticular bedding generally results from a net decrease in depositional energies, which permits progressively more mud to be deposited. Lenticular bedding is generally found on tidal mud flats, whereas flaser bedding commonly forms in a mixed sand and mud flat environment with greater depositional energy (Dalrymple 1992).

The Benoist reaches a maximum thickness of 64 feet in the center of Section 19 (fig. 12), but it thins to 31 feet in the southeastern part of the field. The thickening and thinning principally occur in the lowermost portion of the unit (fig. 13).

The lateral extent of Boyd Field (2.5 by 1.25 miles) is not large enough to define the orientation of the sandstone bodies; however, the regional isolith map of the Benoist sandstone (fig. 5) suggests that the thicker sandstone

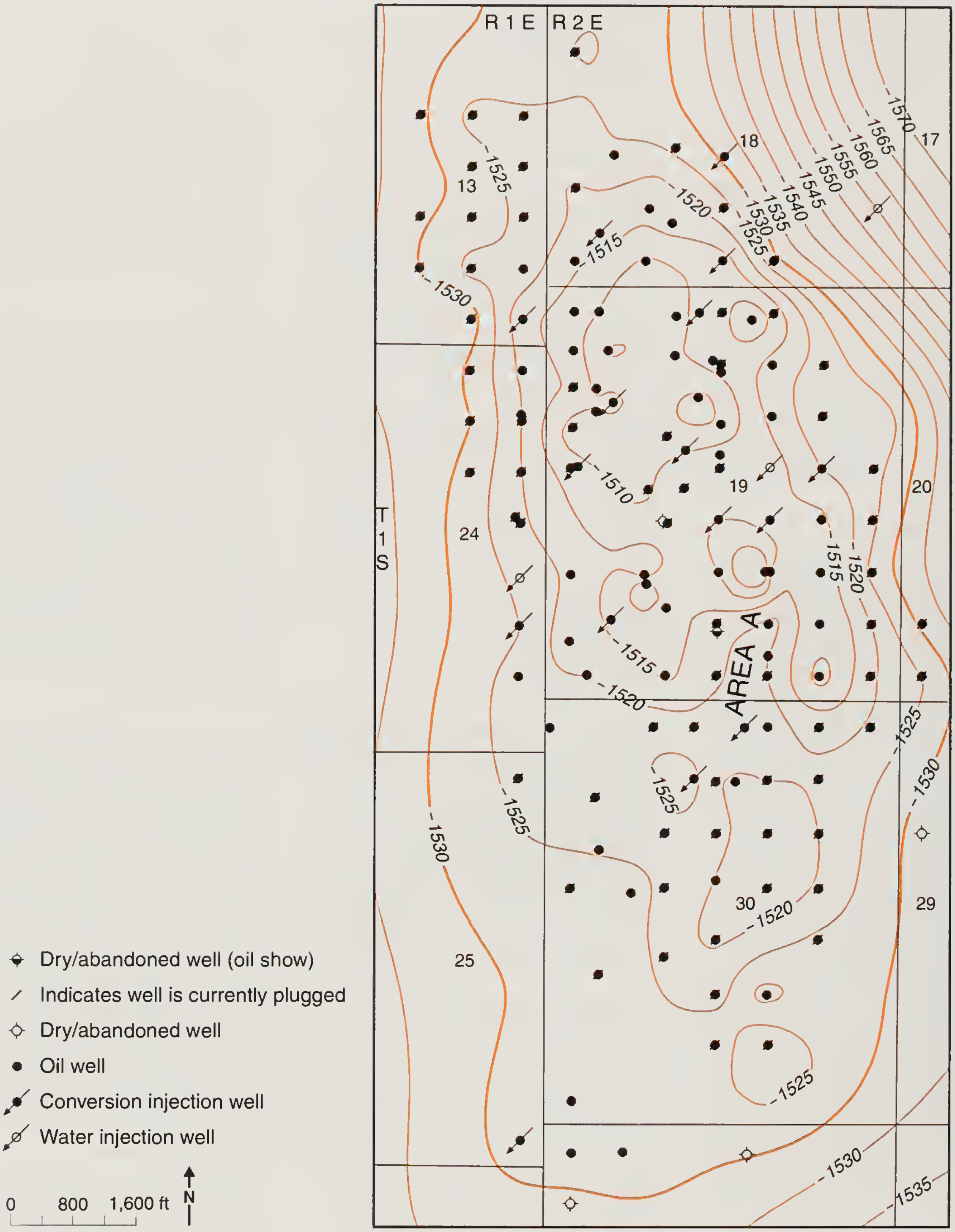


**Figure 7** Structure contour map of the top of the Benoist sandstone at Boyd Field. The subsea depth of −1,530 is the approximate limit of the field. Contour interval is 5 feet.

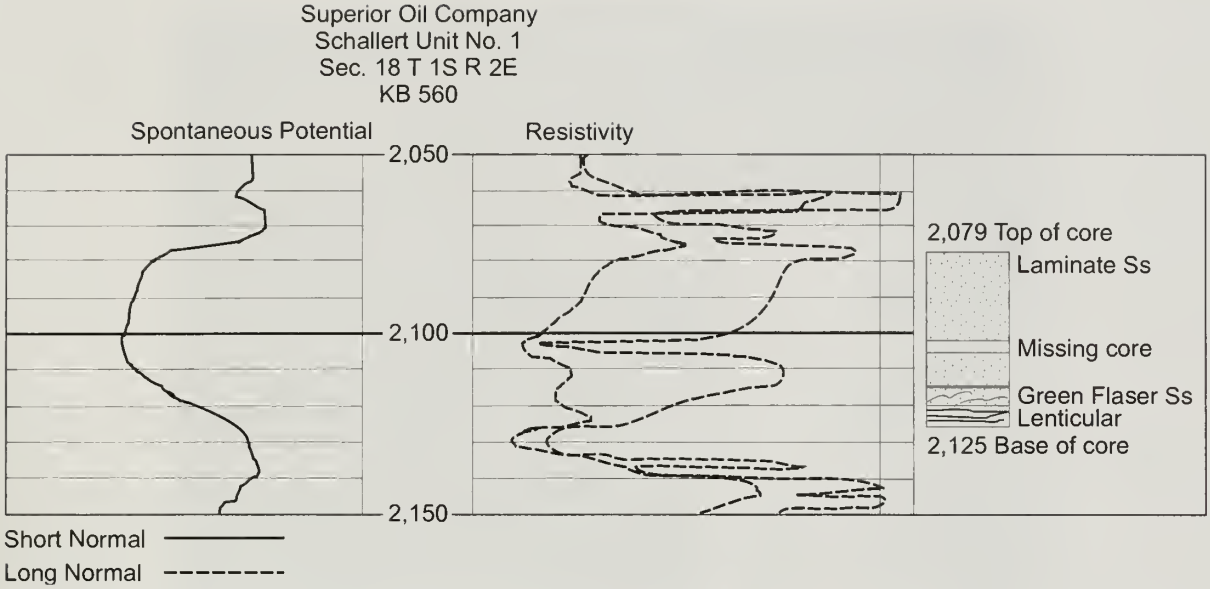


**Figure 8** Wireline log and core description of the Benoist sandstone from the Schallert No. 1 Well in Boyd Field.

**Figure 9** Benoist reservoir sandstone showing shale laminae (arrows) that may impede vertical fluid flow through the reservoir. Superior Oil Company, Shallert No. 1 Well, 2,082 feet.

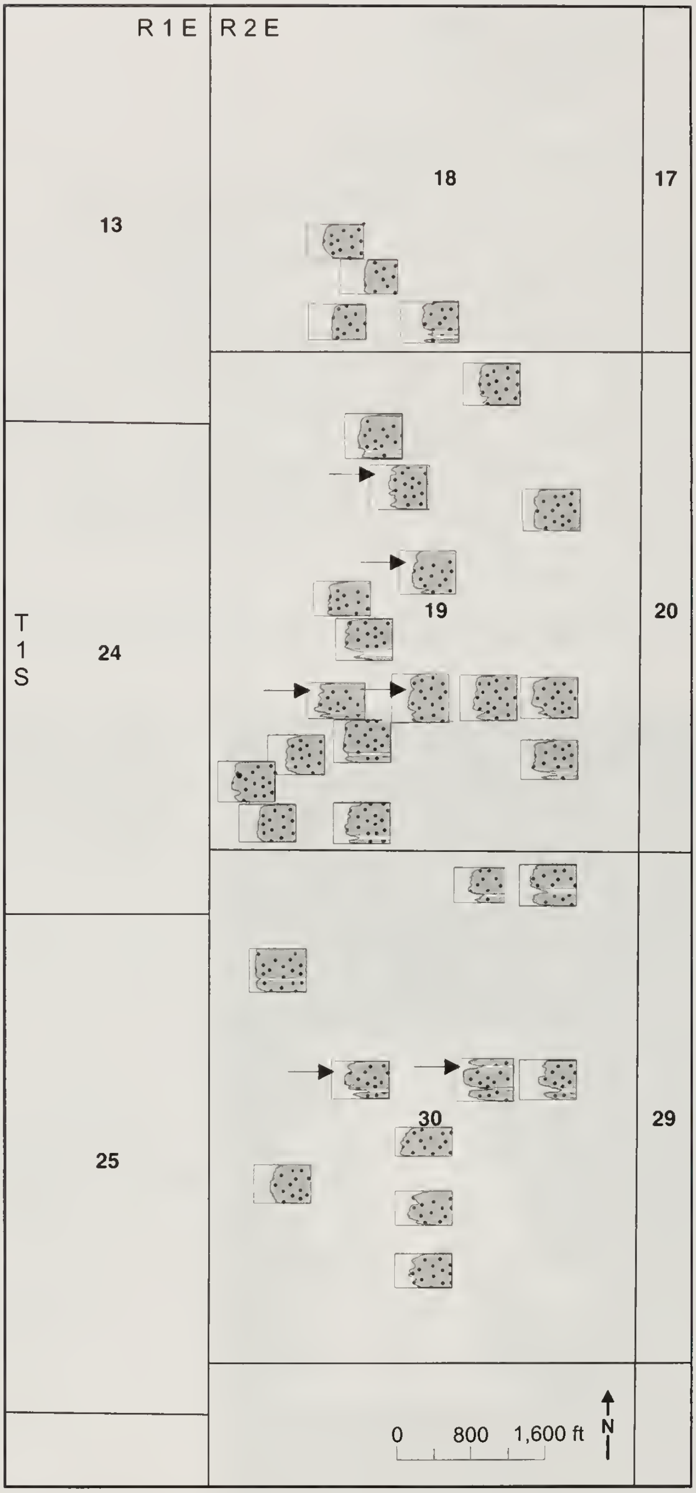


**Figure 10** Areal distribution of characteristics of spontaneous potential wireline curves at selected wells at Boyd Field. The arrows point to a thin correlative shale layer that appears to compartmentalize the reservoir into upper and lower units in some localized areas of the field.

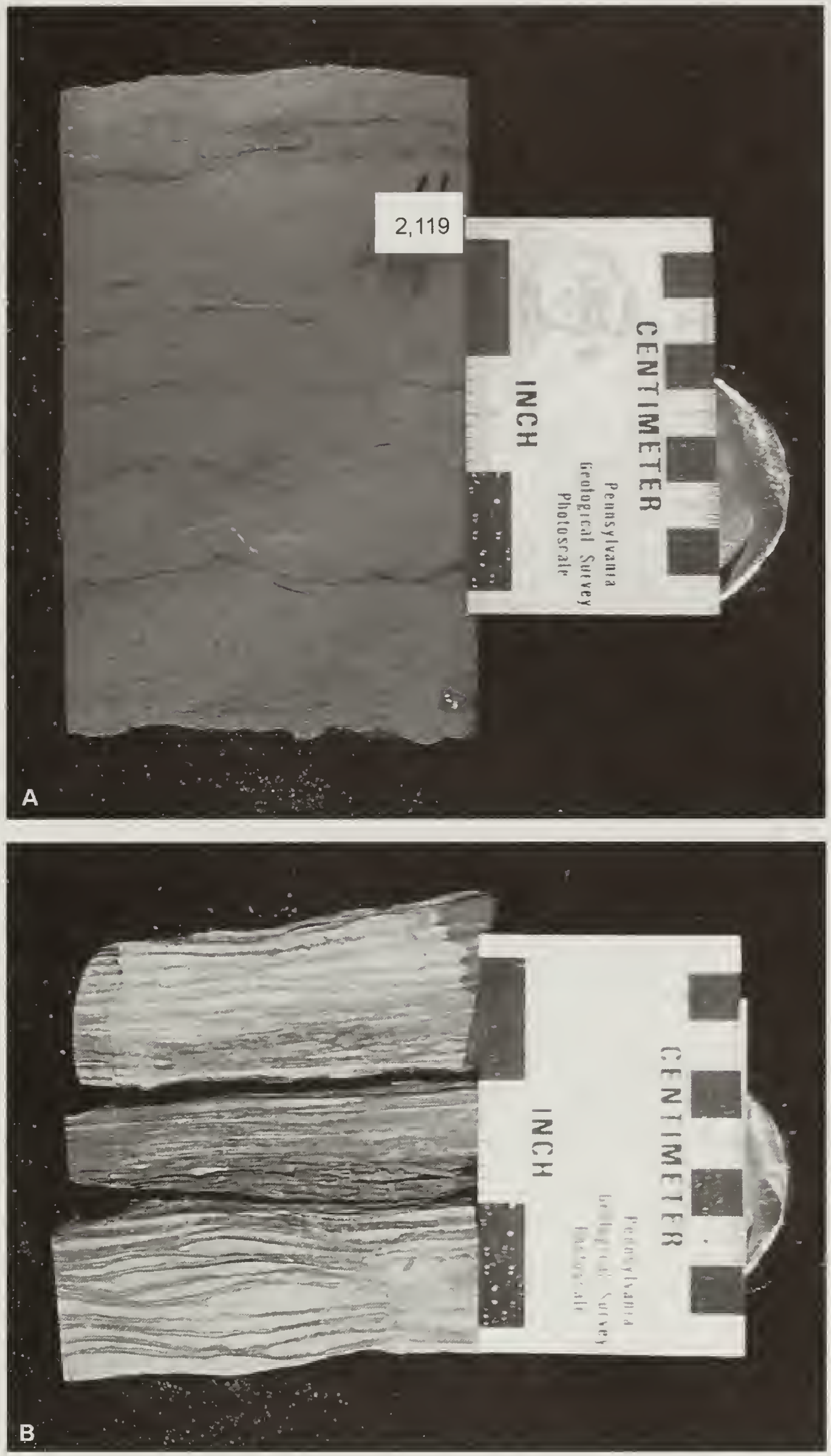


**Figure 11** (a) Core of the Benoist sandstone showing flaser-bedded sandstone from the Superior Oil Company's Shallert No. 1 Well, 2,119 feet. (b) Core of the Benoist showing lenticular and wavy beds, both of which are characteristic of tidally influenced depositional systems. Superior Oil Company, Shallert No. 1 Well, 2,120 feet.

**Figure 12** Thickness map of the Benoist sandstone at Boyd Field. Contour interval is 5 feet.

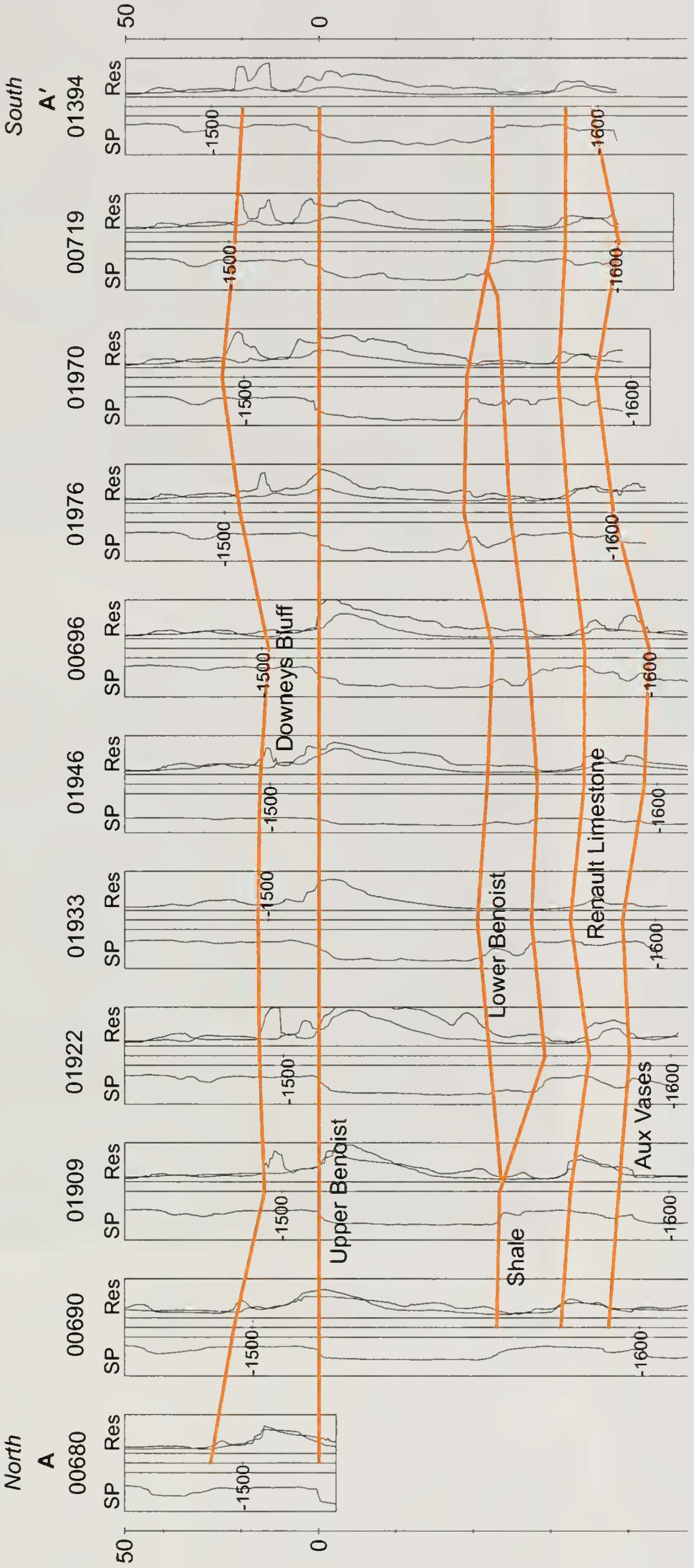


**Figure 13** Cross section A–A′ showing the thickening and thinning of the Benoist interval. The line of cross section is shown in figure 6.

bodies are elongated along a north or northwest trend.

The regional Benoist sandstone isolith map shows two sandstone body orientations that are nearly perpendicular to each other (fig. 5), a series of distributary channels oriented nearly north or northwest, and a delta front oriented northeast to southwest. Additional in-progress mapping shows that the north- to northwest-oriented sandstone bodies continue for more than 60 miles to the north of Boyd Field. Based on regional mapping, these northerly sourced sandstone bodies are interpreted to be distributary channels in a deltaic system. The northeast to southwest orientation of the sandstone bodies near the southern limit of the Benoist suggests that they were deposited as delta front or mouth bar sandstones formed by shoreline processes at the southeastern distal limit of the Benoist delta. Boyd and Dix South Fields occur where the two trends appear to coalesce. The result is a depositional system that reflects both channel and shoreline processes.

Swann (1963) interpreted all of the Chesterian sandstones to have a northeastern source, which he referred to as the Michigan River, but Nelson et al. (2002) and this study do not support a northeastern source for the Benoist sandstone. The paleosols found in the uppermost Benoist (Nelson et al. 2002) and the northerly to northwesterly orientation of the Benoist sandstone bodies suggest that Swann's Michigan River model may not be valid for the Benoist. The source of the Benoist sandstone appears to be similar to the Aux Vases Sandstone, which was sourced from either the Ozark Dome or the Transcontinental Arch, or both (Leetaru 2000, Nelson et al. 2002).

The laminated sandstone facies, which constitutes most of the upper Benoist, by itself is not diagnostic of any particular environment. The best evidence indicating the Benoist was deposited as channel sandstones is the elongation of the sandstone bodies and the character of the SP wireline logs. In the majority of wells in the field, either the SP curve through the reservoir sandstone has a blocky character or the amount of rightward deflection of the SP curve increases slightly from the base to the top of the sandstone. In a sandstone, rightward deflections of the SP curve are commonly found in upward-fining successions (increasing amounts of shale). Although not unequivocal, the upward fining of strata is characteristic of an environment where energy wanes, such as when fluvial or tidal channels are gradually abandoned (Posamentier and Allen 1999). On cross section A–A´, the base of the

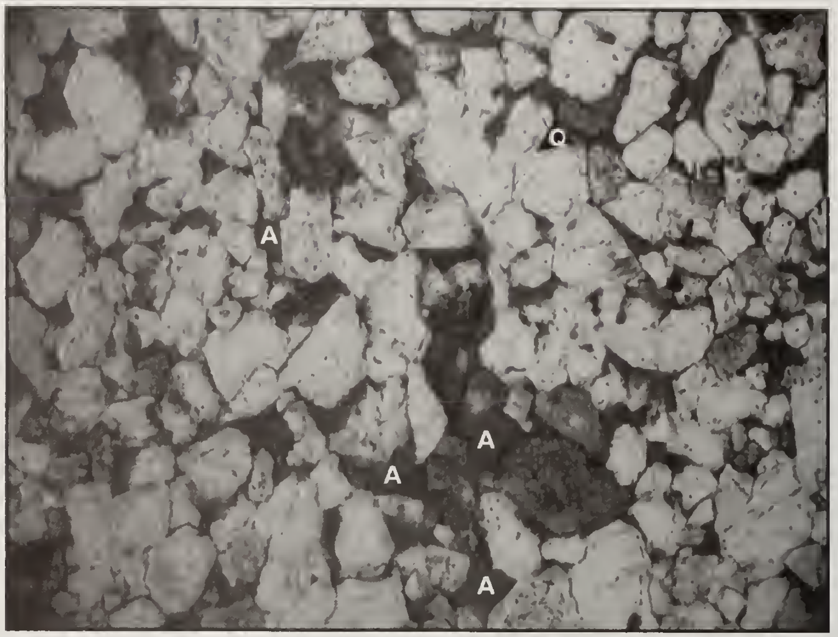


**Figure 14** Photomicrograph of the Benoist sandstone showing the abundant secondary porosity (A) and silica cement in the form of quartz overgrowths (Q). Superior Oil Company, Shallert No. 1 Well, 2,124 feet.

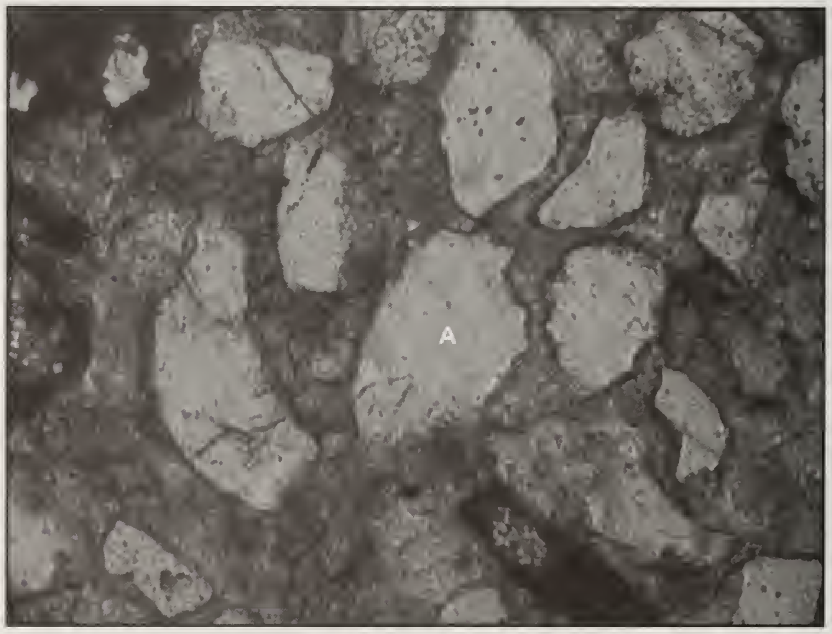


**Figure 15** Photomicrograph of the Benoist sandstone at Boyd Field showing pervasive calcite cement. Individual quartz grains (A) are extensively corroded and embayed. Superior Oil Company, Shallert No. 1 Well, 2,082 feet.

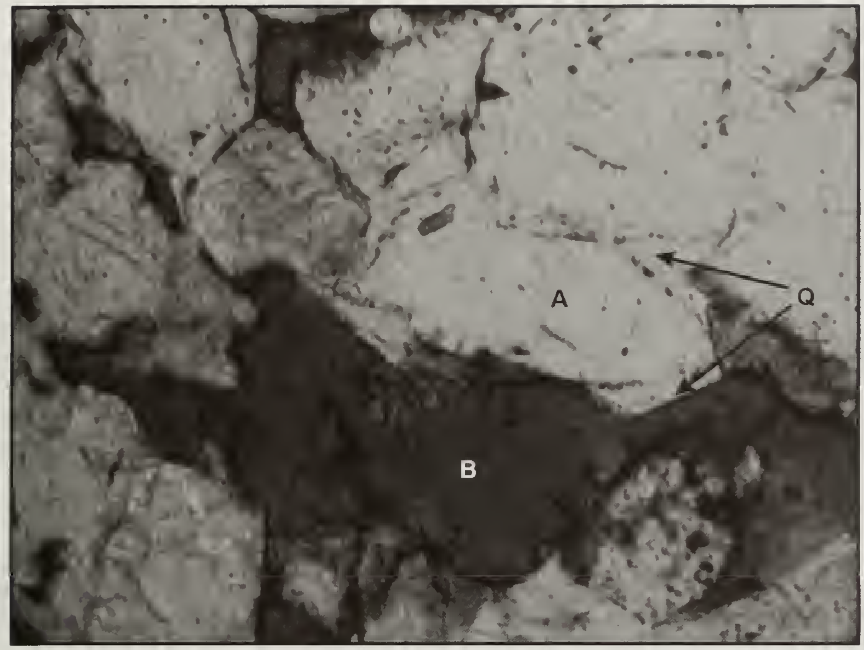


**Figure 16** Photomicrograph of the Benoist sandstone in Boyd Field showing abundant silica cementation in the form of quartz overgrowths (Q). Clay rim cement coats the original grain (A). Some of the porosity still has the outline of a former feldspar grain (B). Superior Oil Company, Shallert No. 1 Well, 2,124 feet.

**Table 1** Summary of data obtained by Superior Oil's tests of core and reservoir fluids from Boyd Field.

| Category | Measurement |
|---|---|
| Average permeability to air (md, corrected for Kinkenberg effect) | 209 |
| Average permeability to brine (md, Boyd-produced water) | 187 |
| Average permeability to fresh water (md) | 173 |
| Residual oil saturation (%) | |
| Irreducible minimum | 18.7 |
| At approximately 5 pore volumes | 27.7 |
| API[1] oil gravity at 60°F | 39.5 |
| Oil viscosity at 90°F reservoir temperature (centipoise) | 3.2 |
| Formation volume factor at saturation pressure of 331 psi and 94°F | 1.069 |

[1] API, American Petroleum Institute.

Benoist sandstone appears to be scoured into the underlying shales (fig. 13).

**Petrography** The Benoist sandstone is primarily a medium-grained quartz arenite. Some samples contain as much as 5% potassium feldspar grains and up to 2% polycrystalline lithic grains composed of chert. The original quartz grains were subrounded to subangular, but these grains subsequently have been altered by the addition of quartz overgrowths that form a syntaxial rim cement (fig. 14). The quartz overgrowths can clearly be distinguished from the original grains by the presence of thin "dust lines" and the angular nature of the grain to grain or pore contacts. The overgrowth faces in open pores commonly form 120° angles with each other.

Calcite cement was not common in the studied thin sections. The sole example was from a concretion where a large poikilotopic patch of calcite encloses many quartz grains (fig. 15). The individual quartz grains appear to be floating within the calcite cement. The quartz grains have irregular embayments indicative of etching or corrosion. Such corrosion is a common feature of calcite cementation and is found in many other sandstones (Carozzi 1993).

The porosity in the Benoist reservoir facies is both primary and secondary (formed by dissolution) (fig. 16). The evidence for secondary porosity includes (1) oversized pores that generally are the same size as the individual grains in the matrix, and (2) about 10% of the porosity that is contained in partially degraded feldspar grains (fig. 16). Many of these degraded feldspar grains have abundant micropores that do not contain recoverable hydrocarbons. Based on the volume of secondary pores and the remaining feldspar, the original sandstone, before diagenetic alteration, may have contained as much as 10% feldspar.

A petrographic comparison of the underlying Aux Vases Sandstone (Leetaru 1993) with the Benoist shows the Aux Vases to have significantly more calcite cement. The quartz overgrowths that are common in the Benoist are also typical of the overlying Cypress Sandstone (Grube 1992).

## Production Characteristics

At Boyd Field, several well completion methods were used to produce from the Benoist sandstone. Many of the wells were completed open hole, but some were artificially fractured using between 5 and 20 quarts of nitroglycerine. Nitroglycerine fracturing enhanced the production from this sandstone, but had the unintended side effect of allowing fluid communication with the underlying Aux Vases Sandstone reservoir (Leetaru 1993).

During the late 1940s and early 1950s, Superior Oil's research center at Rio Bravo, California, conducted extensive testing on core and reservoir fluids from Boyd Field (Campbell and Rickman Consultants 1954). Table 1 summarizes the data from the study. Only the results of the Superior Oil Company's research are available. The methodologies they used cannot be compared with modern methods.

The Benoist reservoir at Boyd Field has a partial water drive. As is typical of water drive reservoirs, a brine-saturated reservoir sandstone underlies the productive oil interval in every well in the field. However, the steep drop in reservoir pressure during the first two years of production (fig. 17) suggests that solution gas expansion may have contributed to the reservoir drive mechanism. During this two-year period, the Benoist reservoir produced more than a million barrels of oil. A strong water drive should have allowed for production with minimal pressure drops at the well bore (Hartmann and Beaumont 1999). Pressure began to stabilize after the initial steep drop because of the re-injection of produced water back into the reservoir sandstone. By 1958, more than 25 million barrels of water had been reinjected into the reservoir.

Wireline log measurements of the Benoist reservoir commonly indicate a reservoir resistivity of 30 ohm-m in the oil-productive intervals. Resistivity curves from the field show the oil-water transition zone to be approximately 10 to 15 feet thick. The original oil-water contact was at –1,542 feet. The elevation of the original oil-water contact rose by more than 1 foot per year for the first 10 years (fig. 18). Wells drilled in the 1990s show the remaining oil column in the field to be only a few feet thick. The transition zone contains water and oil and produces both in a production test. Capillary pressure curves are used to compare fluid saturations of different rock types at selected heights above the oil-water contact. The Benoist sandstone saturation profile from capillary pressure analysis reveals a 12-foot transition zone (fig. 19). The capillary pressure curve also indicates that the range of pore throat dimensions is relatively narrow. For comparison, a reservoir rock with a broader distribution of pore throat dimensions would have a slope above the transition zone approaching 45° (Vavra et al. 1992). Rocks with well-sorted pore throat distributions generally have a high oil-recovery efficiency (Vavra et al. 1992).

The total original oil in place for Boyd Field for the producing horizons in the Benoist, Aux Vases, and Trenton is estimated to be slightly more than 29 million barrels of oil. To date, the field has produced 15 million barrels of oil

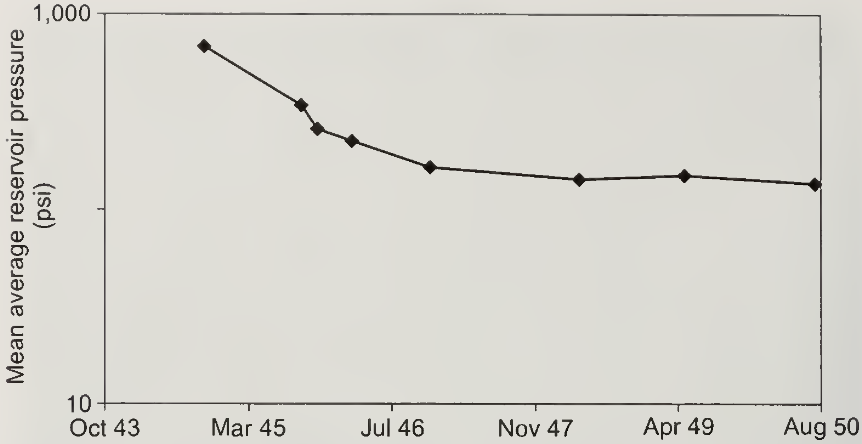


**Figure 17** Pressure history of the Benoist reservoir at Boyd Field. The early steep decline in pressures suggests that some of the initial drive may have come from expansion of solution gas.

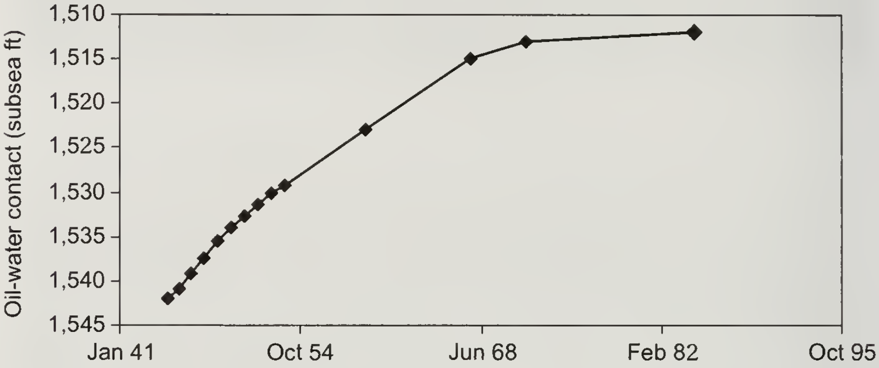


**Figure 18** Change in the elevation of the oil-water contact over time in the Benoist sandstone reservoir. The graph stops at 1984 because thereafter the oil-water contact becomes increasing difficult to identify for the field in general. By the 1990s, there were only 1 to 3 feet of oil column left in the most productive parts of the field.

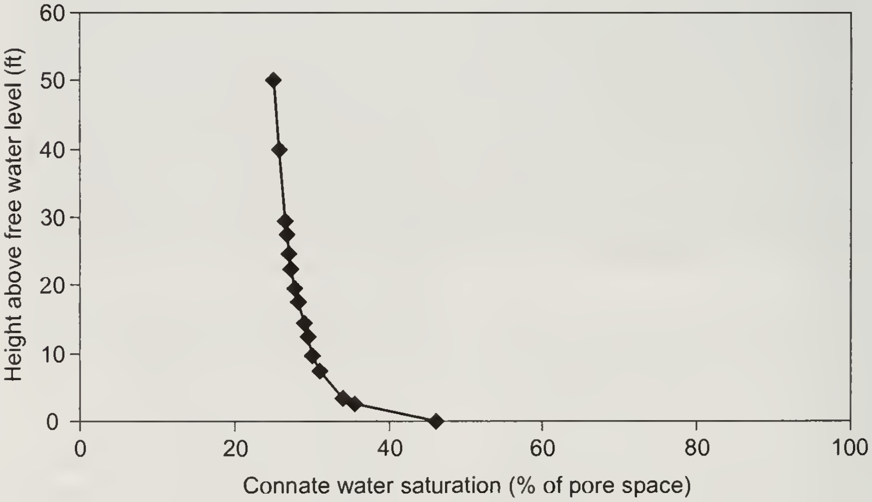


**Figure 19** Mercury injection capillary pressure curve for the Benoist sandstone reservoir. The graph shows the connate water saturation of the reservoir sandstone at various heights above the oil-water contact. The steep curve indicates little variation in pore throat diameters.

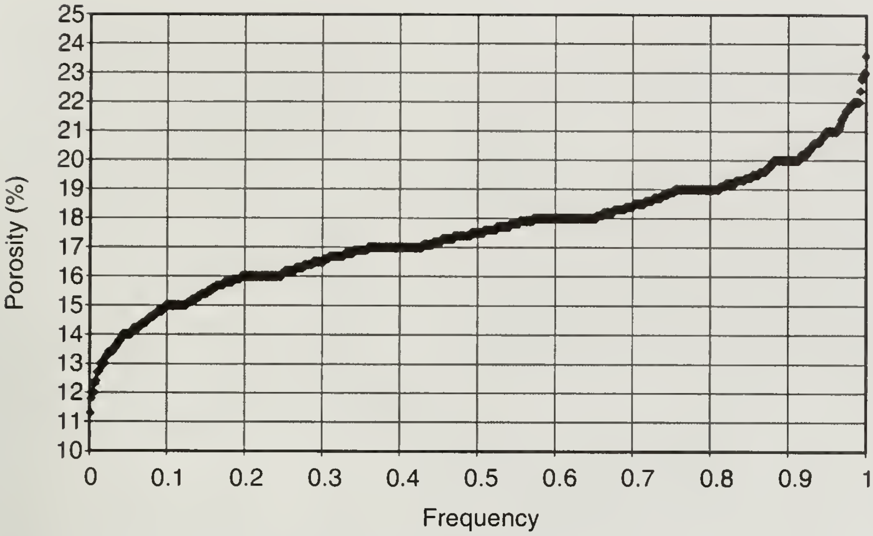


**Figure 20** Cumulative distribution of core porosities of the Benoist sandstone at Boyd Field. The curve is based on 967 analyses.

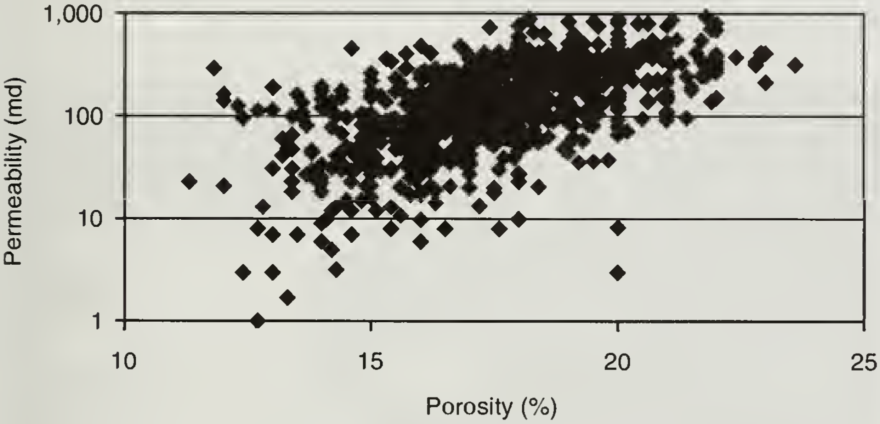


**Figure 21** Cross plot of the permeability versus porosity of the Benoist sandstone from core measurements at Boyd Field.

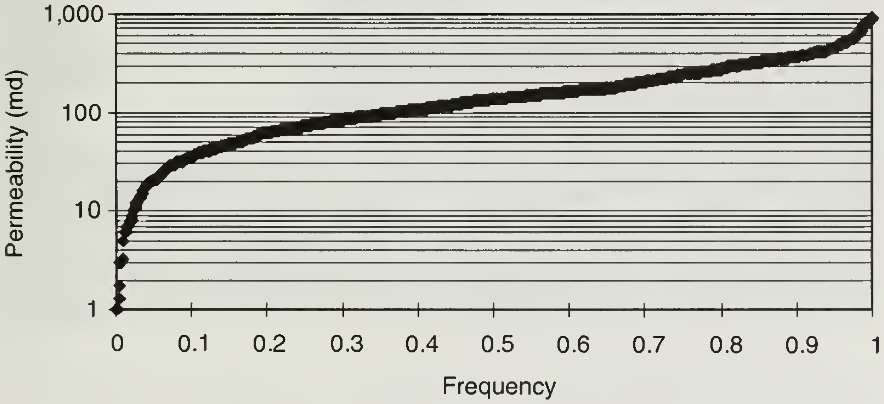


**Figure 22** Cumulative distribution of measured permeabilities of the Benoist sandstone from cores at Boyd Field. The curve is based on 1,064 analyses.

and, therefore, has recovered 52% of the original oil in place.

Based on the measurements made on core samples, the Benoist sandstone reservoir rock in an average well at Boyd Field has a median porosity of 17.5%; the range is 11.5 to 23.5% (fig. 20). There is a logarithmic relationship between porosity and permeability (fig. 21). The average horizontal permeability to air for the Benoist sandstone at Boyd Field is 150 md. Eighty percent of the core permeability measurements falls between 35 and 300 md (fig. 22). In most samples, the horizontal permeability was greater than the vertical permeability. Horizontal permeability measurements were expected to be greater than vertical measurements because the horizontal shale laminations present in the Benoist were expected to impede vertical fluid flow. However, almost 30% of the samples had a vertical permeability that was greater than the horizontal permeability (fig. 23). In addition, multiple vertical fractures of up to 1 foot in length were observed in the core from the Shallert No. 1 Well (fig. 24). Some of the fractures observed in the core had minor amounts of calcite cement, suggesting partial healing. The presence of these vertical fractures helps to explain the otherwise unexpected relationships between vertical and horizontal permeability.

The presence of vertical fractures within the Benoist reservoir could also help to explain the prevalence of water coning, which occurs when water prematurely enters a production well. The problem of coning was recognized early in the productive life of Boyd Field. The Benoist wells within the field had an initial period of high oil production and then a rapid increase in water production. According to engineering studies done in the 1950s (Campbell and Rickman Consultants 1954), the greatest problem in completing wells from the Benoist reservoir was avoiding the coned water from the underlying water layer. All of the wells in the field experienced severe coning, and the disposal of this extra water added significantly to the cost of operating Boyd Field.

## Three-dimensional Reservoir Architecture

The two-dimensional map of the Benoist sandstone thickness does not adequately show the heterogeneity of the Benoist reservoir (fig. 12). Therefore, a three-dimensional model of the lateral and vertical changes in the normalized SP, resistivity, permeability, and porosity of the Benoist reservoir was constructed using Landmark Corporation's Stratamodel™ program. This three-dimensional model revealed the complexity of the reservoir architecture.

The SP curve cannot be quantitatively compared among wells because each well's SP curve is a relative measurement that varies depending on the wireline logging operator and the salinity of the water in the borehole and the formation. The standard method for normalizing SP curves for quantitative comparison is to define a constant shale line for the right edge of the scale and a clean sandstone line for the left edge of the scale. A clean sandstone contains only a small amount of clay minerals and therefore has the greatest SP deflection. The normalized SP values are relative to the clean sandstone and shale value on the wireline log. The normalized SP curve is one approximation of the volume of shale ($V_{shale}$) measurement (fig. 25).

Because 80% of the sandstone samples have permeabilities greater than 70 md (fig. 22), and because the SP log does not appear to differentiate excellent reservoir facies (greater than 200 md) from good reservoir facies (less than 200 md but greater than 50 md), the relationship is weak between permeability and SP values on wireline logs (fig. 26).

This lack of sensitivity in the testing methods is important because the three-dimensional modeling study showed three high-permeability intervals (greater than 200 md from core measurements) in Boyd Field that are not resolvable with the SP wireline log (fig. 27). The available evidence indicates that, although these horizontal flow units are laterally continuous between wells in the field, they are

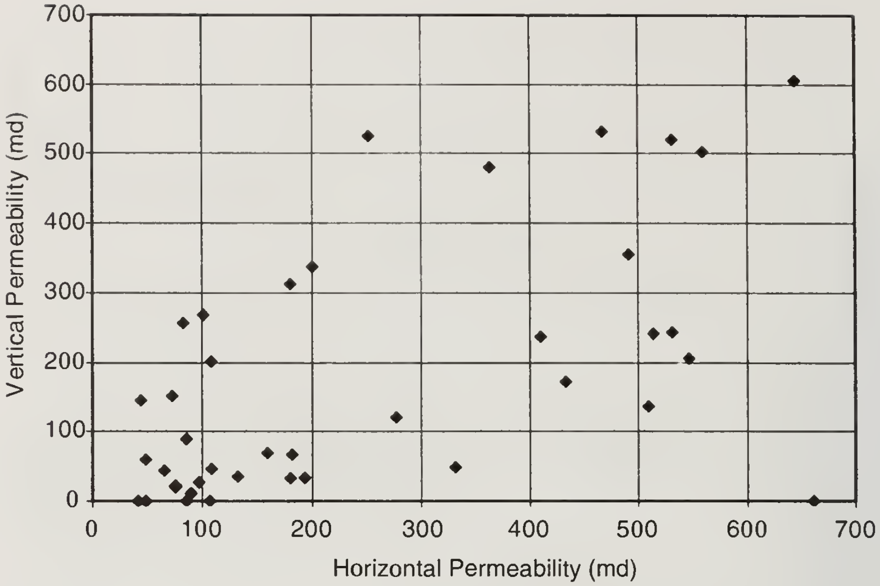


**Figure 23** Cross plot of horizontal versus vertical permeability for the Benoist sandstone reservoir in Boyd Field. Samples with vertical values greater than horizontal equivalents may be fractures.

**Figure 24** Photograph of Benoist sandstone core from Boyd Field showing a vertical fracture extending most of the length of the core. The white-colored material along the fracture is calcite cement. Superior Oil Company, Shallert No. 1 well, 2,114 feet.

vertically separated by intervals with lower permeability. However, there is no significant vertical compartmentalization in the northern portion of the field. The shale-rich layer approximately 10 feet below the top of the reservoir may locally compartmentalize the reservoir (fig. 10). The thickest contiguous interval of high permeability occurs in the lowest part of the section in Zone C (fig. 27), but Zone C is below the oil-water contact and is not important to oil recovery. Zones A and B (fig. 27) are oil-bearing and could form preferential horizontal pathways for fluid flow.

### Future Strategies

Depending on oil prices, Boyd Field may be a candidate for advanced, enhanced oil recovery techniques such as the use of polymers. Polymers have been successfully used at nearby Salem Field (6 miles to the east) to recover additional oil from the Benoist reservoir (Widmyer and Williams 1988). Polymers change the viscosity of the water and allow the recovery of more oil from intervals with lower permeability. The Benoist reservoir at Salem Field has layers of higher and lower permeabilities similar to those found in the Boyd Field three-dimensional model and may be an analog for additional oil recovery in Boyd Field. The three-dimensional model of Boyd Field shows the presence of zones of higher permeability separated by low-permeability intervals. Polymers could be used at Boyd Field to increase oil production.

There is little opportunity for further development of the Benoist reservoir within the central portion of the field. The current operator has drilled several new development wells within the field. These infill wells had an initial production of only a few barrels of oil per day, suggesting that earlier production techniques have already recovered most of the oil in the Benoist reservoir.

Outposts to the field, especially in the southern end, have the potential to recover additional oil. Four successful wells drilled in the 1990s were located 1,600 feet from the original southern limit of the field (fig. 6). The initial outpost well, the Trice Oil and Gas Gephart No. 1, had an initial production of 57 barrels of oil per day and 12 barrels of water per day. The Gephart No. 1 oil-water contact was 6 feet below the top of the Benoist sandstone. The operator encountered water coning problems similar to those occurring in the wells to the north. The four wells have produced 6,000 barrels of oil in six years. The four outpost wells are interpreted to be on a subtle low-relief structure similar to the one at Dix South Field (fig. 3).

## Dix South Field

### Introduction

The relatively small Dix South Field, located in Jefferson County, Illinois (fig. 1), contains two non-commercial producing Benoist wells (fig. 28). Although Dix South Field (fig. 3) has not produced commercial amounts of hydrocarbons from the Benoist sandstone, the study of this field illustrates important characteristics of production from Benoist structures with little structural relief such as the Boyd Field outpost (fig. 29).

### Methodology

The sandstone geometries were determined from an analysis of 19 wireline logs. These geometries were modeled using the Landmark Z-MAP Plus™ software. There were no whole cores available from this field; however, thin sections were made from biscuit-sized samples of core from two wells.

### Oil Production

The small areal extent of the low-relief anticlinal structure at Dix South Field did not allow large amounts of oil to be trapped. In addition, Dix South Field and the larger Salem Field to the north are on the same general structure (Nelson 1995); therefore, Dix South Field may have been partially drained by the larger Salem Field. The two wells in the field, Sargent No. 1 and Williams No. 1, were not economical. The Sargent well produced oil from April 1941 until December 1945; cumulative production was 10,922 barrels. The Williams well produced from September 1941 until November 1943 and had a total production of 2,483 barrels.

### Structure and Stratigraphy

The structure map for the top of the Benoist sandstone around Dix South Field (fig. 29) shows a north-south–trending anticline with only 5 to 10 feet of relief. The sandstone ranges from 30 feet thick to more than 60 feet thick within the field, and there appears to be a northeast trend to the elongation of the Benoist sandstone bodies (fig. 30). The sandstone isolith (fig. 30) varies inversely with the thickness of a basal shale layer (fig. 31).

The stratigraphic cross section B–B´ (fig. 32) illustrates the observations noted on the isopach and isolith maps and is similar to that for Boyd Field. The Benoist sandstone in Well No. 24609 is thicker than in the three adjoining wells and appears to have scoured into and replaced the underlying shale, suggesting that the Benoist sandstone was deposited, in part, in channels on a fluvial deltaic coastal plain.

### Petrography

The samples from the Benoist sandstone at Dix South Field were similar to those from Boyd Field, located 3 miles to the west. The samples are classified as a subarkose sandstone and have an estimated visual porosity ranging from 13 to 16%. As at Boyd Field, the feldspar grains underwent dissolution, and much of the porosity is secondary. The clay mineralogy (as determined by x-ray diffraction) consists of illite-smectite and minor amounts of chlorite and kaolinite.

## Conclusions

Regional mapping of the area surrounding Boyd and Dix South Fields and previous work by others suggest that the Benoist sandstone was deposited in a fluvial-deltaic coastal plain depositional system that was reworked by coastal processes. Within the two fields, the reservoirs consist of distributary channel sandstones that have scoured into underlying shales. Some of these sandstones have an up-

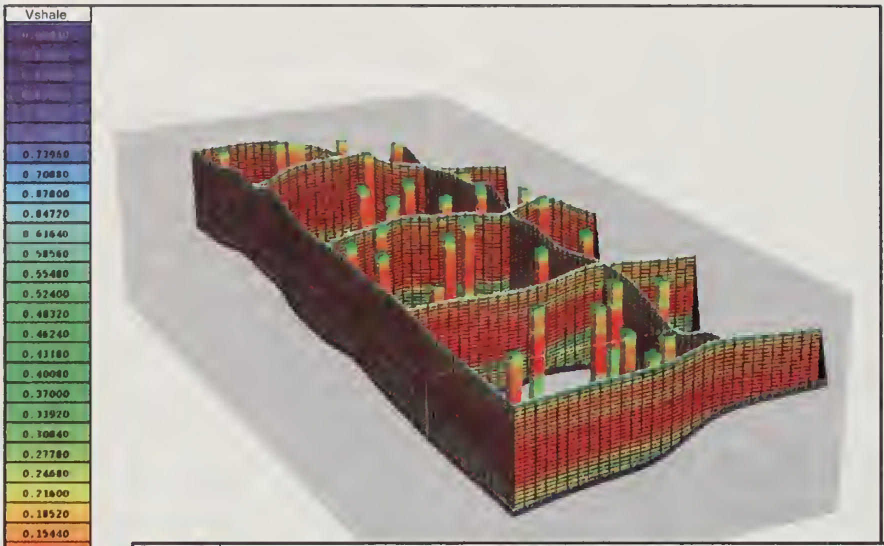


**Figure 25** Three-dimensional model of variation in the normalized spontaneous potential curves of well logs across Boyd Field. Red colors indicate the lowest shale content. Blue colors indicate higher shale content.

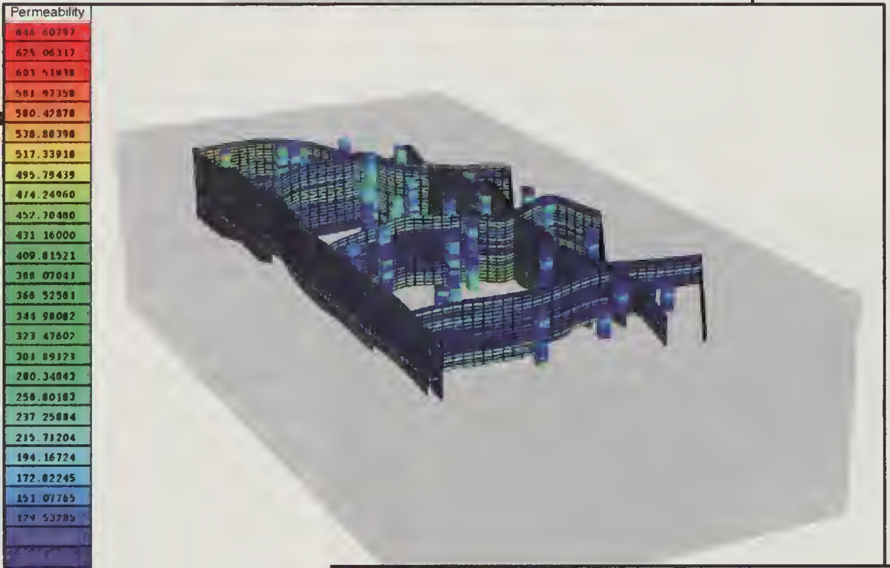


**Figure 26** Variation in measured permeabilities of cores in Boyd Field. Red through green shades indicate higher permeability. Blue shades indicate a permeability of <200 md. The orientation of the model is identical to that of Figure 25. The permeability model has fewer wells with data; therefore, the model has a smaller areal extent.

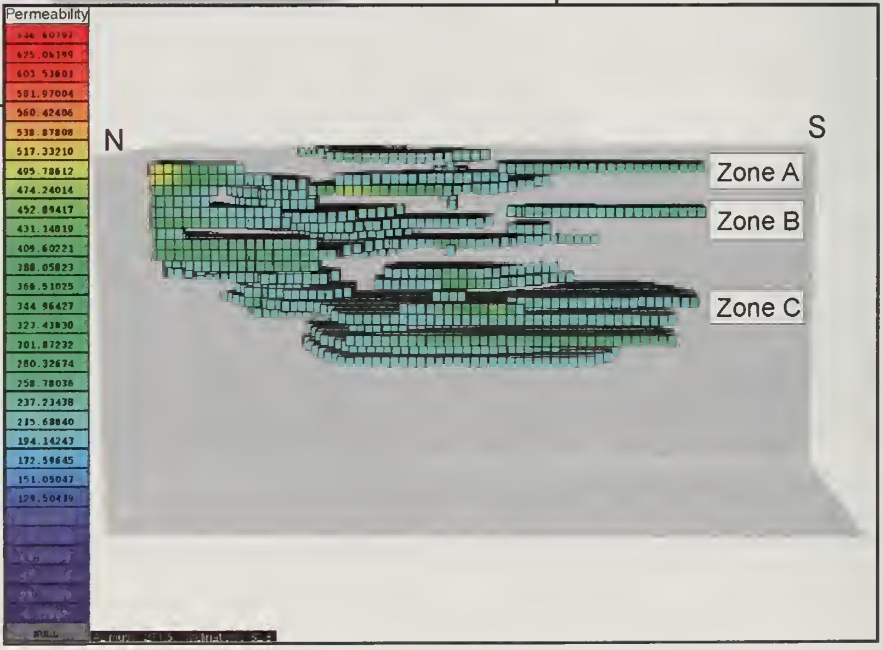
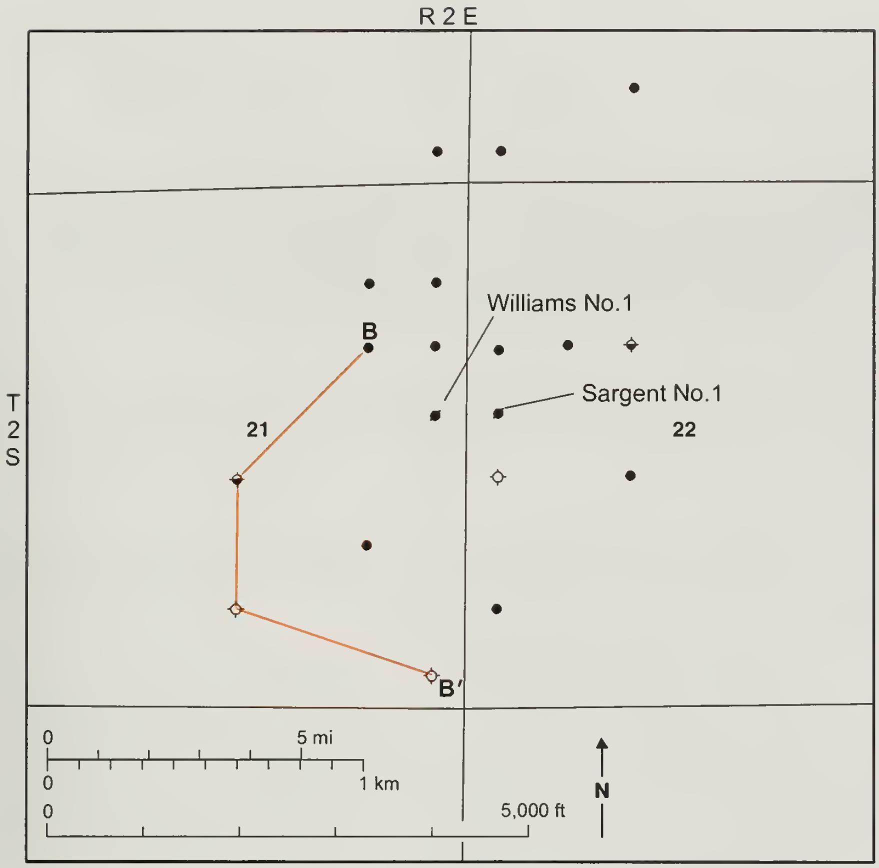
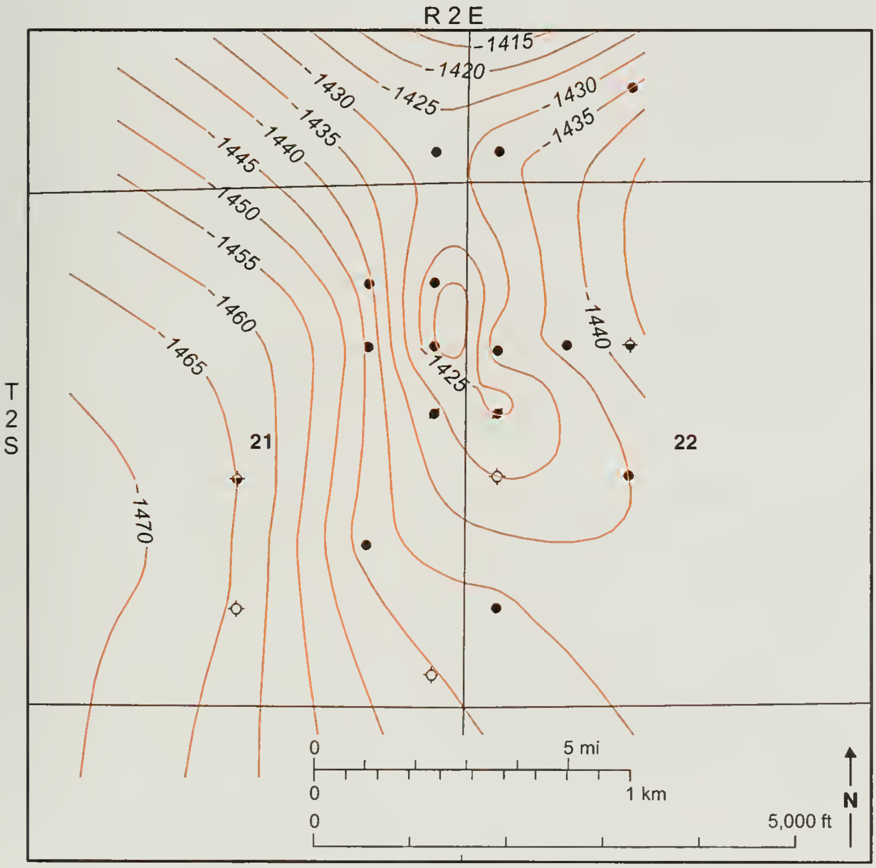


**Figure 27** Distribution of core permeability values greater than 200 md in the Benoist sandstone across Boyd Field. The view is looking east and each grid block is 1 foot thick. The model is approximately 1 mile in length. The different tones signify different permeability values. Zones A, B, and C are separated from one another by intervals with permeability values of less than 200 md.



- ◆ Dry/abandoned well (oil show)
- ⁄ Indicates well is currently plugged
- ○ Dry/abandoned well
- ● Oil well
- ● Oil and gas well

**Figure 28** Base map for Dix South Field showing the line of cross section B–B´.



- ◆ Dry/abandoned well (oil show)
- ⁄ Indicates well is currently plugged
- ○ Dry/abandoned well
- ● Oil well
- ● Oil and gas well

**Figure 29** Structure contour map of the top of the Benoist sandstone at Dix South Field. Contour interval is 5 feet.

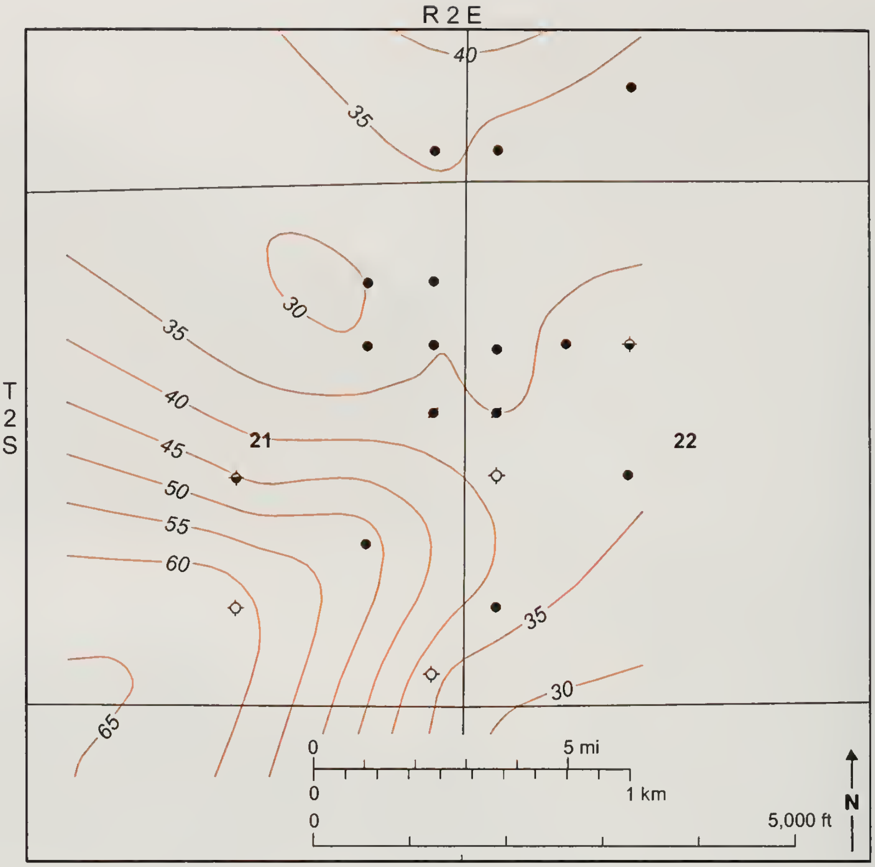


**Figure 30** Sandstone isolith map of the Benoist sandstone at Dix South Field. Contour interval is 5 feet.

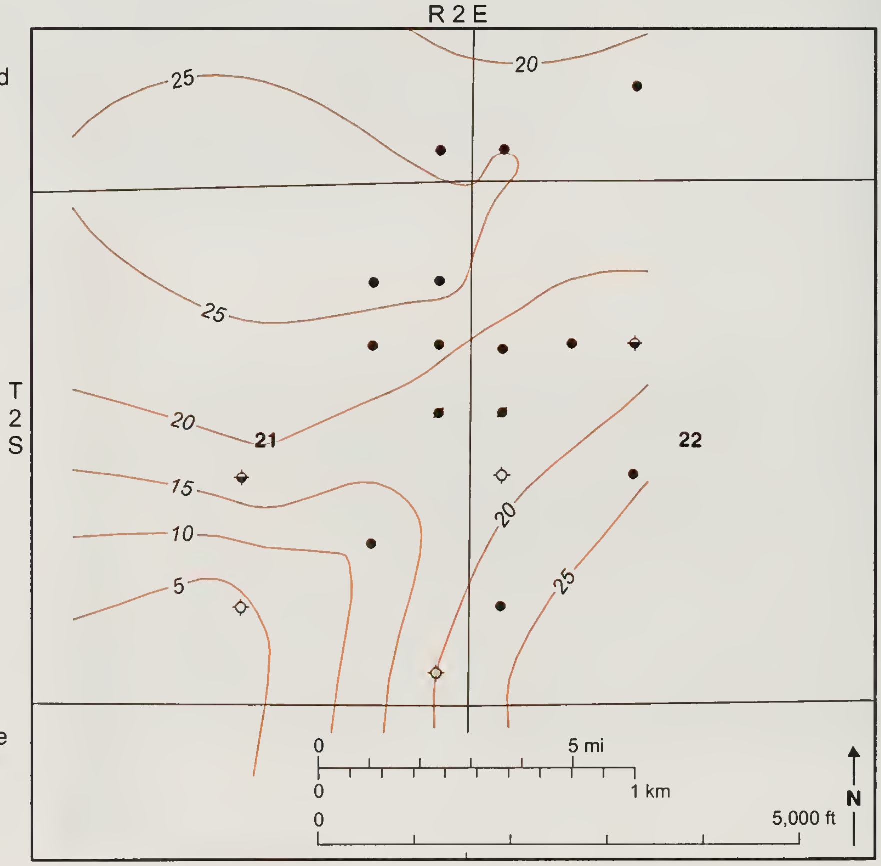


**Figure 31** Isopach map of the shale interval between the base of the Benoist sandstone and the top of the Renault Limestone at Dix South Field. Contour interval is 5 feet.

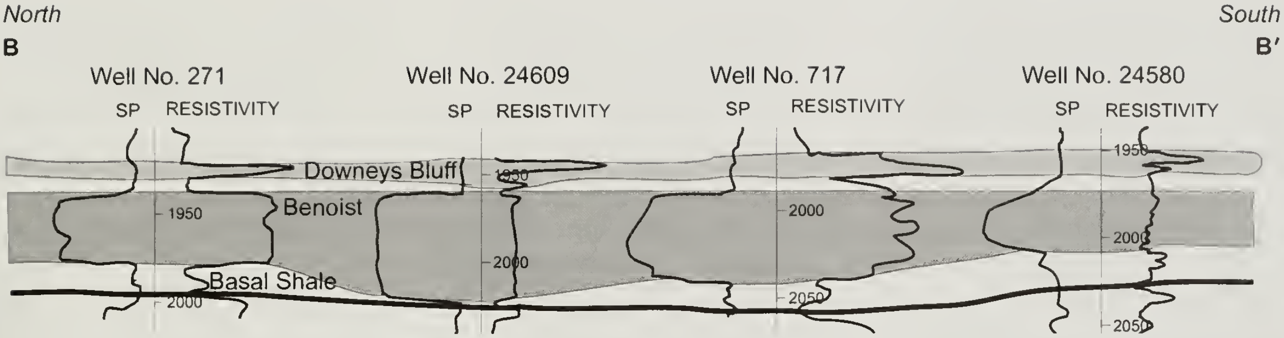


**Figure 32** Cross section B–B′, showing the thickening and thinning of the Benoist sandstone reservoir at Dix South Field. The cross section shows scouring into the underlying shale. Line of cross section is shown in Figure 28. SP, spontaneous potential.

ward-fining pattern on the SP wireline log, which is suggestive of a channel sandstone environment.

Wireline logs at Boyd Field show that the oil-water transition zone is approximately 10 to 15 feet thick. Mercury injection capillary pressure data also show the Benoist to have a 12-foot oil-water transition zone. In addition, the capillary pressure data show the sandstone has a narrow range of pore throat dimensions that should contribute to high recovery efficiency.

Quartz overgrowths have significantly reduced the amount of the primary porosity of the Benoist sandstone within both Boyd and Dix South Fields. The majority of the porosity in the Benoist sandstone at both fields is secondary, formed by the dissolution of feldspar grains.

In 30% of the samples tested at Boyd Field, the vertical permeability was found to be substantially greater than the horizontal permeability, even though the sandstone had abundant horizontal thin shale laminations across most of the reservoir. The greater vertical permeability values may have been caused by vertical fractures in the sandstone. A whole core from the field showed vertical fractures extending 1 foot or more along the core face. Since the beginning of production, the reservoir has been plagued by water coning and premature production of water. Water coning occurred not only in the main part of Boyd Field, but also at the recent extensions of the field and at Dix South Field. This problem of water coning must be resolved before subtle structures in the Benoist sandstone can have commercial oil wells.

A three-dimensional visualization of permeability shows the presence of higher and lower permeability zones in the Benoist sandstone at Boyd Field. This stratification of permeability indicates that premature breakthrough of water could be expected during a water flood program. Operators at the nearby Salem Field used polymers to increase recovery during water flooding of a similar stratified permeability Benoist reservoir. If used at Boyd and other Benoist reservoirs, polymers might help increase oil production.

The Boyd Field extension and the Dix South Field are important because they represent analogs of what is left to be discovered in the Benoist reservoirs in the area surrounding these two fields.

## Acknowledgments

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