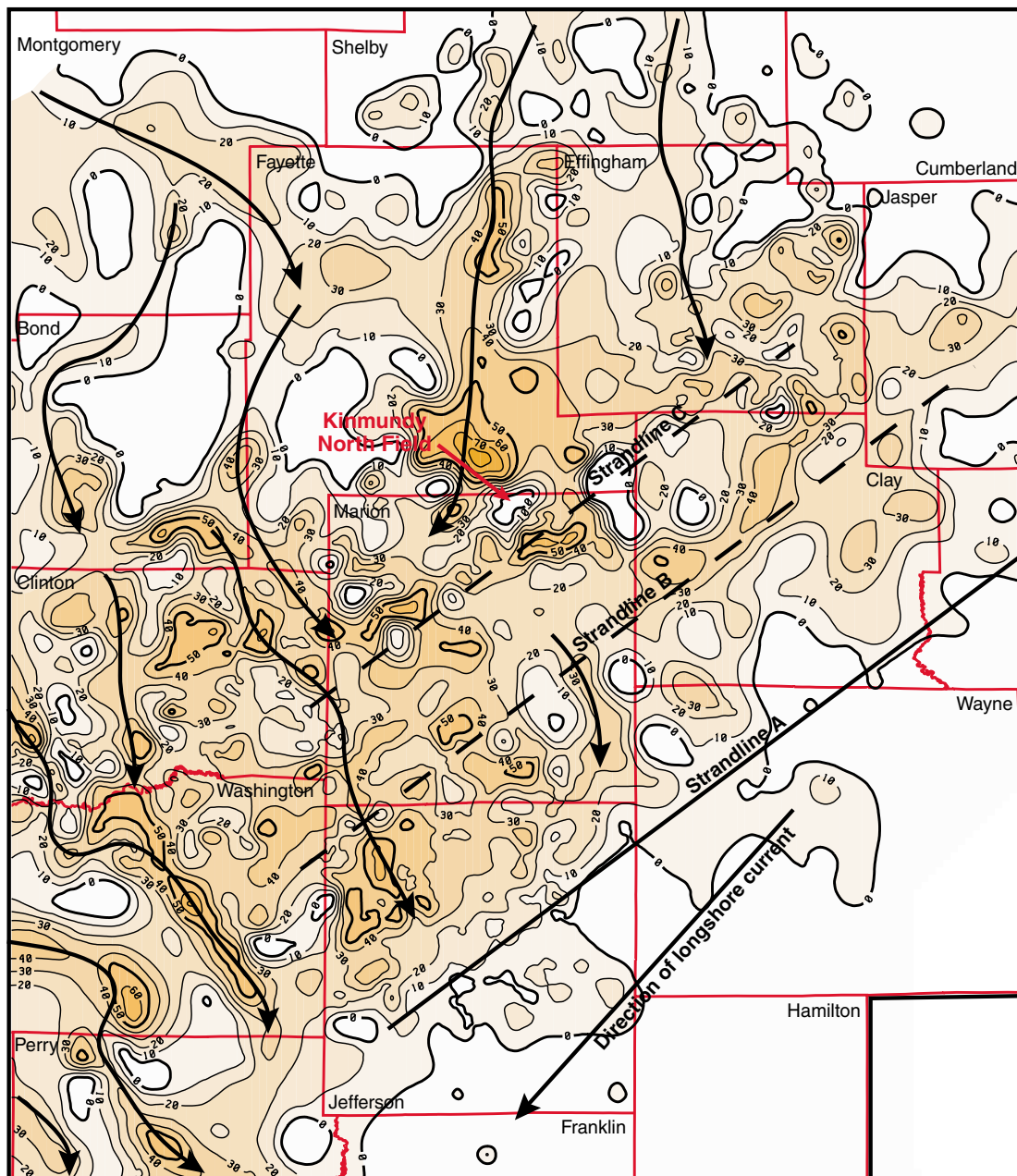




The Benoist (Yankeetown) Sandstone Play in the Illinois Basin

Hannes E. Leetaru, Kristine Mize, and James S. Cokinos



Circular 568 2005

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Front Cover: Map showing regional Benoist sandstone isolith (net feet of sandstone) with major depositional features highlighted. Arrows show the depositional trend of distributary mouth bars. The northeast-trending lines highlight three strandline systems.

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Abstract

Oil is produced from numerous structural and stratigraphic traps in the Mississippian (Chesterian) Benoist sandstone (Yankeetown Sandstone) in the Illinois Basin. This regional geologic study is the first of this important oil-producing formation.

Over 1,800 wireline logs were used to prepare regional structure and isolith maps of the Benoist for an area of approximately 7,000 square miles in south-central Illinois. In addition, six individual Benoist reservoirs were studied for their trapping mechanism and heterogeneity.

Introduction

For almost 100 years, the Mississippian Benoist sandstone, formally designated as the Yankeetown Sandstone outside the petroleum industry, has been a major oil-producing horizon in south-central Illinois. Surprisingly, little has been published about the Benoist even though 500 million barrels of oil have been produced from this formation, the third most prolific in the Illinois Basin (Davis 1990). Benoist oil reservoirs are still being discovered, and, as this study shows, there are numerous opportunities for further exploration and development drilling.

The term *Benoist* has been used by the oil industry since 1910 when the first Benoist sandstone reservoir was drilled by the Southwestern Oil and Gas Company's Benoist No. 1 well in Sandoval Field, Marion County, Illinois (Bell 1927). A few years later, Weller (1914) described the Yankeetown chert in an outcrop near the Yankeetown School in Monroe County, Illinois. In the late 1930s, the Yankeetown chert, Bethel Sandstone, and Benoist sandstone were stratigraphically miscorrelated. The Bethel and Benoist commonly were considered identical formations (Weller and Sutton 1940). It was not until the 1950s (Swann 1963) that the stratigraphic equivalency of the Yankeetown and Benoist was established.

The Benoist reservoir is an important oil-producing formation, and it also

The Benoist sandstone was deposited as part of a fluviially dominated deltaic system in a cratonic basin. Regional mapping of the Benoist sandstone isolith shows two distinct linear orientations. The northwest-trending sandstone bodies were originally part of a distributary mouth bar-channel system, whereas the northeast-oriented sandstone bodies appear to have been deposited as a series of strandlines dominated by coastal processes. The reservoirs within these strandline sandstone bodies form stratigraphic traps caused by the updip-pinchout of the reservoir sandstone.

has been used for natural gas storage (Buschbach and Bond 1973). In 1961, Illinois Power Company started injecting natural gas into the Benoist reservoir at Hookdale (now named Beaver Creek NE) in Bond County, Illinois. A second small Benoist gas storage project is located in Stubblefield South Field, also in Bond County.

The study area for this report encompasses over 7,000 square miles, 17 counties, and most of the Benoist producing fields (fig. 1). Wireline logs from more than 1,800 wells were examined (fig. 2), and the formation tops and isopach values were integrated into this study. The well control was relatively evenly distributed. Most of the mapping area has at least four wells per township, and some portions have as many as one correlated well in every section.

Reservoir characterization studies were completed in six different Benoist oil fields (fig. 3). These studies have been used to illustrate the importance of stratigraphy in the trapping and recovery of oil from the Benoist sandstone.

Regional Geology

Stratigraphy

The Benoist sandstone (Yankeetown Formation, lower Chesterian Series, Mississippian System) (fig. 4) is bounded at its top by an unconformity that marks a significant strati-

graphic boundary (Nelson et al. 2002). This unconformity surface has been observed along both the outcrop belt and in subsurface cores. No significant regional unconformity is apparent between the Benoist (Yankeetown) and the underlying Renault Limestone.

The Renault Limestone is a cross-bedded oolitic limestone that ranges from a few feet to over 30 feet in thickness across the study area (Willman et al. 1975). The Renault separates the Benoist reservoir sandstone from the Aux Vases Sandstone, a major oil-producing interval within the Illinois Basin. In some areas, such as Salem Field, the Renault does not appear to form a seal for hydrocarbon movement, and the Benoist and Aux Vases have a common oil-water contact (Swann and Bell 1958).

In the study area, the Benoist (Yankeetown) is commonly overlain by the 3- to 15-foot-thick Downeys Bluff Limestone, which is characterized by abundant reddish colored (hematite-stained) crinoidal fragments. Directly above the Downeys Bluff Limestone is the Bethel Sandstone. The two sandstone units have similar lithologies and wireline log signatures and have many times been confused with each other. The Bethel Sandstone is absent in the western part of the mapping area but does occur in the northeastern part where it is distinguished from the Benoist by the presence of the Downeys Bluff Limestone. Kinmundy North is the only field we studied that contains both the Bethel and Benoist sandstones.

The top of the Benoist is commonly characterized by red sandstone and shale beds (Swann 1963). In addition, Nelson et al. (2002) identified horizons that resemble paleosols in the uppermost Benoist interval in both cores and outcrops along the western margin of the basin. Lycopod logs (spore-bearing vascular land plants such as *Lepidodendron* sp.) occur locally in the Benoist interval in outcrop (Weller and Ste. Clair 1928, Devera, personal communication 2003). In outcrop and at least 5 miles basinward in the subsurface, the upper part of the Benoist and its equivalent strata are characterized

by abundant chert. The chert may have formed as a result of soil development on interfluvial areas during a marine regression (Nelson et al. 2002). Bedded chert such as that found in the Benoist forms in the modern soils that are typical of arid climates (Follmer, personal communication 2003).

Structural Framework

Based on the structure contour map on top of the Beech Creek Limestone (fig. 5), the DuQuoin Monocline appears as the most significant structural feature in the study area. In southwest-

ern Jefferson County, the DuQuoin Monocline bifurcates into western and eastern segments. The DuQuoin Monocline gradually becomes less pronounced at the northern part of the mapping area; slope is 3% to the north compared with a 9% slope in the southern part. Unlike the underlying Aux Vases Sandstone (Leetaru 2000), Benoist sandstone deposition does not thicken or thin along the highs and lows of the DuQuoin Monocline, suggesting that deformation did not occur during its deposition. Most of the larger Benoist oil fields are located over anticlinal features (fig. 5).

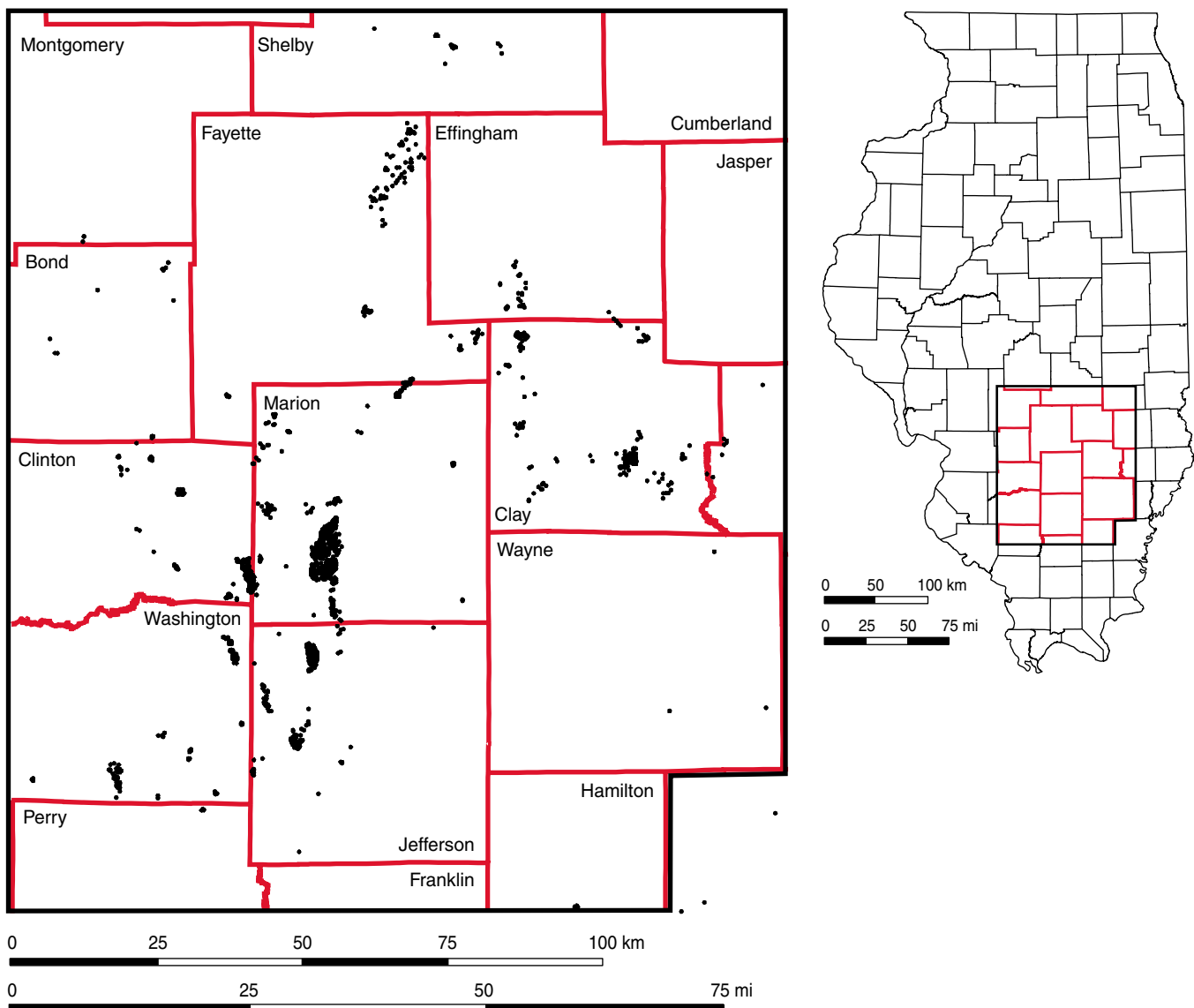


Figure 1 Map of Illinois showing Benoist oil fields in the 17-county study area (outlined).

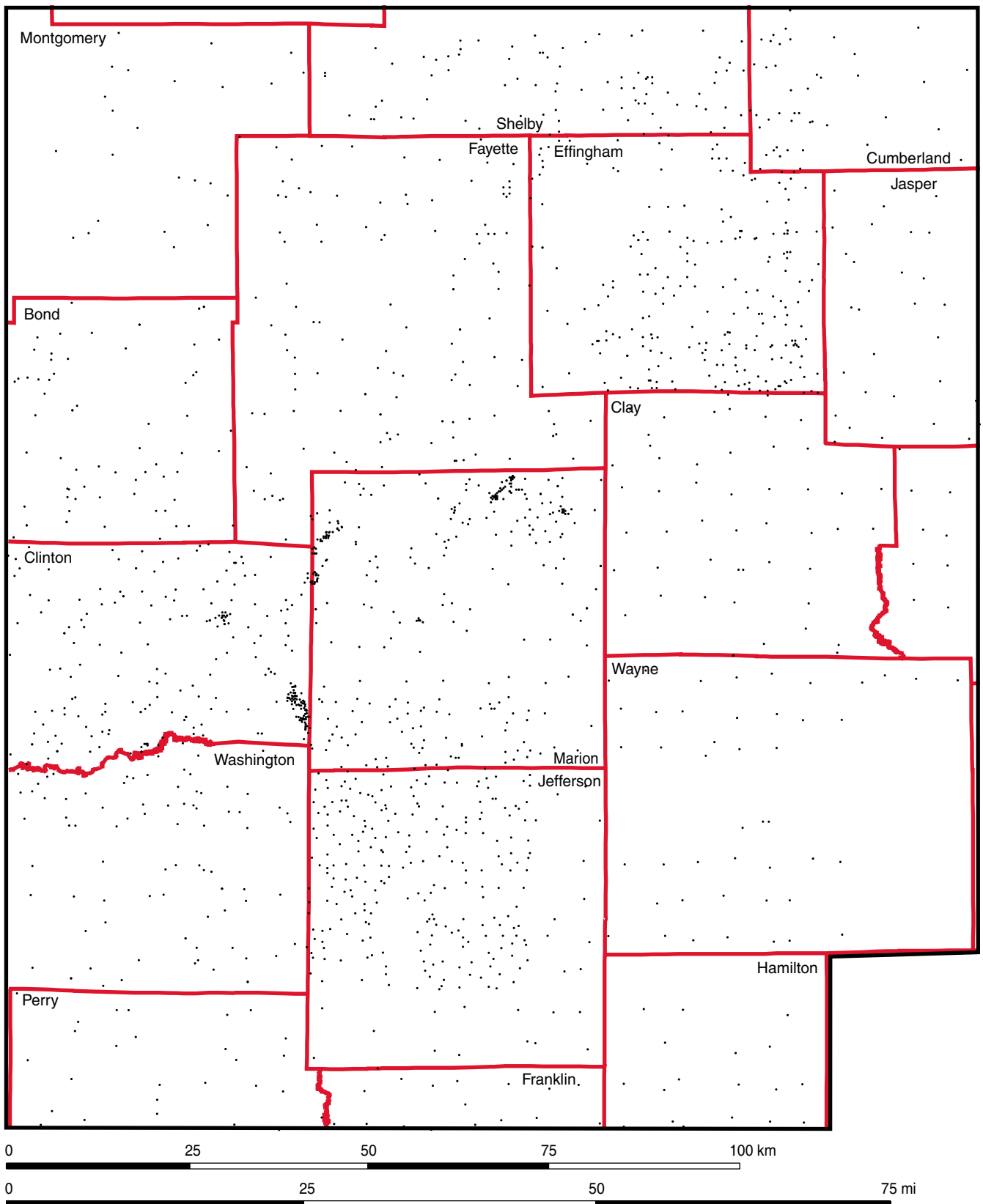


Figure 2 Map of the 17-county study area showing the locations of wells used in making the regional isolith and structure maps of the Benoist sandstone.

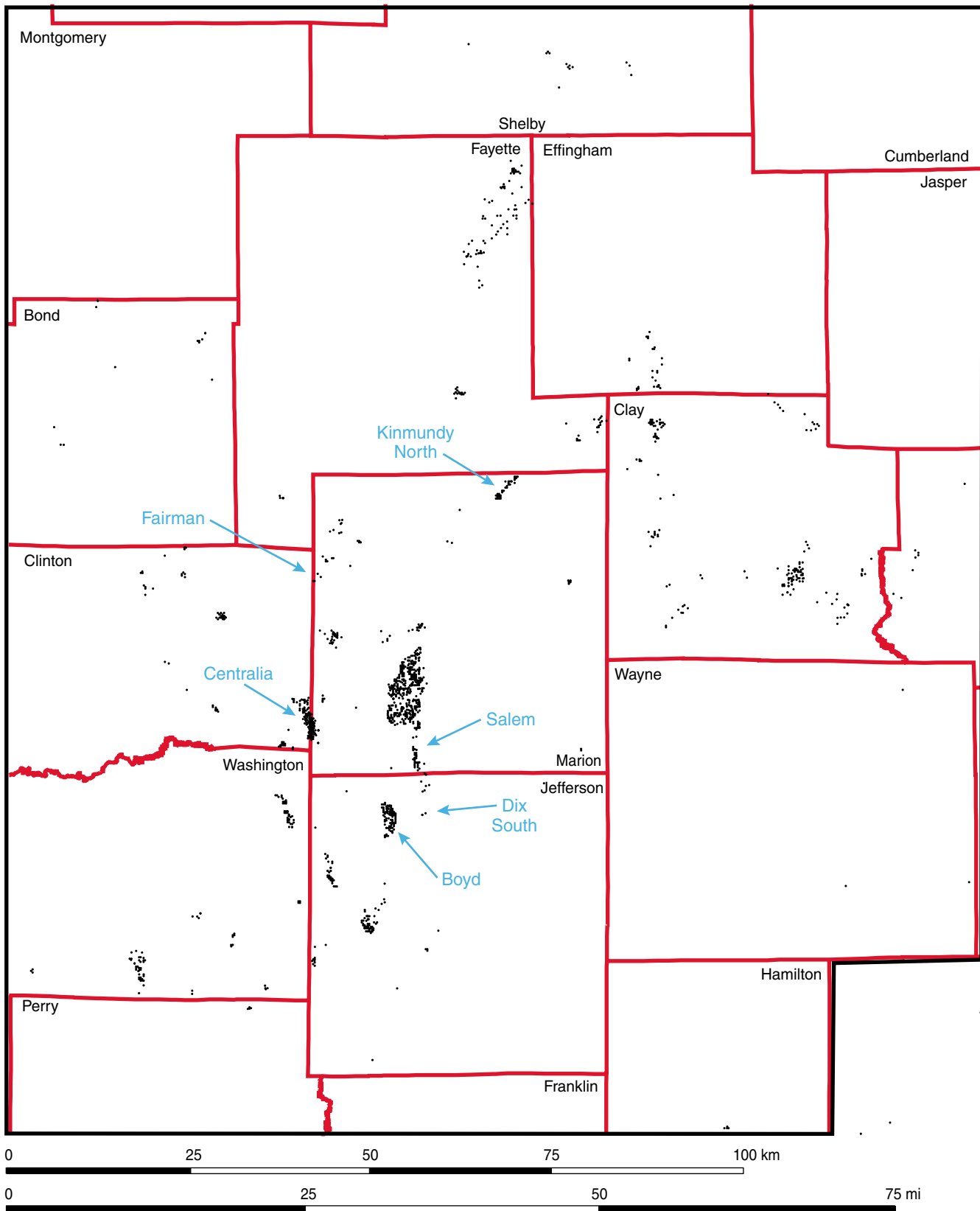


Figure 3 Location of the wells producing oil from the Benoist sandstone in the study area and of the individual field studies referenced in this report.

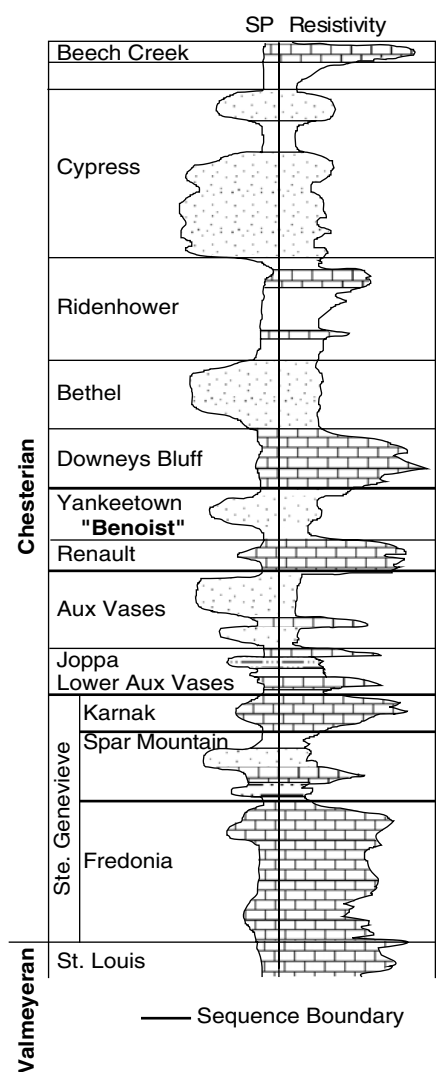


Figure 4 Stratigraphic column of Mississippian rocks from the Beech Creek Limestone to the St. Louis Limestone for southern Illinois. SP, spontaneous potential.

Benoist Depositional Environments

Benoist sandstone isolith values provide additional information about sedimentary environments and reservoir geometries. These values were calculated using the spontaneous potential (SP) wireline log in conjunction with the resistivity wireline log. Sandstone and shale baselines were defined using the SP curve. The clean sandstone baseline value is considered the greatest leftward deflection on the curve. The shale baseline value was estimated

from the average SP value for a shale interval. The strata were classified as a sandstone when the SP curve value was no more than half the difference between the shale and sandstone baseline values for that well.

The Benoist sandstone isolith shows two primary depositional axes with orthogonal orientations. The elongation direction of the thickest sandstone bodies (fig. 6) is toward the southeast. These sandstone bodies range from 1 to 4 miles wide and can be up to 20 miles long. Based on the regional geometries and core data from the field studies in this report, these thick sandstone bodies are interpreted to be part of a distributary channel system that prograded from the north and northwest toward the south and southeast. Areas without sandstone are interpreted to have formed in an interdistributary bay environment.

The second sandstone body trend is elongate in a northeast-southwest direction for about 60 miles. There appear to be three different strandline systems, each about 5 miles wide, that are oriented perpendicular to the distributary channel system (fig. 6). Strandline A is the most distal of the strandlines, and there is no significant Benoist sandstone deposition southeast of this strandline. The presence of strandlines B and C is postulated based on a general increase in the thickness of the sandstone bodies. The three different strandline trends are interpreted to represent stabilizations of the Benoist shoreline and the deposition of thick nearshore deposits. Strandlines B and C trends may have been heavily reworked by fluvial and tidal processes; hence, their amorphous nature. The study of Kinmundy North Field, located parallel to the northwest edge of strandline C, suggests that the Benoist reservoir formed as a stratigraphic trap. The reservoir sandstone pinches out updip against a shale that is interpreted to be a lagoonal deposit. There is not enough evidence to speculate on the relative ages of the three strandlines.

Many of the distal ends of the Benoist sandstone bodies along strandline A have a southwestward deflection (fig. 6) that is thought to reflect the direction of longshore (littoral) drift.

Similar to present-day coastal environments, longshore drift occurs when a single predominant wind direction causes the waves to contact the shoreline obliquely. This deflection of the Benoist sandstone bodies suggests a predominant southwestern longshore current direction. According to Blakey's (2004) paleogeographic reconstructions of continents, Illinois was located somewhat south of the equator in late Mississippian time, oriented with its elongation approximately N 30° E. This hypothesis fits well with the expected direction of the northwest trade winds, causing waves to impinge on the inferred coastline mostly from the southeast.

The most useful application of the isolith map is in evaluating the variation of reservoir heterogeneity in an area. The Benoist reservoirs in fields such as Centralia and Salem (fig. 3) were deposited as channels, crevasse splays, distributary mouth bars and channels, and interdistributary bay deposits. The lateral extent of sandstone bodies in these environments commonly is relatively limited. For example, at Centralia Field, the channel body is thousands of feet long, but the width of the channel is less than 1,000 feet. Such high degrees of reservoir heterogeneity are likely to result in an overall poor initial primary and secondary recovery. Oil recovery can be improved by using development drilling and waterflooding that is carefully targeted to ensure that injector and producing wells are within the same sandstone body.

In areas such as at Boyd Field (fig. 3), the Benoist channel sandstone and the strandline deposits were probably reworked by shoreline processes, and the directional trends are no longer preserved. Instead, the sandstone forms a relatively homogeneous blanket sandstone over 10 square miles or more. The original operator of Boyd Field noted a drop in reservoir pressure as fields surrounding Boyd Field were discovered and developed. This drop in pressure suggests that all of the Benoist reservoirs surrounding Boyd Field were in pressure communication. This continuity is also supported by the Benoist sandstone isolith map, which shows a continuous sandstone package in the Boyd Field area (figs. 3 and 6).

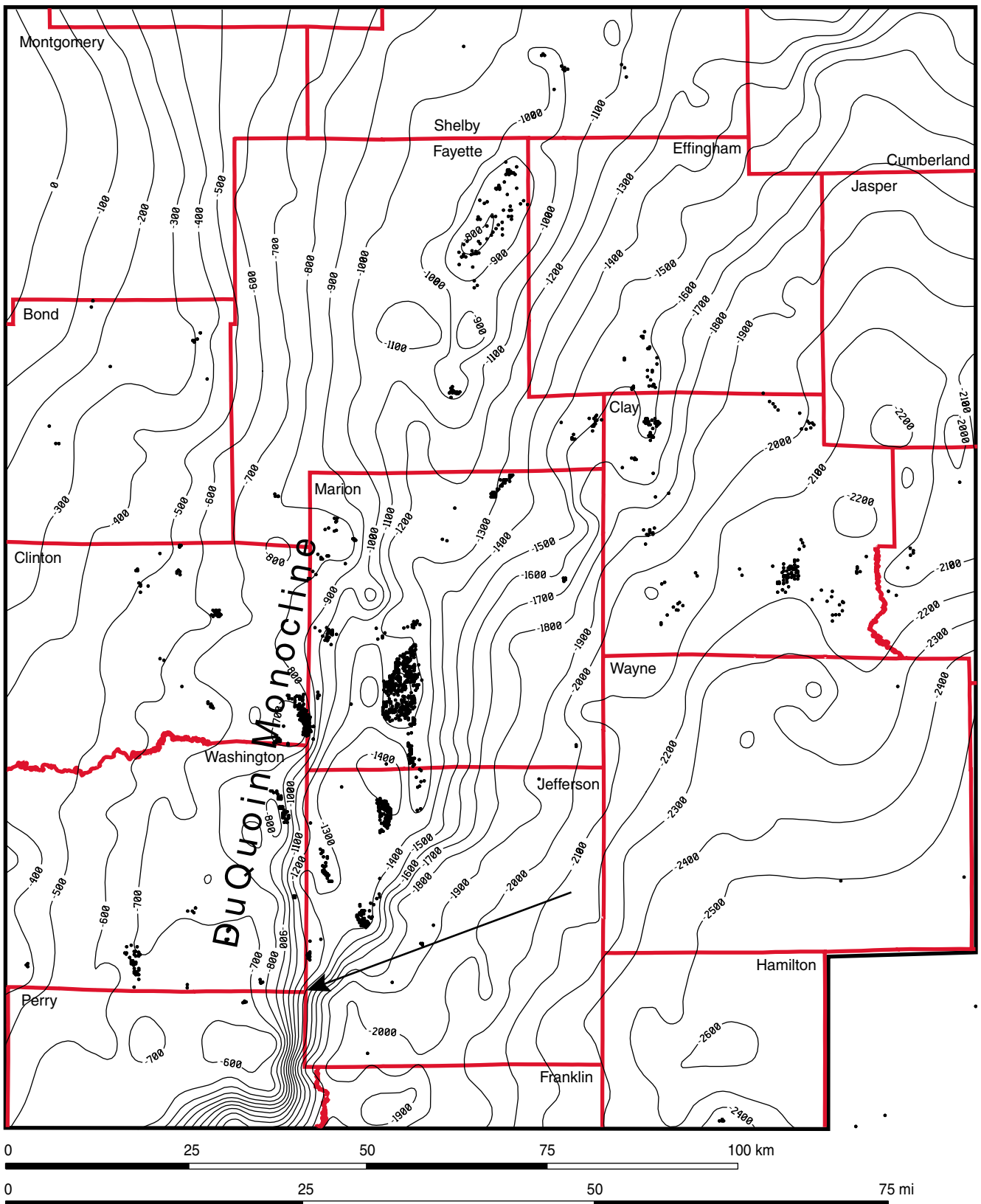


Figure 5 Map showing structure contours on top of the Beech Creek Limestone. Arrow points to the bifurcation of the DuQuoin Monocline into a western and eastern region north of this point. Locations of wells producing oil from the Benoist sandstone are also shown. Contour interval is 100 feet.

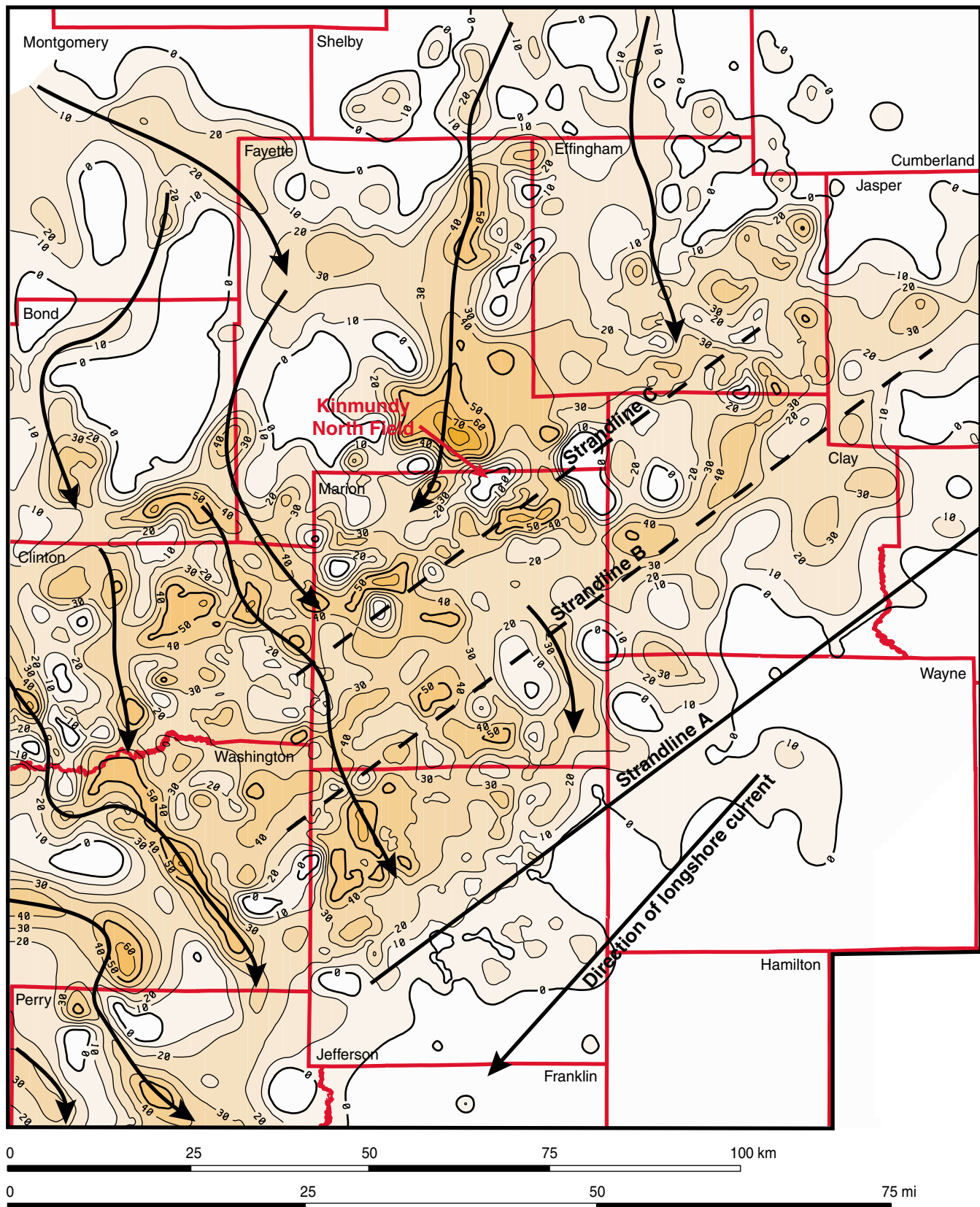


Figure 6 Map showing regional Benoist sandstone isolith (net feet of sandstone) with major depositional features highlighted. Arrows show the depositional trend of distributary mouth bars. The northeast-trending lines highlight three strandline systems. Contour interval is 10 feet.

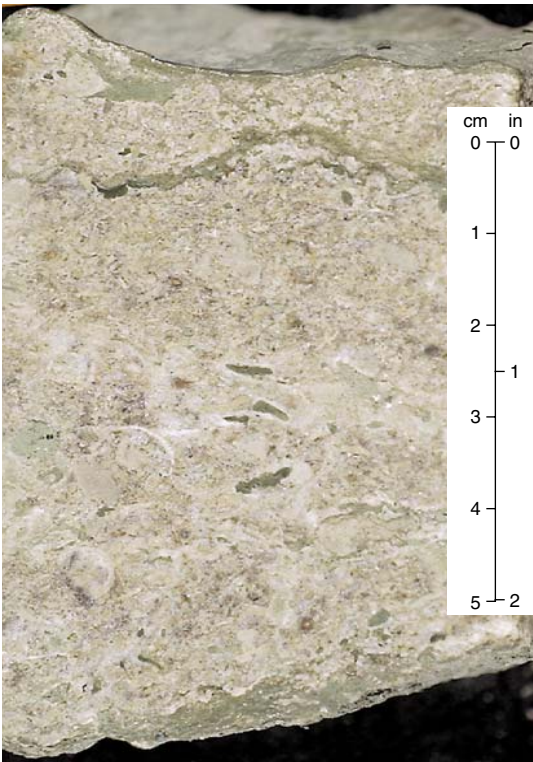


Figure 7 Photograph of core showing limestone and shale conglomerate within a sandstone matrix. Shell Oil Hanseman No. 2 Well, depth 1,362 feet.

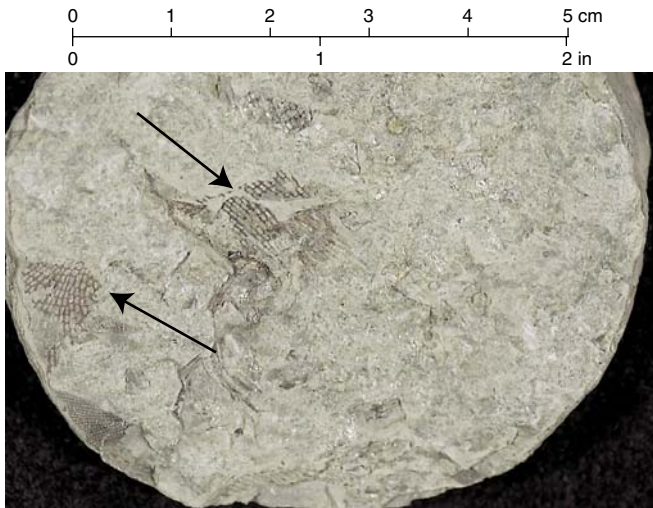


Figure 8 Photograph of core showing bryozoan mudstone bedding plane containing fenestrate bryozoans (arrows). Shell Oil Hanseman No. 2 Well, depth 1,374 feet.

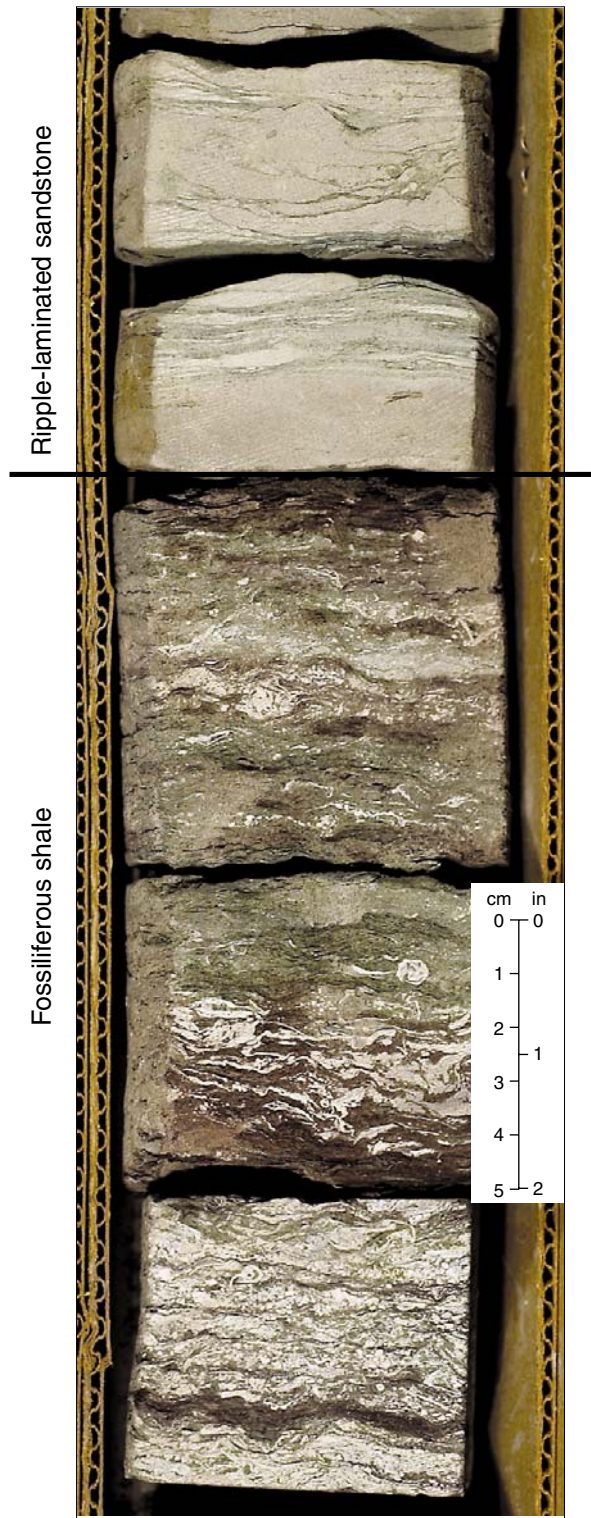


Figure 9 Photograph of core showing fossiliferous shale. The fossils are shown as the white layers. This facies is bounded at its top by a ripple-laminated sandstone. Shell Oil Company, Criley No. 4-A Well, depth 1,358 feet.

Facies

Ten facies were identified in the Benoist Sandstone based on whole drill cores from 36 wells in Centralia Field and descriptions of cores from two wells in Salem Field. One facies description from the Downeys Bluff is also included because the calcareous mudstone facies of the Benoist is transitional between the two formations. The facies were differentiated on the basis of lithology, sedimentary structures, presence and absence of burrowing, and constituents such as fossils.

Conglomerate

Many of the cored wells have a conglomerate interspersed between sandstone and shale beds. The conglomerate is composed of ripped up mudstone clasts as well as echinoderm and brachiopod fragments within a matrix of fine- to medium-grained quartz grains (fig. 7). The coarse texture of the grains and the relatively thin interval (less than 2 feet) suggests an episodic high-energy environment. The juxtaposition of this conglomeratic facies between overlying and underlying lower-energy environments that deposited shale and sandstone is commonly found in storm deposits (Johnson and Baldwin 1996). An alternative interpretation (Widmyer et al. 1988) is that these facies are channel lag deposits. The evidence as to which of the two alternatives would be the more realistic is not conclusive, but we think that storms are the more likely cause for the conglomeratic facies of the Benoist.

Bryozoan-rich Mudstone

A green mudstone containing impressions of fenestrate bryozoans (fig. 8) is commonly found at the base of the Benoist sandstone. The bryozoan fossils were not extensively abraded, which is indicative of quiet-water deposition and short transportation distance. Bryozoans are marine organisms that do not grow in brackish or freshwater conditions; therefore, this facies was probably deposited at the distal edge of the prograding Benoist delta.

Fossiliferous Red Shale

The fossiliferous red shale (fig. 9) contains abundant brachiopod, echinoderm, and bryozoan fragments. This facies is common in many of the Benoist cores and occurs in numerous stratigraphic intervals within the Benoist. The marine fossils indicate open marine conditions, whereas the red color suggests subsequent oxidation and subaerial exposure. The facies was probably deposited in nearshore subtidal environments in close proximity to the delta or in the interdistributary bays near the seaward edge of the prograding delta.

Slickensided Mudstone

The color of the slickensided mudstone is mottled and ranges from dark gray to red. The mudstone beds are commonly 1 to 2 feet thick (fig. 10). Predominant are the numerous small intersecting fractures, which have a thin clay film that gives their surfaces a shiny, slickensided appearance. We interpret these features as having formed in vertisols during pedogenesis by the alternating drying and wetting of smectite-rich sediment (Gustavson 1991) within a tidal flat or floodplain.

Bioturbated Sandstone and Mudstone

This facies contains extensive burrows and disrupted beds. The original mixture of well-stratified alternating beds of shale and fine-grained sandstone has been disrupted by bioturbation. Alternating sandstone and mudstone layers are commonly found in tidally influenced depositional systems. Bioturbation is common in many depositional environments during periods when the sedimentation rate was relatively low (Coleman and Prior 1982).

Parallel-laminated to Rippled Sandstone

Individual beds may contain plane parallel laminations that range into ripple cross-laminations (fig. 9). These types of sedimentary structures form in a wide variety of deltaic and marine environments.

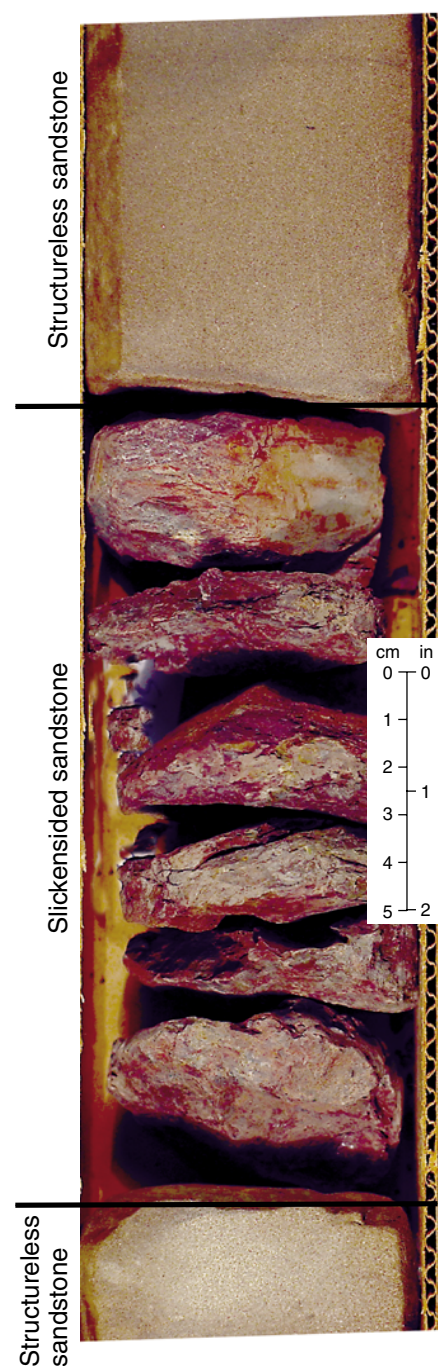


Figure 10 Photograph of core showing red mudstone with slickensided surfaces bounded at both the top and base by a Benoist reservoir sandstone with no apparent sedimentary features. Shell Oil Company Alison No. 3, depth 1,384 feet.

Contorted Sandstone

The contorted beds produce a deformed sandstone with some preserved cross- and laminated bedding. This type of sedimentary deformation is commonly associated with rapid deposition of sand onto water-rich, early liquified substrates (Coleman and Prior 1982) and can occur on the flanks of deltaic channels.

Structureless to Cross-bedded Sandstone

Some of the reservoir is characterized by massively bedded sandstone with no sedimentary structures (figs. 10 and 11) that may grade into a cross-bedded sandstone. The structureless sandstone may originally have been cross-bedded, but the primary structures were erased by bioturbation or liquefaction.

Fractured Sandstone

At both Boyd Field (Leetaru and Mize 2003) and Centralia Field, the Benoist sandstone is characterized by calcite-cemented vertical fractures (fig. 11). This post-depositional feature has significantly modified the reservoir properties within the field. At Boyd Field, many of the core analyses show significantly greater vertical permeability than horizontal permeability. The vertical fractures appeared to provide vertical conduits for fluid flow. The presence of fractures in more than a single field suggests that these fractures are common.

Calcareous Mudstone

The calcareous mudstone facies contains wavy discontinuous bedding and abundant echinoderm fragments. Calcareous mudstone occurs at the transition between the top of the Benoist sandstone and the Downeys Bluff Limestone (fig. 12). The contact of this mudstone with the underlying Benoist reservoir sandstone is abrupt and appears to be erosional. The mudstone is interpreted to be a transgressive facies that overlapped the Benoist delta. The erosional contact with the underlying Benoist sandstone may be a ravinement surface that formed during a marine transgression.

Downeys Bluff Limestone

The Downeys Bluff is characterized by echinoderm fragments that have a red hematitic stain (fig. 13). The Downeys Bluff Limestone appears to have no effective porosity or permeability and may be a partial seal for hydrocarbon entrapment in the Benoist reservoir sandstone.

Petrology

The Benoist sandstone is primarily a moderately to well-sorted, fine- to 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 their roundness was subsequently altered by the addition of quartz overgrowths that form a syntaxial rim cement (fig. 14). The quartz overgrowths can be clearly distinguished from the original

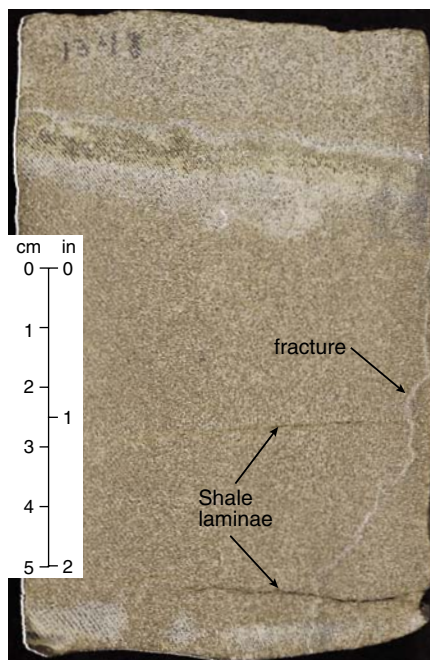


Figure 11 Photograph of core showing reservoir sandstone with a vertical fracture filled with calcite cement. The sandstone is relatively devoid of apparent sedimentary structures except for discontinuous shale lamina. Shell Oil Buchler No. 1, depth 1,348 feet.

grains by the presence of thin internal “dust lines” marking the original grain boundaries and the angular nature of the grain-to-grain or grain-to-pore contacts. The overgrowth faces in open pores commonly form 120-degree angles with each other.

The porosity in the Benoist reservoir facies is both primary and secondary (formed by dissolution) (fig. 14). The evidence for secondary porosity includes (1) oversized pores that generally are the same size as the individual grains in the matrix and, (2) from

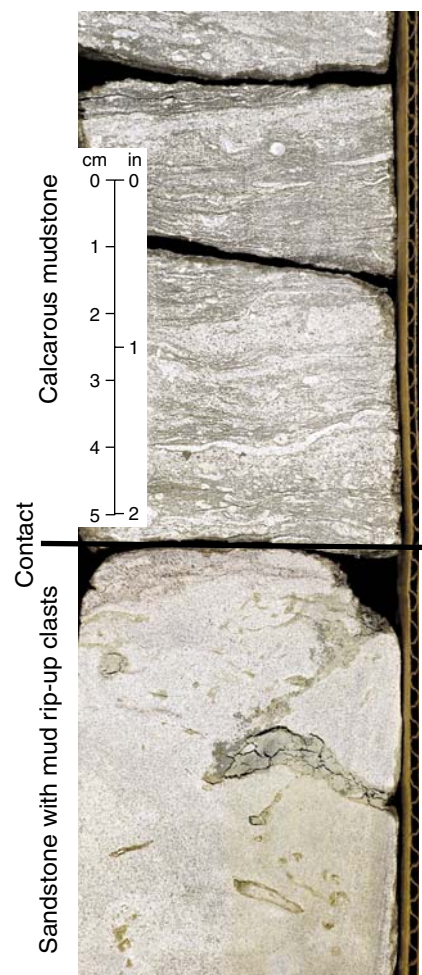


Figure 12 Photograph of core showing transitional facies between the Benoist sandstone to an overlying calcareous mudstone. The sandstone has large shale rip-up clasts. The contact between the two facies is interpreted to be a ravinement surface. Shell Oil Buchler No. 1, depth 1,342 feet.

visual estimation, showing that about 10% of the porosity is contained in partially degraded feldspar grains with abundant microporosity (fig. 14).

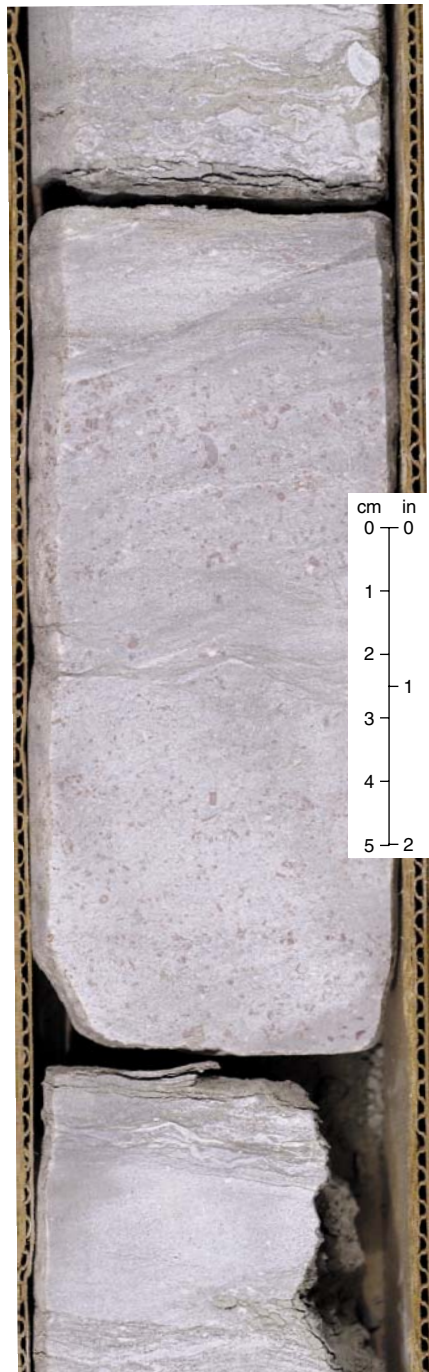


Figure 13 Photograph of core of the red crinoidal limestone within the Downeys Bluff Limestone. Shell Oil Company, Allison No. 3, depth 1,370 feet.

In places, the pores have been partially or totally occluded with calcite cement. In addition, there are minor amounts of clay minerals in the form of chlorite, illite, mixed layered illite/smectite, and kaolinite. From scanning electron microscopy, the individual sand grains were found to be commonly coated with both illite and ferrous chlorite (Widmyer et al. 1988).

Reservoir Characterization

This section discusses the characteristics of the Benoist reservoir in six different oil fields within the study area: Boyd and Dix South, Salem, Centralia, Fairman, and Kinmundy North. The fields were selected because of their different trapping mechanisms and the different amounts of information available in each. For example, Kinmundy North is a pure stratigraphic trap, whereas Fairman is purely structural. Boyd, Salem, and Centralia Fields have abundant geologic data, including core from which to develop better reservoir characterization models of their traps, but Fairman and Dix South Fields have only wireline log data.

Boyd and Dix South Fields

The Benoist sandstone at Boyd and Dix South Fields was featured in a recent report (Leetaru and Mize 2003), and the results of that study are summarized here for comparison. The Benoist reservoir at Boyd Field has produced over 15 million barrels of oil. The Benoist sandstone is characterized by vertical fractures, which form conduits for early coning of water during production. Coning occurs when water prematurely enters the well bore because of vertical fractures. The problem of coning was recognized early in the life of the field. 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.

Multiple vertical fractures up to one foot in length were identified in whole core from the Benoist reservoir sandstone at Boyd Field. Additionally, almost 30% of the measured permeability values from Benoist core showed

vertical permeability to be greater than horizontal permeability, which was unexpected because the horizontal shale laminations present in the Benoist were expected to impede vertical fluid flow.

Trice Oil and Gas Company drilled an extension to Boyd Field and encountered water coning problems similar to those found in the main part of the field. Based on a review of the Benoist production history at Boyd, Trice Oil and Gas found that they minimized the problem of water coning by reducing the wells' initial fluid production rates.

Dix South Field is a marginal field that has produced fewer than 20,000 barrels of oil from the Benoist reservoir. Dix South produces from an anticline with less than 10 feet of structural closure. The field exemplifies the problem of producing from fractured reservoirs on subtle low-relief anticlines. A thin oil column less than 10 feet thick and early water coning significantly reduced the potential recovery from Dix South Field.

Salem Field

Salem Field, located in Marion and Jefferson Counties (fig. 3), extends over 27 square miles and is up to 4 miles wide and 13 miles long. The field contains over 6,000 wells that produce from strata ranging from Mississippian to Ordovician age (fig. 15). In the central portion of the field, the Benoist reservoir sandstone is encountered at an average depth of 1,725 feet and is 45 feet thick.

Salem Field was discovered in July 1938. In its first year, the field ranked seventh in the United States on the basis of daily production; in its first year, the field produced 20 million barrels of oil (Arnold 1939), most of which is thought to have come from the Benoist sandstone (Arnold 1939).

Our study included only a 24-square-mile area in the south-central part of Salem Field (fig. 16) because the densely drilled northern part of the field had few wireline logs and negligible other data to use for either correlation or facies study. Wireline logs for 200 wells in southeastern

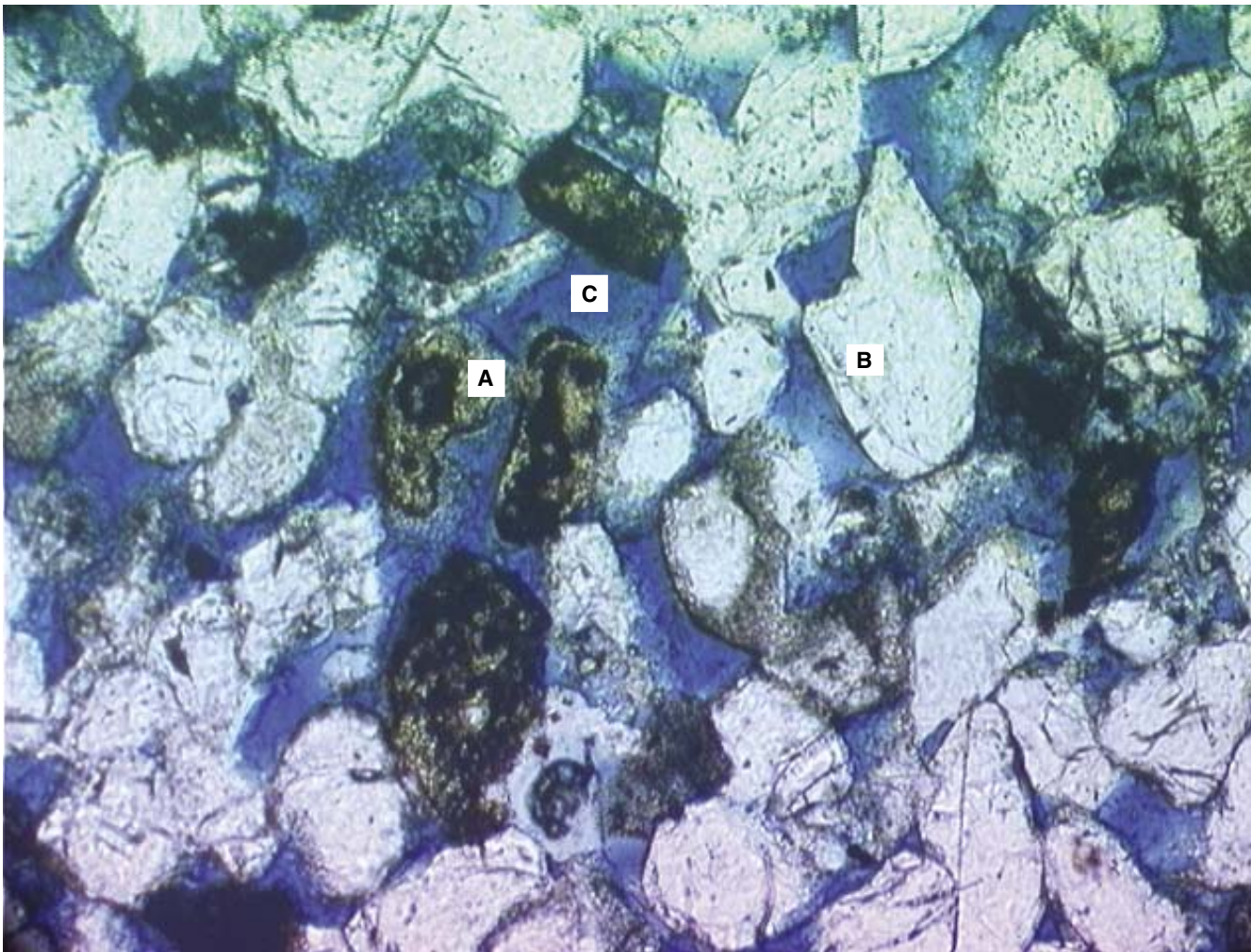


Figure 14 Photomicrograph of the Benoist reservoir sandstone: (A) potassium feldspar grains undergoing degradation, (B) silica cementation in the form of quartz overgrowths, (C) secondary porosity formed from dissolution of grains. Shell Oil Company, Hanseman No. 2 Well, depth 1,367 feet.

Salem Field were digitized and used in correlating the electrofacies of the Benoist sandstone. An electrofacies is defined as “the set of log responses which characterizes a bed and permits it to be distinguished from the others” (Serra 1985). In addition, two wells, Texaco Company Well T17W Tract 108–109 and the Texaco Well T24 Tract 107, had detailed core description information available for relating sedimentary facies to the wireline logs. A smaller eight-square-mile area with dense well control (179 wells; fig. 16) was used to create a three-dimensional geologic model of the reservoir characteristics.

Structure There are almost 280 feet of structural relief on the top of the Downeys Bluff Limestone (fig. 17) in the Salem Field. The highest point of the Salem Anticline occurs just north of the mapping area. The southern part of the anticline is offset to the east and is significantly narrower than the northern part. The southern part of the field has 20 to 40 feet of structural closure and is one mile wide, whereas the northern part can reach up to 4 miles wide.

Benoist Reservoir No whole core from the Benoist sandstone at Salem Field was available in the ISGS Geologic Samples Library. However, the

field operator provided detailed core descriptions for the Texaco Well T24 Tract 107 (figs. 16, 18) and the Texaco Well T17W Tract 108–109 (fig. 19) located 2 miles north of the detailed mapping area. Both cores illustrate the variation of permeability with the shale volume (V_{shale}) curve.

The Benoist sandstone in the Texaco Well T24 Tract 107 (figs. 16, 18) has an upward-fining succession that ranges from fine- to medium-grained at the base of the core to very fine-grained near the top of the sandstone. The permeability of the reservoir sandstone ranges from 200 to 300 millidarcies (mD) in the lower part of

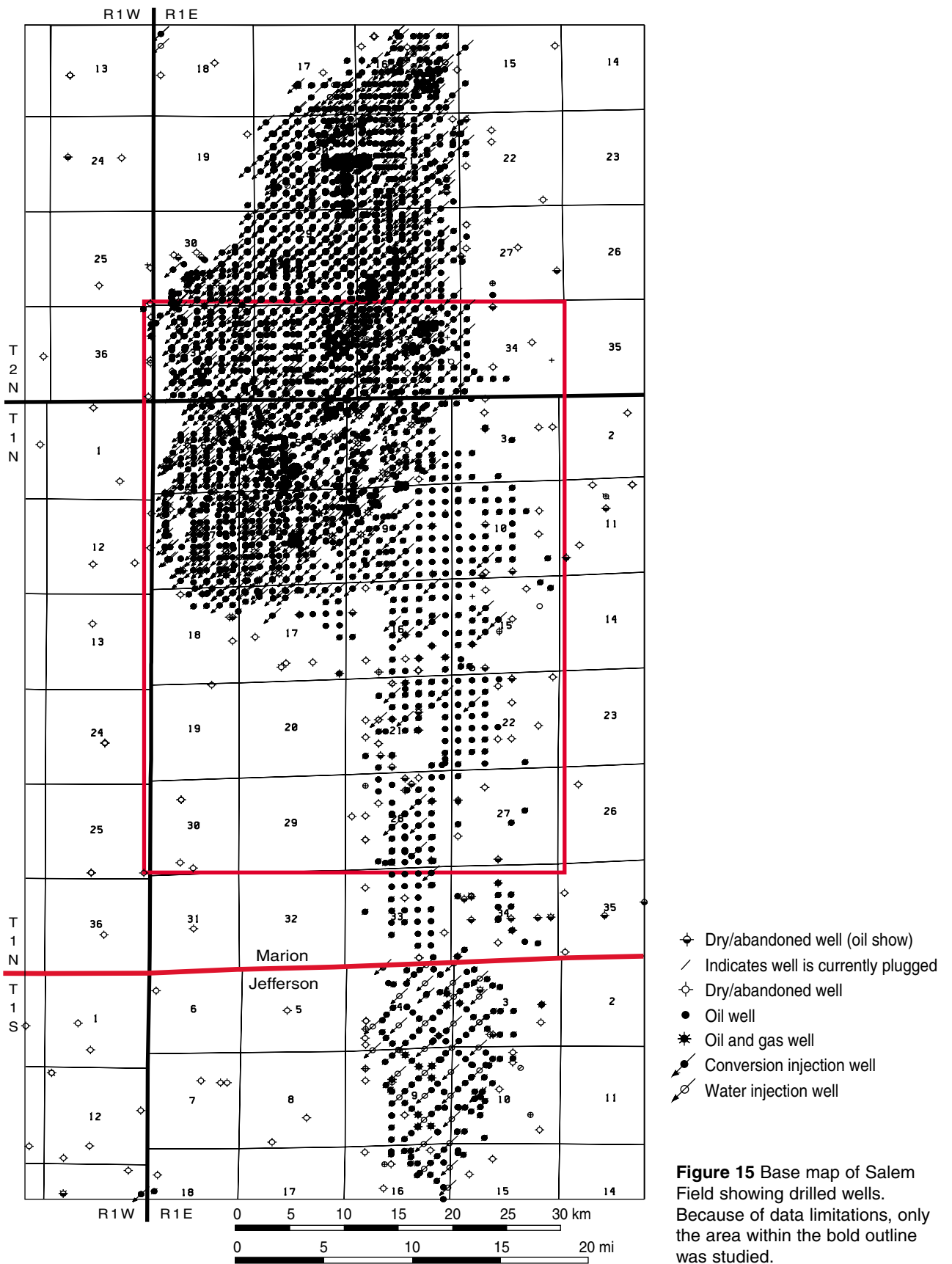


Figure 15 Base map of Salem Field showing drilled wells. Because of data limitations, only the area within the bold outline was studied.

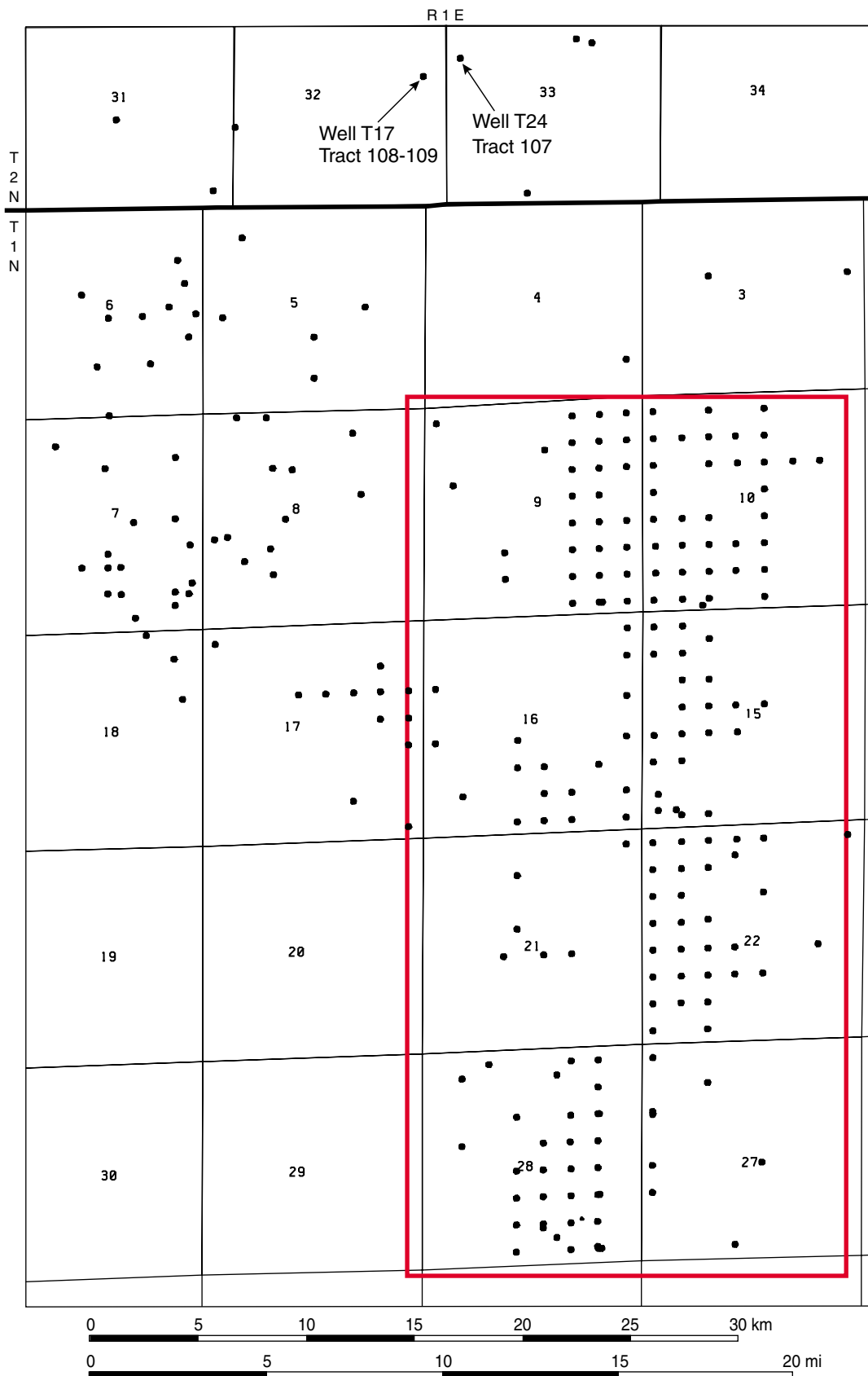


Figure 16 Salem Field study area with the location of wells used in this study and the location of the two cored wells. The three-dimensional model was generated for the area within the bold outline.

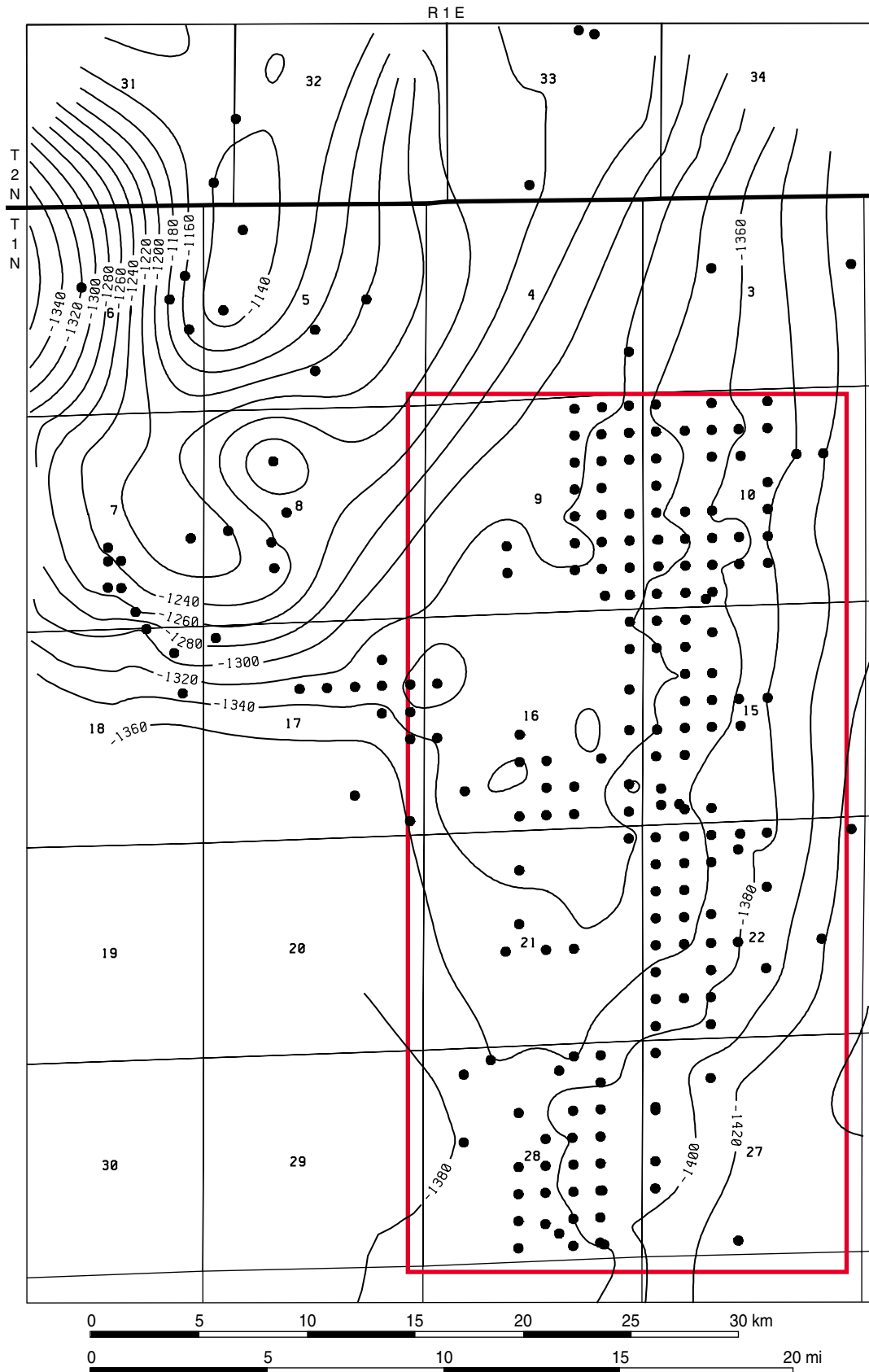


Figure 17 Map showing the structure on top of the Downeys Bluff Limestone at Salem Field. Contour interval is 20 feet.

the sandstone and 100 to 200 mD in the upper part. Sandstones with less than 0.1 mD of horizontal permeability are fine- to very fine-grained and have either extensive calcite cement or multiple shale laminae and green clay partings within the sandstone. The reservoir bedding is horizontal or slightly inclined, and there are some isolated cross-bedded intervals. Although there is a large range in permeability values, porosity ranges only from 15 to 20% in the core.

The upper part of the Benoist relative to the basal part of the sandstone in the Texaco Well T24 Tract 107 (fig. 18) has an increase in Vshale and a corresponding decrease in permeability. The Vshale curve through the Benoist in the Texaco Well T17W Tract 108–109 well

(fig. 19) shows a blocky massive character with only a slight increase in the Vshale values in the top 10 feet of the sandstone. The permeability measurements also show no distinctive change.

Lateral Variation in Depositional Environments The Benoist sandstone isolith in the study area ranges from 0 to 55 feet of sandstone (fig. 20). Near the east-central part of the study area, there is a linear feature 3.5 miles long by 800 feet wide (identified by the south-trending arrow) with sandstone isolith values of less than 20 feet. The feature is bounded on either side by much thicker (55 feet or greater) sandstone bodies. The depositional pattern of the sandstone isolith is suggestive of an abandoned distributary channel-bar complex similar to those described

in the Mississippi delta (Coleman and Prior 1982). In this depositional setting the abandoned channel is filled with fine-grained material, whereas the adjoining distributary mouth bars have thick sandstone deposits. The rest of the sandstone isolith map does not show any distinctive features and may instead be part of the interdistributary bay strata composed of small channels, crevasse splay deposits of sandstone and shale, and flood basin fines deposited within the bay.

Cross section A–A' (fig. 21) is a stratigraphic section with a datum on top of the Downeys Bluff Limestone. This cross section is perpendicular to the north-south linear feature observed on the Benoist sandstone isolith (fig. 20). Well 3 (fig. 21) has a distinctive

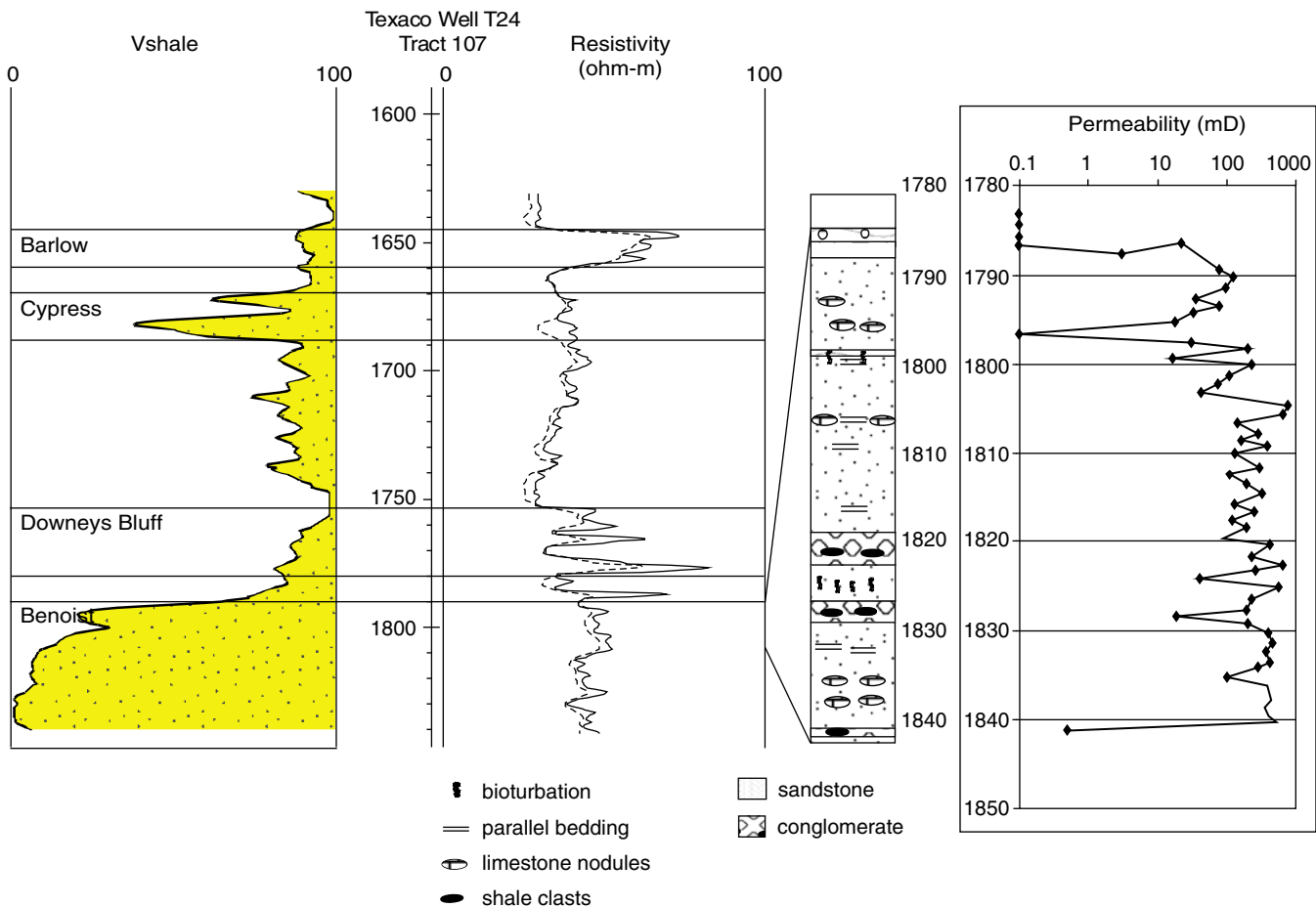


Figure 18 Diagram showing wireline log, permeability measurements, and core description of Texaco Well T24 Tract 107. The key to the symbols used in the core description is found in Appendix 1. (Core description is from an unpublished report by Texaco Corporation.)

upward-fining pattern on the Vshale curve, and the sandstone with the best reservoir quality sandstone occurs near the base of the Benoist. The wells on either side of Well 3 have a blockier Vshale pattern, suggesting they contain relatively massive sandstone with no significant shale breaks that could vertically compartmentalize the reservoir.

Cross section B-B' (fig. 22) is one mile south of cross section A-A' (fig. 20) and crosses the distributary channel (Well 5) and distributary mouth bar system (Wells 7, 8, 9, and 10). The sandstone in Well 5 again has an upward-fining sedimentary succession portrayed by the Vshale curve. The Benoist sandstone in the three westernmost wells has the somewhat "serrated" log pattern that is com-

monly found in an interdistributary bay setting in which isolated sandstone bodies have splayed off the main distributary channel-mouth bar complex.

Cross section C-C' (fig. 23) is southernmost in the Salem Field study area. Well 4 contains no Benoist sandstone, and Wells 5 and 6 contain only a basal sandstone. Well 4 is interpreted to have been a former distributary channel that was filled in by shale. As illustrated by the Benoist sandstone isolith map (fig. 20), the adjoining Wells 5 and 6 are also in a partially shale-filled channel. During channel abandonment, coarse basal channel sand is overlain by fine-grained silts and shales (Coleman and Prior 1982); therefore, the reservoir sandstone in

these channels occurs lower in the section and is generally not productive. The basal sandstone is probably a remnant of the coarser-grained channel lag sandstone found in many fluvial and distributary channel systems (Reineck and Singh 1975).

Figure 24 illustrates the relationship of the Benoist Vshale curves and the sandstone isolith. The thickest and best-quality reservoir sandstone occurs along the margins of the distributary channel system. Most of the wireline logs from these wells have a blocky to upward-fining log character on the Vshale curve. Benoist sandstones with serrated Vshale patterns are interpreted as having been deposited in interdistributary bays as small channels or crevasse splays.

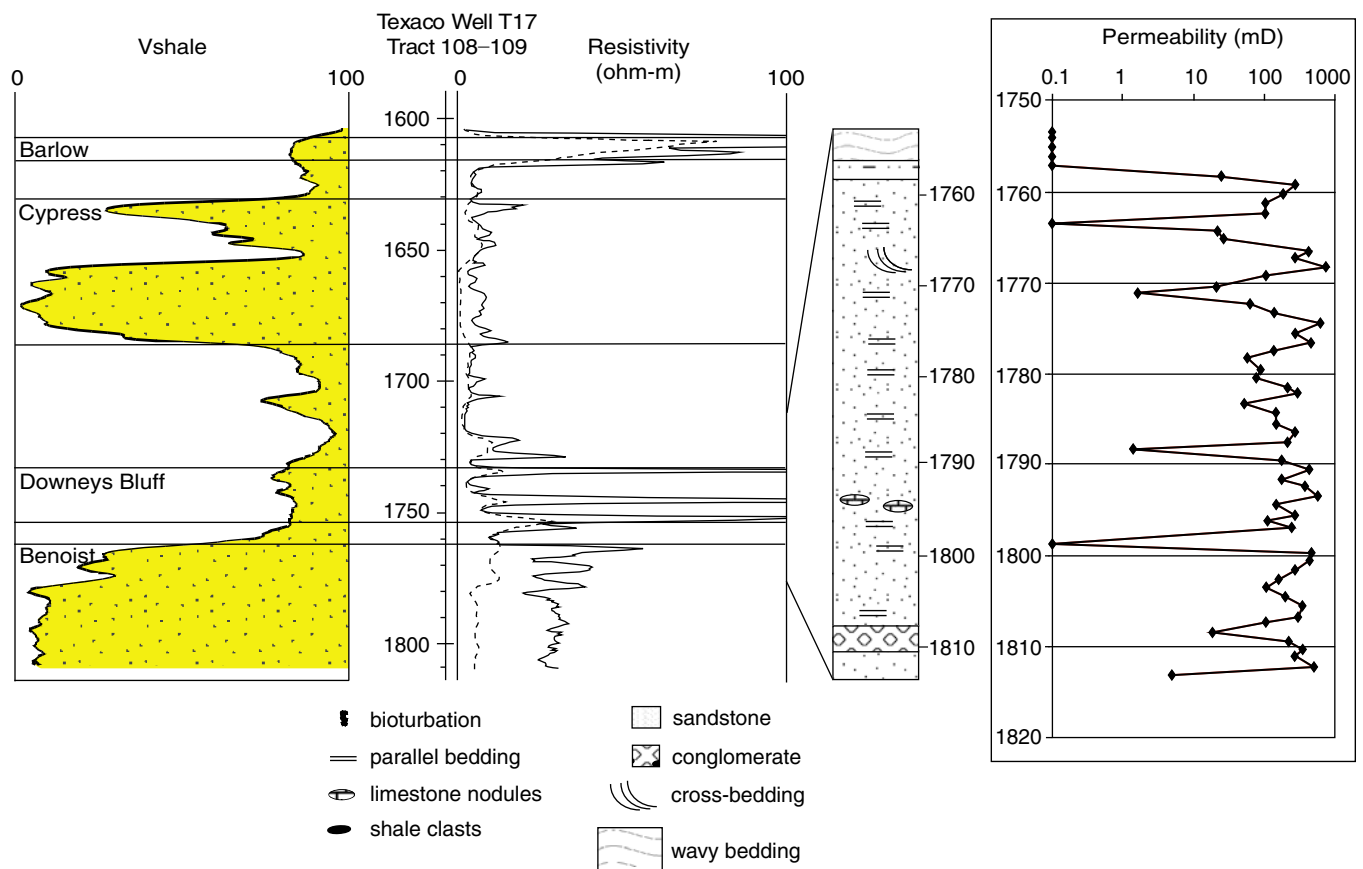


Figure 19 Diagram showing wireline log, permeability measurements, and core description of Texaco Well T17 Tract 108-109. The key to the symbols used in the core description is found in Appendix 1. (Core description is from an unpublished report by Texaco Corporation.)

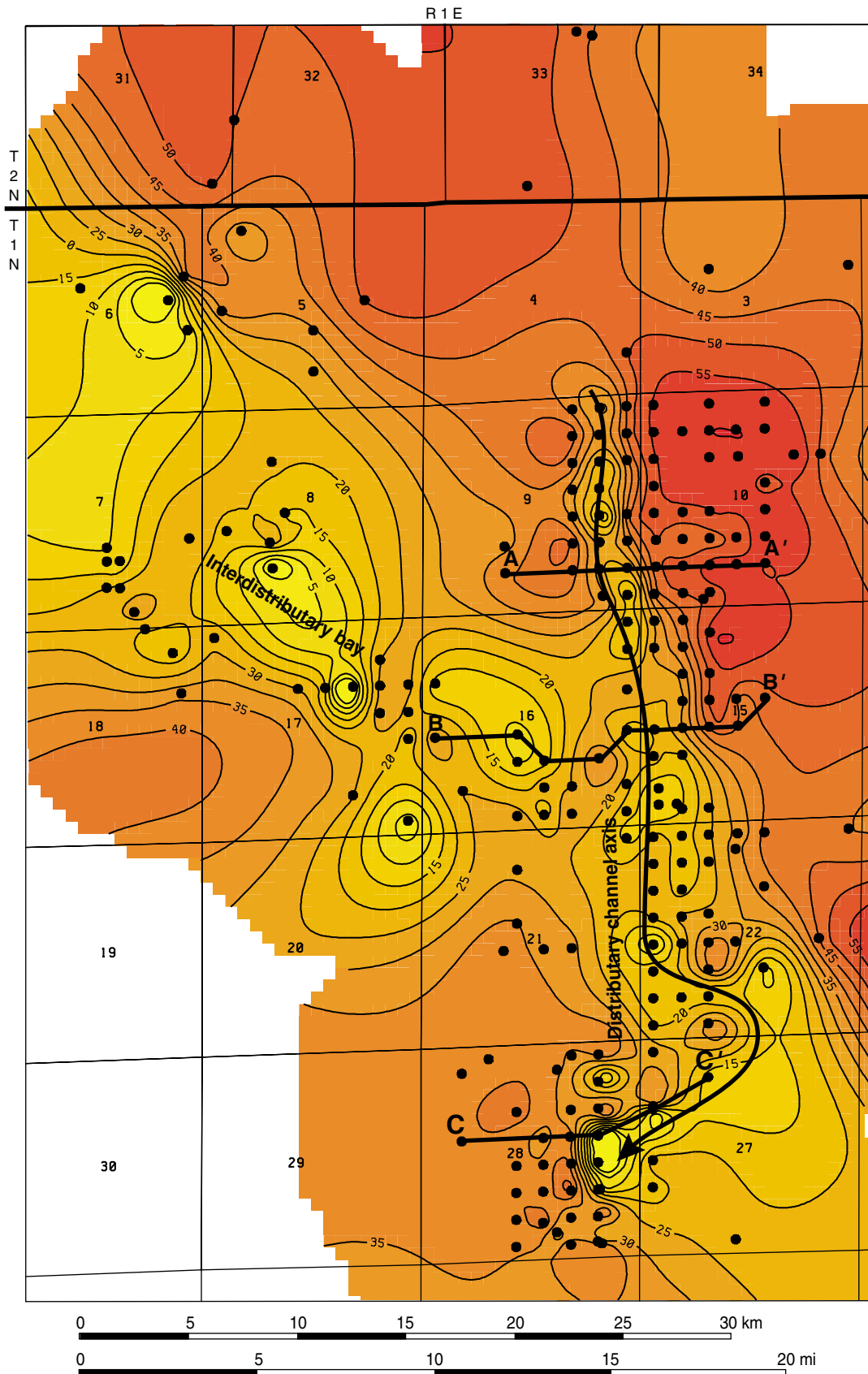


Figure 20 Map of the Benoist sandstone isolith (net sandstone) at Salem Field. The three cross sections discussed in this study are shown. The north-south-meandering arrow overlays a possible channel in the Benoist. The darker-shaded contoured areas signify thicker sandstone isolith values. Contour interval is 5 feet.

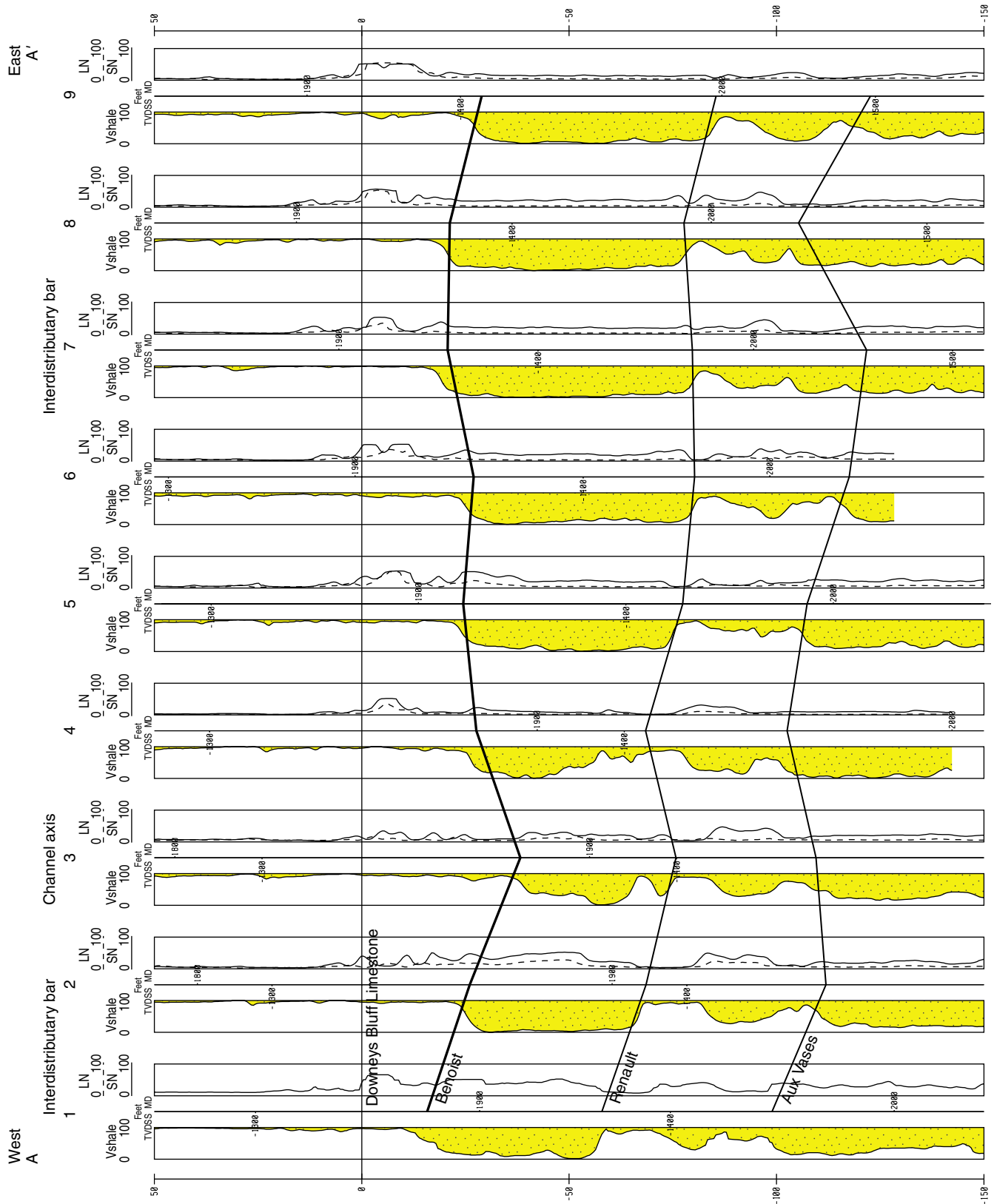


Figure 21 Stratigraphic cross section A-A' through the northern part of the Benoist channel in Salem Field. Vshale, shale volume; LN, long normal; SN, short normal.

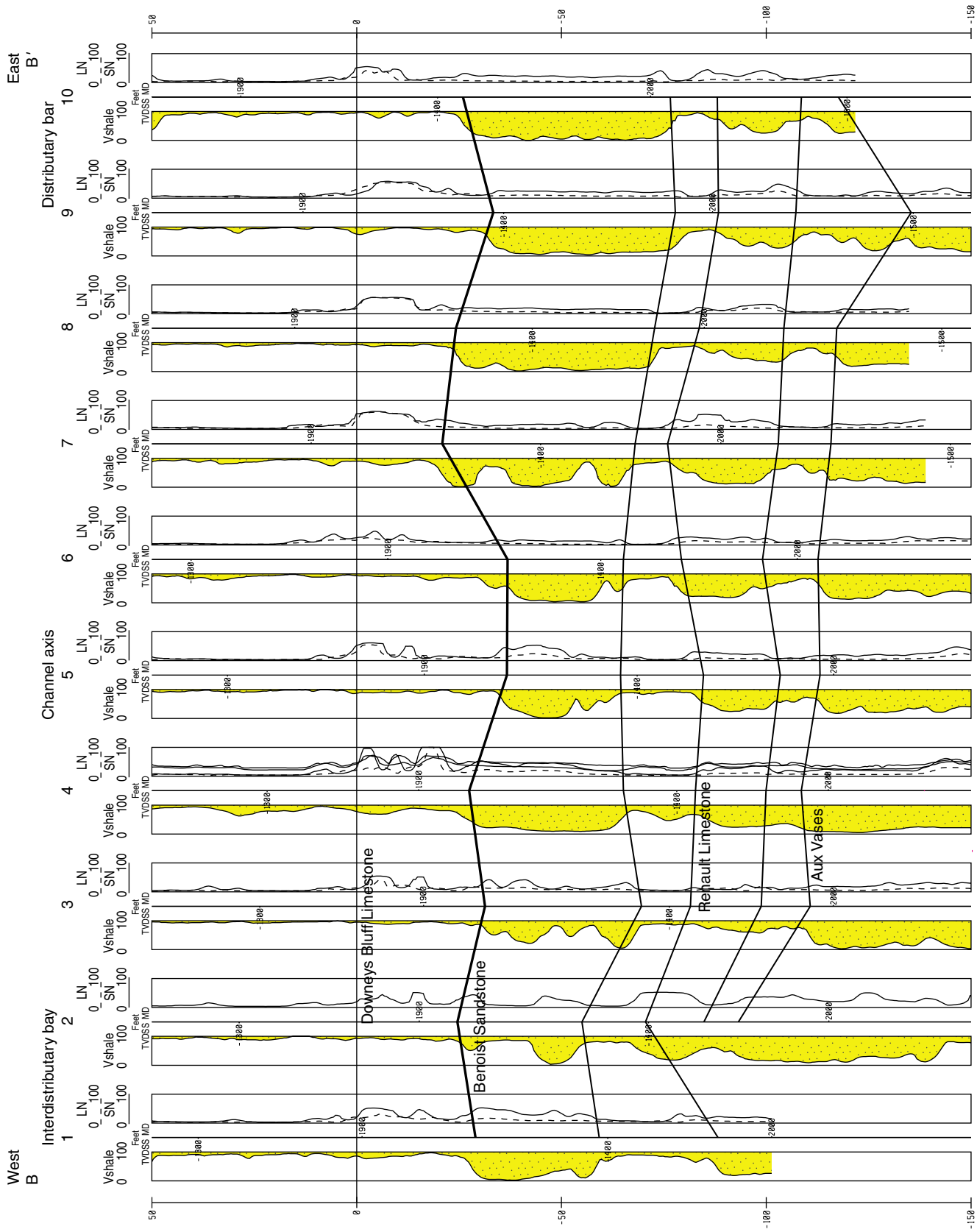


Figure 22 Stratigraphic cross section B-B' through the southern part of the Benoist channel in Salem Field. Vshale, shale volume; LN, long normal; SN, short normal.

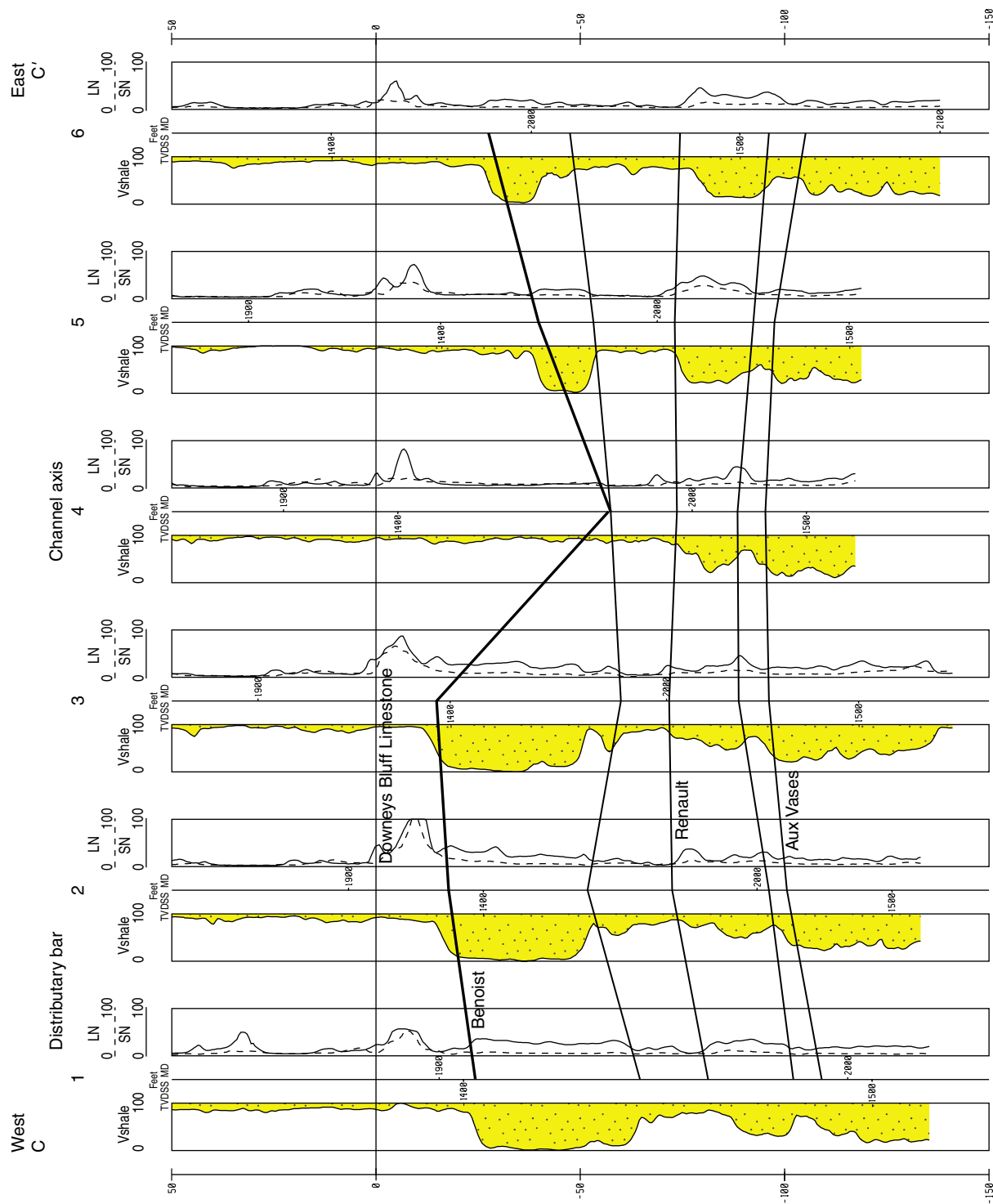


Figure 23 Stratigraphic cross section C-C' shows that Well 4 has no Benoist sandstone present. Vshale, shale volume; LN, long normal; SN, short normal.

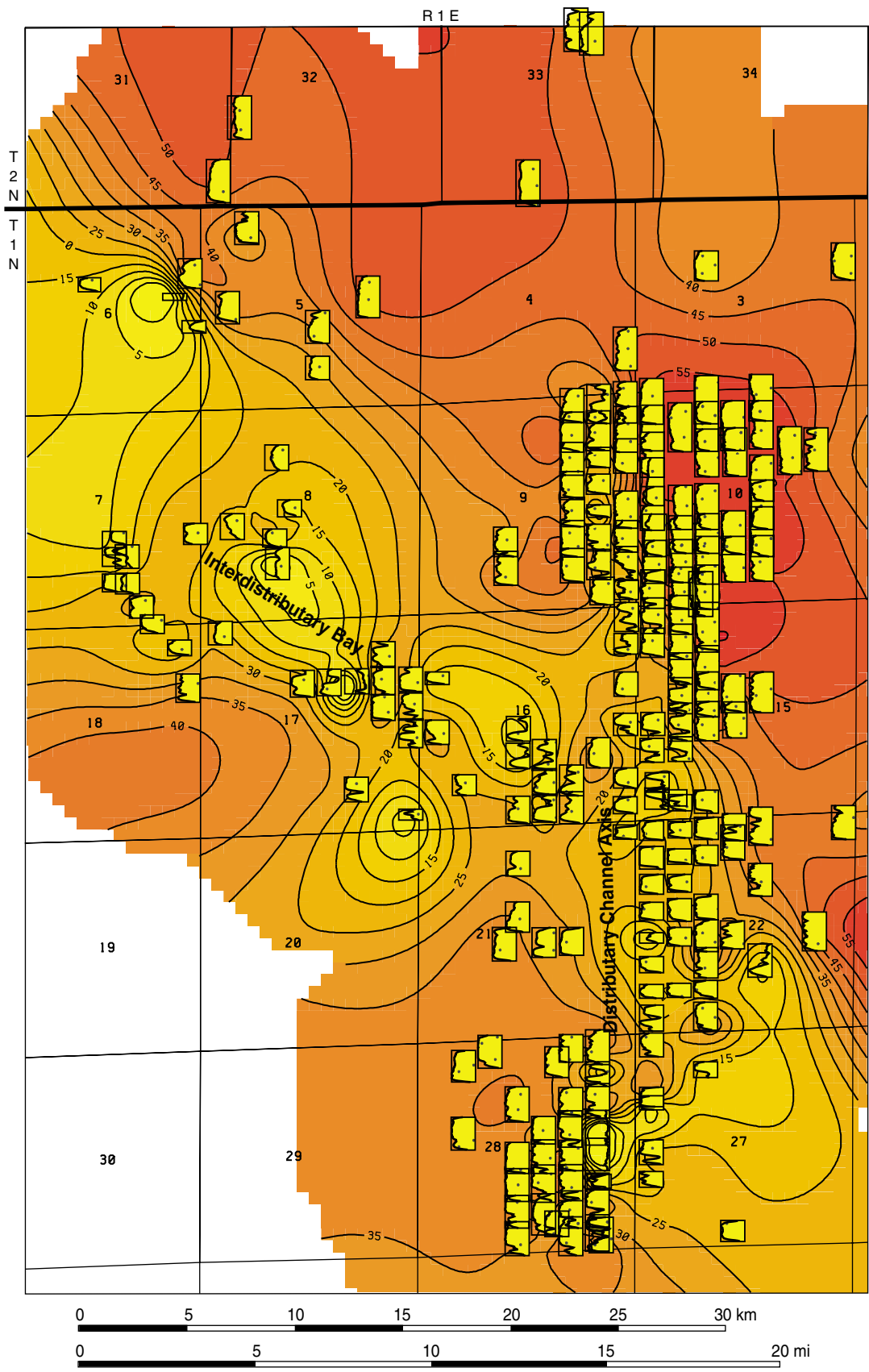


Figure 24 Benoit sandstone isolith with overlay of the shale volume log signature of only the Benoit sandstone at Salem Field. The darker-shaded contoured areas signify thicker sandstone isolith values. Contour interval is 5 feet.

Three-dimensional Model of Salem Field A three-dimensional model of the Benoist reservoirs in the Salem Field study area was constructed using 175 of the wireline logs. Variation in Vshale across the study area is shown in Figure 25. The purple and bluish intervals are low-permeability shales with Vshale values near 100%. The model shows that the basal part of the Benoist sandstone with low Vshale values shown as red to yellow appears to be continuous across most of the study area, but the uppermost Benoist, where the hydrocarbons would be trapped, is not continuous. This finding suggests that the drainage area of each well may be limited by the areal extent of the uppermost Benoist sandstones.

Tertiary Recovery The original operators of the field produced their wells as fast as they could with no consideration for efficient reservoir management (Arnold 1939). It is probable that only a small part of the oil was recovered during primary recovery. Although much of the Benoist sandstone reservoir at Salem Field has been waterflooded, the initial waterflood left extensive residual oil in the pore space because of differential permeabilities around the different strata. The lower two thirds of the reservoir sandstone has permeability values that are 50% greater than those of the upper part of the Benoist (Widmyer et al. 1988). During the 1980s, Texaco observed that the lower strata had residual oil saturations of 28%, whereas the upper Benoist had residual oil saturation values of 36%. In order to recover additional oil, Texaco began a polymer flood of the Benoist sandstone in Salem Field. The company injected a brine-tolerant surfactant followed by a biopolymer. This tertiary project was not as effective as hoped (Widmyer et al. 1988) because the polymer degraded faster than anticipated, and the injection rates may have been too high. However, during the first 5 years of the flood, an additional 457,354 barrels of oil were recovered. The operator's initial chemical treatment costs were as high as \$8.53 per barrel; subsequently, costs were reduced to less than \$2.11 per barrel (Widmyer et al. 1988).

Future Strategies There are no wireline log data for many of the wells in Salem Field, and realistic reservoir characterization of the field is difficult without that information. The Texaco experience suggests that further tertiary recovery could successfully recover additional oil from this field as long as oil prices remain high, the cost of chemicals is kept low, and a realistic geologic model of the reservoir is used.

Centralia Field

Centralia Oil Field is a northwest-trending anticline located on the western flank of the DuQuoin Monocline (figs. 3 and 5). The field has more than 55 feet of closure and is 6 miles long and 1 mile wide (fig. 26). The Benoist reservoir sandstone is encountered at an average depth of 1,350 feet. Centralia Field was discovered in 1937 and has produced 58 million barrels of oil from Pennsylvanian, Mississippian, Devonian, and Ordovician strata.

Structure The structure map on top of the Downeys Bluff Limestone (fig. 27) shows a northwest-trending anticline with 45 feet of structural closure. The highest position within the field occurs at -845 feet near the center of the field in Section 1. Three higher areas separated from one another by lower saddles characterize the anticline. Although the same wells were used in generating both maps, the structure on top of the Benoist sandstone (fig. 28) is similar but not identical to the top of the Downeys Bluff Limestone that overlies it (fig. 27). The difference between the two contour maps is caused by the stratigraphic thickening and thinning of the strata between the top of the Downeys Bluff Limestone and the top of the Benoist sandstone.

Lateral Variation in Facies The Benoist sandstone isolith map for Centralia Field shows a distinctive north-south-meandering feature where the sandstone ranges from 25 to 50 feet thick (fig. 29). On either side of this feature, the sandstone thins to less than 15 feet thick. The meandering feature is interpreted to be a smaller secondary channel off a larger distributary channel-bar system similar to the one described in Salem Field. This

secondary channel is less than 2,000 feet wide at its widest point. The Benoist channel appears to have scoured into the underlying shales (Wells 3 and 4, fig. 30). Wireline logs of the Benoist sandstone within the channel have a massive blocky character with no significant shale breaks (Wells 3 and 4, fig. 30). Not all channels are filled with sandstone; at Salem Field, the Benoist channel was filled with shale due to channel abandonment.

Outside the channels, the net sandstone is thin and occurs in multiple thin reservoir compartments separated by laterally continuous shales (Wells 1 and 6, figs. 31 and 32). Because of their thin nature (less than 15 feet) and upward-coarsening pattern on wireline logs, the sandstones are interpreted to have been deposited originally as crevasse splays in an interdistributary bay (fig. 32). The best reservoirs in the crevasse splay deposits mostly are located in the upper part of the Benoist because of the upward coarsening of the strata.

Three-dimensional Modeling of the Benoist Sandstone A northwest-trending series of cross sections (fig. 33) of the Benoist sandstone shows that the sandstone strata with the best reservoir quality (those with low Vshale values) are discontinuous across the field, generally extending laterally for a thousand feet or less. The dark blue strata are non-reservoir facies. The sandstones with Vshale values greater than 30% (green to blue and purple) typically are poor-quality reservoirs with large amounts of shale as continuous laminae or scattered throughout the sandstone.

The three-dimensional model (fig. 34) shows the areal distribution of sandstone with a Vshale content of less than 30. The best-quality reservoir is commonly about 1,000 feet wide and is coincident with the channel axes identified on the sandstone isolith map. The field was well developed by the initial drilling (10-acre spacing) that occurred after its discovery, but planning of a secondary waterflood or tertiary polymer flood similar to that of the Benoist reservoir at Salem Field must take into account the three-dimensional geometry of the reservoir.

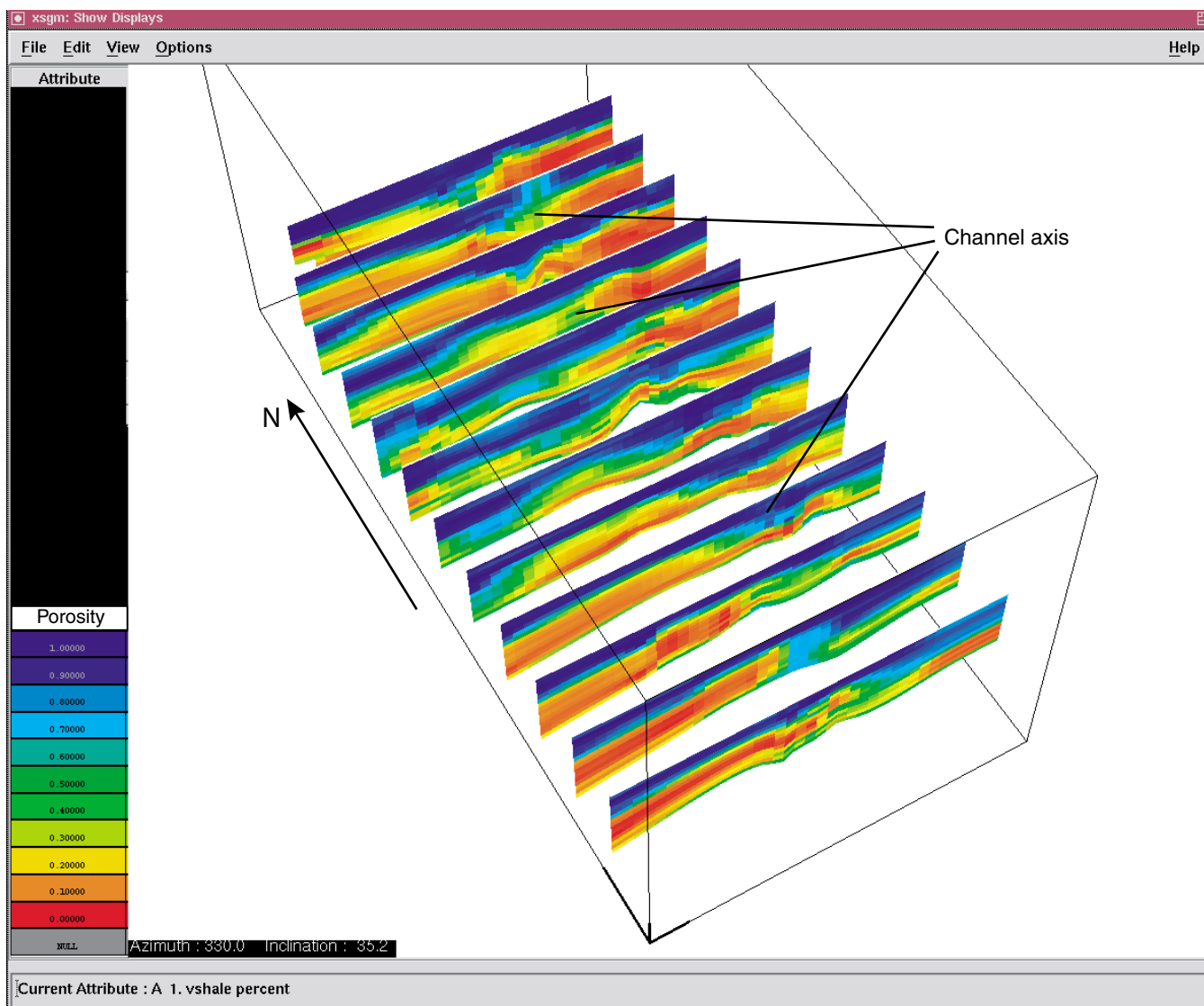


Figure 25 Fence diagram showing the distribution of the shale volume (Vshale) values across the study area at Salem Field. The datum for the sections is the top of the Downeys Bluff Limestone. Red indicates the best-developed sandstones; the blue zones represent nonreservoir facies composed of shales and limestones.

A geologically planned waterflood would concentrate on the larger reservoir compartments and would locate the injection wells and producing wells in the same reservoir compartment. Some additional wells likely will be needed to optimally waterflood the field.

In Salem Field, we observed a general relationship between permeability and Vshale values. This relationship assumes that permeability is inversely proportional to the amount of clay minerals in the sandstone. Although it

is generally true that sandstones with low Vshale values have the best permeability, in some cases, permeability also is reduced by calcite and quartz cementation that blocks the pore throats. A cross section of the permeability values (fig. 35) shows that the permeability is greatest in the upper part of the reservoir and decreases in the deeper layers of the model. This model also shows that some layers have permeabilities that are almost 1 darcy. In the same Benoist reservoir, there are adjoining layers with

permeabilities of less than 100 mD. These large variations in permeability from place to place cause early breakthrough of injected water during a waterflood and significantly reduce oil recovery. The permeability variation suggests that this field is a potential candidate for using tertiary recovery techniques such as adding polymers to the injected water to improve oil recovery. The polymers will block the high-permeability swept zones and direct more of the water through the bypassed zones.

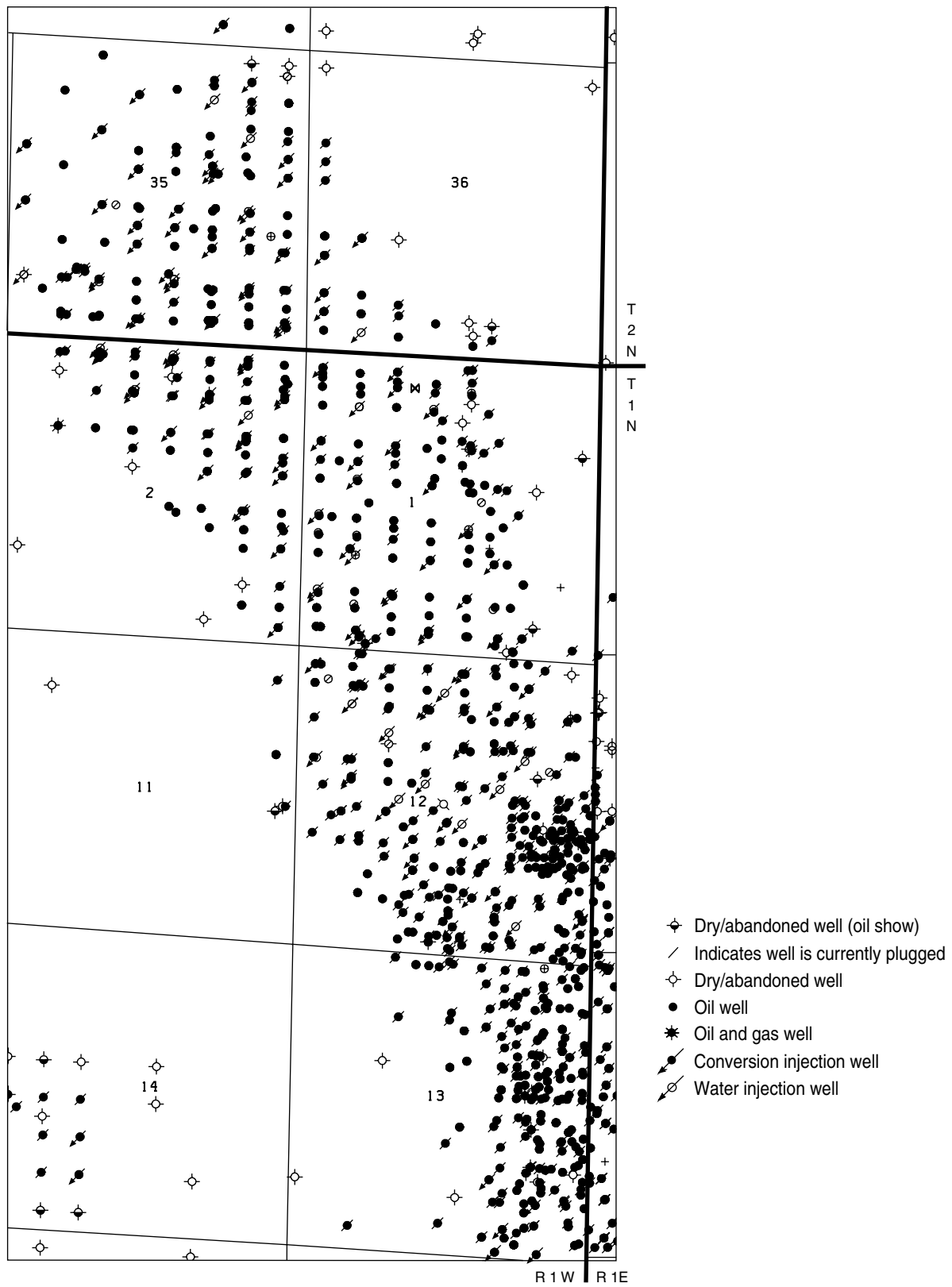


Figure 26 Map of Centralia Field showing all of the wells.

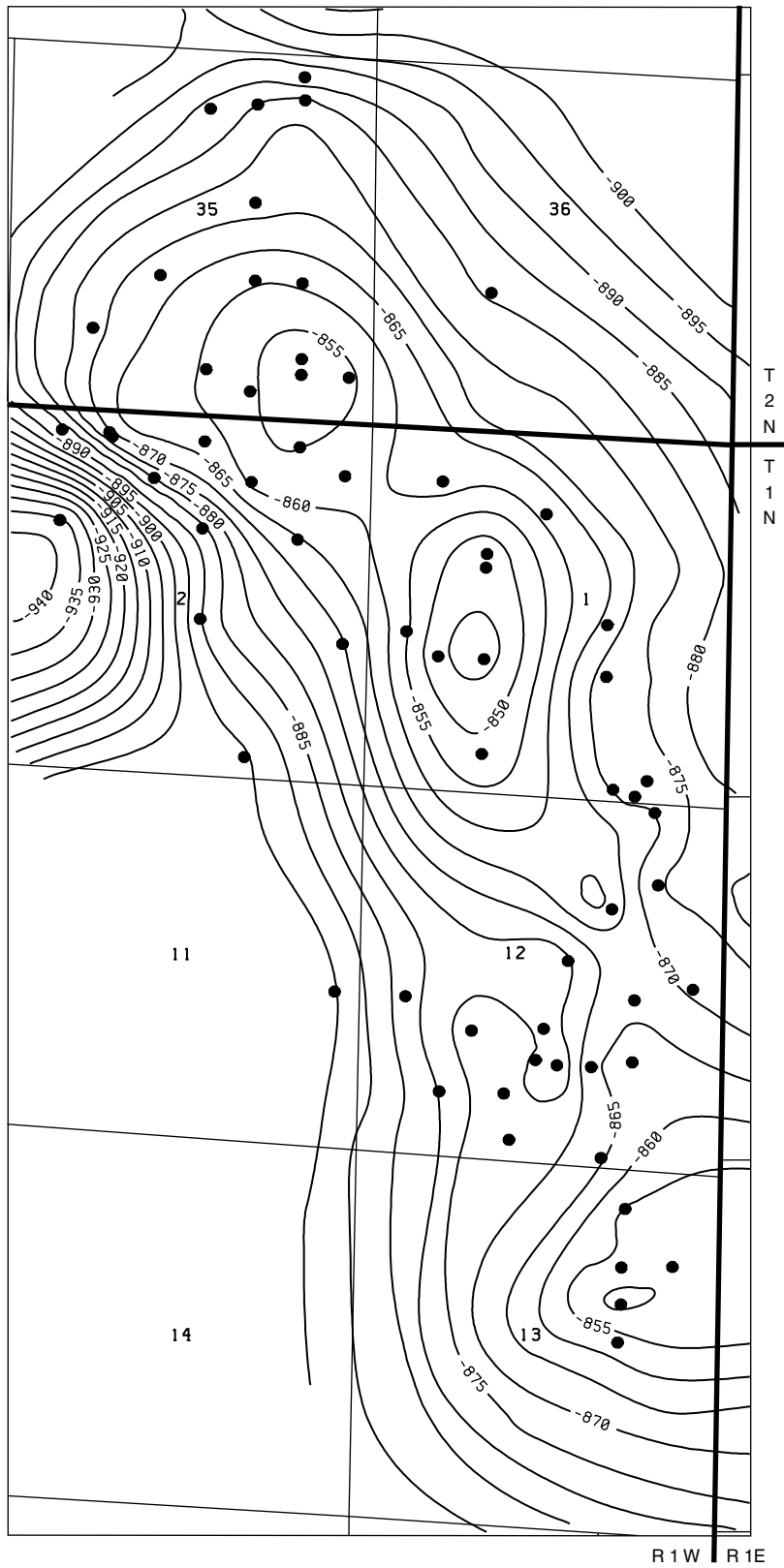


Figure 27 Structure map on top of the Downeys Bluff Limestone in Centralia Field. Contour interval is 5 feet.

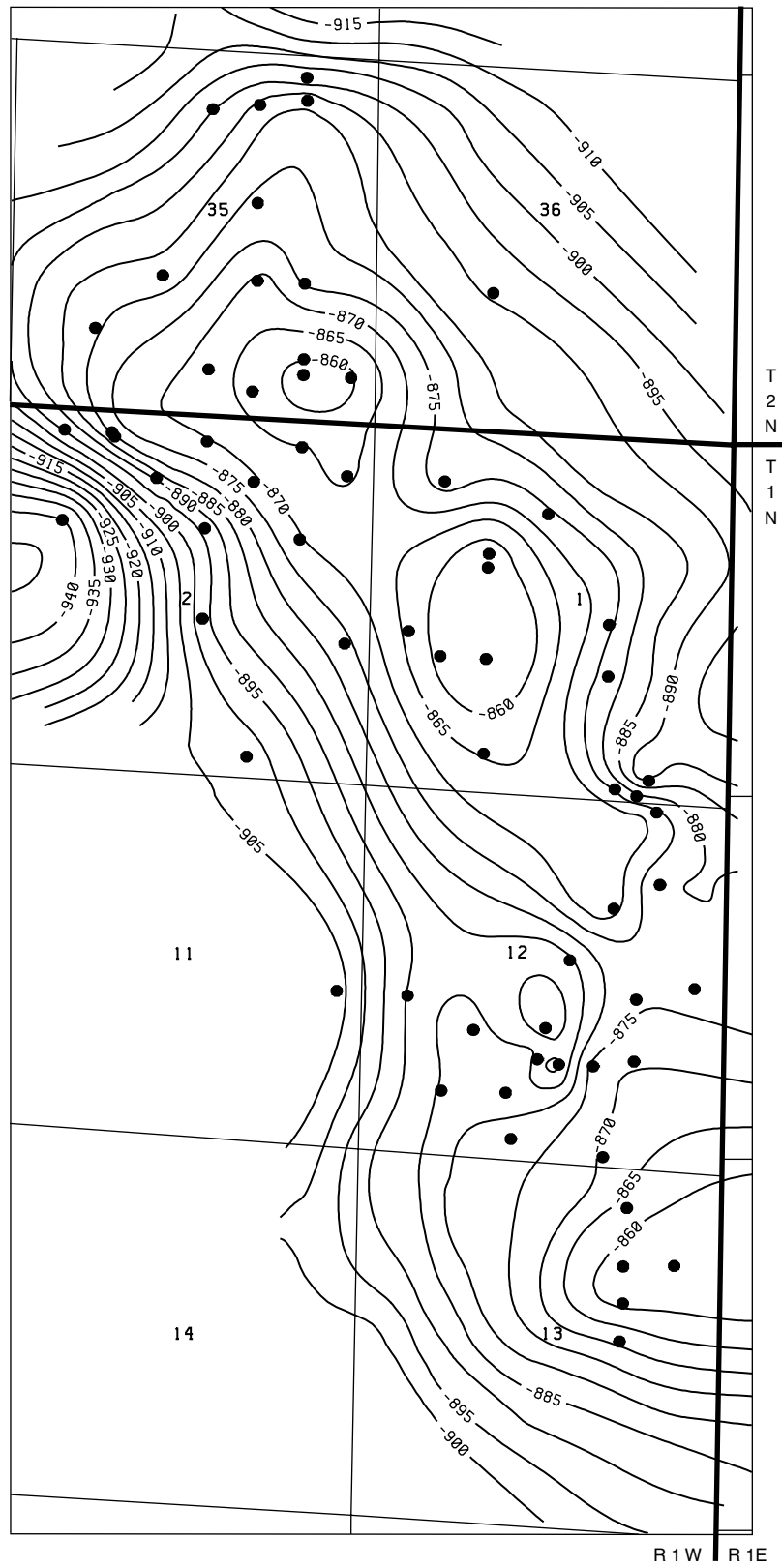


Figure 28 Structure map on top of the Benoist sandstone. Contour interval is 5 feet.

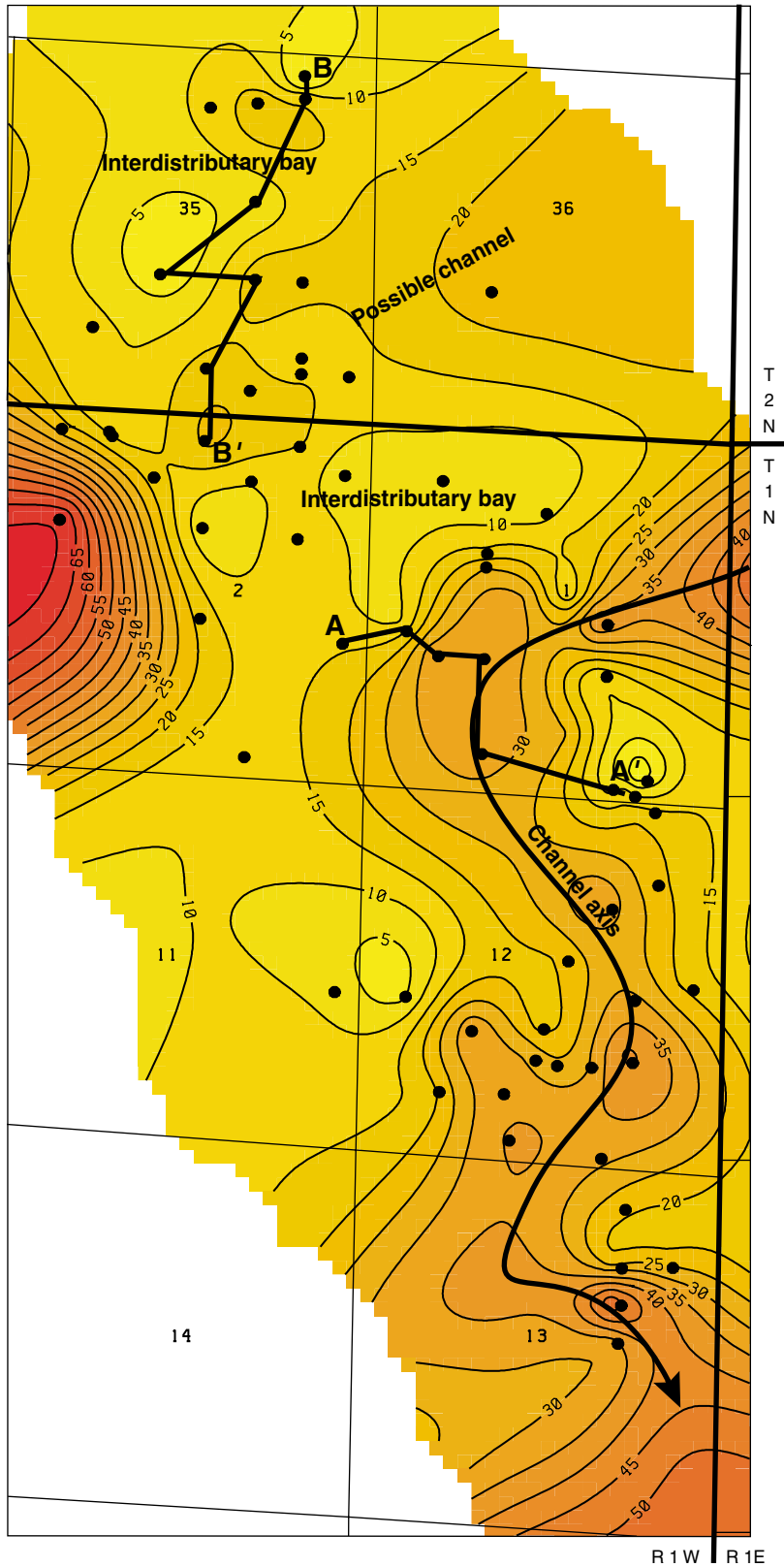


Figure 29 Benoit sandstone isolith at Centralia Field showing the location of the two cross sections. Areas with darker shading have greater net sandstone volume. The most significant feature on this map is the north-south-trending channel. Contour interval is 5 feet.

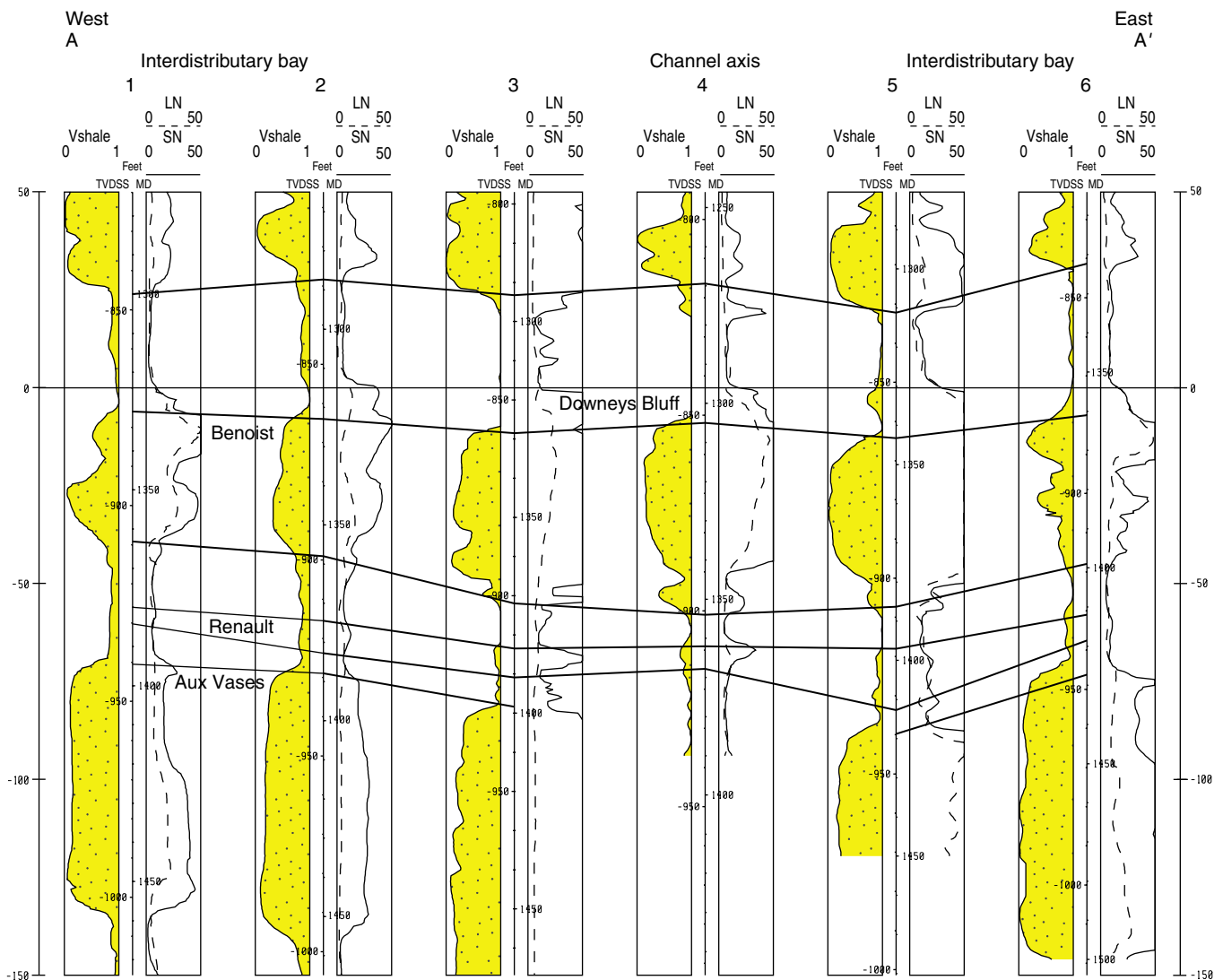


Figure 30 Stratigraphic cross section A–A' is perpendicular to the strike of a possible Benoit channel.

Future Strategies The Benoit sandstone at Centralia Field was deposited as part of a channel and crevasse splay/interdistributary bay in a deltaic environment. The main Benoit channel is only 3,000 to 4,000 feet wide and over 3 miles long. The parts of the Benoit that were deposited as crevasse splays in the interdistributary bay have a more limited areal extent. The lateral extent of the different types of deposits in the Benoit reservoir are important in planning a geologically controlled waterflood. Water injection and oil-producing wells need to be along the strike of the channel

sandstone in order to be effective. A waterflood program in the crevasse splay will be limited by the size of the individual splay deposit.

The permeabilities of adjacent layers of the Benoit reservoir sandstone can differ by more than an order of magnitude. These variations in permeability would create numerous bypassed oil zones during the conventional waterflooding of the field. Polymer flooding could increase oil recovery from this field by changing the viscosity of the water and allowing the bypassed zones to be swept by water.

Fairman Field

Fairman Field, located in Clinton and Marion Counties (fig. 3), is only 1.5 miles long and 0.5 mile wide. Approximately 50 wells there have produced oil from Devonian and Mississippian age formations, including the Benoit (fig. 36). The Benoit reservoir sandstone is encountered at a depth of 1,450 feet.

Structure Fairman Field overlies a northeast-trending anticline, the origin of which is interpreted to be a pre-Silurian high (Nelson 1995). There is 25 feet of structural closure at the

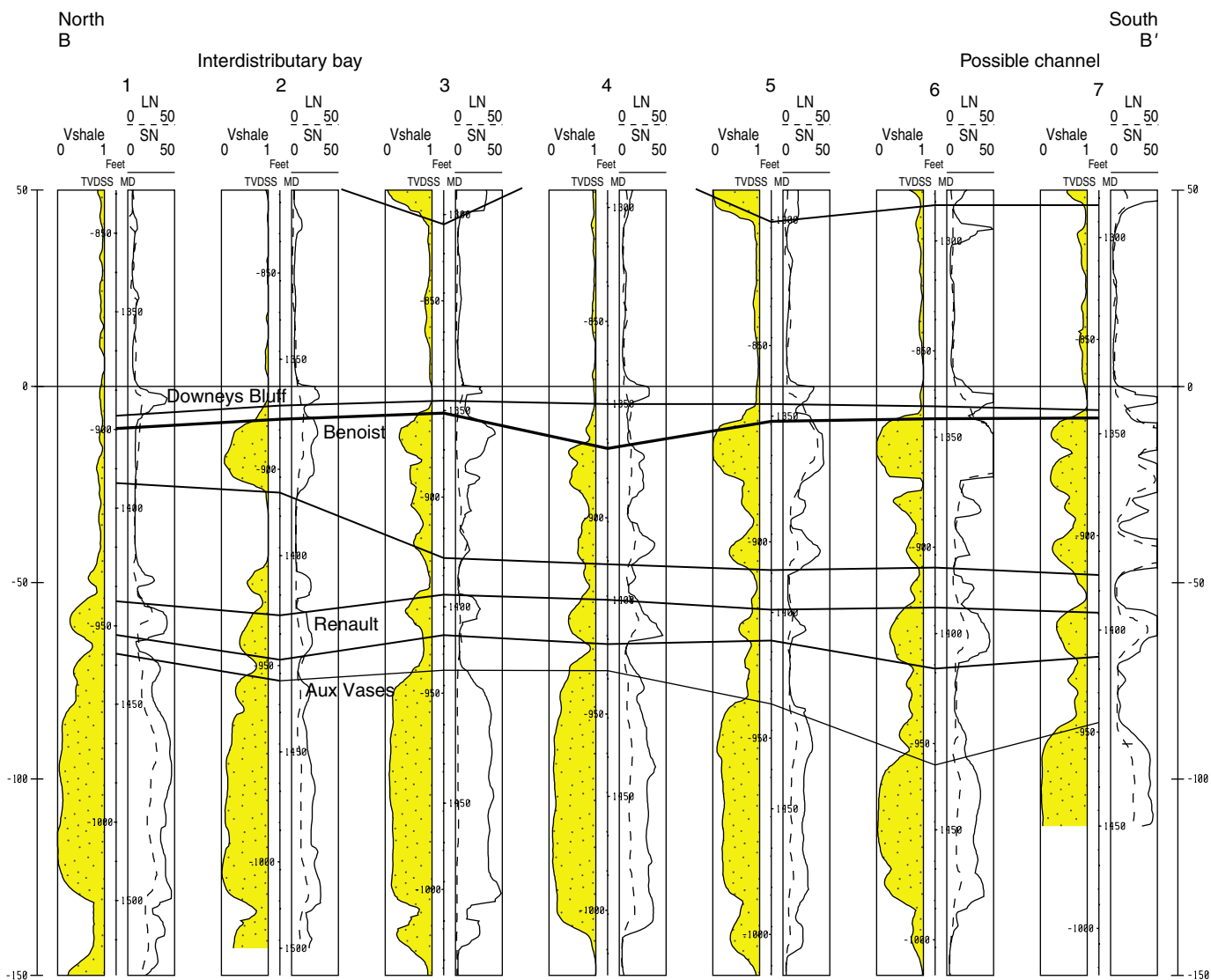


Figure 31 Stratigraphic cross section B–B' shows the character of the Benoist sandstone in an interpreted interdistributary bay–crevasse splay deposit.

top of the Benoist sandstone (fig. 37) with two distinct high areas separated from each other by a saddle-like structure.

Lateral Variation of the Sandstone

The Benoist sandstone isolith map, based on logs that fully penetrate the unit, shows no sandstone present in the northern part of the mapping area (fig. 38), but to the west of the main structural high, the sandstone is over 55 feet thick. The well control is inadequate to delineate the orientation of the Benoist sandstone isolith maxima and minima. The south-north

stratigraphic cross section (fig. 39) illustrates the northerly pinchout of the Benoist reservoir (Well 5). The SP curves show a pattern of upward-increasing shale content in the Benoist, reflecting deposition under progressively lower energy conditions. The underlying Aux Vases Sandstone is 70 feet thick but has no hydrocarbon production in the field.

Future Strategies Fairman Field is an example of a simple Benoist structural trap. The pinchout of the sandstone occurs off the domal structure and has no effect on the hydrocarbon trapping

mechanism. As a simple structural trap, Fairman Field does not present many opportunities for infill drilling to increase oil production. Operators would need to find new structural extensions to this field in order to find additional oil reserves.

Kinmundy North Field

Kinmundy North Field, located in northern Marion County (fig. 3), is 2 miles long and 0.5 mile wide (fig. 40). The trapping mechanism is an updip pinchout of the Benoist sandstone, and there are at least four different oil-

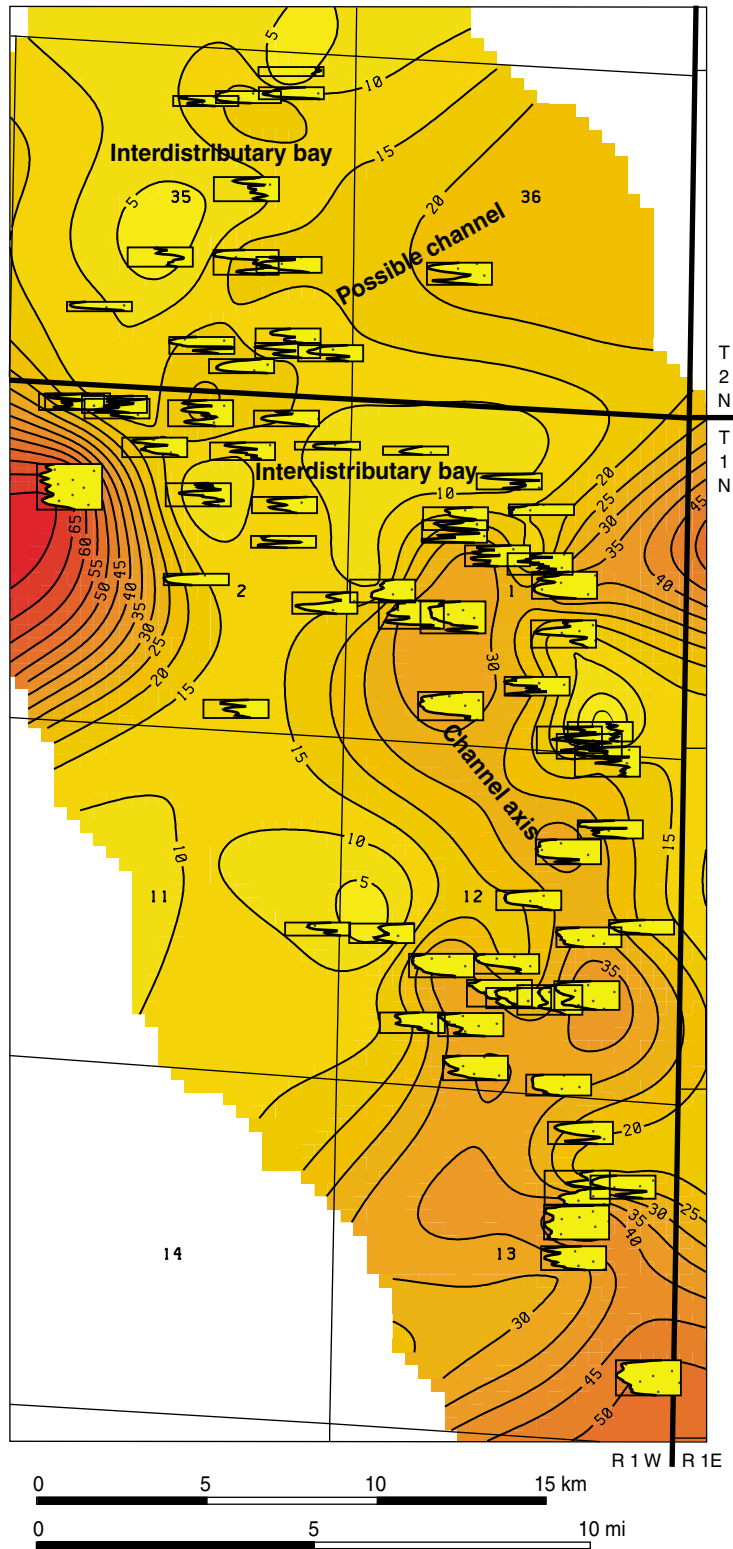


Figure 32 Benoit sandstone isolith at Centralia Field. All of the calculated Vshale values from the individual wells overlay the map. The displayed wells were also used in creating the three-dimensional model of the Benoit sandstone at Centralia Field. Contour interval is 5 feet.

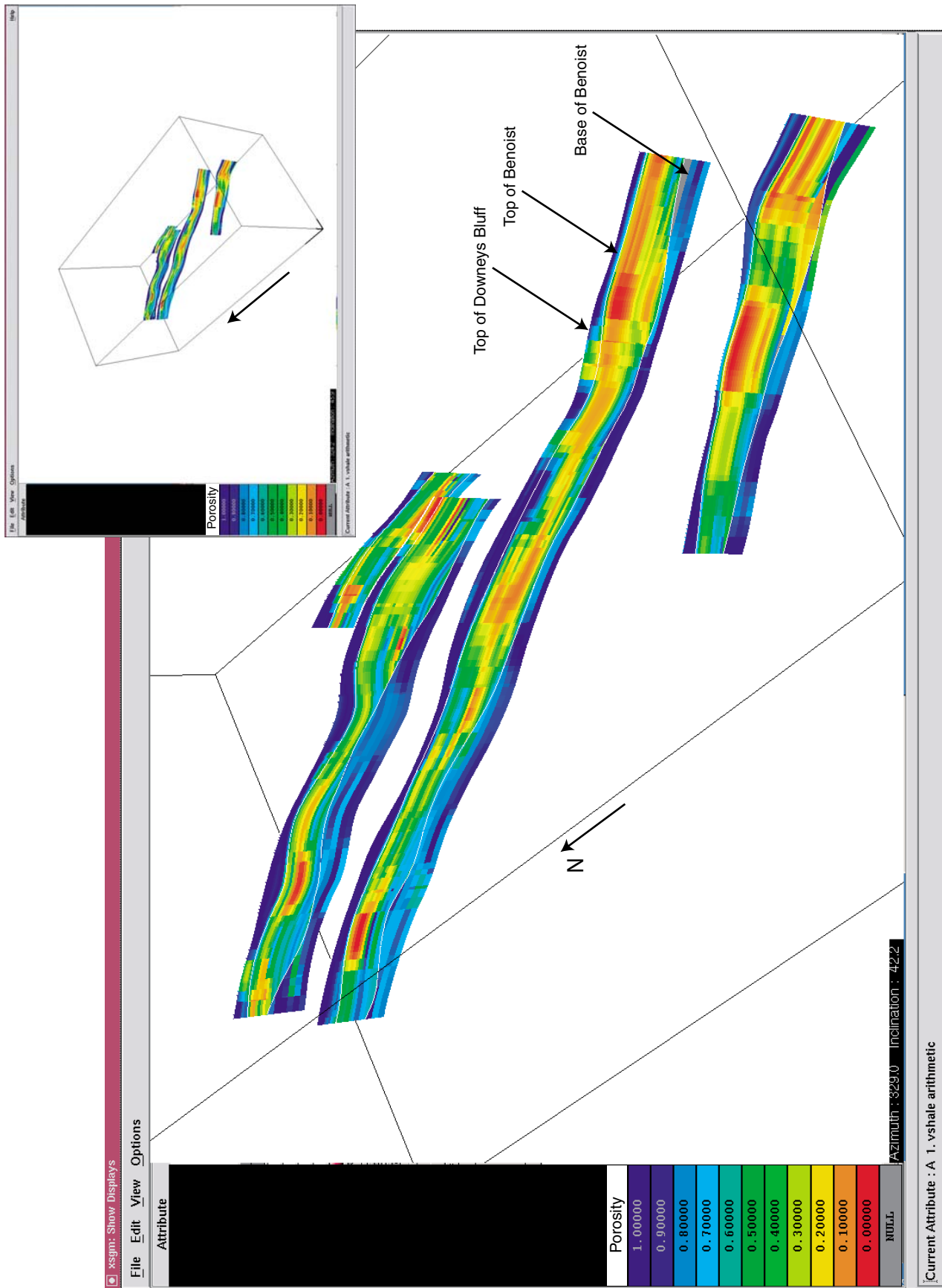


Figure 33 Four cross sections across the Benoist reservoir sandstone at Centralia Field. The bright red areas have the lowest shale volume (Vshale) and are considered the best reservoir facies. The light green areas between the red and yellow low Vshale values are poor-quality reservoir sandstone. Blue areas represent non-reservoir shales or limestones. Inset map shows the location of the cross sections.

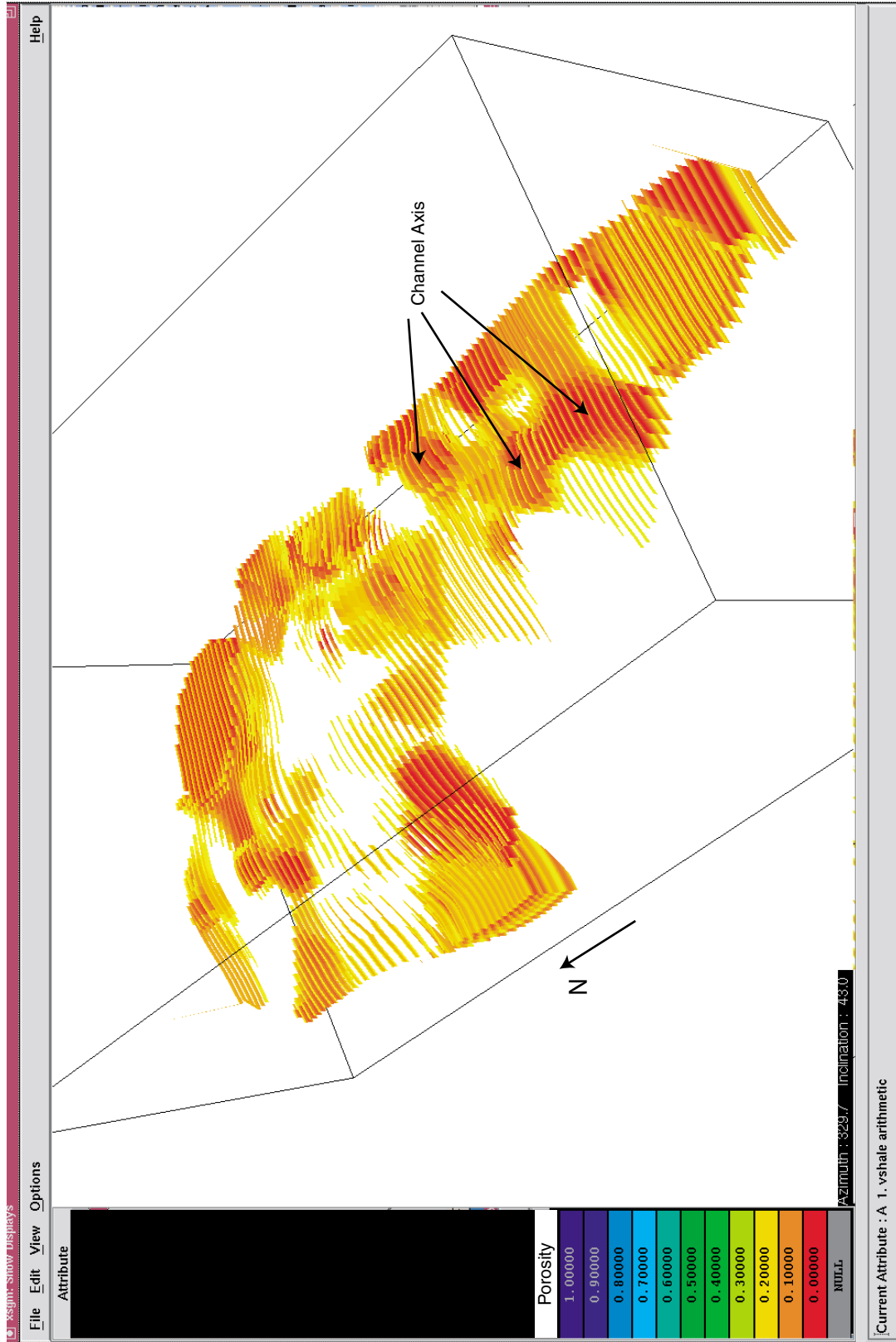


Figure 34 Three-dimensional model of all of the zones in the Benoist sandstone that have a shale volume (Vshale) less than 0.3. These strata with the low Vshale are the best reservoir-quality facies within the Benoist reservoir at Centralia Field.

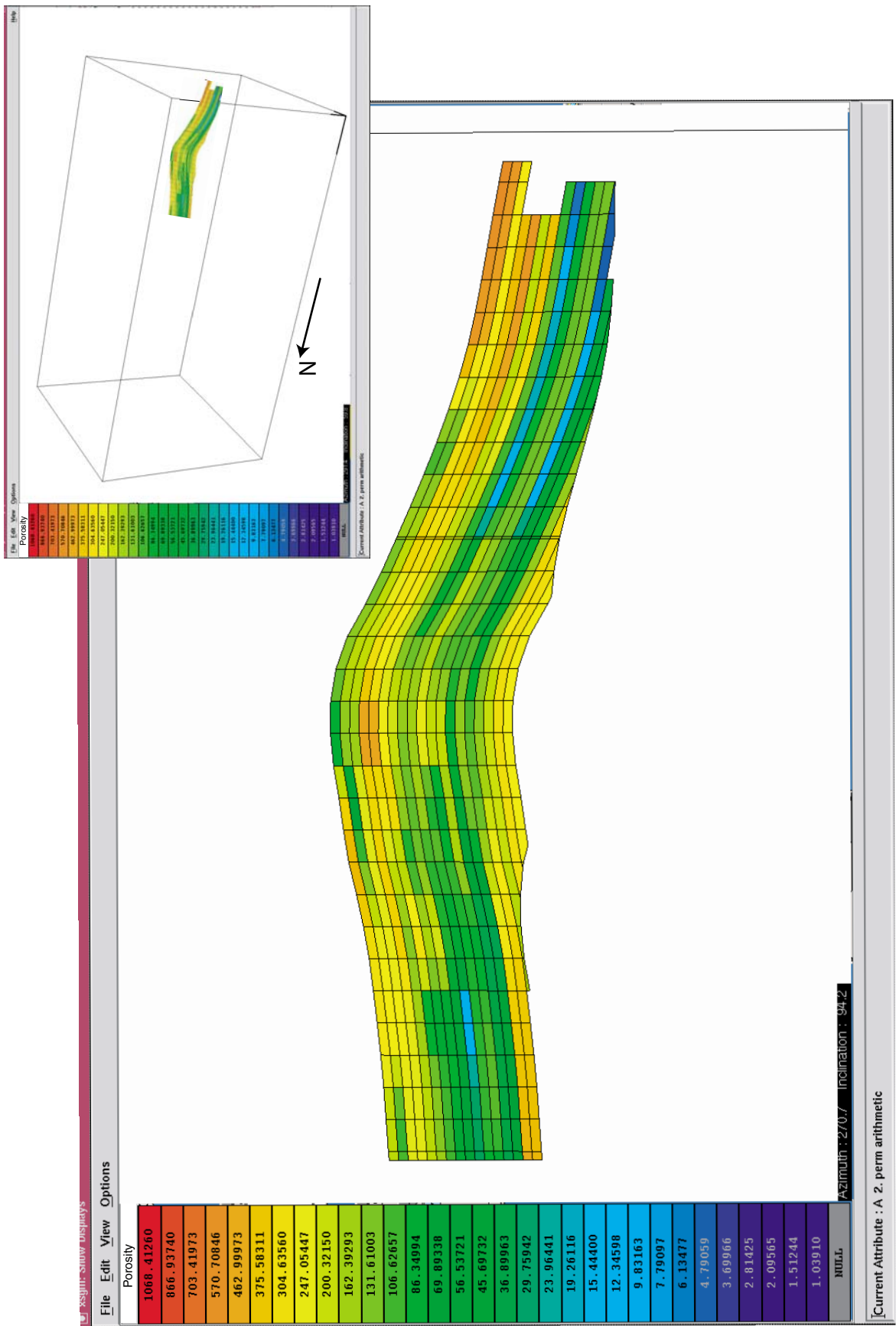


Figure 35 The cross section shows the variability of permeability (as derived from core analysis) of part of the Benoist reservoir sandstone at Centralia Field. Inset map shows the location of the cross section.

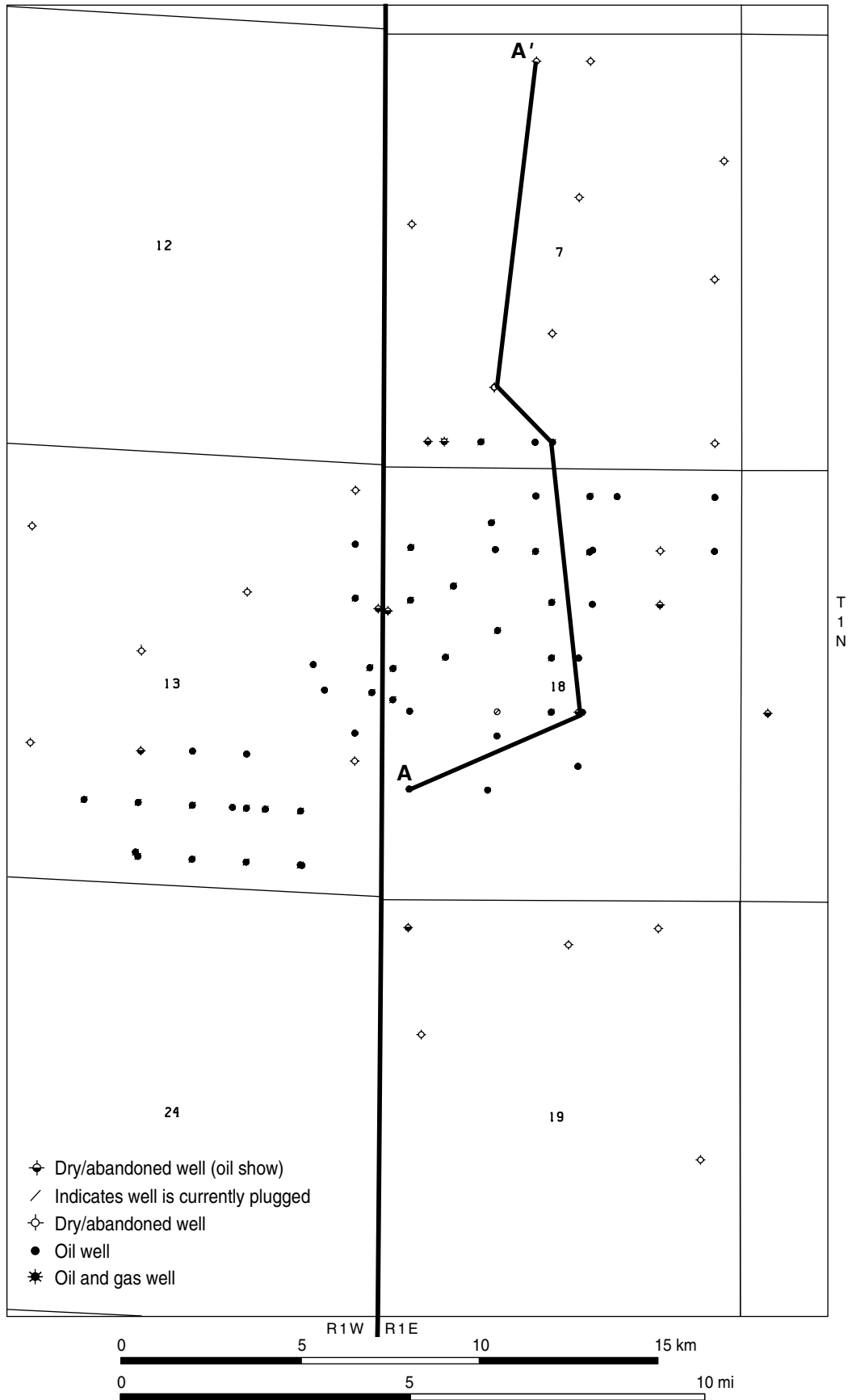


Figure 36 Base map of Fairman Field showing the location of all wells and cross section A–A'.

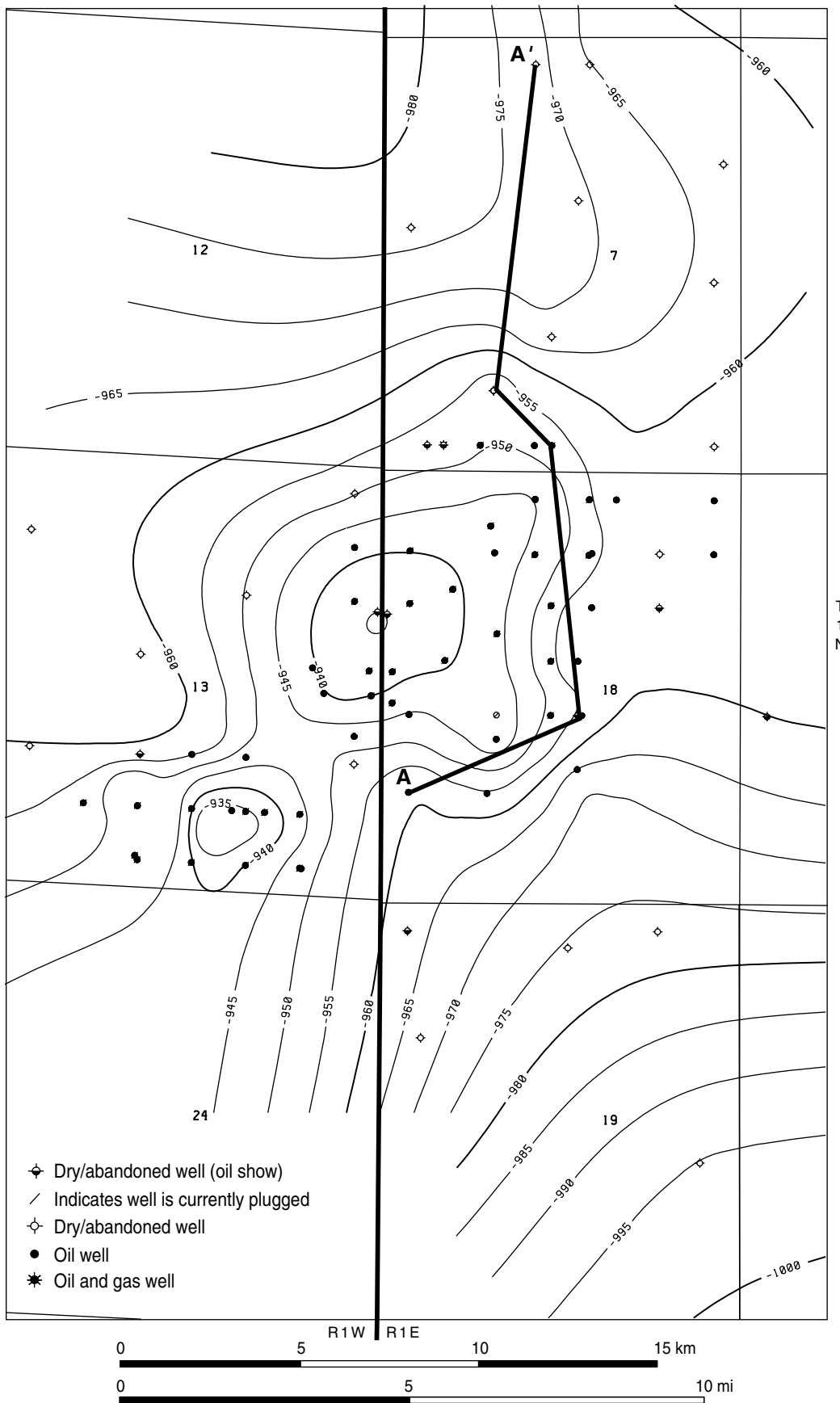
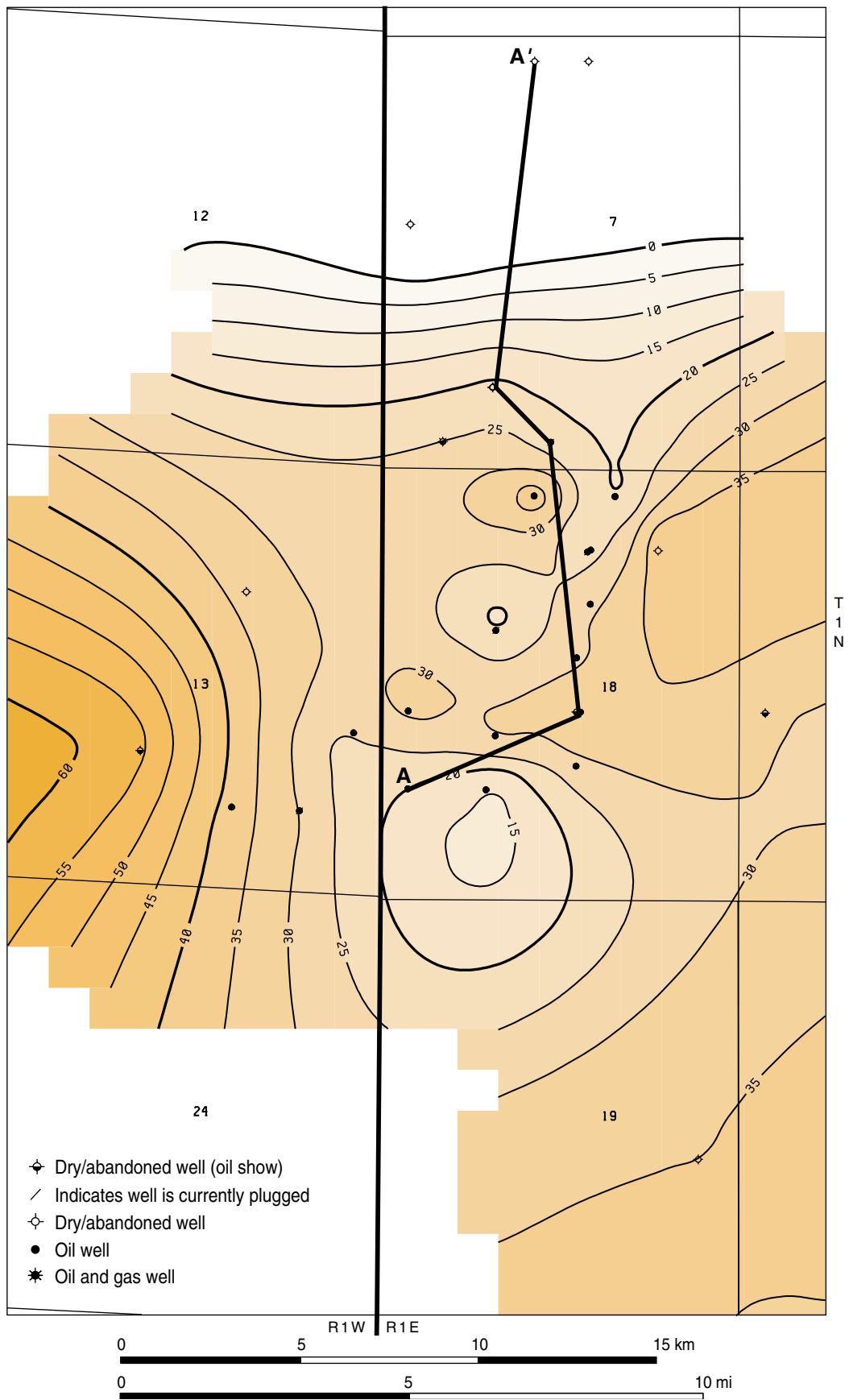


Figure 37 Structure map on top of the Downeys Bluff Limestone. Contour interval is 5 feet.



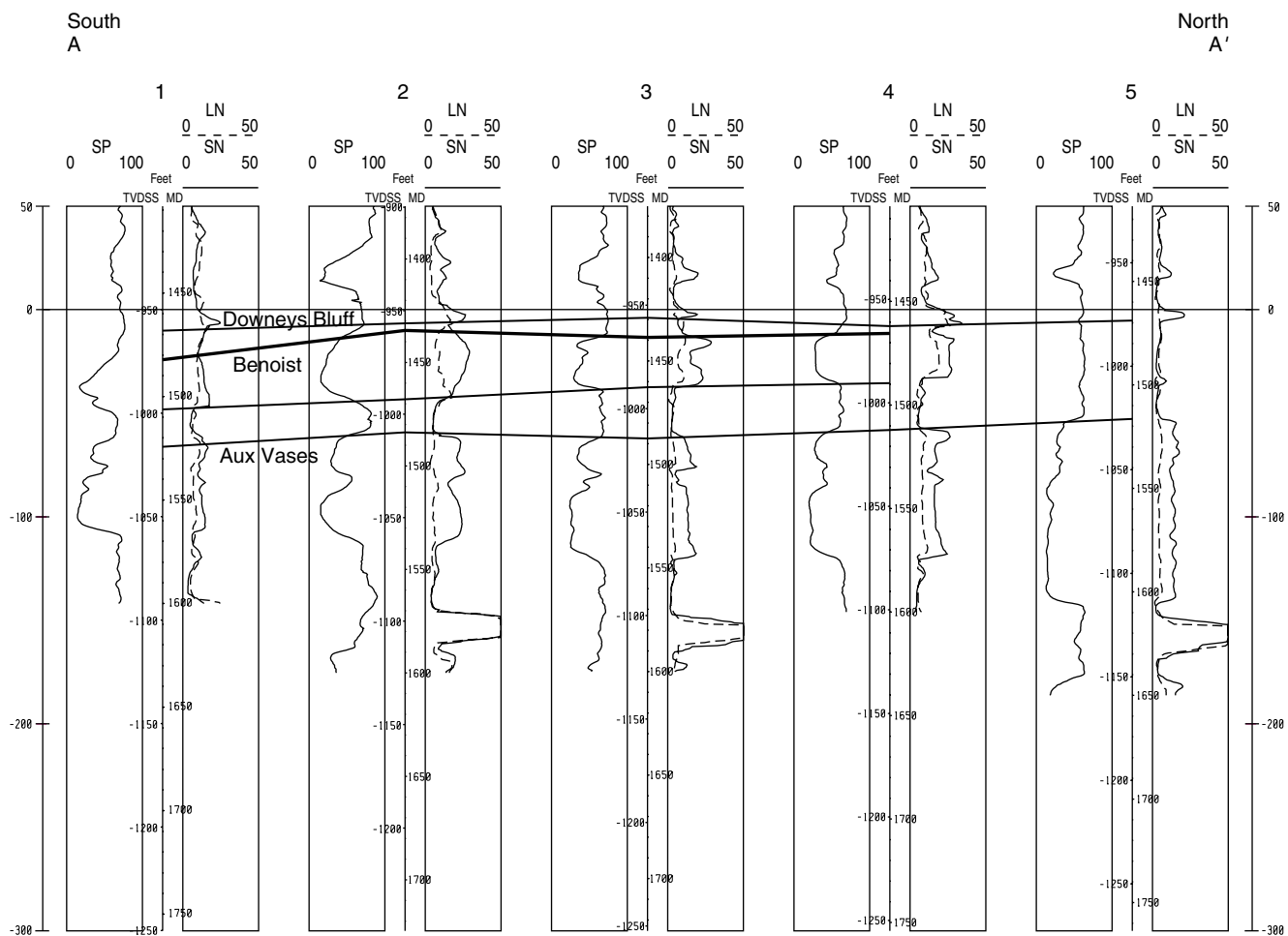


Figure 39 Stratigraphic cross section A–A' across Fairman Field. The datum is the Downeys Bluff Limestone.

water contacts within the boundaries of the field.

Structure The regional dip is to the southeast, and structural closure plays a minor role in the trapping mechanism at Kinmundy North Field. The southern part of the field has only 10 feet of structural closure, whereas the rest of the field has no observed structural closure on top of the reservoir sandstone (fig. 41).

Reservoir Architecture The Benoist sandstone isolith shows an irregular pinchout of the sandstone (fig. 42). Consequently, a well may penetrate 30 feet of Benoist sandstone, but an adjoining well less than 1,000 feet away may encounter no sandstone (fig. 43). The oil is trapped in the individual sandstone lobes at the pinch-

out, and wells drilled outside the lobes produce water even though they may be structurally higher. Each lobe forms a separate trap with its own oil-water contact. Some of the Benoist producing wells in the northeastern part of Kinmundy North Field are structurally 20 feet below adjoining Benoist wells that produce water. Four different reservoir compartments have so far been discovered at Kinmundy North Field with drilling that has progressed northeastward along the strike of the sandstone pinchout.

The importance of drilling within the area of the sandstone lobe is dramatically shown by Well 4 in Figure 44. The Benoist sandstone in this well is structurally higher than the other wells in the cross section, but the well was not located within a sandstone lobe, and

there was no place for the oil to be trapped. The easternmost well on this structural cross section encountered Benoist 5 feet below the top of the Benoist in the adjoining well, and yet both wells produce oil.

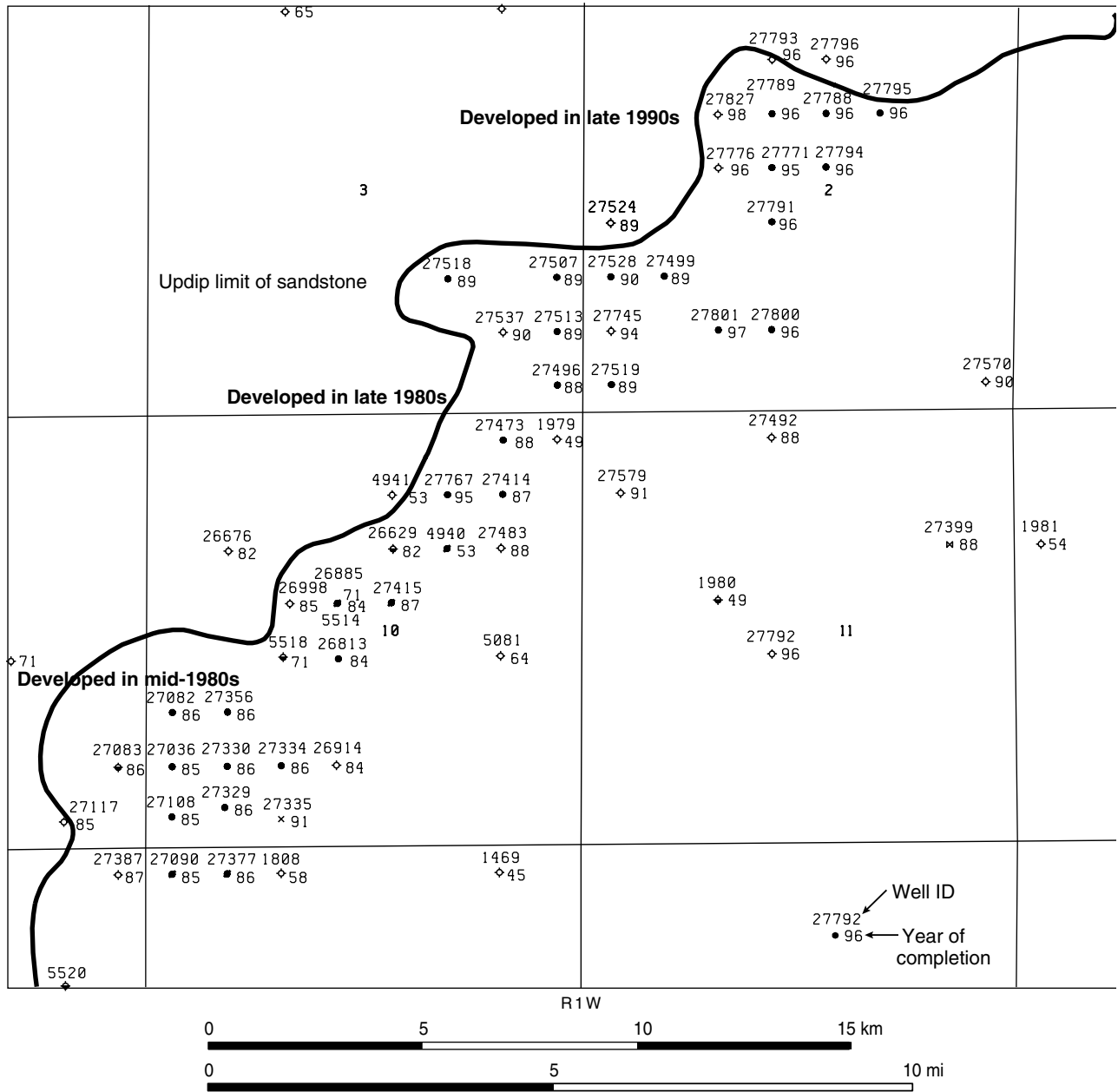
Cross sections across the Kinmundy North Field illustrate some of the stratigraphic correlation problems encountered by geologists within the Illinois Basin. Historically, the Benoist and Bethel sandstones have frequently been confused with each other. Wireline logs in many parts of the Illinois Basin have a consistently recognizable Downeys Bluff Limestone marker to separate the two sandstone units. However, as seen in Wells 1, 2, and 3 (fig. 43), the Downeys Bluff is not present everywhere, and, if there is only one sandstone body, then recognizing

which one is present is significantly more difficult.

Depositional Model The depositional model for the Benoist sandstone at

Kinmundy North Field is based strictly on the geometry of the sandstone isolith (fig. 42) and the regional trend of the sandstone bodies (fig. 6). The Benoist sandstone pinches out toward the

northwest, and the strike of the Kinmundy northwest pinchout is parallel to the postulated shoreline. On the regional sandstone isolith map there are two distinct sandstone trends.



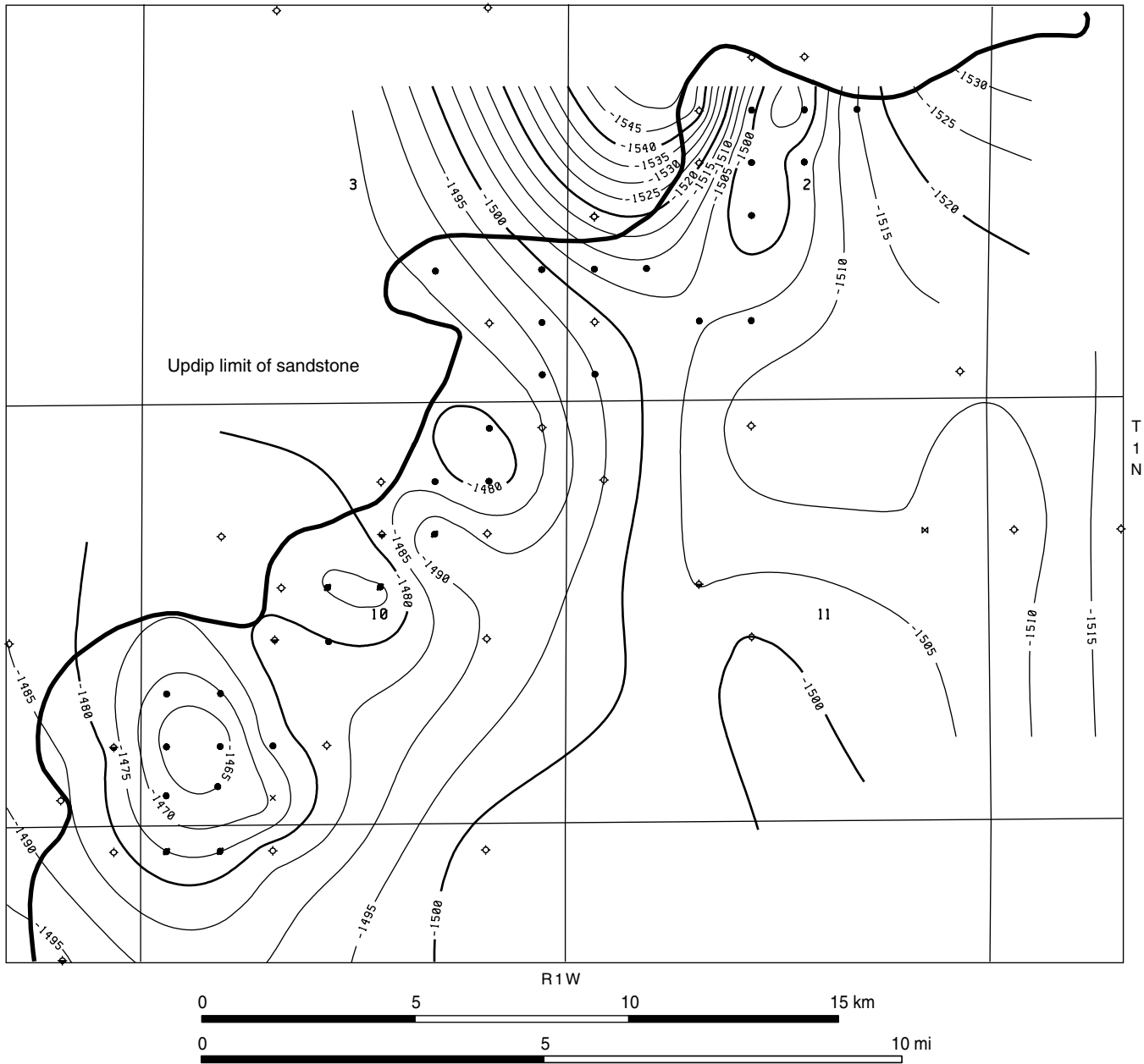
- ◆/ Dry/abandoned well (oil show)
- ◆/ Indicates well is currently plugged
- ◆ Dry/abandoned well
- Oil well

Figure 40 Map of Kinmundy North Field showing the location of all of the Benoist well penetrations. The map also shows the year that each well was completed. Above each well is an abbreviated API number for identification.

The southwest-northeast-trending sandstone bodies are interpreted to represent shoreline and barrier island deposits. The proposed barrier island would be similar to what is observed

on the flanks of many present-day deltaic systems. A barrier island model is consistent with the northwestward pinchout of the Benoist sandstone into lagoonal shales and mudstones.

History of Hydrocarbon Production
The initial oil production of some wells at Kinmundry North Field ranged up to 80 barrels per day (fig. 45). The wells with the highest initial produc-



- ◆ Dry/abandoned well (oil show)
- ／ Indicates well is currently plugged
- ◇ Dry/abandoned well
- Oil well

Figure 41 Structure map on top of the Benoist sandstone at Kinmundry North Field. Contour interval is 5 feet.

tion were located in the northeast and southwest lobes. The two central lobes did not produce as much oil because there was less volume for trapping.

The map of well completion dates (fig. 40) shows that the field is still undergoing development and extension to the north. The southern part of the field

was discovered in the mid-1980s and was quickly developed within the first year after discovery. During the next few years, the field was extended north-

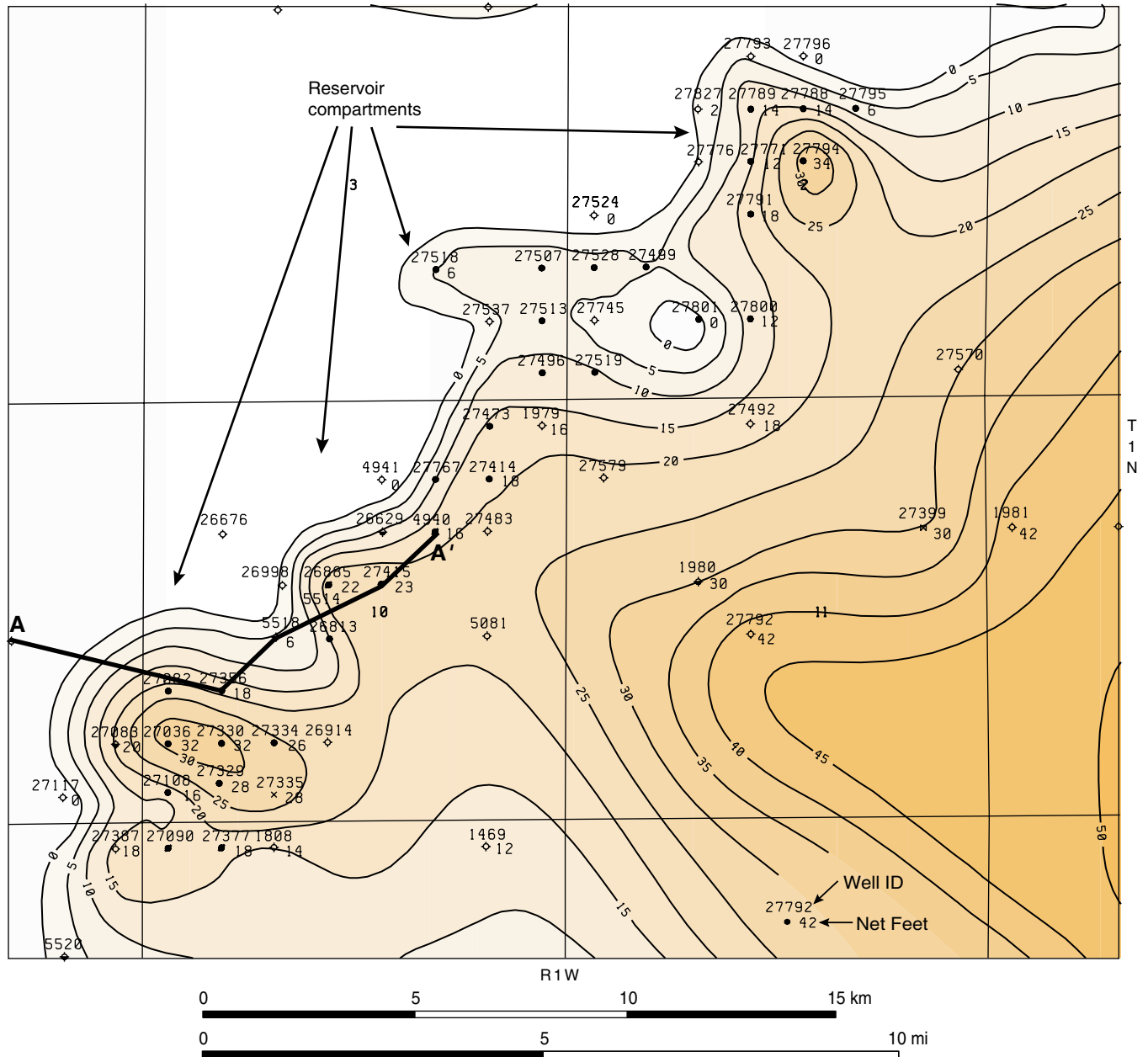


Figure 42 Benoist sandstone isolith map of Kinmundy North Field. Locations of cross sections are also shown. Darker areas contain thicker Benoist sandstone deposits. Contour interval is 5 feet.

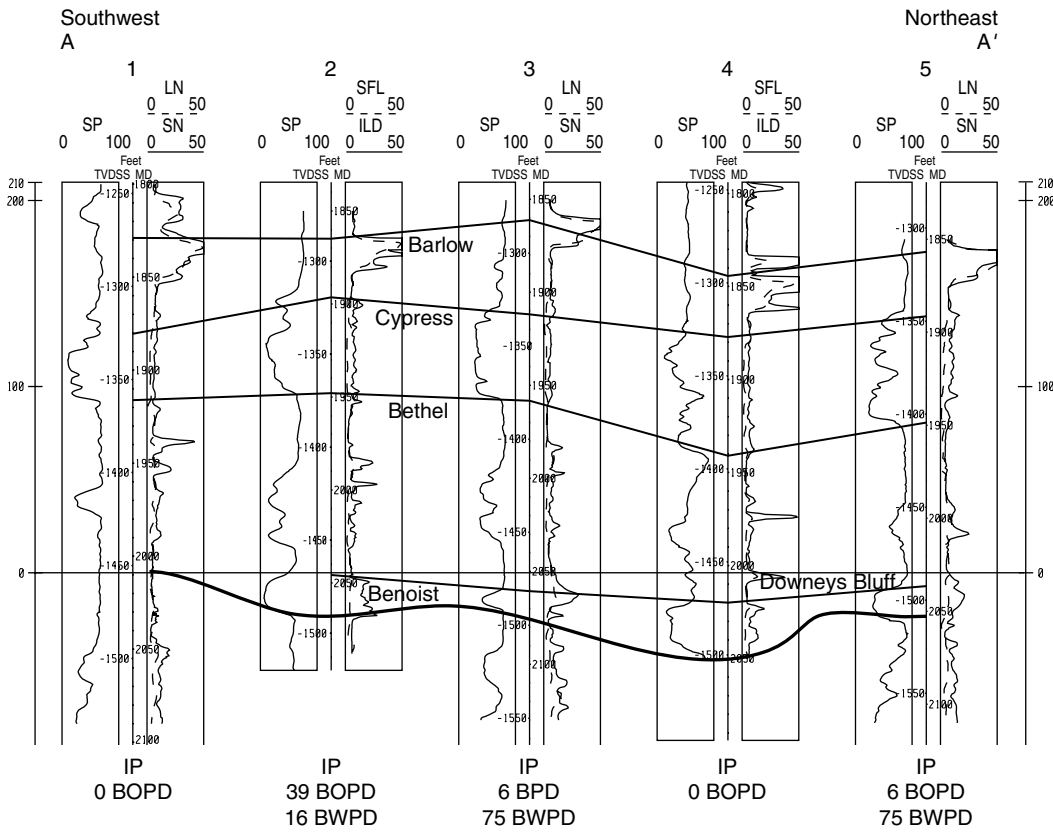


Figure 43 Stratigraphic cross section A–A' showing the lack of Benoit sandstone in Well 1. BOPD, barrels of oil per day; BWPD, barrels of water per day; ILD, deep induction log; LN, long normal; SFL, spherical focus log; SN, short normal; SP, spontaneous potential.

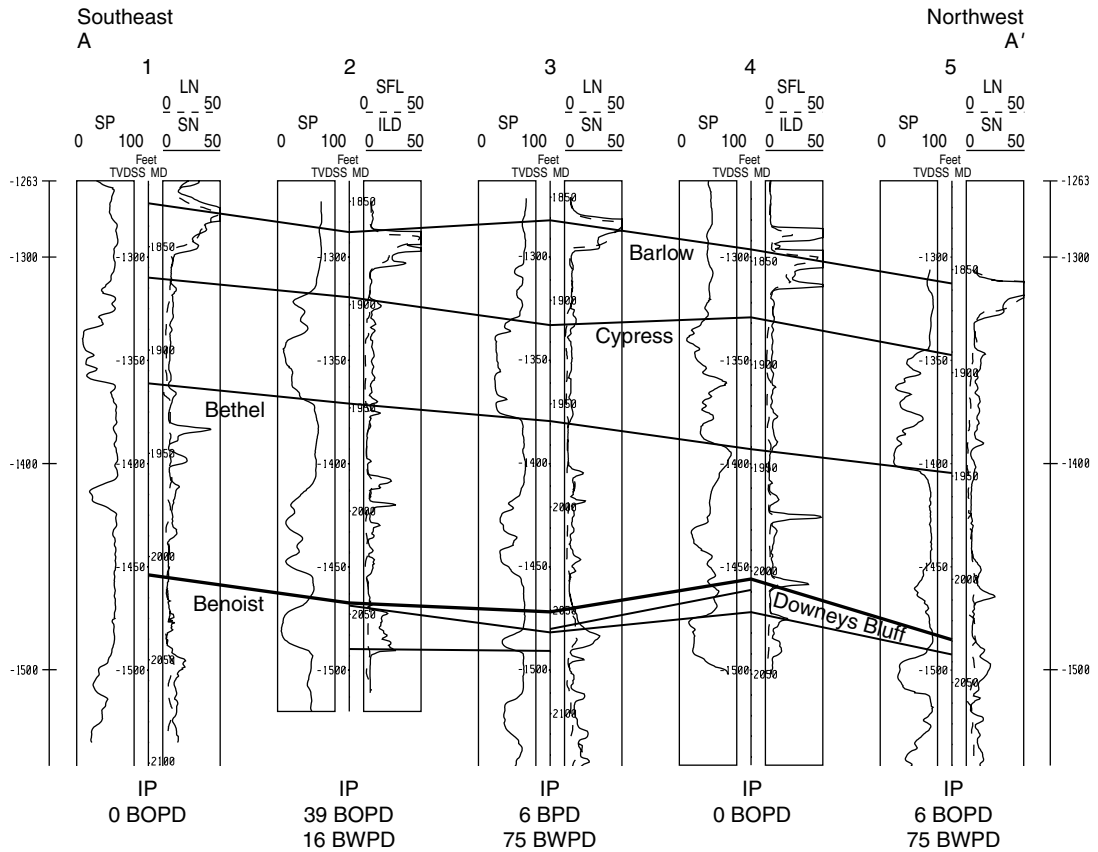


Figure 44 Structural cross section A–A' showing the structural relationship of the Benoit sandstone in different parts of Kinmundy North Field. BOPD, barrels of oil per day; BWPD, barrels of water per day; ILD, deep induction log; LN, long normal; SFL, spherical focus log; SN, short normal; SP, spontaneous potential.

ward, but these wells were not as prolific as the early discoveries. There was a 10-year hiatus until the next advance in development. In the late 1990s, the most northerly lobe was discovered.

Future Strategies Exploration for new reservoir compartments along the trend of the interpreted barrier island should continue. The barrier island geologic model may be used to

find field extensions along the trend of the updip pinchout of the reservoir sandstone. Since the early 1980s, the operators of the field have found four different reservoir compartments.

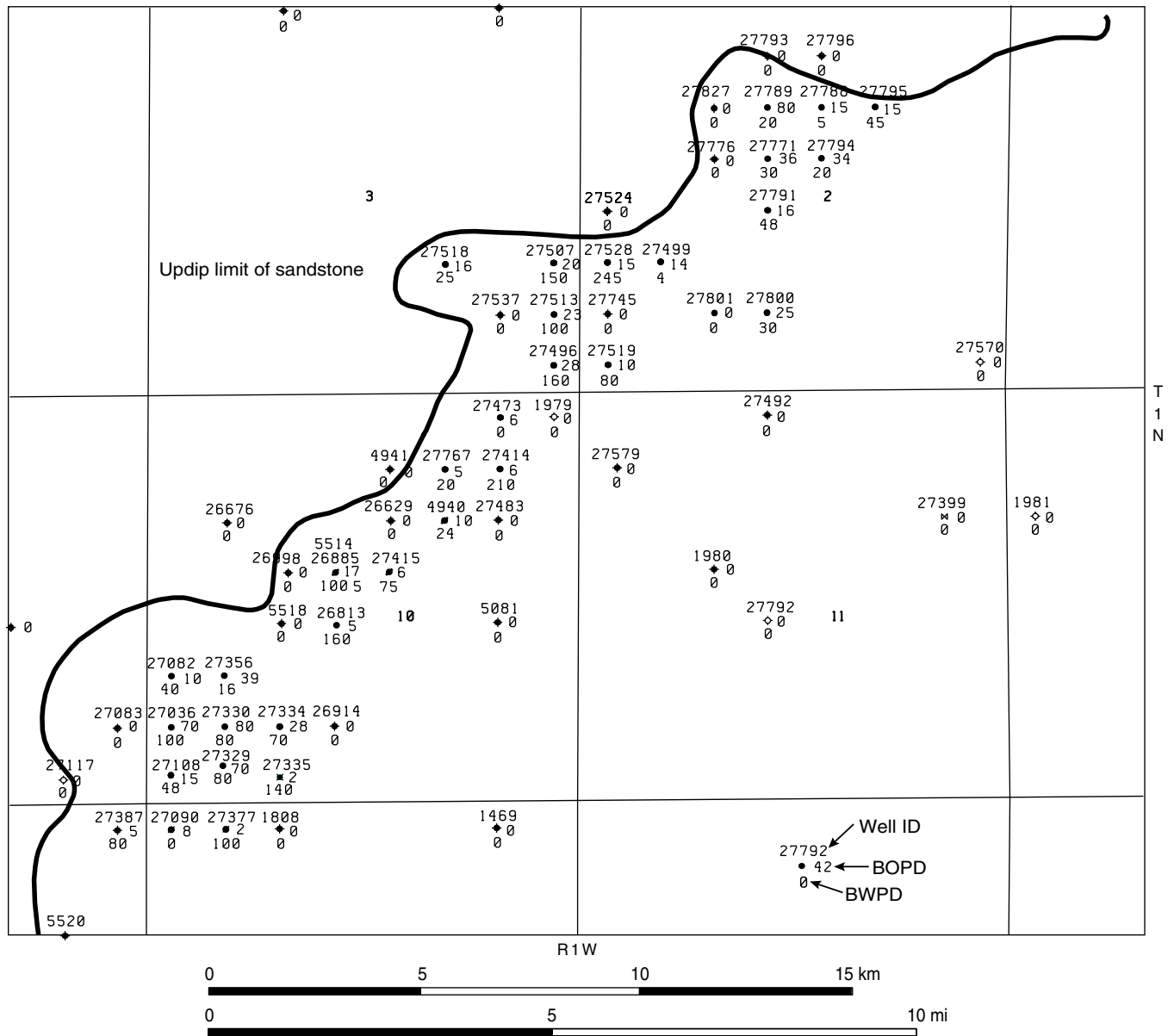


Figure 45 Map of the initial production values of oil and water from the Benoist sandstone reservoir at Kinmundy North field. BOPD, barrels of oil per day; BWPD, barrels of water per day; ILD, deep induction log; LN, long normal; SFL, spherical focus log; SN, short normal; SP, spontaneous potential.

Conclusions

The six reservoir characterization studies suggest that the Benoist sandstone in many parts of Illinois remains a viable target for oil exploration and development. This study shows that a single well cannot delineate an exploration prospect, nor can one or two wells determine the lateral continuity of a reservoir. The reservoirs in five of the six studied fields comprise the sandstone bodies of limited areal extent; intervening areas contain non-reservoir facies.

The Benoist sandstone was deposited by a fluvial-deltaic depositional system. The main river in this system flowed from the northwest. The Benoist reservoirs laid down within the fluvially dominated portion of the depositional system generally are heterogeneous. The channels in which the sandstones were deposited may extend in one direction for 10 miles or more. These channel deposits, including the distributary bars, may range over 1 mile in width. Outside the channel and distributary bar environment, the sandstone bodies are neither thick nor laterally extensive. The sandstones deposited in the interdistributary bay environment probably originated from crevasse splays formed by breeches in the channel levees during floods.

The strategies that must be applied to develop reservoirs within the channel-distributary bar system differ from those used for the interdistributary bay crevasse splay deposits. Wells in channel reservoirs must be located along the length of the channel where the sandstone bodies have good reservoir continuity but are narrow. Because of their lateral continuity, these types of reservoirs are good candidates for secondary and tertiary recovery.

The sandstone reservoirs formed within the interdistributary bay deposits, as found in Centralia and Salem Fields, have a lateral continuity of less than 1,000 acres; therefore, most additional recovery would probably be achieved by infill drilling.

Reservoirs formed as barrier islands, such as at Kinmundy North Field, can

form stratigraphic traps, even without structural closure. These types of sandstone bodies could exist along any of the mapped strandlines of the Benoist delta. The best opportunities for additional Benoist oil can be found by exploring along the trend of these shorelines looking for the updip pinch-out of barrier island sandstones into the lagoonal or interdistributary shales.

Areas with continuous sandstone, such as those around Fairman and Boyd Fields, are not good targets for increasing production by infill drilling. Increasing the production from these types of fields will require outpost drilling to look for field extensions or a tertiary recovery program using polymers or CO₂ to recover bypassed oil in less permeable strata.

The Benoist sandstone remains a viable exploration and development target for additional oil production in the Illinois Basin. The type of depositional system will determine the amount of heterogeneity within a field and the type and quality of trapping mechanism. Fields located within the channel-crevasse splay system will have greater sandstone heterogeneity than those fields located within a reworked sandstone system. The reservoir models and regional framework presented here can be used to develop strategies for improved oil recovery.

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APPENDIX



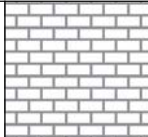


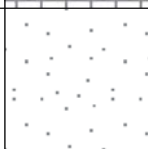


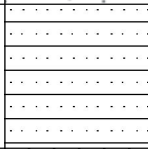


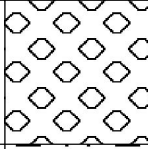



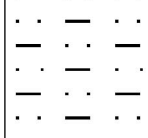


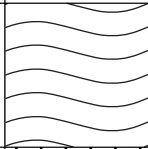


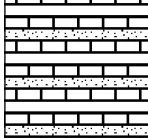












 	Cross bedded Bioturbated		Limestone
 	Sharp contact Flaser		Sandstone
 	Horizontal laminae Herringbone cross bedded		Interbedded sandstone shale
 	Wavy bedded Rippled		Conglomerate
  	Calcite cemented Calcite nodule Shale clast		Siltstone
 	Wood chip Root trace		Shale or mudstone
 	Ooid Shell fragment		Bedded limestone, sandstone, and shale
 	Crinoid Coral	 	Hummocky Red color
 	Mud cracks Contorted bedding	 	Graded bed
 	Fractures Stylolites		Shale partings
	Rock fragment		

Figure A1 Symbols used in core description.