

SUBSURFACE GEOLOGY OF THE MORROWAN LOWER DORNICK
HILLS (CROMWELL SANDSTONE) AND THE
DESMOINESIAN KREBS (HARTSHORNE
AND LOWER BOOCH SANDSTONES)
IN NORTHERN PITTSBURG
COUNTY, OKLAHOMA

By

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PREFACE

This thesis is a study of the subsurface geology of the Desmoinesian Krebs (Lower Booch and Hartshorne Sandstones) and Morrowan Lower Dornick Hills (Cromwell Sandstone) in 12 townships of northern Pittsburg County, Oklahoma. The recent decline in domestic oil prices has led many explorationists to seek a more cost effective prospectus for future drilling proposals. With that purpose in mind, this investigation is an attempt to provide valuable information regarding shallow gas reservoir development in the western Arkoma Basin.

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CHAPTER I

ABSTRACT

The Desmoinesian Hartshorne, Lower Booch and Morrowan Cromwell Sandstones are present in the subsurface of the Arkoma Basin. The Cromwell Sandstone is the lowest member of the Union Valley Formation. The Hartshorne Formation consists of four named members. The four members are the Lower Hartshorne Sandstone, Lower Hartshorne Coal, Upper Hartshorne Sandstone and Upper Hartshorne Coal. The Lower Booch, or Warner Sandstone, is the lowest sandstone member in the McAlester Formation. Locally, all of these sands produce significant amounts of gas.

The Cromwell, Hartshorne and Lower Booch Sandstones represent distinct periods of regressive sedimentation in deltaic environments. The Upper Hartshorne and Lower Booch Sandstones were studied in more detail. Cores from these two units represent several deltaic facies, including the prodelta, delta front, and delta plain facies.

The cratonic delta models of Brown (1979) were applied to all three units. The Cromwell Sandstone appears to represent a high constructive, lobate delta system. The Hartshorne and Lower Booch Sandstones represent high constructive, elongate delta systems.

Extensive subsurface mapping was an important part of this study. Two structure maps were prepared on regionally persistent marker beds to illustrate the structural framework of northern Pittsburg County,

Oklahoma. Three isopach maps are also included, which demonstrate the depositional framework of the area. Net sandstone isolith maps illustrate the sand body geometry of the Cromwell, Hartshorne, and Lower Booch Sands.

Subsurface mapping demonstrated the petroleum trapping mechanisms within the area. The Cromwell Sand was found to produce exclusively from structural type traps. The Hartshorne and Booch Sands produce mainly from combination and stratigraphic traps. In all three units, gas production is associated with distributary channel deposits.

The petrology and diagenesis of the Upper Hartshorne and Lower Booch Sandstone were studied in detail to determine the petrographic character of reservoir quality sands. The Upper Hartshorne Sandstone is a very fine to fine-grained sublitharenite. Porosity ranges from 4% to 10%, and results from the dissolution of detrital matrix, feldspar grains, and authigenic cements. The Lower Booch Sandstone is a fine to medium-grained sublitharenite. Porosity in the Lower Booch ranges from 4% to 23%, and results from the dissolution of detrital feldspars, detrital matrix, and authigenic carbonate cements. The optimum reservoir sand for both units is a fine to medium-grained sublitharenite with 10% to 20% porosity. Porosity in both the Upper Hartshorne and Lower Booch Sands is obstructed by kaolinite, illite, chlorite and authigenic carbonate cements.

CHAPTER II

INTRODUCTION

Location of Study

This thesis study is a subsurface analysis of the Morrowan Lower Dornick Hills (Cromwell Sandstone) and Desmoinesian Krebs (Hartshorne and Lower Booch Sandstones) Formations in the western part of the Arkoma Basin, Oklahoma. The area of study covers 432 sq. mi. of northern Pittsburg County, and a small part of eastern Hughes County in east-central Oklahoma. The exact location of the study area is defined by Township(s) 5 through 7 North, Range(s) 12 through 15 East, Oklahoma (Figure 1).

Subsurface geological mapping covered all twelve townships of the study area. Only one core was available within the study area, which is located at Sec. 34, T. 6N., R. 13E. Two additional cores were obtained from wells located outside of the study area. The cores were located at Sec. 31, T. 10N., R. 18E. and Sec. 24, T. 8N., R. 17E.

Objectives

The major objectives of this study include:

1. Subdivision of probable regressive and transgressive sedimentation episodes and cycles within the subsurface section.
2. Correlation of all lithologic units within the subsurface section by means of stratigraphic electric log cross sections.

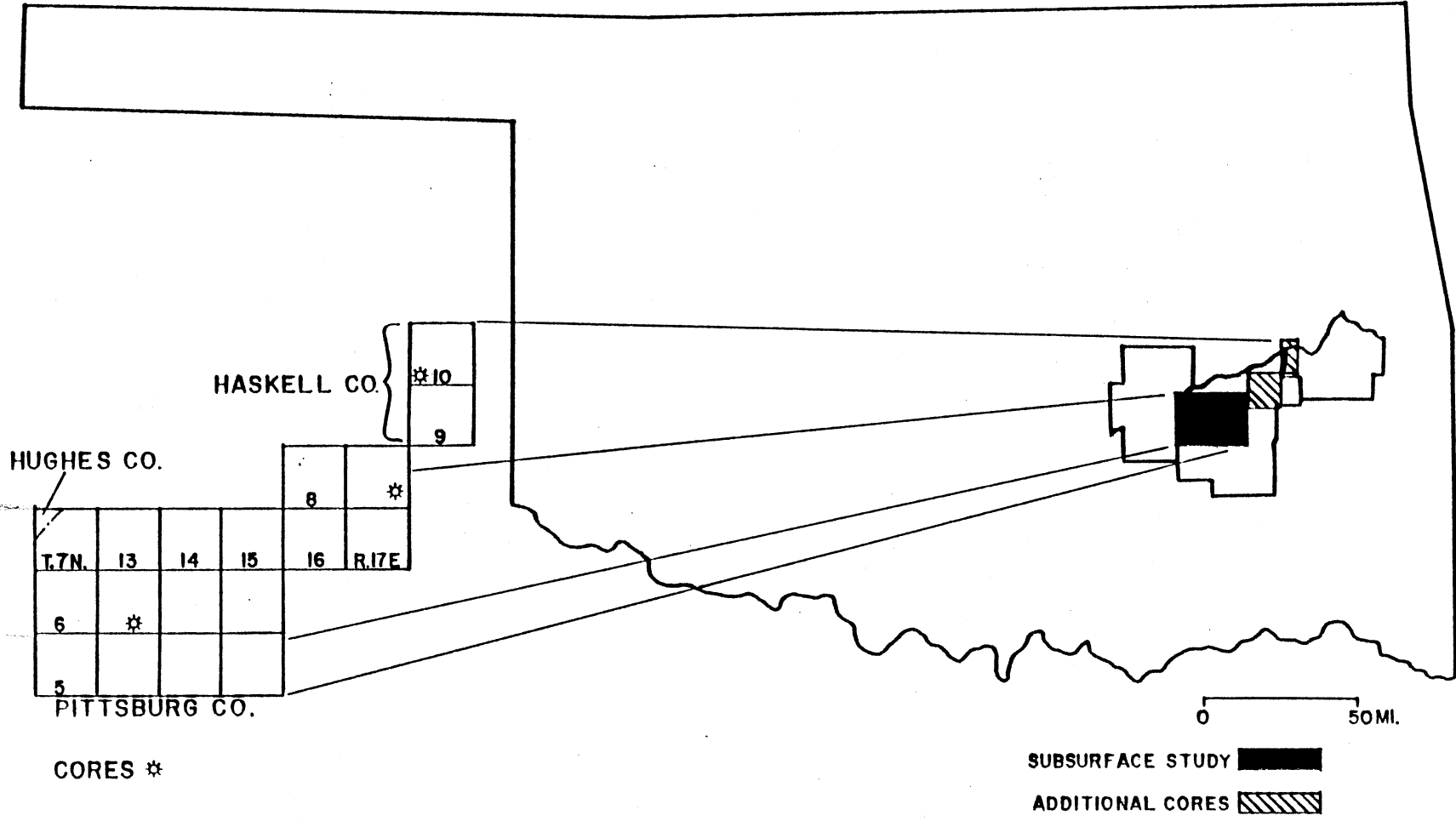


Figure 1. Location Map of the Study Area.

3. Recognition of specific depositional facies contained within certain genetic intervals, based on the sand body geometry and depositional framework illustrated by subsurface maps.
4. Application of depositional models, in order to explain various elements of the facies tract, based on sand body geometry and depositional framework demonstrated by subsurface maps.
5. Reconstruction of the regional tectonic and depositional history to explain the distribution of specific facies elements and producing units.
6. Preparation of structure contour maps on top of the Wapanucka Limestone and Lower Hartshorne Coal to demonstrate the importance of local structural features.
7. Investigation of local gas production and petroleum trapping mechanisms.
8. Evaluation of the petrology, diagenesis, and porosity types from cores of the Booch and Hartshorne sandstones.

Methods of Investigation

Petrographic data were compiled from three cores. The Apache Corporation, No. 1 Hunt-Garret core was located within the study area. The Kerr-McGee Corporation No. 1 Finch, and Cities Service Company No. "A"-1 Mason cores were located northeast of the immediate study area. All three cores were measured and described on standard petrologic log sheets to evaluate petrologic character. Each core was calibrated to the appropriate electric well log in order to understand the nature of log response to sandstone lithology and to aid in the interpretation of depositional environments.

A total of 66 thin sections were prepared from core samples. Thin sections were used to determine detrital constituents, diagenetic constituents, porosity types, and diagenetic history of the Hartshorne and Lower Booch sandstones. The application of cross-cutting relationships associated with authigenic constituents were utilized to reconstruct the appropriate diagenetic histories.

Thin sections containing significant amounts of dolomite cement were stained with potassium ferricyanide solution to differentiate ferroan from non-ferroan dolomite. Powdered rock samples were prepared from the identical location of each thin section. X-ray diffraction analysis of all powdered samples was run from 2-35 degrees 2θ to aid in mineral identification. The clay fraction was removed from 34 powdered samples and used for heated and glycolated x-ray diffraction runs from 2-15 degrees 2θ . X-ray diffraction of clay fractions assisted in the identification of authigenic clay minerals and the determination of relative amounts of each authigenic clay mineral. Scanning electron microscopy was utilized to observe the crystal growth habit of authigenic constituents and to further understand the reduction of pore volume due to authigenic clays and cements.

Subsurface data were obtained from a variety of sources. The subsurface data base was compiled from electric well logs, sample logs, scout tickets, Herndon Maps, and one seismic map.

Three stratigraphic cross sections were constructed to illustrate the stratigraphy of the study area (Plates I to III). Structure contour maps were prepared on top of the regionally persistent

Wapanucka Limestone and Lower Hartshorne Coal in order to illustrate the subsurface structure of the study area (Plates IV and V).

Three interval isopach maps (Plates VI through VIII) were prepared to show the dramatic change in thickness of format units between the Arkoma shelf and the basin proper. Bissell (1984) defined map cycles (genetic intervals) within the Hartshorne and McAlester Formations; Bissell's map cycles were applied to the same formations in this study. Bissell incorporated the ideas of Busch (1974) and Brown (1979) in order to delineate map cycles. Busch (1974) originated the term "genetic interval of strata" to describe a single sedimentation episode; each genetic interval is delineated by a "time-lithologic marker bed" (limestone or coal), unconformity, or a shallow marine to non-marine facies change. Brown (1979) noted that a deltaic sedimentation episode includes an early phase of progradation, an abandonment and destruction phase, and a final phase of marine transgression. The same principles were applied in this study to delineate format units.

Net sand isolith maps were prepared for the Cromwell, Lower Hartshorne, Upper Hartshorne, and Lower Booch Sandstones (Plates IX to XII); these maps were essential to the understanding of sand body geometry, depositional environments, and petroleum trapping mechanisms.

In part, the petroleum geology of the area was evaluated by preparing a current cumulative gas production map. Gas production statistics were recorded from annual production reports. All of the producing fields were identified, and the probable trapping mechanisms were described.

Previous Investigations

Several regional studies have been published that describe the geology of Pittsburg County, Oklahoma. The earliest studies of this area in the Arkoma Basin dealt with the stratigraphy of economic coal beds. Drake (1897) mapped the McAlester District coal fields and surface features; Drake also divided the rocks into three groups but did not include a description of these groups. White (1898) dated plant fossils from the Hartshorne Coal and suggested a Pennsylvanian age for the rocks of the McAlester District. Taff (1899) named all of the formations of the Southeastern Oklahoma Coal Field, but failed to recognize the Atoka Formation. Also, Taff included a geologic map showing all of the formation boundaries within the area. In 1900 an additional report on the coal fields of Indian Territory was published by Taff. This report was similar to the previous study, but a geologic map showing the outcrop pattern of each coal field was added.

The first study to reveal the possibility of potential petroleum reserves in Pittsburg County was written by Shannon and others (1917). Clawson (1930) gave a detailed description of the petroleum geology of the area. This report was in response to the early drilling activity of several major oil companies. This study described Morrowan through Desmoinesian stratigraphy and the prominent structural features of the area. Clawson included a simplistic isopach map of the combined Atoka, Hartshorne and McAlester Formations.

The first comprehensive study of the area was written by Hendricks and others (1936). This study described the Pennsylvanian stratigraphy of the Arkoma Basin in detail and included isopach maps of the Atoka and McAlester Formations. Hendricks (1939) evaluated the

fuel resources and geology of the McAlester District. In this investigation, Hendricks mapped the surface geology and presented very accurate descriptions of each structural feature. A subsurface structure map on top of the Lower Hartshorne Coal was included, but the map was prepared with very little well control due to the lack of drilling.

Descriptions of stratigraphy and structural features from all of the above publications were important in the early stages of this study. These early publications facilitated a basic understanding of the regional geologic setting of the study area.

The Cromwell Sandstone has been the subject of several studies in Coal and Pontotoc Counties, but very little information was found with regard to Pittsburg County. Hollingsworth (1934) gave a general description of the Cromwell Sandstone from the type locality in Pontotoc County. Laudon (1959) correlated the Cromwell Sandstone with the Hale Sandstone of the eastern Arkoma Basin in Arkansas. Laudon's correlation included wells that are located in the study area. Withrow (1969) divided the Cromwell Sandstone into three lithofacies and evaluated the Cromwell production of the Franks Graben Area in Coal and Pontotoc Counties. Withrow also suggested that the Cromwell represents reworked sediment from a northern source area. A field study of the Centrahoma Field in Coal County, in which the Cromwell Sandstone is a major pay zone, was written by Anderson (1975). Anderson also postulated a marine deltaic depositional environment for the unit.

The Hartshorne Formation has attracted considerable attention in recent years. Haley (1961) demonstrated an eastern source area for

Hartshorne sandstones in Arkansas. The surface stratigraphy of the Hartshorne Formation was outlined by McDaniel (1961). McDaniel (1968) applied sedimentary structures to hydrocarbon exploration in the Hartshorne sandstones of Pittsburg County. More importantly, McDaniel documented a deltaic depositional environment for the Hartshorne Formation. Catalano (1978) interpreted the source area and depositional environment of the Hartshorne Formation for Haskell and LeFlore Counties. Catalano's work concentrated on the economic geology of the Hartshorne Coalbeds.

Houseknecht and Iannachione (1982) reported the problems of coal mining as related to specific Hartshorne facies in the Arkoma Basin. A guidebook, written by Houseknecht (1983), was a major contribution to the understanding of the Hartshorne deltaic system and tectonic history of the Arkoma Basin. Houseknecht's regional study explained the stratigraphy of the Hartshorne Formation over the entire Arkoma Basin. Houseknecht (1983) mapped the Lower and Upper Hartshorne Sandstone members in Oklahoma and Arkansas. Detailed petrographic information regarding quartz cementation in the Hartshorne Sandstones was written by Houseknecht (1984).

A number of studies have been published about the Lower Booch Sandstone member of the McAlester Formation. All of these studies were located in areas adjacent to the study area of this thesis.

Reed (1923) mapped the Booch Sandstones and was the first to suggest a deltaic depositional environment. Scruton (1950) studied the Lower Booch Sandstone in outcrop and described the petrology and depositional environment of the unit. The Booch delta was mapped by Busch (1953). Busch's sandstone isolith map confirmed the deltaic

environment postulated by previous workers, and his work became the classic example of deltaic sedimentation in the Mid-Continent.

Karvelot (1972) reconstructed the regional distribution of Lower Booch Sandstone channels in parts of four counties in east-central Oklahoma. Bennison (1979) demonstrated the importance of Desmoinesian coal cycles in eastern Oklahoma. Bennison divided the Hartshorne and McAlester Formations into coal cycles to illustrate individual episodes of deltaic sedimentation.

Bissell (1984) correlated outcrop sections of Warner Sandstone with the Lower Booch Sandstone, which is the subsurface equivalent to the Warner Sandstone. Also, the Lower Booch Sandstone was mapped in parts of Haskell, McIntosh, Muskogee, and Pittsburg Counties, Oklahoma by Bissell. Bissell's net sandstone isolith map is essentially a southeastward extension of Busch's (1953) map of the Booch Sandstone. A petrographic study of McAlester Formation sandstone members was also conducted by Bissell (1984). The portion of this thesis devoted to the Lower Booch Sandstone is a southward extension of Bissell's (1984) subsurface investigation.

CHAPTER III

STRATIGRAPHY

Introduction

The Lower and Middle Pennsylvanian in the Arkoma Basin of Oklahoma are subdivided into the Morrow, Atoka, and Desmoines Series (Table I). This study includes the stratigraphy of formations deposited in earliest Morrowan through early-middle Desmoinesian time and involves sandstones of Morrowan and Desmoinesian age. Atokan and Desmoinesian age rocks crop out within the Arkoma Basin; Morrowan rocks crop out northwest of the basin region. The lower Atokan through middle Desmoinesian strata thicken from 2000 feet in the northwest to in excess of 10,000 feet in the southeast corner of the study area.

Pennsylvanian System

Morrowan Series

The Morrowan Series contains the Springer Formation and Lower Dornick Hills Group. The Morrowan section thickens southward across the area, but this moderate thickening is not comparable to that observed in the overlying Atokan and Desmoinesian section. Morrowan rocks in the Arkoma Basin are shales, siltstones, mature sandstones, and massive shelf limestones.

TABLE I

LOWER AND MIDDLE PENNSYLVANIAN STRATIGRAPHY

Desmoinesian Series	Marmaton Group	Holdenville Sh. Wewoka Fm. Wetumka Sh. Calvin Fm.
	Cabaniss Group	Senora Fm. Stuart Sh. Thurman Ss.
	Krebs Group	Boggy Fm. Savanna Fm. McAlester Fm. Hartshorne Fm.
Atokan Series	U. Dornick Hills Group	Atoka Fm.
Morrowan Series	L. Dornick Hills Group	Wapanucka Fm. Union Valley Fm.
		Springer Fm.

Morrowan strata record continuous sedimentation from Mississippian into Pennsylvanian time (Laudon, 1959). Morrowan time was characterized by non-marine to shallow marine sedimentation and included at least one period of regression (deltaic progradation) followed by a basin-wide transgression event.

Springer Formation

The Springer Formation was named by Goldston in 1922 for the town of Springer in Carter County, Oklahoma (Frezon, 1962). The common usage of the names "Penn Caney" and "Springer" for the shale sequence between the overlying Morrowan Cromwell Sandstone and the underlying Mississippian Mayes Limestone caused to a great deal of confusion in the early stages of this study. Frezon (1962) noted that the "Penn Caney" shale could be correlated with the Springer Formation of Carter County, Oklahoma (the type locality for the Springer Formation); thus the name "Springer" shale has been used by Arkoma Basin workers in recent years. Frezon (1962) considered the lower part of the shale sequence to be of Chesterian age based on the study of the fossil goniatite fauna and suggested a Morrowan age for the upper part of the shale sequence based on the nature of gradational contact with the overlying Morrowan Cromwell Sandstone. The Springer Formation delineated by Frezon (1962) is the Springer Formation of this study.

The Springer is dominantly shale with local lenses of silty shale and fine-grained sandstone. Only five wells in the study area were deep enough to penetrate the entire Springer section; in these five wells, the unit ranges from 70 feet in thickness in the northwest to 350 feet in the southeast.

Lower Dornick Hills Group

Union Valley Formation. The Lower Dornick Hills Group contains the Union Valley Formation and the Wapanucka Formation in ascending order. The Union Valley Formation was named for the Union Valley Schoolhouse north of the town of Frisco in Ponotoc County, Oklahoma (Withrow, 1969). In earlier literature the unit was considered a member of the Wapanucka Formation but was elevated to "formation" status by Hyatt in 1936 (Withrow, 1969). The Union Valley Formation consists of the Cromwell Sandstone and the overlying Union Valley Limestone.

The informal name "Jefferson" has been applied to the lower part of the Cromwell Sandstone in earlier studies, and the unit was considered to be of Springer age. As mentioned previously, Frezon (1962) considered the sandstone unit directly overlying the Springer Shale to be of Morrowan age and placed the unit in the Union Valley Formation. Withrow (1969) informally divided the Cromwell into a lower and upper submember. The submember convention is useful in subsurface work and alleviates confusion over age designations. The Cromwell Sandstone of this study is the lower member of the Union Valley Formation and is considered younger than the Springer Shale.

The Cromwell Sandstone is conformable with the underlying Springer Shale and is bounded at the top by the Union Valley Limestone. The Cromwell is a medium-grained sandstone, commonly calcite cemented, and usually contains a small percentage of glauconite. The unit attains a thickness of 150 feet in the study area.

The Union Valley Limestone is the upper member of the Union Valley Formation and is bounded by the Cromwell Sandstone below and an unnamed shale above. The Union Valley is a fine to medium crystalline limestone and locally contains glauconite and fine to medium-sized sand grains (Frezon, 1962). The Union Valley Limestone averages 50 feet in thickness and is the lowest limestone member of the Morrowan Series.

Wapanucka Formation. The Wapanucka Formation is divided into a lower shale member and an upper limestone member. The formation overlies the Union Valley Formation conformably, and the upper limit is defined by the unconformity between the Wapanucka Limestone and the Atoka Series above.

The lower member is an unnamed shale and consists of gray to black shale with local limestone beds and sand lenses. The upper member is the Wapanucka Limestone and was named for the town of Wapanucka in Johnston County, Oklahoma (Frezon, 1962). The Wapanucka Limestone ranges from 70 feet to 200 feet in thickness within the study area. The Wapanucka is brown to gray in color, fine to coarsely crystalline, and commonly oolitic. Shale interbeds are present in the upper part of the unit. (Frezon, 1962). The Wapanucka is an obvious subsurface marker and can be correlated across the entire area.

Atokan Series

The Atokan Series contains the Upper Dornick Hills Group. Atoka strata thicken dramatically across the study area from the northwest to the southeast; thickness ranges from 1300 feet to 7700 feet. Atokan rocks are alternating sandstones and shales and were deposited

in non-marine, shallow marine, and deep marine environments (Houseknecht, 1983). The Desmoinesian Series overlies the Atokan Series. A major unconformity exists between the Atokan Series and the older Morrowan Series.

Upper Dornick Hills Group

Atoka Formation. The Upper Dornick Hills Group consists of the Atoka Formation. This formation was named for the town of Atoka in Atoka County, Oklahoma (Taff, 1900). The Atoka Formation contains three sandstones that are recognized within the study area. In ascending order these sandstones are the Spiro Sandstone, Red Oak Sandstone, and Gilcrease Sandstone.

The Spiro Sandstone can be correlated across the eastern half of this study area. The Spiro lies directly on the unconformity between Atokan and Morrowan strata. The base of the Spiro is defined by a sharp reentrant angle of the gamma ray or SP curve on well logs, and the Atoka Shale directly overlies the unit. Spiro sands are very fine to fine-grained, and are typically cemented by calcite cement and quartz overgrowths (Lumsden et al., 1971). The Spiro averages 30 feet in thickness in the study area.

Spiro sediments were derived from the platform to the north and deposited southward as a sheet sandstone in a high energy coastal environment (Lumsden et al., 1971; Houseknecht, 1986a).

The Red Oak Sandstone is of middle Atokan age and is bounded above and below by shale of the Atoka Formation. The Red Oak is present in six wells in the extreme southeast corner of the study area. The Red Oak is a very fine to fine-grained sandstone and

sometimes contains shale clasts and carbonate rock fragments (Vedros and Visher, 1978). The sandstone attains a maximum thickness of 65 feet within the study area. The Red Oak Sandstone is representative of a deep sea fan system deposit (Vedros and Visher, 1978).

The Gilcrease Sandstone occurs in a few wells in the northeast part of the study area. The Gilcrease is located in the upper-middle section of the Atoka and is bounded at the top and bottom by Atoka shales. Harvey (1961) described the unit as a lenticular sand body. The Gilcrease Sandstone ranges in thickness from 20 to 40 feet. Gilcrease sands are fine to medium-grained and calcite cemented.

The Atoka shales are usually black to gray in color, locally calcareous, and contain thin coal and limestone beds in some areas (Frezon, 1962). No attempt has been made to correlate individual Atoka shales in this study.

Desmoinesian Series

The Desmoinesian Series is divided into the Krebs, Cabaniss, and Marmaton Groups. The Krebs Group is the only unit of Desmoinesian strata included in this study. Desmoinesian rocks in the Arkoma Basin include dark shales, sandstones, thin coals, sandy limestone lenses, and siltstones (Oakes, 1953; Branson, 1956b). The Desmoinesian section thickens from the shelf area of the Arkoma southward into the actual basin.

Desmoinesian sediments were distributed toward the southwest in "alluvial" through "shallow marine environments" (Houseknecht, 1983). Depositional environments were "constructive deltas, coal swamps, and

shallow shelf areas" (Houseknecht, 1983). The Desmoinesian records several cycles of deltaic sedimentation.

Krebs Group

Hartshorne Formation. The Krebs Group is divided into the Hartshorne Formation and overlying McAlester Formation and was named for the town of Krebs in Pittsburg County, Oklahoma. The Hartshorne Formation lies conformably on the Atoka Formation and consists of the Lower Hartshorne Sandstone, Lower Hartshorne Coal, Upper Hartshorne Sandstone, and Upper Hartshorne Coal members in ascending order (Branson, 1956a).

The stratigraphy of this formation requires some explanation. Within the study area, the Lower Hartshorne Sandstone is laterally persistent and is present in every well drilled deep enough to penetrate the Hartshorne section. The Lower Hartshorne Coal directly overlies the sandstone in most wells, but the coal is occasionally scoured out by Upper Hartshorne channels. The Upper Hartshorne members are only present in the southeastern half of the study area.

Houseknecht (1983) pointed out that the Lower Hartshorne Coal appears to split into two coalbeds in the southern part of the Arkoma Basin of Oklahoma (Figure 2). This relationship explains the absence of the Upper Hartshorne members in the northwest part of the study area, where the coal beds converge into one unit (the Lower Hartshorne Coal).

The Hartshorne Sandstones are very fine to medium-grained sands, quartz cemented, and contain abundant shale clasts in local areas. The sandstones are considered to be of deltaic origin. The Upper

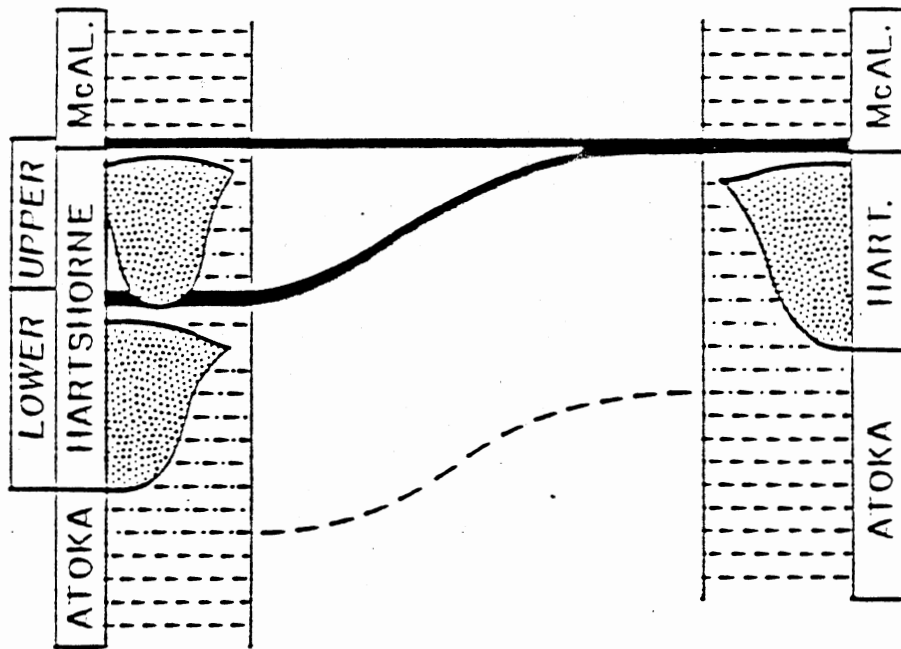


Figure 2. Stratigraphy of the Hartshorne Formation
(from Houseknecht, 1983, p. 56).

Hartshorne Sandstone ranges from 0 to 100 feet in thickness within the study area, and the Lower Hartshorne Sandstone attains a maximum thickness of 160 feet. The Hartshorne Coals contain 1 to 3 percent sulfur and are of medium-volatile bituminous rank; the coal beds are considered economic and are mined in Pittsburg County (Catalano, 1978). The coal beds are typically 1 to 2 feet thick within the area.

McAlester Formation. The McAlester Formation is conformable with the underlying Hartshorne Formation and is bounded at the top by the base of the Brown Limestone (Spaniard Limestone of surface usage) of the Savanna Formation. The McAlester Formation was named for the town of McAlester in Pittsburg County, Oklahoma. The unit thickens from northwest to southeast in the study area, and thickness ranges from 450 to 2,250 feet. McAlester rocks are mostly shale, but five named sandstones also occur within the section. Several thin coal beds are also present within the McAlester. In ascending order, the named members of the formation are the McCurtain Shale, Warner Sandstone (Lower Booch of subsurface usage) Warner coal, Lequire Sandstone (Upper Booch of subsurface usage), Cameron Sandstone, Stigler Coal, Tamaha Sandstone, Tamaha Coal, and Keota Sandstone (Bissell, 1984).

The McCurtain Shale directly overlies the Hartshorne Formation and is below the Warner or Lower Booch Sandstone. The McCurtain is a dark shale containing siltstone lenses and thin limestone layers locally. The unit ranges from 50 feet thick in the northwest to 260 feet thick in the southeast.

The Warner or Lower Booch Sandstone is bounded at the top by an unnamed shale member. Bissell (1984) suggested that the Lower Booch is actually two sandstone bodies; this is consistent with observations

made in this study. The Lower Booch commonly appears on well logs as two sandstones with an intervening shale layer. This shale layer contains the coal referred to as the Warner coal (Oakes and Knechtel, 1948). Where the sandstones appear as one unit the coal is absent. The Lower Booch ranges from 20 to 110 feet in total thickness. The sandstones are fine to medium-grained, gray to brown, massive and cross-bedded; the upper sand body is commonly thinly bedded (Bissell, 1984). The Lower Booch is described in detail in later sections of this thesis.

The unit above the Lower Booch Sandstone is an unnamed shale member. Oakes and Knechtel (1948) described this unit as a gray shale from outcrops in Haskell County, Oklahoma. The shale varies in thickness from 50 to 300 feet in the study area and grades upward into the overlying Lequire or Upper Booch Sandstone (Bissell, 1984).

The Upper Booch Sandstone is below the Cameron Sandstone in the study area. The Upper Booch is a very fine to fine-grained sand, gray in color, and locally shaley to silty in character (Oakes and Knechtel, 1948). The thickness of this unit is highly variable within the study area; thickness ranges from 10 to 60 feet.

The Cameron Sandstone is discontinuous and is often considered to be part of the Upper Booch member (Oakes and Knechtel, 1948; Bissell, 1984). The Cameron is indistinguishable from the Upper Booch Sandstone in most logs and for the purpose of this study is considered to be part of that unit. The relationship of the two sandstones is shown in Figure 3. The Cameron was described by Oakes and Knechtel (1948) as thinly bedded, fine grained, and containing shale interbeds.

The Stigler Coal overlies the Upper Booch and Cameron Sandstones,

but is difficult to distinguish on well logs within the study area. Bissell (1984) indicated a thickness of two feet for the Stigler Coal in Haskell County, which is directly to the northeast of this study area.

An unnamed shale member is present above the Stigler Coal and lies below the Tamaha Sandstone. The shale unit is gray, fissile, and silty according to Bissell (1984). In the area of study, the Tamaha Sandstone appears as a siltstone on most logs; occasionally, a 10 to 20 feet thick sand unit occupies the middle section of the Tamaha. The Tamaha Coal is very thin and can be observed in outcrops in Muskogee County according to Bissell (1984); the Tamaha Coal is not recognizable on well logs in the study area. An unnamed shale conformably overlies the Tamaha Sandstone and Tamaha Coal.

The unnamed shale member between the Tamaha Sandstone and the Keota Sandstone attains a maximum thickness of 175 feet. Bissell (1984) described the unit as a "brown silty shale". The Keota Sandstone conformably overlies this unnamed shale unit. The Keota is an interval of sandstone lenses separated by silts and shales (Figure 4). The Keota sands are "green to buff" in color and are commonly very fine-grained (Bissell, 1984). Within the study area, the Keota ranges in thickness from a few feet to approximately 125 feet of interbedded sands, silts, and shales. The Keota is conformably overlain by an unnamed shale member.

The unnamed shale that overlies the Keota Sandstone is the highest member of the McAlester Formation. The shale is silty, brown, and contains a thin coal bed known as the Spaniard coal (Oakes and Knechtel, 1948; Bissell, 1984). This shale unit averages 50 feet in

thickness and rests below the Spaniard Limestone (or Brown Limestone of subsurface usage). The Brown Limestone is the lowest member of the overlying Savanna Formation. The base of the Brown Limestone is the top of the McAlester Formation. The Brown Limestone is not present over the entire study area, and where it is absent the top of the McAlester is placed at the top of the highest Keota Sandstone body.

Genetic Intervals

Introduction

The Lower through Middle Pennsylvanian subsurface section has been divided into two types of genetic intervals. The entire section was divided into format units based on the previous works of Visher and others (1971) and Busch (1974). Format units were used for the purpose of mapping intervals of strata thought to be genetically related. The upper Atoka through lower-middle Desmoinesian section, for the purposes of this study, has been divided into cycles based on previous work by Bennison (1979) and Bissell (1984). Cycles were delineated for the purpose of recognizing regressive through transgressive sedimentation episodes related to Hartshorne and Booch deltaic systems.

Format Units

As mentioned previously, Busch (1974) outlined a "genetic interval of strata" as a single sedimentation event defined by specific marker beds including limestones, coal beds, surfaces of unconformity, and shallow marine to non-marine facies changes. A "genetic sequence of strata" was defined as two or more "genetic

intervals of strata" (Busch, 1974). Visher and others (1971) divided the Lower and Middle Pennsylvanian into format units, which were defined as "time-stratigraphic subdivisions". The format units utilized in this study are similar to those defined by Visher and others (1971), but three of the boundaries were redefined to incorporate current ideas regarding upper Atokan and Springieran strata.

For the purpose of correlation and subsurface mapping, the study interval was divided into the following format units (Figure 5). In ascending order these format units are: the Springer format from the top of the Mayes Limestone to the base of the Cromwell Sandstone; the Wapanucka format from the top of the Springer Shale to the base of the Atoka Shale; the Atoka format from the top of the Wapanucka Limestone to the base of the shale underlying the Lower Hartshorne Sandstone; the Hartshorne format from the top of the uppermost Atoka Shale (strict marine) to the base of the McCurtain Shale; the McAlester format from the top of the Upper Hartshorne Coal to the top of the Brown Limestone. Three of these divisions require further explanation.

The boundary between the top of the Springer format and the base of the Wapanucka format is considered arbitrary. Previously, the Cromwell Sandstone was described as consisting of an informal upper and lower submember. If the lower submember contains the Cromwell prodelta facies, then the placement of the format division at the top of the Springer appears to be correct. But, if the upper Springer Shale contains shales of the Cromwell prodelta facies, the boundary should be placed in the upper part of the Springer section. Frezon

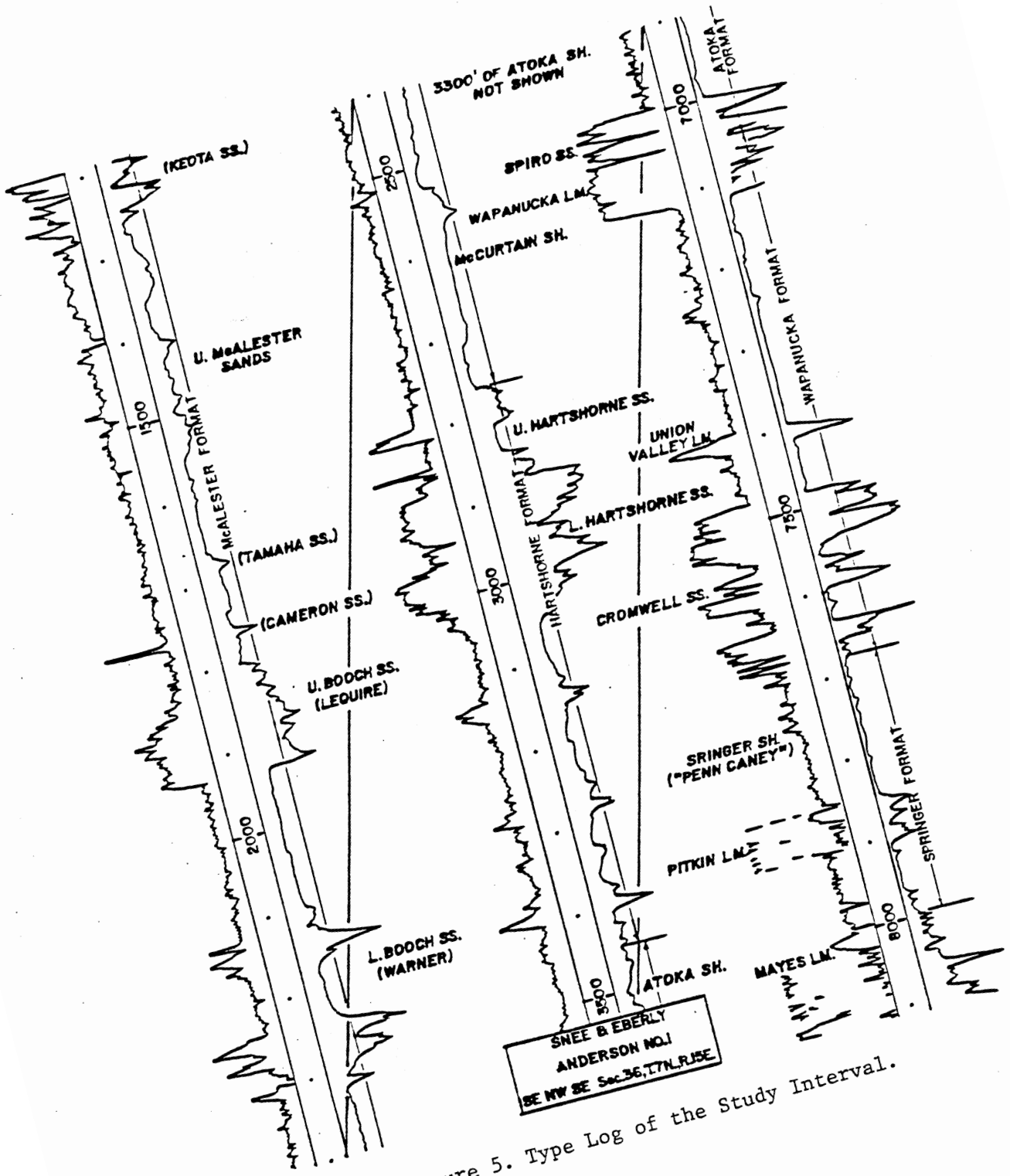


Figure 5. Type Log of the Study Interval.

(1962) described the Springer as grading upward into the Cromwell without an apparent break; for this reason the latter appears to be the correct division between the Springer and Wapanucka formats. Since there are no core data to prove this theory, and for the ease of clearly illustrating subsurface correlations, the division was placed at the top of the Springer Shale.

Visher and others (1971) considered the Hartshorne Formation and overlying McAlester Formation as one format unit. Observations made from subsurface data indicated a different source area for the Hartshorne Formation than for the McAlester Formation. For this reason the McAlester format of Visher and others (1971) has been divided into two separate format units, the Hartshorne format and overlying McAlester format. The boundary at the base of the Hartshorne format was also redefined from the boundary at the base of the McAlester format of Visher and others (1971). Houseknecht (1983) noted that the upper Atoka Shale contains the prodelta facies of the Lower Hartshorne member. On several well logs obtained from the study area the SP and gamma ray curves appear flat through most of the Atoka section; but directly below the Lower Hartshorne Sandstone, usually within 100 to 300 feet, the log signature commonly exhibits a slight coarsening upward profile. This feature is thought to be representative of the Hartshorne prodelta facies; therefore, the base of the format unit is placed at bottom of this characteristic log profile.

Cycles

The cyclicity of Desmoinesian strata in the Mid Continent has been recognized in several studies. The cycles utilized in this study are those delineated by Bissell (1984).

Cycles were used to further describe specific episodes of deltaic sedimentation included in format units and were helpful in determining subsurface mapping units for the McAlester Formation and Hartshorne Formation.

Bennison (1979) studied the cyclothems of northeastern Oklahoma and redefined the definition of a cyclothem in Oklahoma as interpreted by Branson (1954). According to Bennison (1979), Branson's cyclothem contains the following:

. . . shale, clay-ironstone concretions; limestone, or clay-ironstone, the limestone fusulinid bearing; coal; underclay; micaceous silty shale; and sandstone (p.292).

Branson theorized that the sandstone represents a transgressive deposit based on the tendency of the unit to cut into underlying strata (Bennison, 1979).

In contrast with Branson (1954), Bennison (1979) believed the sandstone to be a regressive sedimentary deposit. Bennison (1979) redefined the cyclothem to include:

. . . underclay, or paleosol; weathered siltstone or shaly sandstone with molds of logs; sandstone, cross-bedded; sandy to silty shale, minor sandy limestone; shale, clay ironstone concretions; limestone and black shale with phosphatic nodules; and coal and carbonaceous shales (p.292).

Bennison (1979) suggested that this sequence represents transgression from the coal at the base to the overlying underclay of

the next coal. Bissell (1984) described Bennison's cycle as representing "maximum regression to maximum regression".

Bissell (1984) outlined "map cycles" to illustrate "regressive episodes"; the cycle includes:

. . . phosphatic marine shale, impure fossiliferous limestones and rippled siltstones, prodeltaic shales and delta front siltstones, channel or prograded shoreline sandstones, underclay, coal, and transgressive sandstone or limestone (p.15).

This would represent a "maximum transgression to maximum transgression cycle", and the cycle is named for a "prominent sandstone or coal" contained in the sequence (Bissell, 1984).

The latter cycle ("map cycle" of Bissell, 1984) has application in this subsurface study. The rock units of the "map cycle" as described above were identified in outcrop sections in the McAlester District of Pittsburg County, Oklahoma in an earlier study by Hendricks (1939). Because the required rock units are known to exist; the "map cycles" have been correlated in the subsurface using well logs. Although, each rock type is not readily recognizable on well logs, the essential elements of the "map cycle" are obvious enough to allow for subsurface correlation with a relatively small margin of error.

Hartshorne Cycles

Figure 6 depicts the coal cycles of Bennison (1979), the informal "map cycles" of Bissell (1984), and the "map cycles" utilized in this study. The lower limit of the Lower Hartshorne cycle is at the base of the upper Atoka shales that are interpreted as

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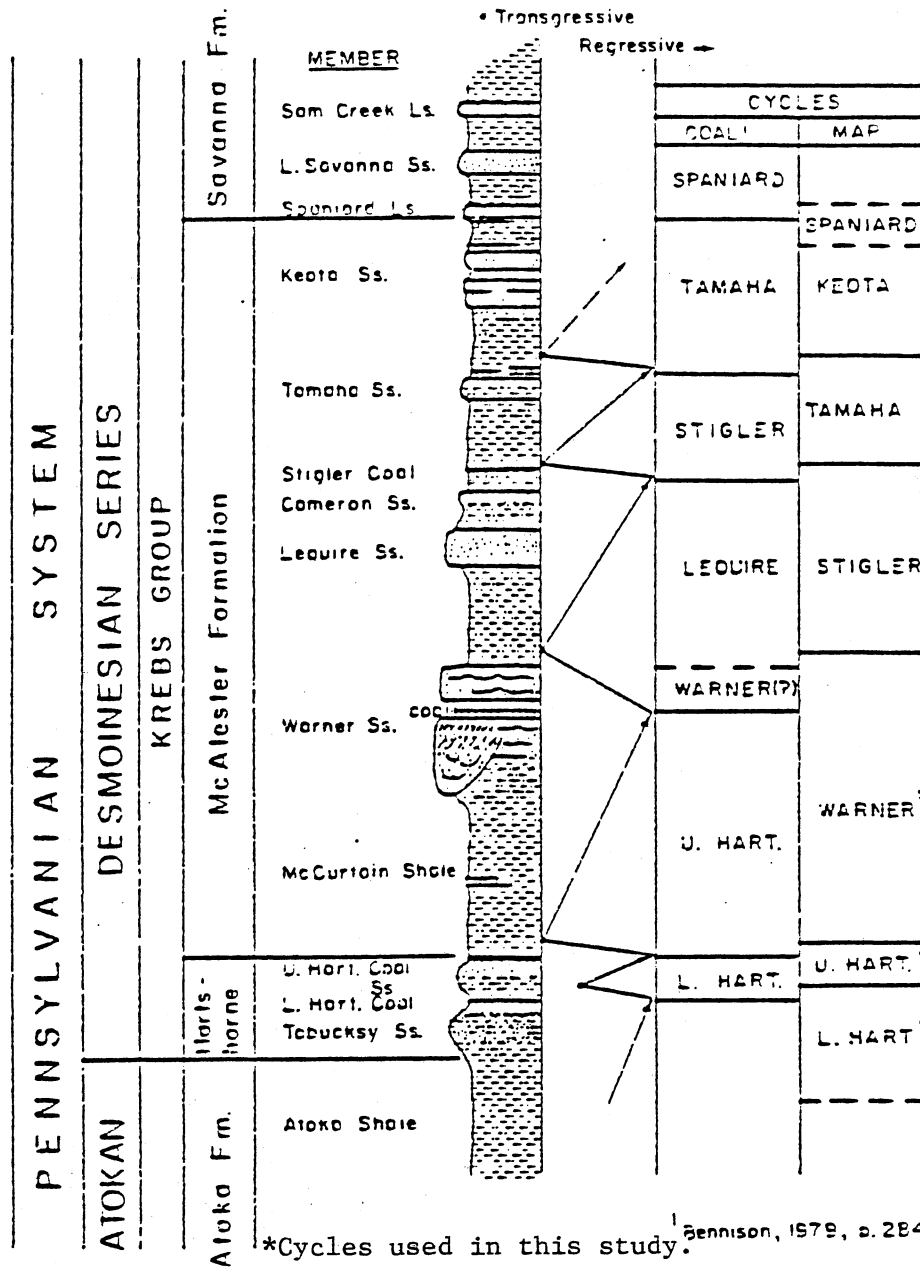


Figure 6. Sedimentation Cycles in the Hartshorne and McAlester Formations (from Bissell, 1984, p.16).

representing the prodelta facies. The upper limit is placed at the top of the Lower Hartshorne Coal.

The lower limit of the Upper Hartshorne cycle is the top of the underlying Lower Hartshorne Coal. A shale section is commonly present between the lower coal member and the overlying sandstone member. The upper limit of the cycle is the top of the Upper Hartshorne Coal. The Hartshorne cycles represent two contiguous regressive through transgressive sequences.

Booch Cycles

The lower limit of the Lower Booch (Warner) cycle is the base of the McCurtain Shale, and the upper limit is the top of the Lower Booch Sandstone. The Warner coal is usually present within the thin shale between the two sandstone bodies that comprise the Lower Booch.

The lower limit of the Upper Booch (Lequire-Cameron) cycle is the base of the shale overlying the Lower Booch Sandstone, and the upper limit is the top of the Stigler Coal. These two cycles represent two stacked regressive through transgressive sequences.

Other McAlester Cycles

Bissell (1984) delineated three additional cycles in the upper McAlester Formation; the cycles are the Tamaha, Keota, and Spaniard. These cycles are difficult to correlate in the subsurface because of the discontinuous nature of the respective sandstones, and the obvious problem of identifying thin coal beds.

The lower limit of the Tamaha cycle is the base of the unnamed shale member overlying the Stigler Coal. The upper limit of the cycle

is the top of the Tamaha Coal. The lower limit of the Keota cycle is the base of the unnamed shale member overlying the Tamaha coal. The upper limit of the cycle is the top of the Spaniard coal; this coal underlies the Brown (Spaniard) Limestone. The limits of the Spaniard cycle are not discernible within the subsurface section; therefore, the presence of the cycle is only inferred at the top of the McAlester Formation. The Tamaha, Keota, and Spaniard(?) cycles represent three regressive through transgressive sequences in the upper McAlester Formation.

Subsurface Correlations

Introduction

Three electric log cross-sections were constructed to illustrate correlations of Lower and Middle Pennsylvanian strata (Plates I, II, and III in pocket). Common subsurface names were utilized for each unit, and the surface nomenclature was applied to the units not ordinarily recognized in the subsurface. Figure 5 illustrates a type log for the study area with the common subsurface names given for each unit, and the corresponding surface nomenclature.

Springer through Atoka Correlations

Plate I is a northwest to southeast stratigraphic correlation. It illustrates the basinward thickening of the lower Desmoinesian and Atokan sections. Part of the Atoka section is not shown, so that the stratigraphy and correlation of the lower formations could be demonstrated.

The top of the Springer was placed below the lowermost sand body of the Cromwell interval. The Cromwell Sandstone occurs as a massive unit or a sequence of progressively thicker sand bodies. The top of the Cromwell is differentiated from the Union Valley Limestone by the character of the resistivity response; Union Valley resistivity typically goes off scale, and occasionally a thin shale break occurs between the limestone and sandstone units. The top of the Union Valley is placed at the base of the overlying shale member of the Wapanucka Formation. The thick Wapanucka Limestone is an obvious subsurface marker and can be easily correlated. When present, the Spiro Sandstone directly overlies the Wapanucka in the study area. The Spiro is commonly 10 to 20 feet thick, and the base of the unit corresponds to a reentrant of varying intensity on the SP or gamma-ray curve.

The Atoka Shale overlies the Spiro Sandstone and maintains a characteristic flat log response. The Red Oak (not present in cross-section) and Gilcrease Sandstones exhibit "ratty" log profiles and occupy the lower middle and upper part of the shale section, respectively. The top of the Atoka Formation was placed at the base of a slight coarsening upwards sequence below the Hartshorne as seen in log 6 of Plate I.

Hartshorne and McAlester Correlations

The electric logs used in Plate II were selected to illustrate the stratigraphy and correlation of McAlester Formation units. The McCurtain Shale is recognized by a flat SP or gamma-ray signature, and locally develops sharp resistivity spikes where the shale becomes

silty or sandy. The Lower Booch (Warner) Sandstone is correlated as the next higher sandstone body, and the shale break between the two sand bodies is usually obvious. The Upper Booch (Lequire-Cameron) Sandstones are the next higher sand units, and the Cameron is present on most of the logs in this cross section. The Tamaha Sandstone is not well developed, and the top is correlated on a small resistivity spike above the Upper Booch interval. The Keota Sandstone occurs as several thin sandstone layers above the Tamaha interval. The top of the highest Keota sand body is the best datum, because the Brown Limestone is not continuous over the study area. When present, the Brown Limestone appears as one or more sharp resistivity spikes above the Keota sands.

Plate III emphasizes the stratigraphy and correlation of members in the Hartshorne Formation. The Lower Hartshorne Sandstone is correlated as the first sandstone above the Atoka shales and is well developed in logs 2, 3 and 4. The Lower Hartshorne Coal is usually noted on scout tickets and typically appears as a sharp spike on the short normal resistivity curve. The lower coal splits between logs 3 and 4; the upper members are present in the remaining six logs.

A thin shale break is usually present between the upper and lower members, but occasionally the Upper Hartshorne Sandstone directly overlies the lower units. In the latter case, a sharp reentrant angle on the SP curve is considered to be the contact between the lower and upper members. The Upper Hartshorne Coal is difficult to recognize in the majority of well logs, but when present appears as a short normal resistivity spike; log 9 illustrates this type of resistivity response.

In summary, the Cromwell Sandstone can be correlated across the entire study area. The lower part of this unit may be referred to as the "Jefferson" or "Second Cromwell" on scout tickets. The Lower Hartshorne members are present throughout the study area, and the Upper Hartshorne members are present where the Lower Hartshorne Coal splits as described by Houseknecht (1983). Bissell (1984) correlated the Upper Hartshorne members across McIntosh County to the north of the study area; this correlation is in error based on the "coal split line" mapped by Houseknecht (1983). The "coal split line" crosses the area of the present study and indicates that the Lower and Upper Hartshorne Coals converge into one coalbed north of this boundary.

The Booch Sandstones are present across the study area, but become thin and shaley to the south. The surface nomenclature for Booch Sandstones is rarely encountered in scout tickets. Locally the Cromwell, Hartshorne, and Booch are prolific gas producing sands.

CHAPTER IV

STRUCTURAL FRAMEWORK

Tectonic Evolution of the Arkoma Basin

Regional Tectonic History

The tectonic evolution of the Arkoma Basin and adjacent Ouachita orogenic belt is best described as complex. This section attempts to establish the general stratigraphic, structural, and tectonic framework of the Arkoma Basin. The interpretation presented in this study is based on the publications of several workers and relies heavily on the recent work of the Consortium for Continental Reflection Profiling (COCORP) and Houseknecht (1983).

Walper (1977) theorized that approximately 900 to 1,000 m.y. ago North America was sutured to another continental block. This continental block is referred to as the "proto-Afro-South American plate" (Walper, 1977); the resulting supercontinent is called "proto-Pangea". A late Precambrian rifting event (Figure 7A) caused the break-up of "proto-Pangea" (Keller and Cebull, 1973). The rifted margin retreated from the spreading center and developed into a divergent plate margin (Walper, 1977). Remnants of this breakup include the Delaware, Wichita, and Reelfoot aulacogens.

Beginning in the Cambrian and continuing through the Devonian Period a south facing passive continental margin developed along the

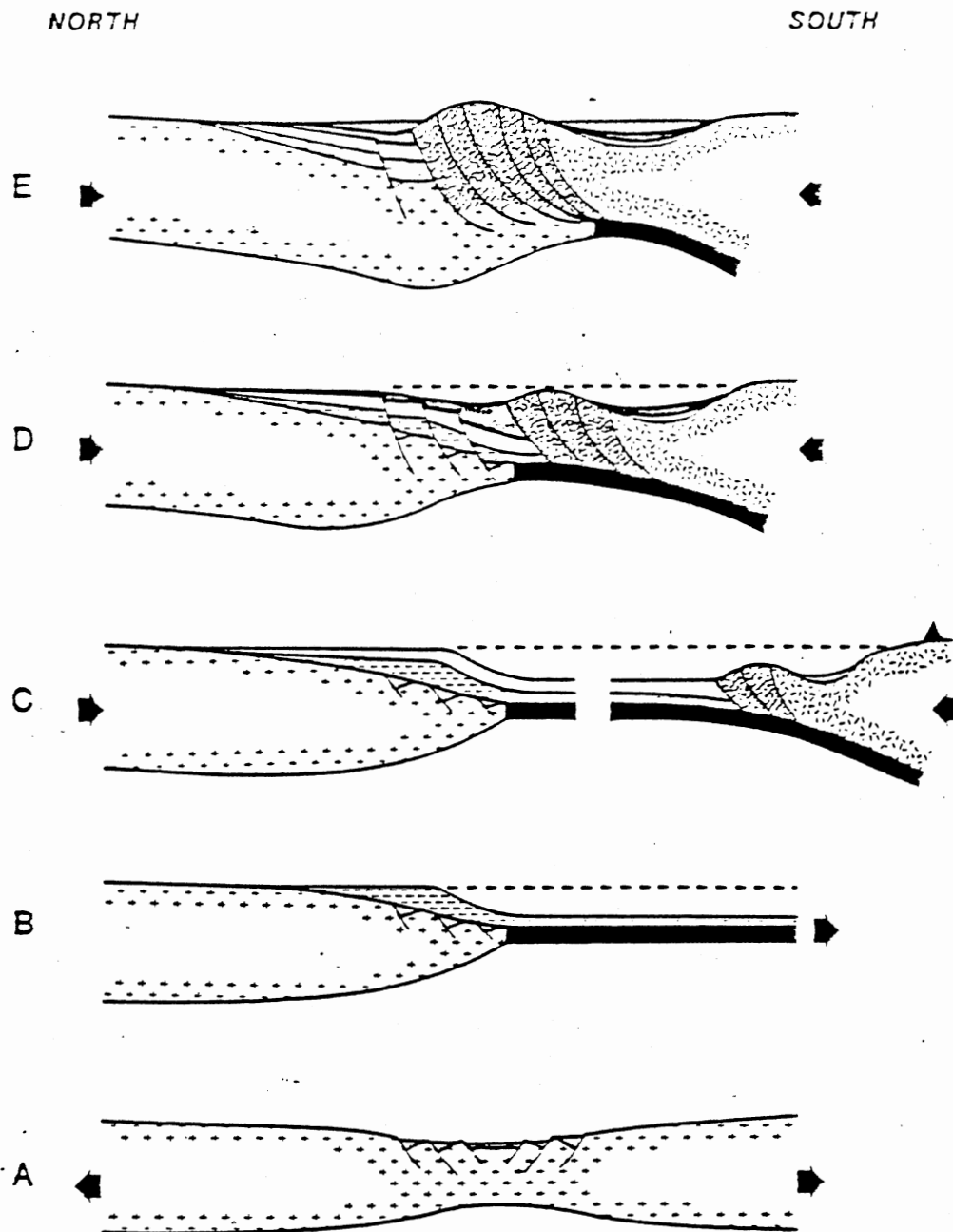


Figure 7. Summary of the Tectonic Evolution of the Arkoma Basin and Ouachita Orogenic Belt; (A) late Precambrian - early Cambrian; (B) late Cambrian - early Mississippian; (C) early Mississippian - early Atokan; (D) early Atokan - middle Atokan; (E) late Atokan - Desmoinesian (from Houseknecht, 1983, p.15).

southern margin of North America as a result of the rifting event (Figure 7B). Subsidence along the margin allowed the deposition of lower through middle Paleozoic shallow water carbonates. This sequence of carbonates exists in the subsurface of the Arkoma Basin (Lillie et al., 1983). The passive margin continued through the middle Paleozoic, and a "shelf-slope-rise geometry evolved" (Houseknecht, 1983). Reagan through Woodford strata were deposited during this time.

During Late Devonian or Early Mississippian time, convergence proceeded and the ocean basin started to close. This was due to the development of a south-dipping subduction zone along the southern margin of North America (Figure 7C). The exact time when the ocean basin began to close is not known (Houseknecht, 1983), but the presence of tuffs and tuffaceous sandstones in the Stanley Group of the Ouachita Province indicate subduction in latest Mississippian time. "Carboniferous volcanic rocks" have been found south of the Ouachitas and indicate the presence of a magmatic arc on the basinward edge of the overriding plate (Houseknecht, 1983). Most of the volcanic sediments were deposited in a forearc basin (Lillie et al., 1983; Houseknecht, 1983).

Figure 8 depicts the paleogeography of Chester time. During this stage the "remnant ocean basin" became the major site of deposition, and the flysch deposits of the Ouachitas began to accumulate (Houseknecht, 1983). The Stanley Group through lower Atoka units represent the strata deposited in the closing ocean basin. The shelf was simultaneously receiving sediments, and Springer through Spiro strata were deposited during this time. Figure 9 illustrates the

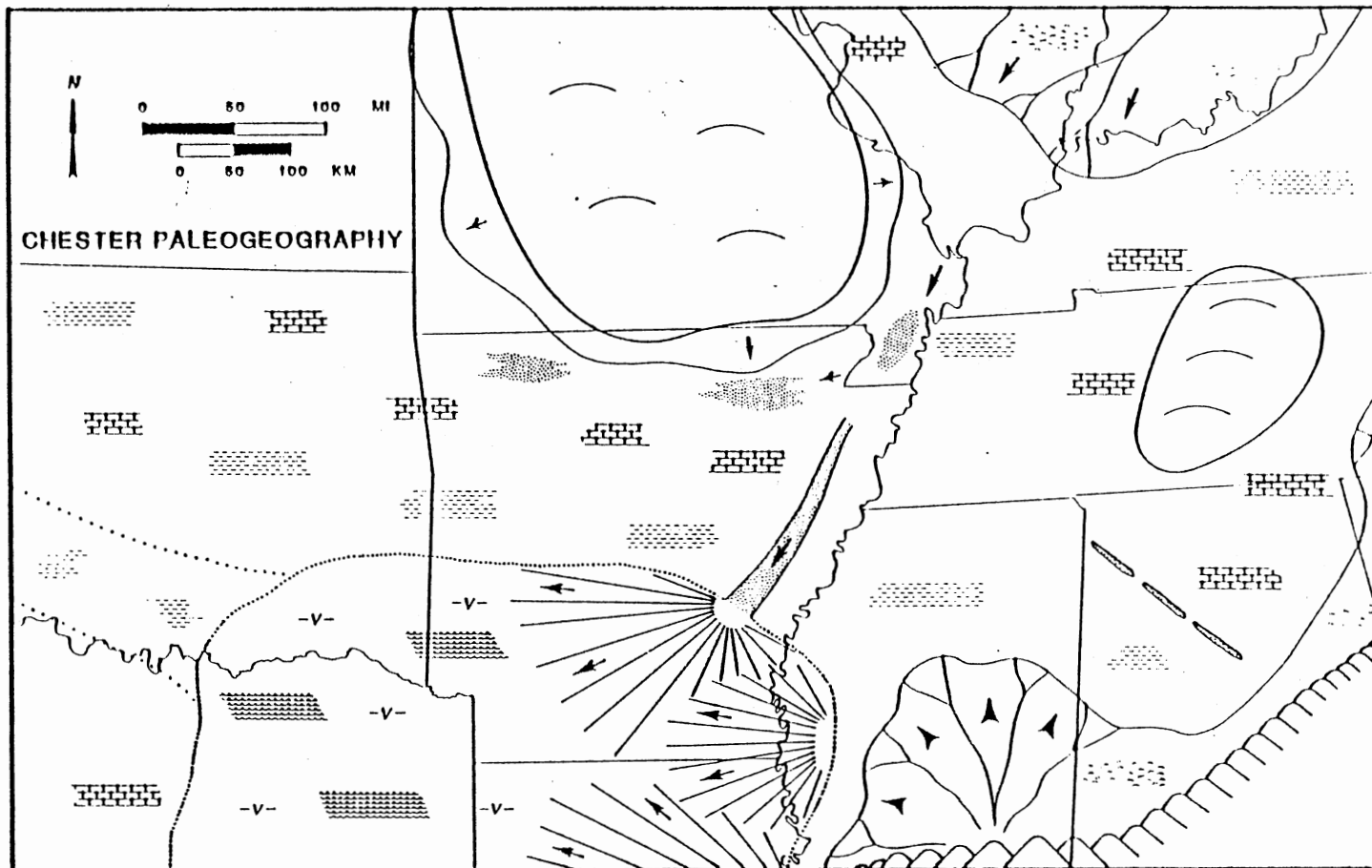


Figure 8. Chester Paleogeography and Sedimentation Patterns
 (from Houseknecht, 1983, p.22).

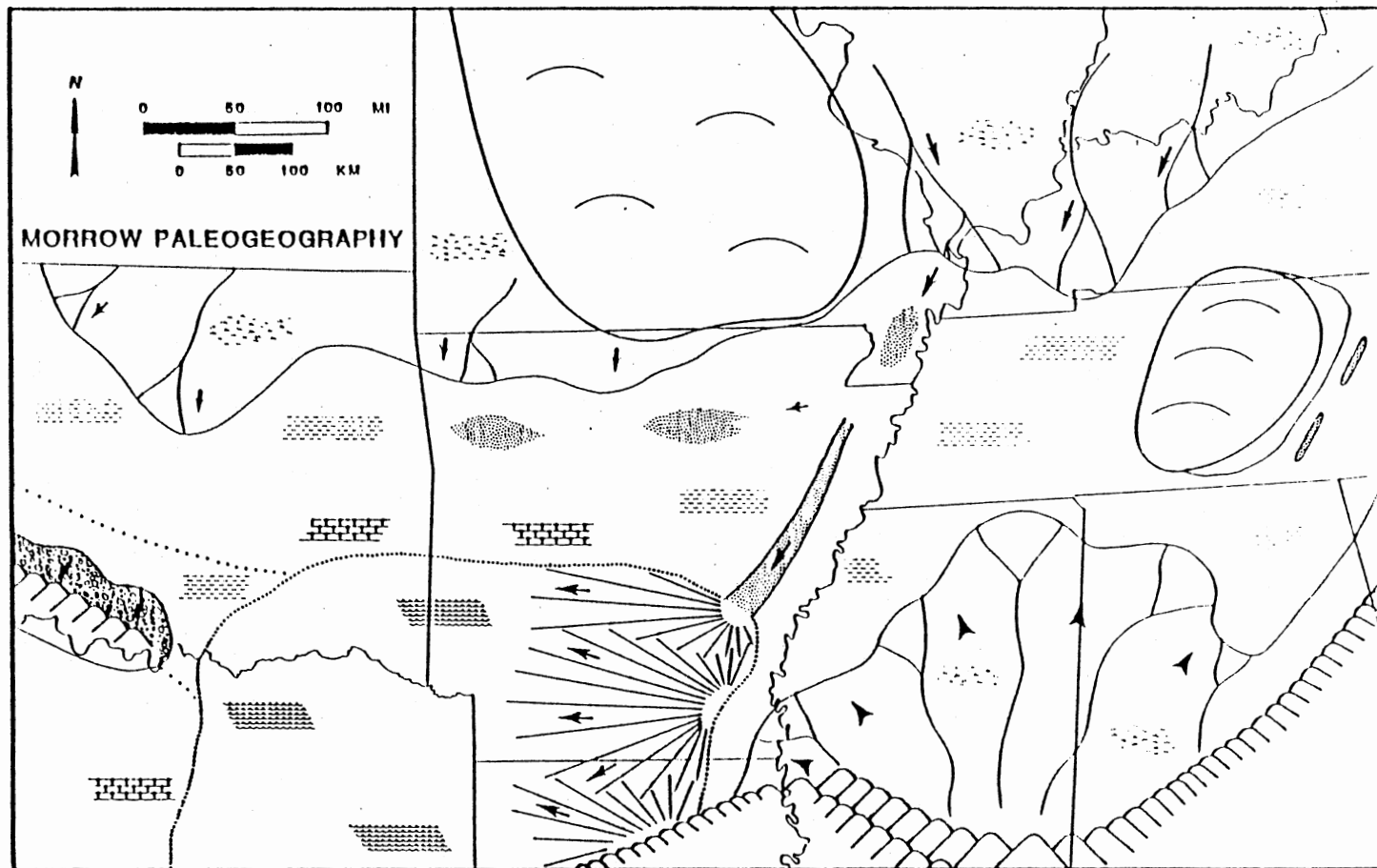


Figure 9. Morrow Paleogeography and Sedimentation Patterns
(from Houseknecht, 1983, p.25).

regional geologic setting for deposition during Morrowan time.

Morrowan sediments were derived from an eastern source area.

The "remnant ocean basin" was subducted by early Atokan time (Houseknecht, 1983). As the subduction complex continued to advance, the southern continental margin was partially subducted (Figure 7D). The net result of continued subduction was "flexural bending" of the rifted margin, which is believed to have initiated normal faulting of Cambrian through lower Atokan rocks (Houseknecht, 1983). The lower through middle Atokan units were deposited across these faults, and the lower Atoka experienced dramatic thickening on the downthrown side of these faults suggesting some type of growth fault movement during deposition (Koinm and Dickey, 1967). Houseknecht (1983) used the name "incipient peripheral foreland basin" to describe the Arkoma in this stage of development. Continued subduction of the plate margin and additional sedimentation accompanied the final closing of the deeper basin in late Atokan time (Houseknecht, 1983). Figure 10 illustrates Atoka paleogeography. The collision between North America and the subduction complex was complete by the end of Atokan time (Figure 7E), and the result was the final stage of development of the Ouachita Mountains and the Arkoma Basin (Houseknecht, 1983).

Figure 11 illustrates the paleogeography of the region during Desmoinesian time. The Ouachitas contributed sediment to the southern margin of the basin. Additional sediment entered the basin from the east and north from the Appalachians and Ozark Uplift respectively. The rocks of the Krebs Group were deposited at this time.

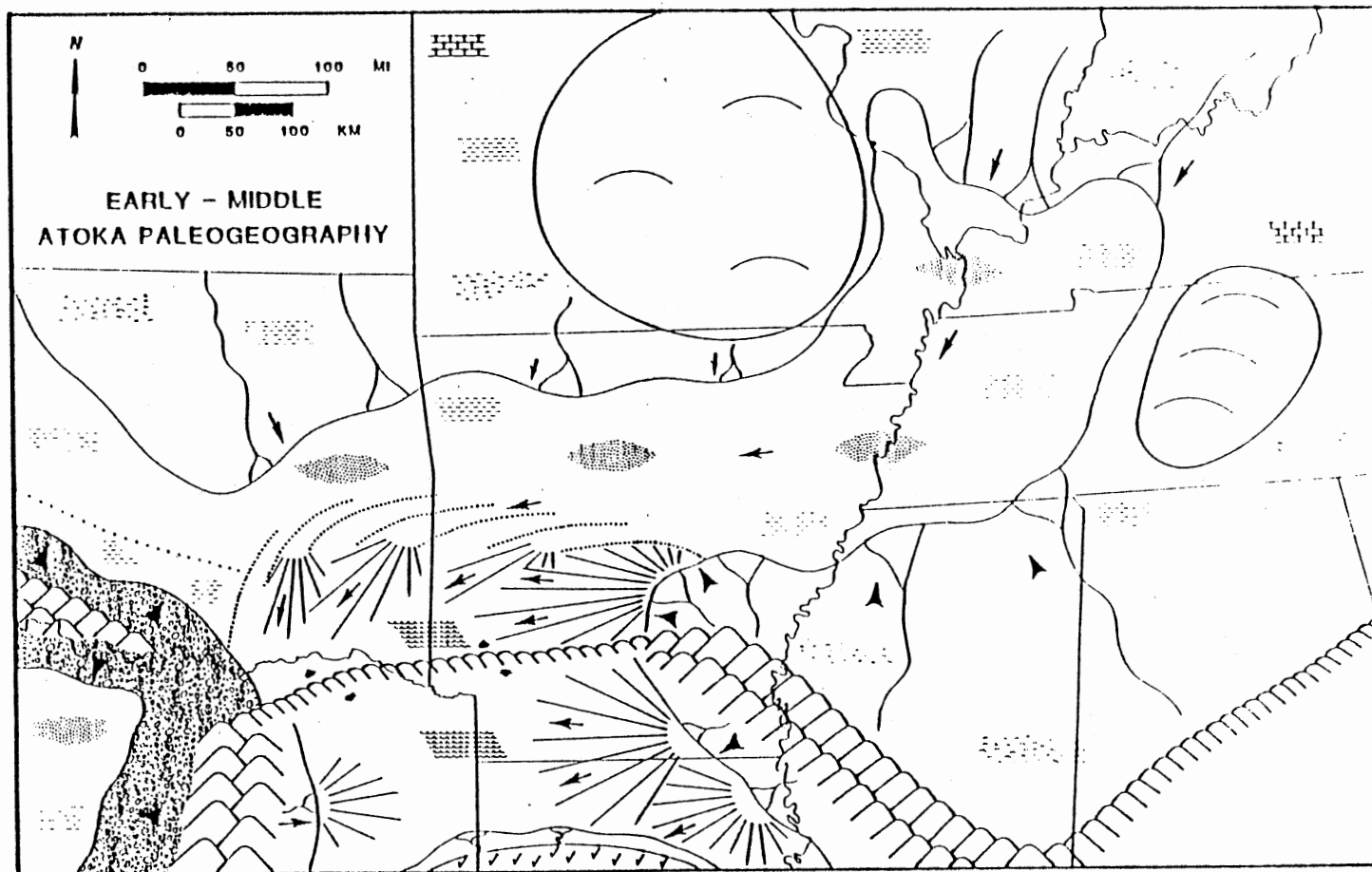


Figure 10. Atoka Paleogeography and Sedimentation Patterns
 (from Houseknecht, 1983, p.28).

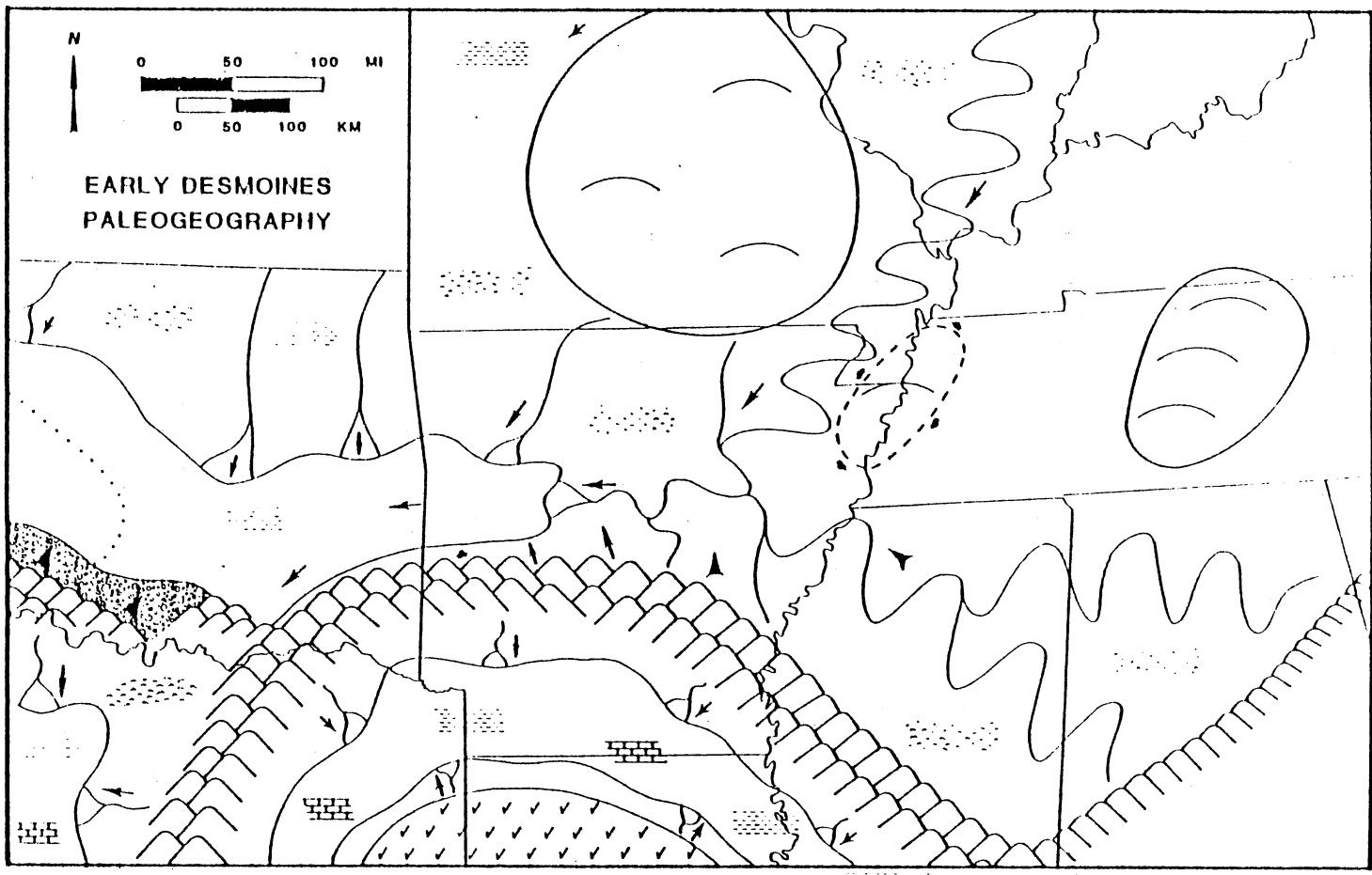


Figure 11. Desmoinesian Paleogeography and Sedimentation Patterns
 (from Houseknecht, 1983, p.31).

Regional Structure

The Arkoma Basin extends from south-central Oklahoma into east-central Arkansas. The basin is surrounded by several important geologic features (Figure 12). To the northeast it is bordered by the Ozark Uplift. The Northern Shelf of Oklahoma lies to the north and the Nemaha Ridge to the northwest. The Arbuckle Uplift borders the southwest margin, and the Ouachita orogenic belt borders the entire southern margin. The Ouachitas are a system of extremely deformed Paleozoic rocks that stretch from Alabama across parts of Mississippi, Arkansas, Oklahoma, and Texas.

The Arkoma Basin is an arc-shaped, broad regional asymmetric syncline on which several folds are superimposed. Houseknecht (1983) referred to it as an "arcuate synclinorium". On the surface, the basin consists of several gently folded synclines with tightly folded anticlines in between. The fold axes follow the general trend of the basin in a "parallel" manner (Berry and Trumbly, 1968). Thrust faults or reverse normal faults are common along anticlinal crests and also underlie the surface structure. Several normal faults occur in the subsurface. Some of these extend into the crystalline basement and also trend parallel to the shape of the basin. Atoka strata thicken across the downthrown side of these faults (Koehn and Dickey, 1967).

Local Structure

Several prominent structural features are present within the study area. All of these features were recognized on the surface and mapped by Drake (1897); Taff (1900); and Hendricks (1939). Structural interpretation was an important part of this study, and these earlier

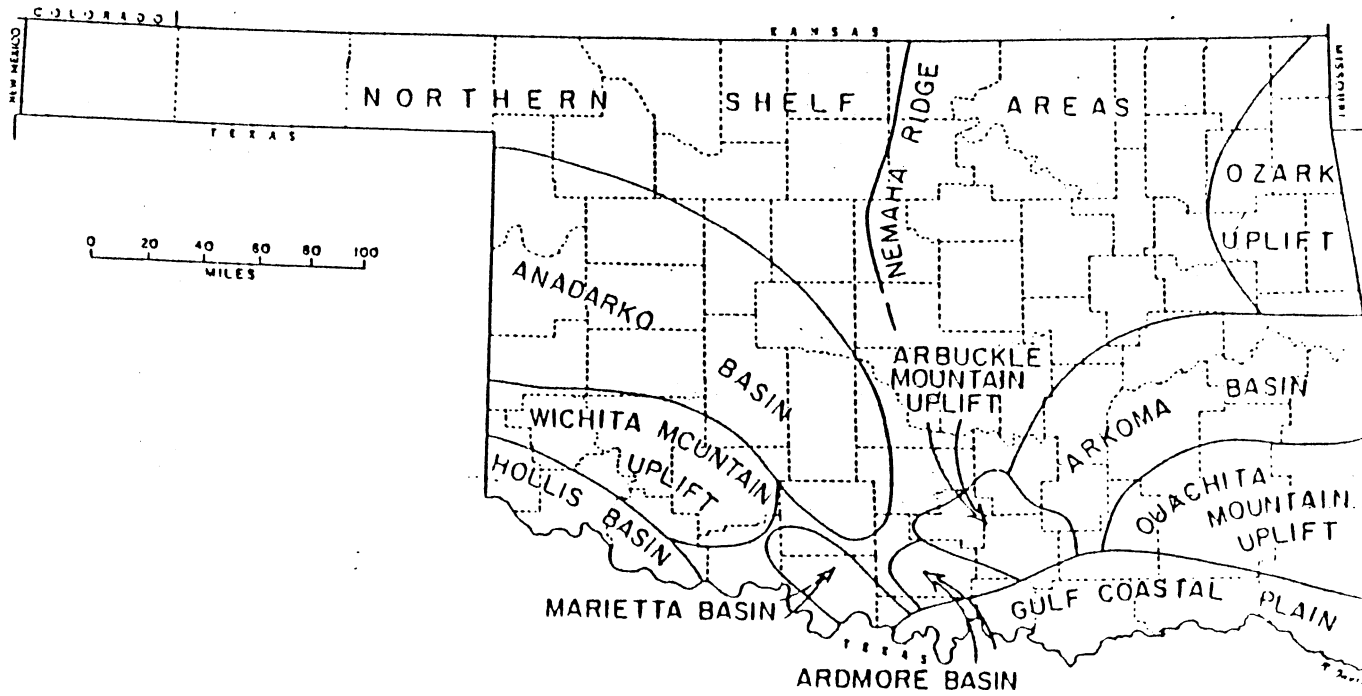


Figure 12. Regional Geologic Setting of the Arkoma Basin.

publications made it possible to recognize subtleties that might otherwise have been overlooked. Local folds and faults affected sedimentation and were involved in the formation of petroleum traps. Figure 13 illustrates the major fold axes and faults as mapped on the surface by Hendricks (1939). Each feature will be described in order of occurrence from the northwest part of the study area to the southeast.

Lilypad Creek Anticline

The Lilypad Creek Anticline was named for Lilypad Creek in northern Pittsburg County (Hendricks, 1939). The fold trends southwestward across T. 7N., R. 14E., and plunges into T. 6N., R. 13E. The anticline is gently folded with shallow dipping limbs (Hendricks, 1939).

Lake McAlester Anticline

The Lake McAlester Anticline was named for Lake McAlester in the south part of T. 7N., R. 14E. The fold trends east-west and occupies most of Secs. 34, 35, and 36, T. 7N., R. 14E., and Sec. 31, T. 7N., R. 15E. The anticline plunges east and is gently folded with shallow dipping limbs.

Flowery Mound Anticline

Flowery Mound Anticline is situated on the eastern edge of the study area and occupies Secs. 1, 2, 3, 4, 9, 10, 11, and 12, T. 6N., R. 15E. This anticline is more tightly folded and trends northeast-southwest plunging toward the southwest. Desmoinesian

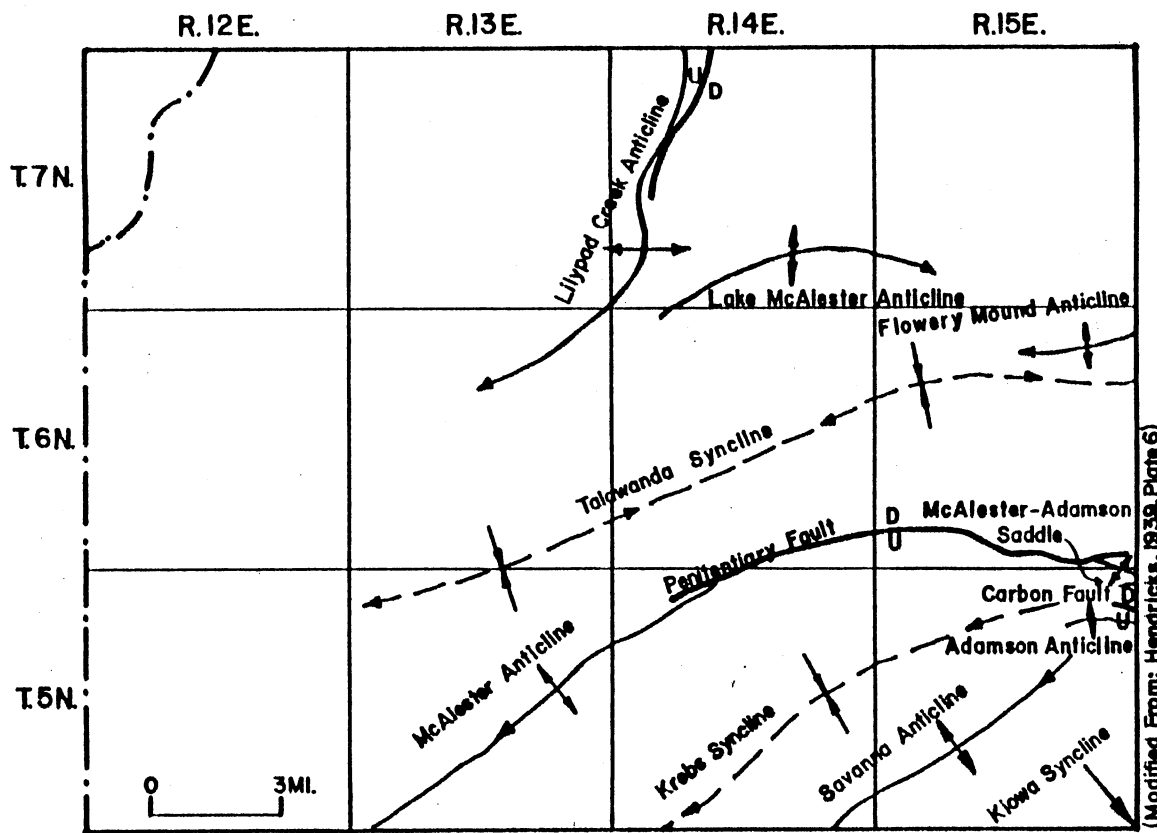


Figure 13. Surface Map of Structural Features.

strata thin dramatically across the crest of the structure and the fold limbs are steeply dipping. The Southeast Reams Gas Field is coincident with the structure, indicating a structural or combination trapping mechanism.

Talawanda Syncline

The Talawanda Syncline is the largest feature within the study area and occupies most of T. 6N., R. 12 through 15E. The syncline is relatively flat and wide with shallow dipping limbs (Hendricks, 1939). The axis of the syncline trends east-west with a northeast turn of the axis on the east side of the study area and a southwest turn on the west side. A slight structural high in T. 6N., R. 14E. divides the syncline into two "troughs" (Hendricks, 1939). The Thurman Sandstone of the Boggy Formation crops out along the flanks of the syncline and provides useful information regarding the time of deformation (Hendricks, 1939).

McAlester Anticline

Taff (1899) mapped and named the McAlester Anticline for the town of McAlester in Pittsburg County, Oklahoma. The anticline is located along the southern edge of T. 6N., R. 14 and 15E., and the axis trends "eastward to northeastward" from the west side of McAlester into T. 6N., R. 16E. (Hendricks, 1939). The anticline is asymmetrically folded to the north, with the northern limb being vertical and overturned, and the southern limb dipping less steeply to the south (Hendricks, 1939). The Penitentiary Fault offsets the crest of the anticline and Atoka Formation through Savanna Formation strata crop

out on the south side (Hendricks, 1939; Iannacchione et al., 1983). The east and west ends of the fold plunge steeply and Boggy Formation shales crop out and wrap around the extreme ends (Hendricks, 1939).

Penitentiary Fault

The Penitentiary Fault can be traced on the surface for "11 miles" across the McAlester Anticline in the southern part of T. 6N., R. 14 and 15E. (Hendricks, 1939). Atoka, Hartshorne, and McAlester strata are offset by the fault, and measured displacement ranges from approximately 3200 feet in the west to 4000 feet of maximum displacement in Sec. 25, T. 6N., R. 14E., on the east end of the surface trace (Hendricks, 1939). In T. 6N., R. 15E., the fault intersects "the axis of the McAlester anticline", and the surface trace dies out into the McAlester shale (Hendricks, 1939). The Savanna Sandstone rests against the north side of the fault and rocks of the Atoka, Hartshorne, and McAlester formations crop out against the fault from the southside (Hendricks, 1939; Iannacchione et al., 1983). Strictly from a surface vantage, the fault appears to be a thrust event resulting from north directed compression.

Krebs Syncline

The Krebs Syncline was named for the town of Krebs in Pittsburg County. The syncline appears southwest of Krebs and stretches southwestward through T. 5N., R. 14 and 15E. The "axis plunges 4° to 10°" to the southwest and continues in the same direction beyond the limits of the study area (Hendricks, 1939). The syncline is broad and

slightly asymmetric with beds on the southeast flank dipping more steeply than beds on the northwest flank.

Carbon Fault and Adamson Anticline

The Carbon Fault crosses the east boundary of the study area in T. 5N., R. 15E., and borders the north side of the Adamson Anticline. The Hartshorne Formation crops out on the Adamson Anticline in Sec. 12, T. 5N., R. 15E., and the Carbon Fault offsets Hartshorne strata on the north limb of the fold (Hendricks, 1939). Similar to the McAlester Anticline, the Adamson Anticline is asymmetric with the north limb being vertical and overturned, and the south limb dipping less steeply (Hendricks, 1939). The Carbon Fault also appears to be a thrust fault created by north directed compression. According to Hendricks (1939), the Hartshorne strata have been displaced "northward about 1000 feet" along the fault.

McAlester-Adamson Saddle

The Krebs Syncline or an associated synclinal trough extends between the eastern end of the McAlester Anticline and the western end of the Adamson Anticline creating a small saddle. For the purpose of this study, the feature has been termed the "McAlester-Adamson Saddle". The small syncline that creates the saddle is "5 miles" in length and is not obvious beyond the proximity of the saddle (Hendricks, 1939).

Savanna Anticline

The axis of the Savanna Anticline trends northeast-southwest, and

the fold borders the town of Savanna for which it was named (Taff, 1899). The anticline is located in T. 5N., R. 14 and 15E., within the study area. The fold extends northeastward, where it converges with the west end of the Adamson Anticline. The anticline is basically symmetrical within the study area, and dip on limbs at the northeast end are gentle, but dip increases toward the southwest according to Hendricks (1939).

Kiowa Syncline

Only a small part of the northwest flank of the Kiowa Syncline occurs within the study area. This portion of the fold is located in the southeastern corner of T. 5N., R. 15E. The syncline is a relatively "broad and flat" feature with very gentle dip on the northwest limb (Hendricks, 1939). The shape of the fold is straight with the axis trending northeast-southwest. In the western Arkoma Basin, the Kiowa Syncline is the first prominent feature north of the Choctaw thrust fault which surfaces 3 miles to the southeast of the study area.

Time of Deformation

Houseknecht (1983) suggested that most of the "severe structural deformation" in the Arkoma Basin had subsided by late Atokan time, and only "minor compressional deformation" occurred through early Permian time. Therefore, "minor compression" must account for the folding and faulting observed within the study area.

Atoka, Hartshorne, and McAlester rocks are cut by the Penitentiary Fault, and Hartshorne and McAlester strata thin

dramatically across the Flowery Mound Anticline. These relationships suggest significant deformation following Atokan time. Other workers have also suggested a post-Atokan episode of deformation.

Hendricks (1939) observed that Savanna through upper Boggy strata wrap around the ends of prominent anticlines within the study area, and that Thurman Sandstone beds are folded in the Talawanda Syncline. Clawson (1930) noted thinning of the Savanna Formation over anticlines southwest of the study area. Clawson (1930) also observed the orientation of several anticlines which are perpendicular to the folds north of the Choctaw fault. The Lilypad Creek Anticline is indicative of this orientation. Clawson (1930) suggested that two episodes of deformation occurred during the Desmoinesian. The first event was associated with compression from the south i.e., Ouachita thrust, and the second event, which would have created the north-south trending structures, was the result of northeast-southwest oriented compression.

It is suggested that a final surge of north directed compression created the folded and faulted terrain north of the Choctaw fault. This deformation event was an order of magnitude less in intensity than the Atokan overthrust, but was significant enough to create the structural features superimposed on the surface of the Arkoma Basin. The southwest-northeast compression suggested by Clawson (1930) accounts for the north-south trending structures in the northern part of the study area, but the origin of these forces is not clear. Most of the folding and thrust faulting in the study area probably began in early Desmoinesian time and continued through late Desmoinesian time.

Subsurface Structure Mapping

Introduction

Two structure contour maps were constructed for the purpose of evaluating the structural framework of the study area (Plates IV and V in pocket). The first map was contoured on top of the Lower Hartshorne Coal, a regionally persistent marker bed. Because the thickness of the Atoka Formation is so great beneath the Hartshorne Formation, a second map was contoured on top of the Wapanucka Limestone to evaluate the change in structure with depth.

Lower Hartshorne Coal Structure Map

All of the structure features that appear on the surface are mirrored on top of the Lower Hartshorne Coal (Plate IV). The Lilypad Creek Anticline is not an extremely high feature in the subsurface, but the general trend of the anticline is recognizable. The Lake McAlester Anticline appears as two isolated highs shifted slightly to the north from the position of the fold as mapped on the surface. The rest of the folds occupy the approximate position as mapped on the surface.

A rather complex network of normal faults occurs in T. 7N., R. 14E., and trend northeast-southwest. The displacement on the largest fault is approximately 1150 feet. This fault was not mapped on the surface by earlier workers, but it has been recognized on recent surface maps (McDaniel, 1986). Two additional faults were recognized in T. 7N., R. 12E. Displacement on these faults averages 200 feet. As would be expected the deepest depth to datum is coincident with the

Kiowa Syncline in the southeast corner of the area.

Wapanucka Limestone Structure Map

Most of the folds that were prominent in the shallow structure appear to die out at depth (Plate V). Koinm and Dickey (1967) have suggested that structures which appear on the Hartshorne show considerably less relief on the Wapanucka due to plastic deformation in the Atoka Shales.

All of the folds in the northern townships that were obvious on the previous map have become unrecognizable at depth. The network of faults in T. 7N., R. 14E. is relatively unchanged, and the displacement is equivalent to that of the shallow datum. The Talawanda Syncline is still prominent, but appears to have shifted slightly southward.

The Wapanucka Limestone section is repeated on several logs from wells that have penetrated the Penitentiary Fault plane. McDaniel (1986) suggested that the thrust or reverse normal relationship observed in the Wapanucka section is not present in the underlying Paleozoic section, but that a normal sense of movement is indicated by seismic surveys from the area. McDaniel (1986) also suggested that the thrust may have ramped up along a plane of weakness created by the existing normal fault. The presence of the pie-shaped fault mapped in the McAlester area was based on a seismic interpretation provided by McDaniel(1986).

The Krebs Syncline, Savanna Anticline, and Kiowa Syncline are present at depth. Again, the deepest depth to datum is coincident with the Kiowa Syncline in the southeast corner of the area. As

expected, this map illustrates the steep dip of the Wapanucka Limestone toward the deeper part of the Arkoma Basin.

CHAPTER V

DEPOSITIONAL FRAMEWORK

Depositional Setting

Paleoclimate

Figure 14 depicts the reconstruction of the paleoequator with respect to North America during Pennsylvanian time. Heckel (1977) noticed that Pennsylvanian coals formed within 8° of the paleoequator, where sufficient rainfall would have allowed the necessary preservation of plant matter to form coal beds. According to this reconstruction, the Arkoma Basin was located at 6° north of the paleoequator, which accounts for the numerous coal beds present in the Pennsylvanian strata of the region.

In the Pennsylvanian, the basin region was characterized by a humid climate, where marshes, swamps, and deltaic systems dominated the paleoenvironment. Heckel (1977) indicated conditions existing in this region were responsible for creating a thermocline, that allowed upwelling in the Mid-Continent sea, resulting in the deposition of phosphatic black shales.

Source Areas

Several workers have investigated paleocurrents in the Arkoma Basin to determine probable source areas for Pennsylvanian sandstones.

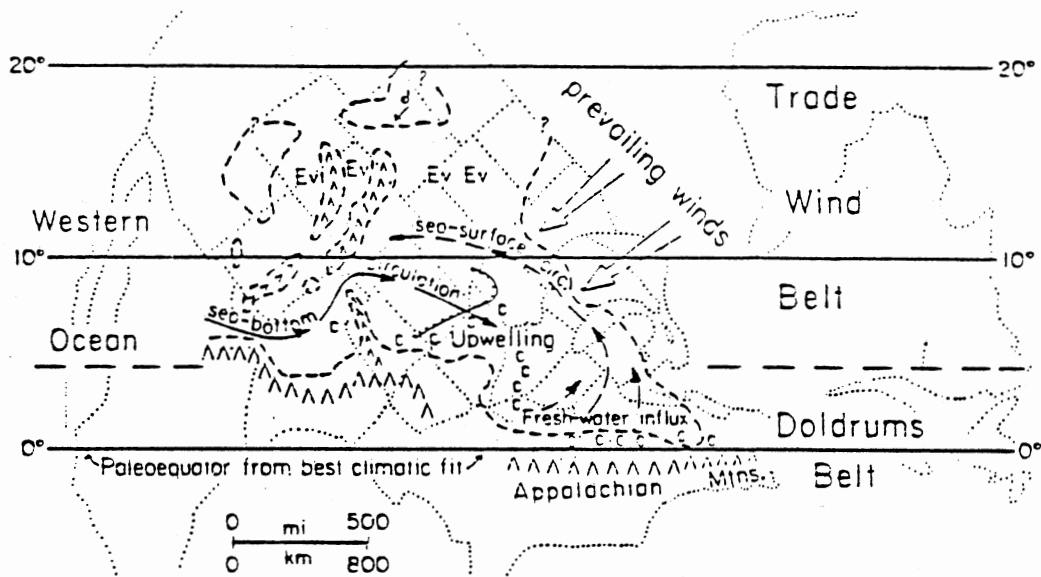


Figure 14. Reconstruction of the Paleoequator During Pennsylvanian Time (from Heckel, 1977, p.1056).

Agterberg and Briggs (1963) measured paleocurrent directions from Atokan and Desmoinesian outcrops and concluded that sediments were transported into the basin from north to south. This direction of dispersal suggests the Ozark Uplift was a major source area (Agterberg and Briggs, 1963). Briggs and Cline (1967) observed paleocurrents indicating a west directed sedimentary dispersal pattern and theorized that south moving currents were redirected to the west in the southern portion of the basin.

McDaniel (1968) determined paleocurrent directions for the Hartshorne Sandstones from ripple marks, cross bedding, and groove casts. This investigation was conducted within the study area of this thesis, and indicated a northeast to southwest current direction, which implies a more eastern source area than the Ozark uplift.

Other workers have suggested possible source areas using petrographic data and subsurface maps as evidence. After petrographic evaluation of the Lower Booch Sandstone, Scruton (1950) postulated an Ozark source area. The Booch sandstone isolith map of Busch (1953) also indicates a northern or possibly Ozark source area. Houseknecht (1983) mapped the Lower and Upper Hartshorne Sandstones over the entire Arkoma Basin in Arkansas and Oklahoma. Houseknecht's map features an ultimate eastern source area. Houseknecht (1983) theorized two major source areas for the Hartshorne Sandstones. First, the easternmost Ouachitas were uplifted in Atokan time, and may have provided detritus to the Arkoma Basin from the east. Second, but a more unlikely source area, the Illinois Basin could have been a "thoroughfare" supplying detritus from the uplifted eastern Appalachians (Houseknecht, 1983).

Observations from this study suggest an eastern source with a prevailing west directed sediment dispersal system for the Morrowan Cromwell Sandstone. The Desmoinesian Hartshorne Sandstones were probably derived from several source areas, including the Eastern Ouachitas, Ozark Uplift, and the Transcontinental Arch (or Siouxia). Houseknecht's (1983) Illinois Basin "thoroughfare" seems an unlikely source based on the ability of a low relief or non-emergent feature to supply sediment.

It is proposed that continuing compression from the south, as well as differential basin subsidence, restricted any possible eastern source areas following the deposition of Hartshorne sediments. Therefore, the Desmoinesian Lower Booch Sandstone was probably derived from a northern source area. The northern source areas may have included the Ozark Uplift and the Transcontinental Arch (or Siouxia). An extensive grain provenance study would be required to further define source areas for the Cromwell, Hartshorne, and Booch Sandstones.

Delta Systems

Introduction

The purpose of this section is to make a general statement regarding the Cromwell, Hartshorne and Lower Booch delta systems. This requires a short history of earlier studies on each unit, and a unifying statement with respect to the findings of this study.

Cromwell Delta

Very little information has been published concerning the depositional environment of the Cromwell Sandstone. Withrow (1969) studied the unit in Coal and Pontotoc Counties, Oklahoma, and described the sandstone as being deposited by "river and ocean currents". From a study of the Centrahoma Field in Coal County, Oklahoma, Anderson (1975) determined the Cromwell was deposited in a "marine-delta complex".

Cromwell electric log profiles and one net sandstone isolith map were used to determine the depositional environment of the unit. These observations indicate that the Cromwell Sandstone represents at least one period of deltaic sedimentation.

Hartshorne Delta

The Hartshorne Formation has been interpreted as a deltaic sequence by several workers. Scruton (1950) described the Hartshorne as characteristic of deltaic sedimentation. McDaniel (1968) presented a deltaic interpretation based on outcrop study and subsurface mapping. Houseknecht (1983) provided a complete investigation of the Hartshorne Formation and described the unit as a "tidally influenced, high-constructive delta". Dr. Houseknecht's work has been very thorough, and few questions remain as to the deltaic environment of the Hartshorne.

In this study, subsurface investigation of the Hartshorne included subsurface mapping, evaluation of electric log profiles, and petrographic analysis of cores. This information was utilized to

determine specific depositional facies within a local area of Hartshorne deposition. These data indicate that the Hartshorne Sandstones represent two episodes of deltaic sedimentation.

Lower Booch Delta

The deltaic environment of the Booch Sandstones is well documented. Reed (1923) suggested a deltaic environment for the Booch based on subsurface mapping. Scruton (1950) described the petrographic character of the Lower Booch Sandstone from several outcrops in northeastern Oklahoma and found the unit to fit the criteria of a Pennsylvanian delta. Busch (1953) provided an excellent sandstone isolith map to document the deltaic environment of the Booch Sandstones (Figure 15). Karvelot (1972) mapped the Lower Booch Sandstone in McIntosh and Haskell Counties, Oklahoma, establishing an east to southeastward extension of Busch's map. In a similar manner, Bissell (1984) mapped the Lower Booch Sandstone across parts of Haskell, McIntosh, Muskogee, and Okmulgee Counties, Oklahoma, and in effect demonstrated a continuation of Lower Booch sand bodies between the areas of the two previous studies. More importantly, Bissell (1984) delineated specific cycles of deltaic sedimentation within the Booch interval.

All of these studies provide sufficient evidence to recognize the Lower Booch Sandstone as a product of deltaic sedimentation. Subsurface investigation of this unit included the construction of one net sand isolith map, evaluation of electric log profiles, and petrographic analysis of one core. The subsurface data were compiled to illustrate the southward extent of the Lower Booch delta and

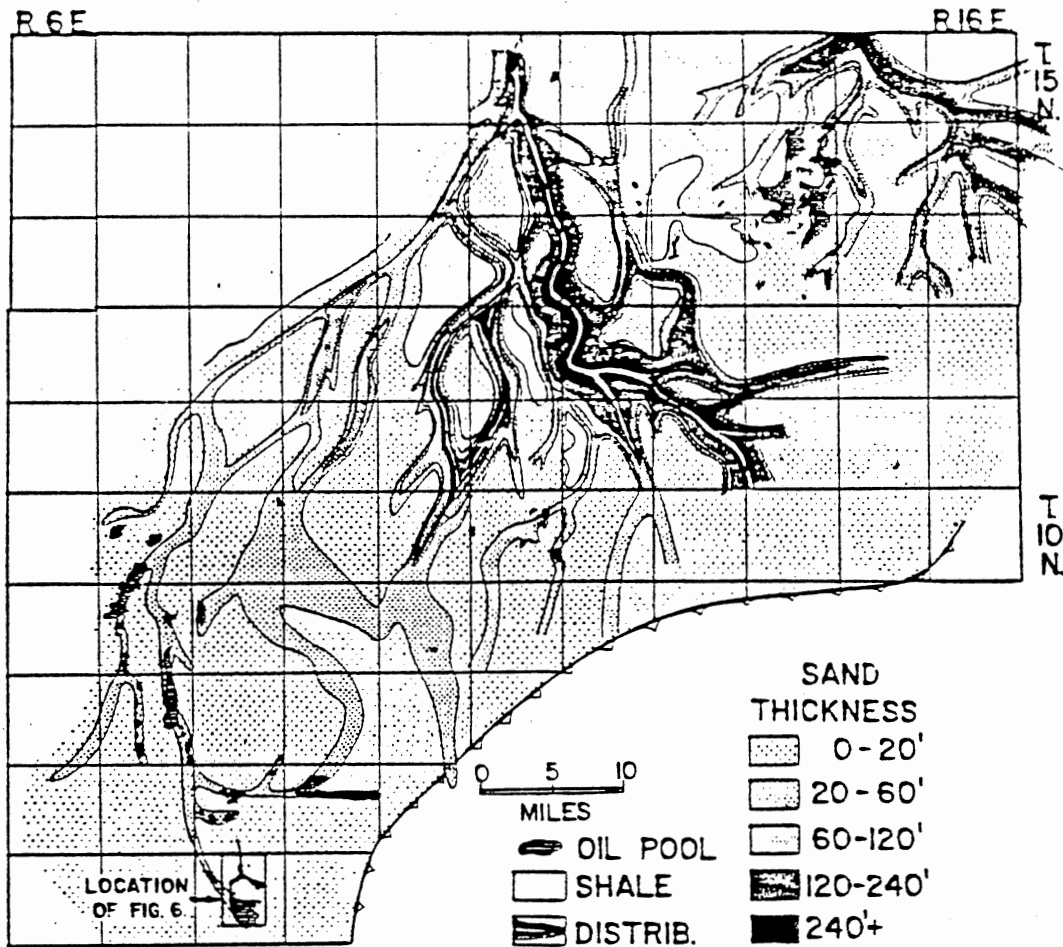


Figure 15. Booch Sandstone Isolith Map, Greater Seminole District, Oklahoma (from Busch, 1971, p.213).

determine specific depositional facies within the study area. The Lower Booch Sandstone was found to represent one or possibly two periods of overall regressive deltaic sedimentation.

Depositional Models for Cratonic Deltas

Introduction

The application of depositional models is desirable in order to further define the specific environments observed in cores and subsurface maps. The high-constructive lobate and high-constructive elongate delta models of Brown (1979) can be directly applied to the three deltaic systems previously described. The ideas of Fisk (1961) and Cleaves (1984) will be incorporated with the general description of cratonic deltas given by Brown (1979).

High-Constructive Deltas

Several workers have cited the importance of cyclic sedimentation in ancient deltaic deposits. A cycle of constructive deltaic sedimentation is composed of several phases. Each phase may include one or more depositional facies, including: basinward progradation of prodelta shales; deposition of delta-front sandstones; "shifting of distributary channels" and development of interdistributary marshes or swamps; additional distributary channel activity; deposition of delta plain facies; abandonment of deltaic sedimentation (Brown, 1979). The destructional phase begins with the transgression of the delta lobe and is accompanied by deposition of shales and thin limestones (Cleaves, 1984).

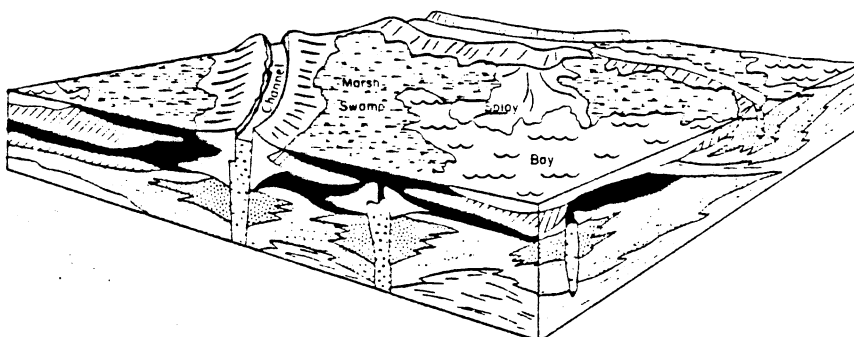
Each phase of deltaic sedimentation is characterized by one or more specific depositional facies. The character and distribution of any one particular facies may differ depending on the type of high-constructive delta with which it is associated. High-constructive deltas are divided into two types, elongate and lobate, which are based on the overall geometry of delta lobes (Brown, 1979).

High-Constructive Lobate Geometry

The high-constructive lobate delta (Figure 16) is distinguished by a relatively thin prodelta facies, delta-front sandstones, abundant distributary channels, channel mouth bar sandstones (that coalesce to form delta fringe sandstones), thin delta plain deposits, overall lobate geometry, and overbank deposits (Brown, 1979, Cleaves, 1984).

Lobate deltas usually prograde into shallow water, which ordinarily results in a thin prodelta facies. Sediment input is moderate, which allows for reworking of channel mouth bar sands, and the sand/mud ratio is high (Brown, 1979). Distributary channels are abundant, but not stacked. Crevasse splays can develop, but are more common in elongate deltas. Growth faults, or "rotational slump blocks", may occur along the delta-front in lobate deltas (Davis, 1983). Destructional phase processes may create sheet sands and barrier islands.

In the subsurface, lobate delta-front sandstones are a "primary reservoir target", and are distinguished by a digitate coarsening upward electric log profile (Brown, 1979). Other reservoir sands include: crevasse splays, distributary channel-fill sands (bar fingers), and barrier islands of the destructive facies (Cleaves,



- Prodelta
- Channel
- Channel-mouth bar
- Delta front
- Levee
- Delta plain (organic matter)
- Interdistributary bay

TEXTURE		STRUCTURES	FACIES
CSE.	FN.		
	LAMINATED MUD & SILT	PRODELTA	
	LIMESTONE	SHELF	
	MUD, SAND, COAL	DELTA PLAIN	
	RARE TROUGHS, HORIZONTAL-BEDDED SAND, SOME RIPPLES	DELTA FRONT (BEDDED SHEETS)	
	CONTEMPORANEOUS SLUMPING IN SOME DISTAL FACIES		
	LAMINATED MUD & SILT	PRODELTA (THIN)	

LOBATE TO SHEET-LIKE SAND BODY

Figure 16. High-Constructive Lobate Delta Model; (A) Block Diagram; (B) Vertical Trends in Texture and Sedimentary Structures (from Brown, 1979, p.51).

1984). Source rocks are surrounding prodelta shales and interdistributary deposits. Petroleum trapping mechanisms are growth faults "roll-over anticlines", and stratigraphic pinchouts (Brown, 1979).

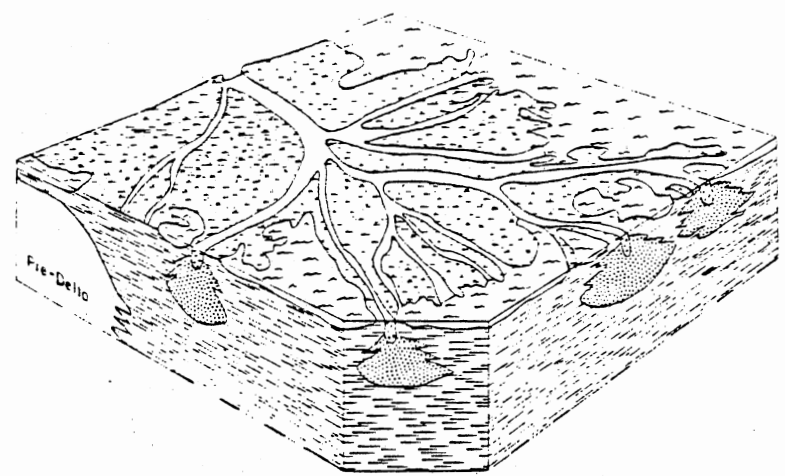
High-Constructive Elongate Geometry

The high-constructive elongate delta (Figure 17) is characterized by a very thick prodelta facies, elongate distributary channels, well developed channel mouth bar sands, thick delta plain, dip-elongate geometry (bird's foot), and crevasse splays (Cleaves, 1984).

Elongate deltas prograde into deep water, allowing for significant aggradation of the prodelta facies. The thick prodelta sequence allows soft sediment deformation and gives rise to contorted beds, mud lumps, and mud diapirism. Sediment input in elongate deltas is high with a low sand/mud ratio (mostly mud).

Distributary channels are straight with little or no meandering, and may be stacked. Elongate distributary channels are stabilized by rapid subsidence resulting in seaward progradation (Cleaves, 1984). As the distributaries advance seaward, elongate sand bodies are created by the channel mouth bar. Fisk (1961) referred to these sand bodies as "bar fingers". Bar fingers were deposited in the delta-front, where rapid subsidence allows deformation of the sand bodies (Brown, 1979).

Fisk (1961) defined the criteria for bar finger sands (Figure 18) as follows: elongate and lenticular sand bodies that decrease in width upstream and bifurcate downstream; boundaries with surrounding silt and shale facies are transitional; the main sand body consists of



Channel mouth bar	Interdistributary bay	Prodelta-distal delta front
Channel		Marsh

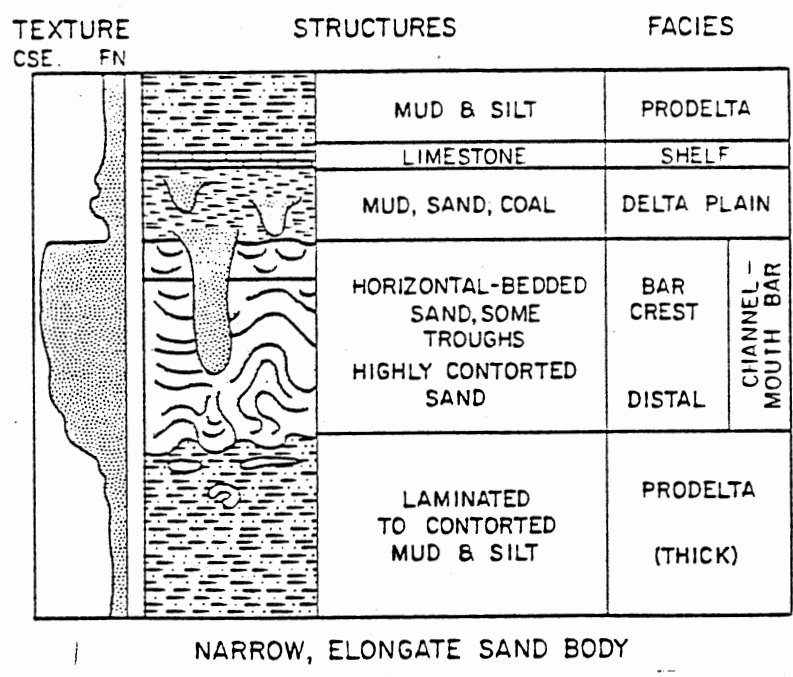


Figure 17. High-Constructive Elongate Delta Model; (A) Block Diagram; (B) Vertical Trends in Texture and Sedimentary Structures (from Brown, 1979, p.51).

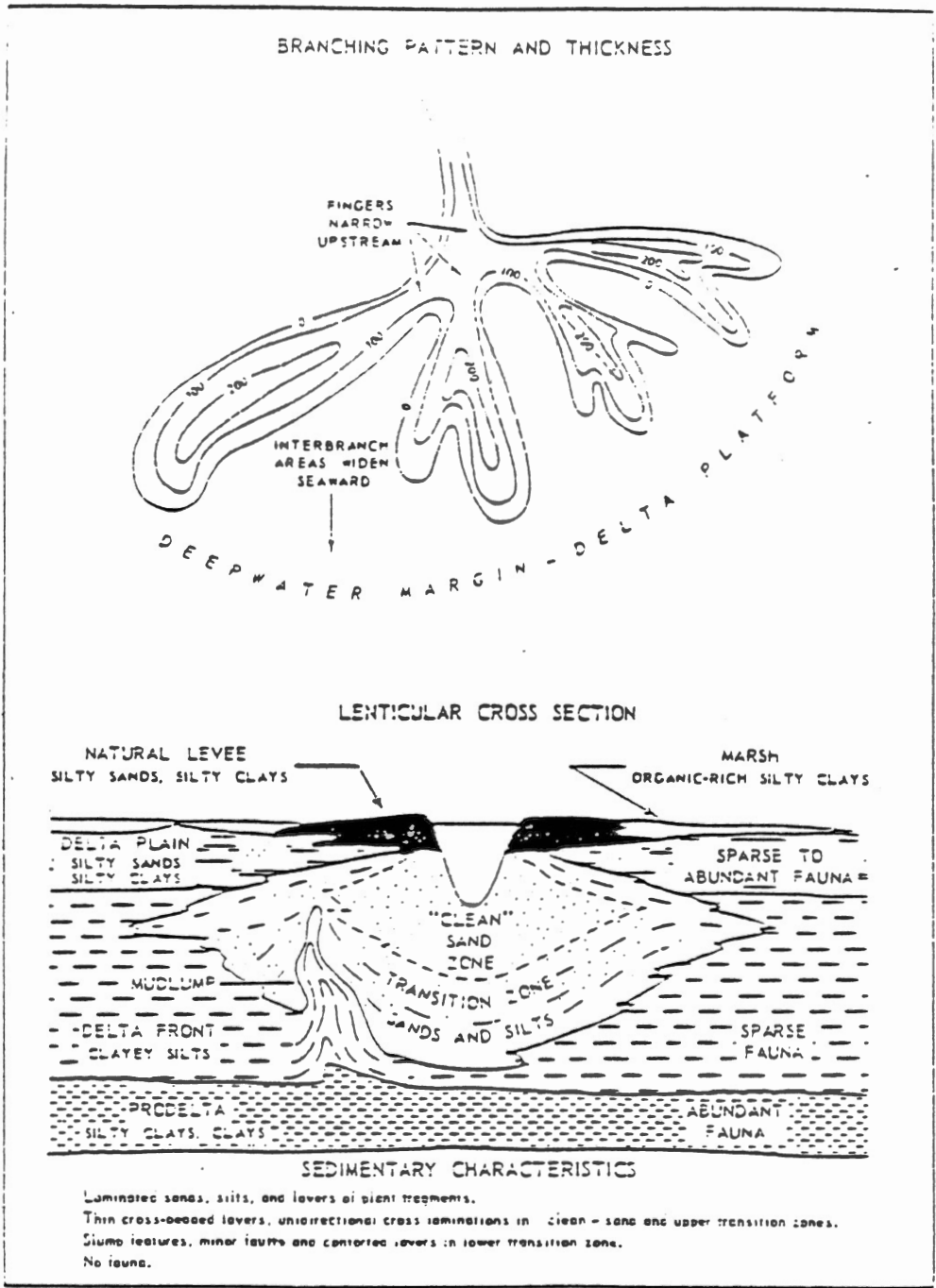


Figure 18. Bar Finger Sandstone Model (from Fisk, 1961, p.49).

clean laminated sands and often exhibit cross-bedding, microfaulting, mud lumps, and contorted beds. The Lower Booch Sandstones are considered to be ancient bar finger deposits (Fisk, 1961).

The abandonment of distributary channels results in filling of channels by bedload sand and mud (Brown, 1979). Once abandonment of a channel occurs, destructional processes may act to rework the delta-front sand facies into barrier islands. Delta plain deposits include natural levees, point bars, interdistributary bays and marshes, and small lakes. Destructional processes in the upper delta plain generate extensive peat deposits.

In the subsurface, elongate distributary channel sands are recognized by a blocky electric log profile (Brown, 1979). Reservoir sands include elongate distributary channel sands, bar finger sands, and crevasse splay sands (Cleaves, 1984). Source rocks are prodelta shales, interdistributary bay muds, and marine transgressive muds (Cleaves, 1984). Petroleum traps are formed by stratigraphic pinchouts, growth faults, and "roll over anticlines" (Brown, 1979).

This synopsis of high-constructive delta models will accommodate the following interpretation of depositional environments for the Cromwell, Hartshorne and lower Booch delta systems from various subsurface data.

CHAPTER VI

SUBSURFACE STUDY

Introduction

The Cromwell, Hartshorne, and Booch Sandstones are all prolific hydrocarbon reservoirs in the Arkoma Basin. These three units account for more than 95% of the total gas production within the study area. For this reason, these units were studied in more detail. Major emphasis was placed on the Hartshorne and Booch Sandstones.

The extent of the subsurface mapping area is defined by T. 5-7N., R. 12-15E., Pittsburg County, Oklahoma. The subsurface data base was compiled from more than 450 electric well logs, sample logs, scout tickets and various scouting reports. One Hartshorne core was available within the study area. An additional Hartshorne core and one Booch core were obtained from outside the study area. The location of each core is given in Table II.

The purpose of this section is to provide a detailed description of each core and to furnish an interpretation of the depositional environment. The deltaic models previously discussed will be utilized to explain the presence of depositional facies encountered in each core.

TABLE II
CORE LOCATIONS

Core Descriptions: Appendix A		
U. Hartshorne Sandstone	NW-SE-SW	Sec. 34, T. 6N., R. 13E.
U. Hartshorne Sandstone	C-SW	Sec. 24, T. 8N., R. 17E.
L. Booch Sandstone	SW-SW	Sec. 31, T. 10N., R. 18E.

Study of Cores

Apache Oil Corporation, No. 1 Hunt-Garrett (HG)

This well was completed as a Hartshorne gas well. The well produces from Upper and Lower Hartshorne Sand perforations at 3552-3708 feet (log depth). The initial potential flow (IPF) of the well was gauged at 1.25 MMCFGD (million cubic feet of gas per day) through a 1/2 inch choke. Flow tubing pressure was 90 psi (pounds per square inch), and shut-in tubing pressure was 490 psi. The first date of production was August, 1965 and the well is still producing with a cumulative production of 2.7 BCFG (billion cubic feet of gas) as of January, 1987 (Dwight's Production Data, 1987).

The well is located in the NW SE SW, Sec. 34, T. 6N., R. 13E., in the South Pine Hollow Field, Pittsburg County. The interval cored was 3555-3561 feet, where the core barrel jammed and 2-1/2 feet of core was lost, and 3561-3601 feet, approximately 42-1/2 feet total of Upper Hartshorne Sandstone (Appendix A).

The upper and lower contact of the Upper Hartshorne Sandstone were not within the cored interval. The sand was fine-grained through

most of the core, but there was a two foot interval of very fine-grained sand at the base of the core. Small scale trough cross-bedding and horizontal plane beds are the major sedimentary structures in the five foot interval at the bottom of the core. Sedimentary structures are enhanced by siderite and black carbonaceous organic debris and plant fossils are abundant at the base of the core. Stylolites are present throughout the core. Petrographic evaluation of the bottom one foot interval revealed abundant siderite and dolomite cement. Strata between 3583 and 3595 feet are dominated by deformed, or contorted bedding, and plane beds. The interval between 3574 and 3583 feet consists of plane bedded fine-grained sand with minor shale laminae confined to a one foot interval. At the 3584 foot level there are two cobble-sized iron-rich mud clasts. At the top of this interval a very thin coal bed is present. Strata between 3555 and 3574 feet contain small scale trough cross-beds, plane beds, and contorted bedding. Thin shale laminae are common in the lower two foot and upper three foot portion of this interval.

Unfortunately, the condition of this core was extremely poor, and consisted of several broken pieces of hand specimen size. For this reason, a composite photograph is not included. Figures 19 and 20 illustrate the most common sedimentary structures.

This core probably represents the distributary channel facies of the Upper Hartshorne Sandstone. The location of the core is coincident with a northeast-southwest trending Upper Hartshorne Sandstone body (Plate XI). The electric log profile suggests a stacked channel relationship with the underlying Lower Hartshorne Sandstone. Contorted bedding indicates rapid subsidence into the

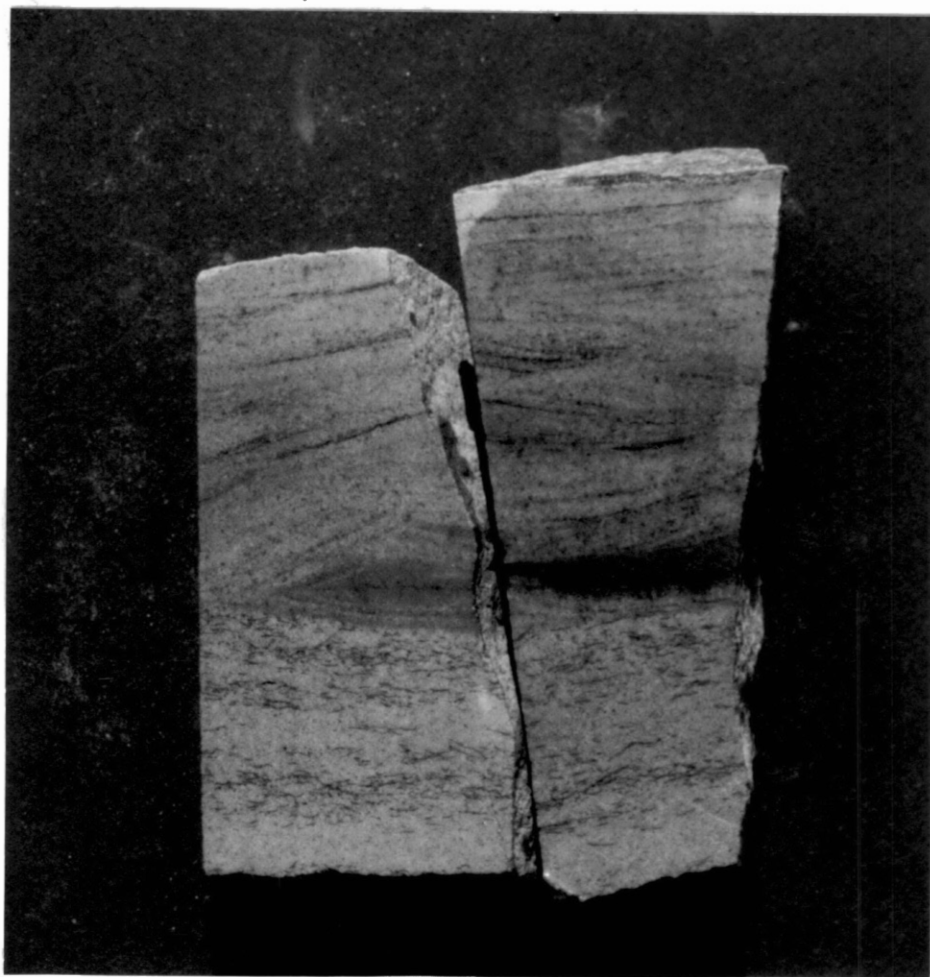


Figure 19. Small Scale Trough Cross-Bedding in the Upper Hartshorne Sandstone (3600 feet) of Core HG (Sec. 34, T 6N., R. 13E.).



Figure 20. Contorted-Bedding in
the Upper Hartshorne
Sandstone (3587 feet)
of Core HG (Sec. 34,
T. 6N., R. 13E.).

underlying prodelta muds. Abundant organic debris and plant fossils at the base of the core suggest the channel prograded through the interdistributary bay facies overlying the Lower Hartshorne channel. The interdistributary facies would have been deposited following the abandonment and subsidence of the lower channel.

Also, a slight coarsening upwards profile is coincident with the grain size transition from fine to very fine-grained sands at the base of the core. Cross-bedding indicates unidirectional flow, which would have been basinward. Although the entire Upper Hartshorne interval is not present in the core, it appears to represent a regressive episode of sedimentation.

Kerr-McGee Corporation, No. 1 Finch (KMF)

This well was also completed as a Hartshorne gas well. The well produces from Upper and Lower Hartshorne Sand perforations at 2101-2295 feet (log depth). The IPF of the well was gauged at 837 MCFGD through a 3/4 inch choke. Flow tubing pressure was 150 psi. The first date of production was March, 1978. The well is considered active, and the cumulative production is 929.8 MMCFG as of January, 1987 (Dwight's Production Data, 1987).

The well is located in the C of SW, Sec. 24, T. 8N., R. 17E., in the Blocker Field on the southwest flank of the Enterprise Anticline, Pittsburg County. The cored interval was 2101-2185 feet, approximately 84 feet of shaley sand were recovered.

The lower contact of the Upper Hartshorne Sandstone is present at the base of the core. Overall, this core consists of alternating shales, clean quartz sand, and shale arenites (Appendix B). The

bottom one foot interval consists of black shale. Directly overlying the shale are several thin coal stringers (less than 1/4" thick) interbedded with fine-grained sandstone. A 10 foot interval of very fine to fine-grained sandstone overlies the coal stringers. This interval is massive and contains a few thin coal stringers.

The massive sandstone is in abrupt contact with the overlying six foot interval of shale-arenite. Shale clasts are composed of stratified black shale and appear to have been ripped up and rapidly deposited. Individual clasts exhibit bioturbation and soft sediment deformation. The sand in the shale-arenite interval is very fine-grained with quartz cement. A four foot interval of massive fine-grained sand with abundant black organic debris overlies the shale arenite interval.

Strata between 2138 and 2162 feet are dominantly shale-arenites. A one foot sand layer is in abrupt contact with the strata above and below at the 2155 foot level. Sands between 2129 and 2137 feet are massive and very fine-grained with few horizontal plane beds; still, the sand is dominantly massive with no obvious sedimentary structures. Stylolites are common in the top part of this interval along with intermittent clay pebbles.

Strata between 2101 and 2137 feet include shale-arenites, very fine to fine-grained sandstones, and black shales. The shale-arenites and sandstones are much the same as similar underlying intervals. A few clay or mud drapes are present in the uppermost sand interval. At the 2105 foot level, mud appears to have been injected into the sand. Shales are black and exhibit soft sediment deformation and

bioturbation. Lenticular bedding is common in the shale intervals and grades upward into wavy bedding at the top of the core.

This core appears to represent a series of delta-front splays punctuated by delta-front sandstones consisting of distal bar and channel mouth bar facies. Furthermore, the sequence is capped by interdistributary bay deposits and overlies shales of the prodelta facies.

The electric log profile suggests the shale interval at the base of the core extends 80 feet downward to the top of the Lower Hartshorne Coal. This shale sequence probably represents the delta plain facies of the Lower Hartshorne Sandstone. Directly overlying the shale sequence is an 11 foot sandstone interval that resembles a distal bar deposit. The shale-arenite units seem to suggest several episodes of splaying across the delta plain. The shale clasts may represent part of the channel log deposited in crevasse splay channels. Sandstone intervals are indicative of channel mouth bar deposits, that developed as elongate channels prograded basinward.

The shale interval directly overlying the uppermost sandstone appears to represent the interdistributary bay facies. Coleman (1976) noted the importance of lenticular bedding and bioturbation within the interdistributary bay facies. Both of these structures are present in the upper shale interval. The lenticular bedding grades upward into wavy bedding suggesting periods of slightly higher sand or silt input, which is normally associated with overbanking during a flooding event (Coleman, 1976).

Cities Service Oil and Gas Corporation,

No. "A"-1 Mason (CSM)

This well was completed as a Lower Booch gas well. The well produces from Lower Booch Sand perforations at 1372-1572 feet (log depth). The IPF was gauged at 2060 MCFGD. The first date of production was June, 1985. As of January, 1987, the well had produced 114.7 MMCFG (Dwight's Production Data, 1987). Pressure readings were not available.

The location of the well is in the SW SW, Sec. 31, T. 10N., R. 18E., in the Brooken Field, Haskell County. The cored interval was 1342-1510 feet, approximately 148 feet of sand and 20 feet of shale.

The entire Lower Booch Sandstone section is contained in the core including upper and lower contacts (Appendix B). The lowermost 11-foot interval consists of black shales, which are laminated and contain few horizontal burrows. The lower contact is abrupt with the overlying Lower Booch Sandstone (Coal, shale and siderite clasts are common at the lower contact).

Strata between 1351 and 1499 feet are fine to medium-grained sandstones, which are typically gray to tan in color. Overall, the interval is massive, containing several individual coarsening upward sequences. Horizontal plane beds, tabular cross-beds, and minor small scale trough cross-beds are common at the top and bottom of the sand interval. Coal laminae and shale clasts are present in the upper 10-foot interval of sand. Shale clasts are observed periodically throughout the core. Soft sediment deformation, contorted beds, and fluid escape structures were also observed.

The 10-foot shale interval at the top of the core is laminated shows some bioturbation. The shales are black and contain several one-inch thick coal stringers.

This core represents a distributary channel-fill sandstone, or bar finger sandstone of Fisk (1961). The core is located within a north-south trending sand body in the Brooken Field (Figure 21). The shale interval at the base of the core probably represents the prodelta facies underlying the distributary facies. Coal, shale, and siderite clasts represent channel lag deposited as distributary channel-fill sands prograded across the prodelta. The thick sand interval consists of delta-front sands, which include channel mouth bar, distal bar, and channel-fill deposits. The abrupt upper contact suggests rapid or sudden abandonment followed by subsidence and development of the overlying interdistributary bay facies.

The electric log profile is characteristically blocky with sharp deflections of the SP and gamma-ray curves at both contacts. This log profile agrees with Brown's (1979) idealized log signature for elongate distributary sandstone bodies.

Subsurface Mapping

Introduction

A total of three isopach maps and four net sandstone isolith maps were constructed for the study area (Plates VI, VII, VIII, IX, X, XI, XII, in pocket). The genetic intervals outlined in Chapter III were utilized to map specific units. Isopach maps were prepared to illustrate thickness trends and basin shape. The interpretation of

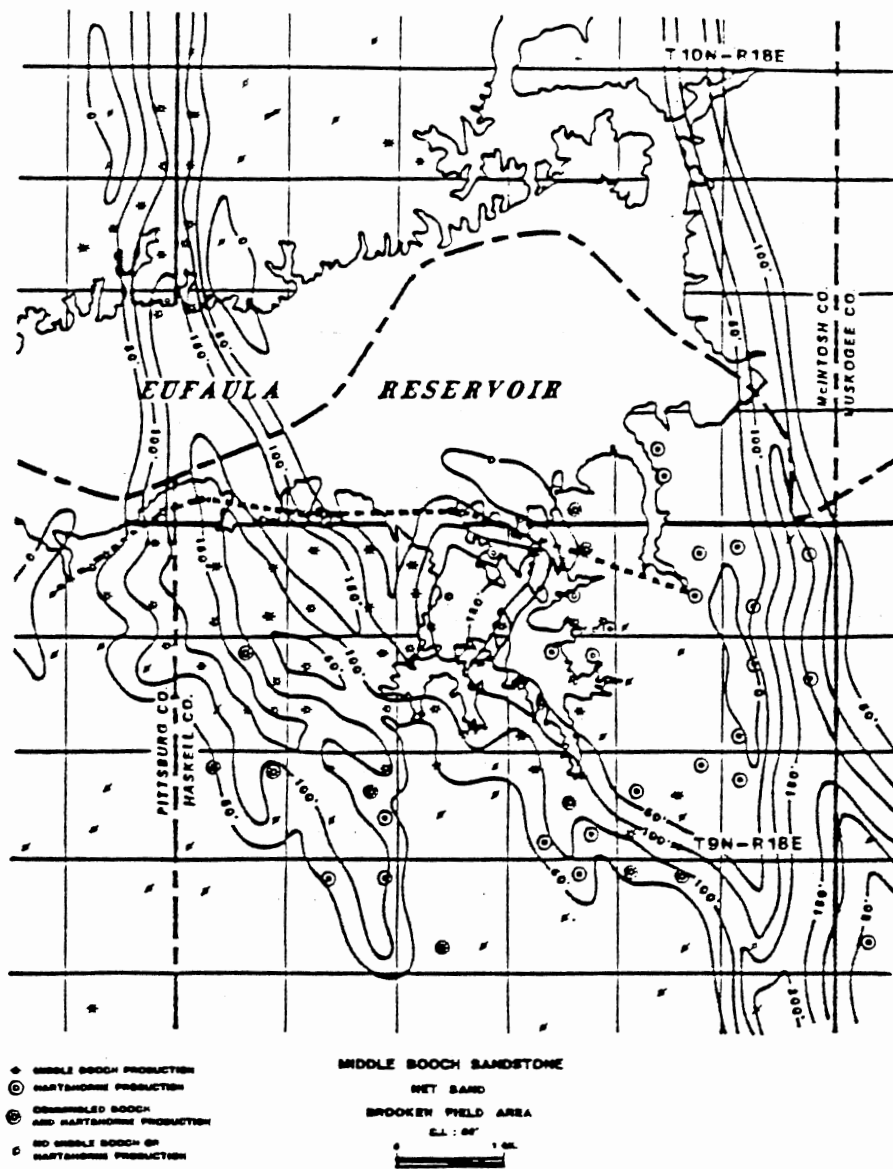


Figure 21. Lower Booch Sandstone Channels in the Broken Field (from Bowker and Seale, 1985, p.173).

depositional environments and recognition of sand body geometry were facilitated by the construction of net sand isolith maps.

Interval Isopach Maps

Atoka Formation - Hartshorne Formation Isopach. The Atoka and Hartshorne formats were combined in order to construct an interval isopach map that would approximate the structure of the lower contact at the beginning of Atoka deposition. This isopach map (Plate VI) represents the configuration of the basin in the study area. The contours are very closely spaced across the southeast part of the map, suggesting rapid subsidence and deposition. This may also indicate a transition from the slope area to a deeper part of the basin. Contour lines are parallel to the shelf edge, which lies to the northwest of the area as mapped by Busch (1953). The anomolous thickening in the northeast quarter of T. 7N., R 14E., may represent early movement along a normal fault.

Significant thinning is coincident with the Flowery Mound Anticline in T. 6N., R. 15E., which suggests some deformation during the time of deposition. The most important observation that can be made from this map is the thickening trend from northwest to southeast. This represents the thick wedge of sediments that accumulated due to basin subsidence caused by the subduction of the continental margin.

McAlester Formation Isopach. The isopach map of the McAlester format (Plate VII) also illustrates the basinward thickening trend. More importantly, the effects of thinning across structural highs indicates the time of folding. Thinning is particularly obvious

across the Savanna Anticline and Flowery Mound Anticline. This suggests that folding was active during McAlester deposition. Thickening within the Talawanda Syncline indicates subsidence and compaction in the underlying Hartshorne sands. The tight contour spacing represents significant subsidence across the entire area. Bissell (1984) noted a slight northward migration of the shelf edge during McAlester deposition. This seems to explain the apparent subsidence across the area.

Lower Booch (Warner) Isopach. This isopach map (Plate VIII) was constructed on the interval of strata between the Upper Hartshorne Coal and the top of the Lower Booch Sandstone. Southeastward thickening is again obvious. Anomalous thickening is associated with the location of Lower Booch distributary channels and may indicate differential compaction with underlying shales.

This series of isopach maps for the Atoka-Hartshorne, McAlester, and Lower Booch is considered to represent three time slices. Although the Lower Booch isopach is essentially the lower one-half of the McAlester isopach, it allows for a more precise interpretation of the time of deformation. Based on thickness trends, the most intense period of deformation began in late Atokan to earliest Desmoinesian time. Deformation continued through the time of McAlester Formation deposition, and minor compression persisted through time of Boggy Formation deposition. Determination of the approximate age of the Penitentiary and Carbon faults is difficult. The Penitentiary thrust fault offsets Atoka, Hartshorne and McAlester strata, which suggests faulting as early as McAlester Formation deposition. Logically, thrusting should have coincided with the most intense period of

folding, but Savanna and Boggy Formation outcrop around the McAlester Anticline may indicate a later date for faulting.

Net Sandstone Isolith Maps

Cromwell Net Sandstone Isolith. Plate IX is a net sandstone isolith map of the Cromwell Sandstone. The distributary channels on this map generally trend northeast to southwest. This indicates a northeast or eastern source for the sand. This orientation is consistent with west-directed paleocurrent measurements north of the Choctaw Fault in lower Pennsylvanian sandstones (Briggs and Cline, 1967). The channels appear to be entering the area from the north and are then redirected to the west or southwest parallel to the axis of the basin (Briggs and Cline, 1967).

The Cromwell interval typically exhibits a digitate, coarsening upward log profile, and a thin prodelta (Figure 22). The assumption is made that the silty shale interval at the base of the Cromwell represents the Cromwell prodelta facies. The Cromwell appears to represent a high-constructional lobate delta based on the model of Brown (1979; see Figure 16). The overlying Union Valley Limestone probably represents a shelf limestone deposited during the transgressive phase of the delta cycle (Brown, 1979). Cromwell sands ordinarily contain glauconite, suggesting marine influence or reworking.

Lower Hartshorne Net Sandstone Isolith. Four distributary channels are shown on the Lower Hartshorne map (Plate X). These distributary channels represent bifurcations of one large channel entering the area from the east. The channels trend east to

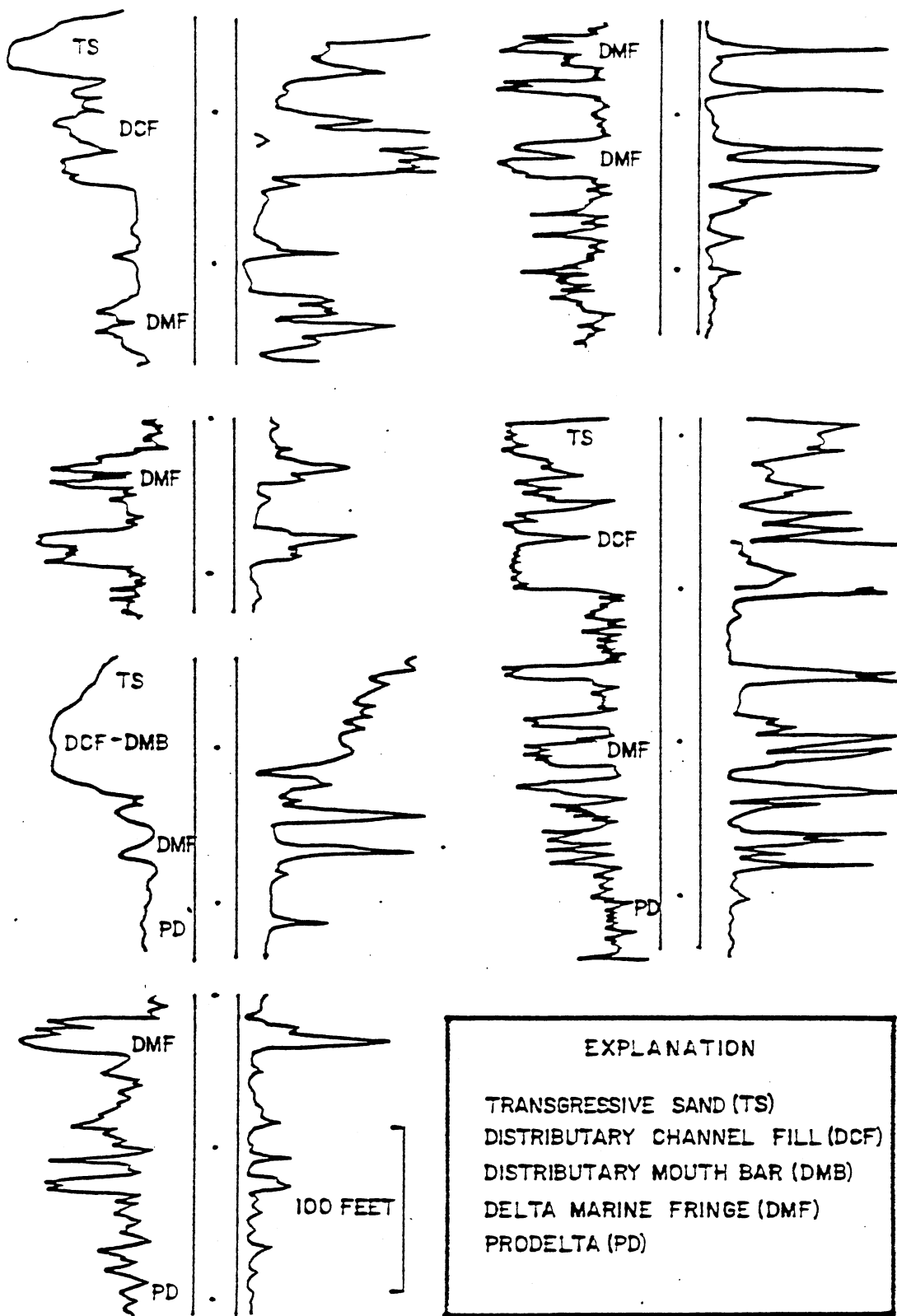


Figure 22. Typical Cromwell Sandstone Electric Log Responses.

southwest. Thickness is variable, with individual sand bodies ranging from less than 10 feet in the north, to in excess of 160 feet in distributaries. The channels are parallel to subparallel with the basin axis. The two thickest channels are located in the Talawanda Syncline, indicating a possible structure control on sedimentation. Three of the channels extend across the entire study area and exit to the southwest. The orientation of channels infers a northern and possibly an eastern source area for the Lower Hartshorne Sandstone.

The areas between channels appear to represent the interdistributary bay facies. Two rather thin sand bodies are present to the north, and are probably crevasse splay sands. The Lower Hartshorne typically exhibits a blocky log profile and a thick prodelta sequence, which are characteristic of a high-constructional elongate delta (Brown, 1979).

Upper Hartshorne Net Sandstone Isolith. The Upper Hartshorne map (Plate XI) illustrates the coal-split line. Obviously there is no Upper Hartshorne deposition northwest of this line, where the upper and lower coals converge (Houseknecht, 1983). The upper sandstone is usually thickest on the immediate basinward side of the coal-split line (Iannachione et al., 1983). Only one upper sandstone channel occurs in the area. It trends northeast to southwest and attains a maximum thickness of 110 feet. This channel overlies the thickest lower sandstone channel, indicating some stacking. Houseknecht (1983) noted the occurrence of stacked Hartshorne channels in the western Arkoma Basin (Figure 23). The Lower Hartshorne Coal bed is typically eroded or absent, where upper sandstone channels stack above the lower channels (Houseknecht and Iannachione, 1982).

In summary, the Hartshorne delta system appears to fit the criteria for a high-constructional elongate delta (Brown, 1979; see Figure 17). Blocky log profile, thick prodelta sequence, small number of channels, and stacking of channels in the Hartshorne Formation support this interpretation. The lower members consist of extensive prodelta and delta-front facies with an overlying distributary channel facies that is transitional with the interdistributary bay facies (Iannachione et al., 1983). The upper members consist of an interdistributary bay facies laterally transitional with the delta front facies and distributary channel facies. Typical log responses for deltaic facies in the Hartshorne Formation are illustrated in Figure 24.

Lower Booch Net Sandstone Isolith. The Lower Booch map (Plate XII) is a southwest continuation of Bissell's (1984) main distributary channel (Figure 25). Several north-to-south trending channels are present across the area. The distributaries not only converge, but also bifurcate at many locations. All of the channels become extremely narrow in the southern portion of the study area. This narrowing trend appears to represent the distal delta. The north-south orientation of channels further substantiates a northern source area as proposed by several workers (Scruton, 1950; Busch, 1953; Agterberg and Briggs, 1963; Briggs and Cline, 1967; Karvelot, 1972; Bissell, 1984). The channels are thickest along the northern boundary of the area, where a maximum thickness of 110 feet is attained. Thickness is variable across the area and channels thicken at the expense of underlying shales.

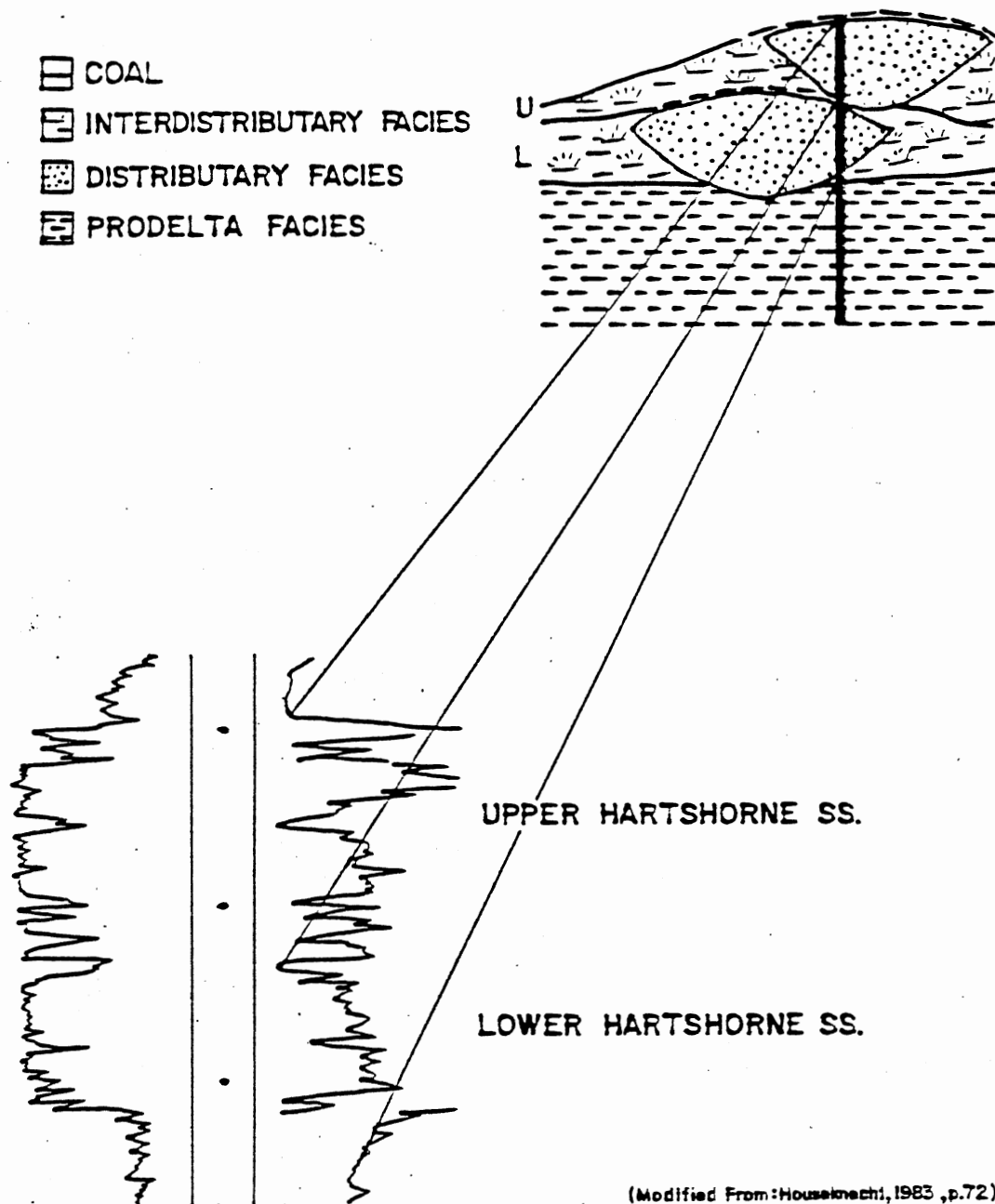


Figure 23. Relationship of Upper Hartshorne Channel to Lower Hartshorne Channel.

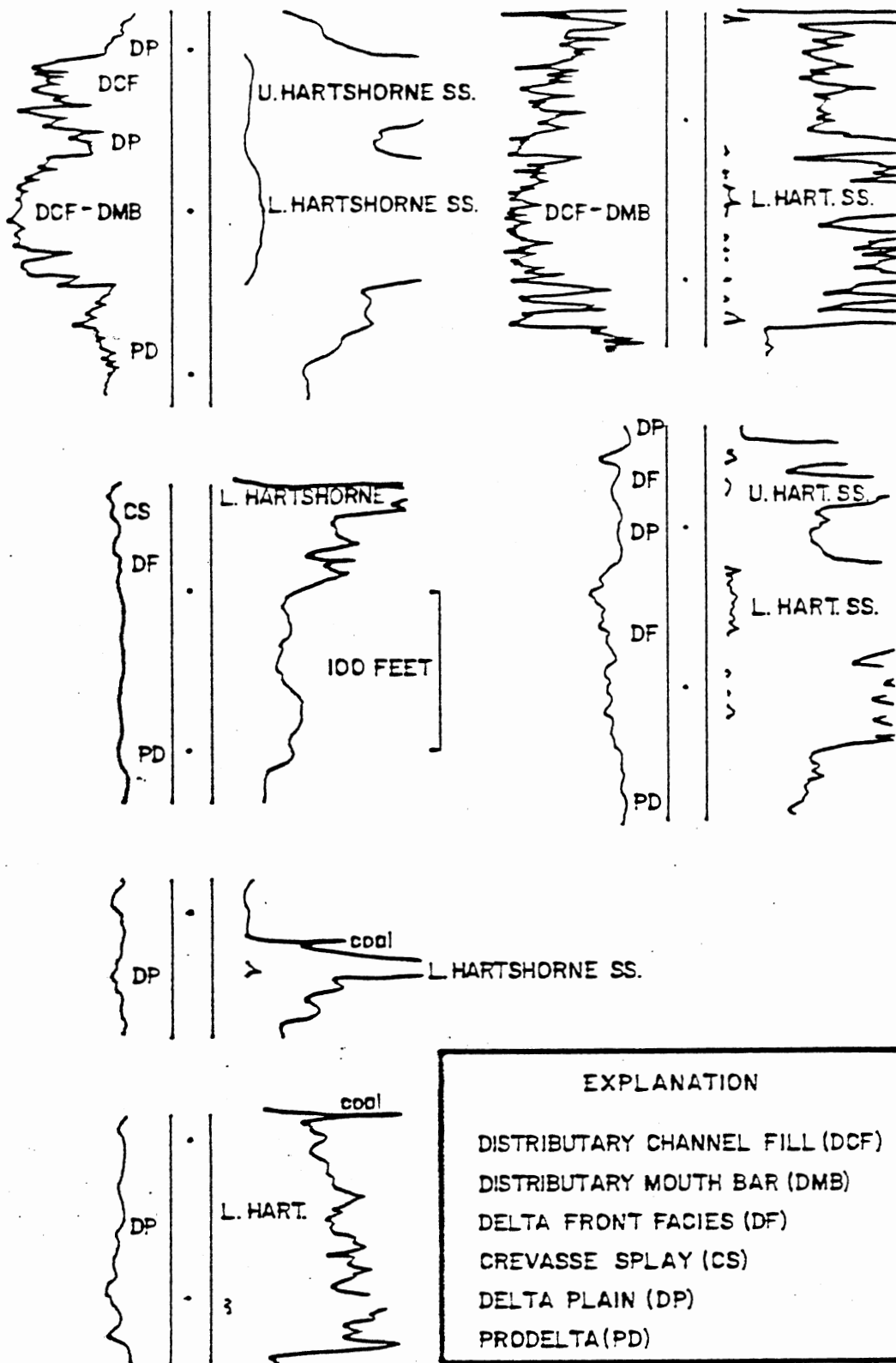


Figure 24. Typical Hartshorne Formation Electric Log Responses.

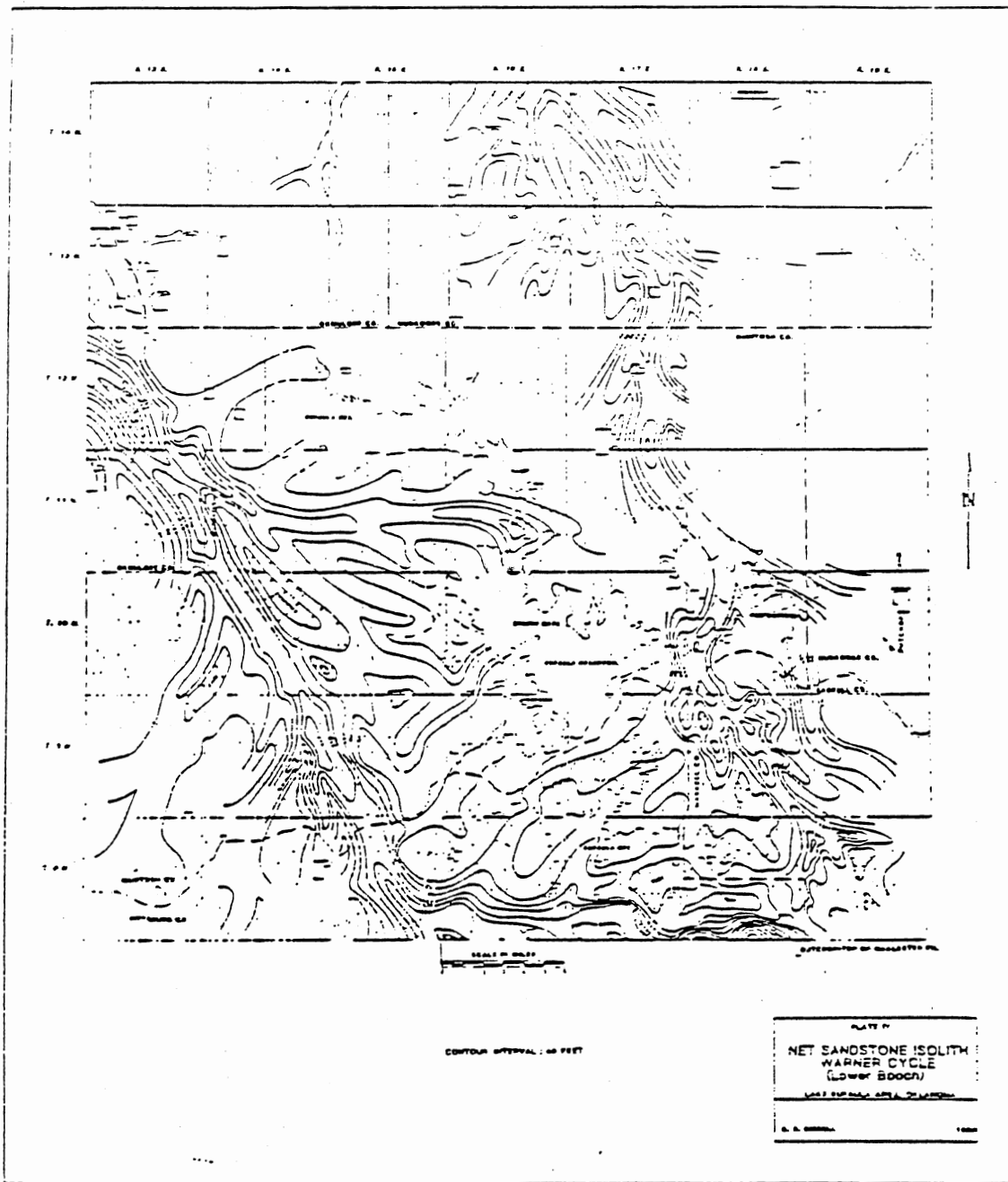


Figure 25. C.R. Bissell's (1984, p.118) Lower Booch Sandstone Map, Eufaula Area, Oklahoma.

The Lower Booch commonly exhibits a blocky log profile and a relatively thick prodelta sequence. Electric log profiles indicate several deltaic facies, including the prodelta, delta-front shales and sands, channel fill sands, interdistributary deposits, and transgressive phase deposits (Figure 26). The Lower Booch Sandstone appears to meet the requirements of a high-constructional elongate delta model as described by Brown (1979; see Figure 17).

In reference to the map, areas between channels probably represent lower delta plain deposits. Generally, the area appears to be the distal part of the delta or in close proximity to the seaward limit of delta-front deposits. The narrow channels to the south consist of delta-front sands and silty shale, which were subjected to marine reworking.

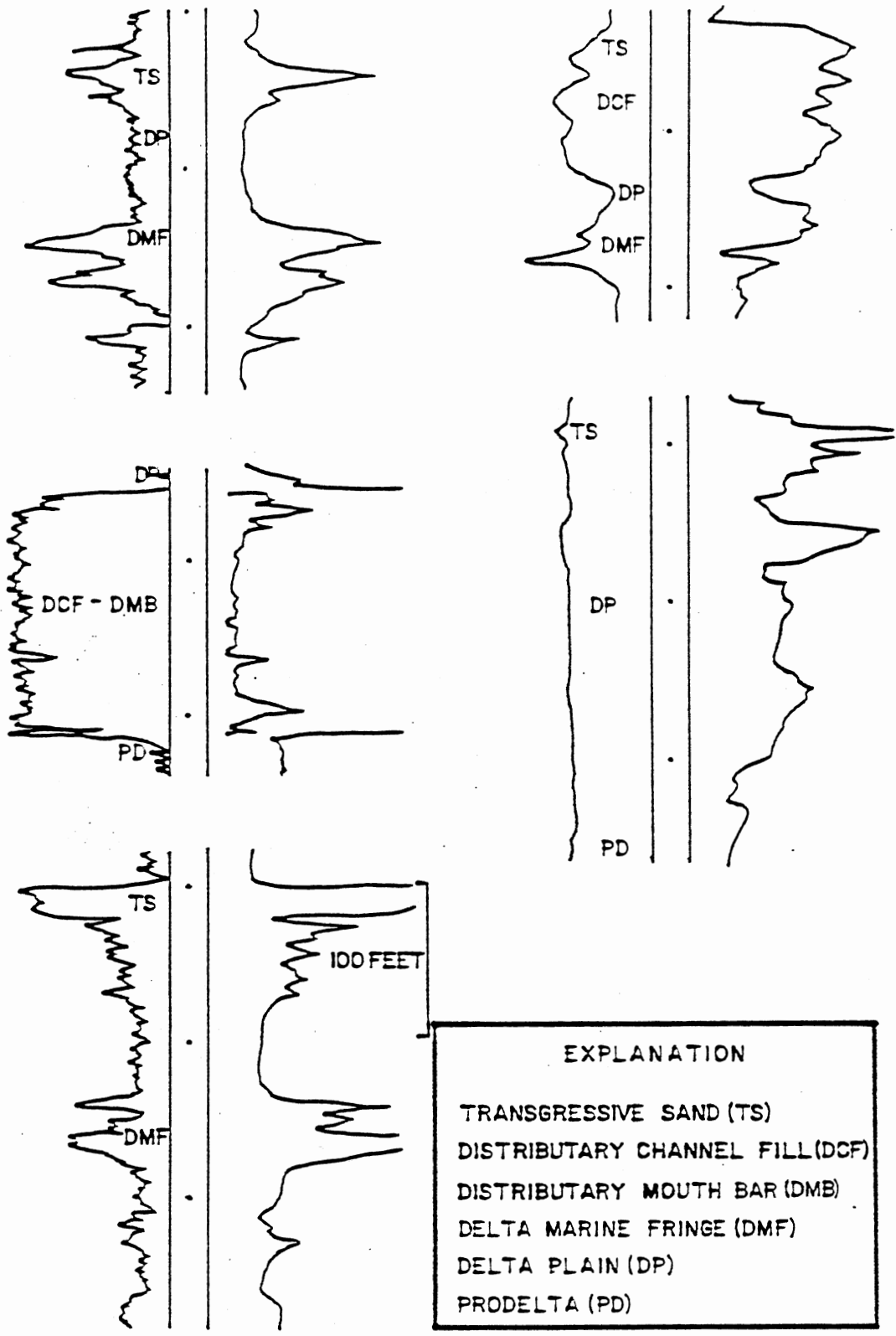


Figure 26. Typical Lower Booch Sandstone Electric Log Responses.

CHAPTER VII

PETROLEUM GEOLOGY

Introduction

Since the early part of this century, the Arkoma Basin has been recognized as a natural gas producing province. In March, 1902, the discovery well was drilled on the Hartford Anticline in Sebastian County, Arkansas. The well produced gas from Atoka sands at a depth of 2,000 feet (Branan, 1968). Most of the surface structures were drilled following this discovery.

The Quinton and Featherston fields represent the first significant gas production in Pittsburg County, Oklahoma. These two shallow fields were discovered in the early 1930's, and production is from the Lower Hartshorne Sandstone (Iannachione et al., 1983). Exploration continued at a moderate pace until the late 1950's, when a wildcat discovery was drilled in the South Pine Hollow area. This discovery initiated a lease play that resulted in considerable drilling activity, which continued through the late 1970's.

Arkoma Basin Natural Gas

Distribution of Natural Gas

In east-central Oklahoma, oil production is associated with the platform or shelf area north of the Arkoma Basin. To the present

time, there have been no oil discoveries in the Arkoma Basin.

Branson (1961) mapped a line separating Pennsylvanian oil production from natural gas production in eastern Oklahoma. The line (Figure 27) extends from southern Pittsburg County northwest to Hughes County, and then follows the hinge line or shelf edge of the basin to southern Muskogee County, where the line turns to the north and trends north-northeast along the western margin of the Ozark Uplift (Branson, 1961). Oil with minor gas production lies to the west of the line, and gas production to the east.

Origin of Natural Gas

The absence of oil was manifested in the early stages of exploration in the Arkoma Basin. Clawson (1930) theorized that most of the Pennsylvanian reservoirs were non-marine in origin, therefore, the lower hydrogen/carbon ratio associated with non-marine organic matter would have been conducive to methane generation.

Most of the Pennsylvanian reservoir sands were deposited in a deltaic environment, where humic organic matter would have been abundant. But, where the deltaic systems prograded into a marine environment, there may have been sapropelic organic matter (Iannachione et al, 1983). Sapropelic organic matter is usually associated with the generation of oil. Iannachione and others (1983) recorded lighter carbon isotope ratios of methane from west to east in the Arkoma Basin. This trend is believed to represent a transition from sapropelic-to-humic dominated source rock. In addition, a gradation from less mature to more mature source rock is indicated by a higher percentage of methane in natural gas samples from the eastern

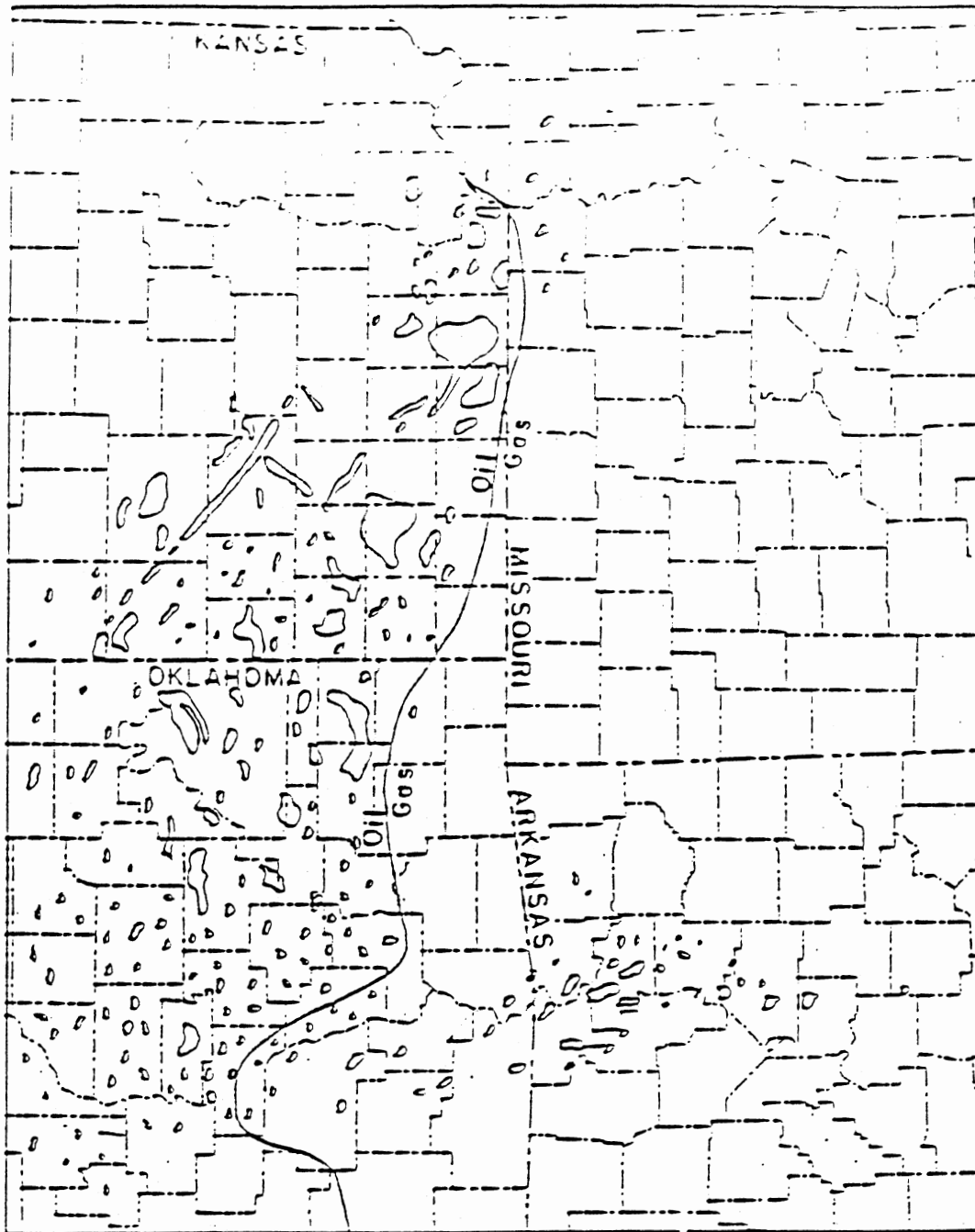


Figure 27. Distribution of Oil and Gas Fields in Eastern Oklahoma (from Branson, 1961, p.455).

Arkoma Basin in Oklahoma (Iannachione et al., 1983). Even though source rocks in the western part of the basin are less mature, natural gas was generated at the expense of heavier hydrocarbons, i.e., oil. Therefore, the basin must have been subjected to temperatures in excess of that required by the oil window (50°-150°C).

Guthrie and others (1986) have suggested that the Arkoma Basin and Ouachita orogenic belt were "thermally overprinted" by a Mesozoic rifting event and plutonic activity in the Mississippi embayment. This event would have provided the higher temperatures required for gas generation, and explains the presence of more mature source rocks in the eastern part of the basin. Within the study area, methane averages approximately 88% of the total natural gas composition (Iannachione et al., 1983).

Local Gas Fields

South Pine Hollow Field

A cumulative production map was prepared to illustrate the distribution of producing sands and local gas fields (Plate XIII). The South Pine Hollow Field is located in parts of T. 5N., R. 12-13E., and T. 6N., R. 13-15E., Pittsburg County, Oklahoma.

Carter Oil Company drilled the No. 1 Ossie Morris in 1959, which was the wildcat discovery. The well is located in the SE SE NW of Section 24, T. 5N., R. 12E. The well produces from Upper and Lower Hartshorne Sand perforations at 3216-3378 feet (log depth), with approximately 122 feet of net pay (McDaniel, 1968). The IPF was gauged at 3.661 MMCFGPD through a 5/8" choke. Flow tubing pressure was 290 psi, and shut-in pressure was 500 psi. The IPCOF (initial

potential calculated open flow) was 5.650 MMCFGPD. The cumulative production for the well was 8.560 BCFG as of June 1, 1986 (Dwight's Production Data, 1986).

Since the original discovery, the producing limits of the South Pine Hollow Field have been well established. Total production to date is in excess of 84 BCFG, with recoverable reserves estimated to be in excess of 100 BCFG.

The field produces from both the Upper and Lower Hartshorne Sandstones. These sand bodies are interpreted to be stacked distributary channels. The linear sand bodies are usually one to two miles in width, and can be traced for several miles. The sandstone is typically fine-grained, with an average porosity of approximately 10%. Porosity and permeability are commonly highest in the thickest part of the channels.

The sand bodies trend northeast-southwest along the axis of the Talawanda Syncline. Because the producing sands are structurally low, the trapping mechanism is considered to be stratigraphic. More specifically, the trap is a permeability barrier. The lateral interfingering of distributary sands with the prodelta and delta plain facies would create such a barrier.

Northwest Reams Field

The Northwest Reams Field (Plate XIII) is located in parts of T. 7N., R. 14-15E., Pittsburg County. The discovery well was the No. 1 White, which was drilled by the Steve Gose Company. The well is located in the C of NE SW of Sec. 5 T. 7N., R. 15E.

The No. 1 White produces from Spiro Sand perforations at 6335-6361 feet, and from Cromwell Sand perforations at 6760-6803 feet. The Spiro zone IPCOF was 1.78 MMCFGPD. Shut-in casing pressure was 1239 psi. The Cromwell IPCOF was 150 MCFGPD. Shut-in tubing pressure was 927 psi. This well is now classified as inactive, with a cumulative production of 265 MMCFG (Dwight's Production Data, 1986).

Most of the gas production in the Northwest Reams Field is from the Cromwell Sandstone. The Cromwell ranges in thickness from 70 to 120 feet within the field. This unit is interpreted as a high-constructive lobate delta, and individual channels are one to two miles wide in the proximity of the field. The sand bodies trend northeast-southwest and are cut by a network of normal faults.

The Spiro Sandstone is productive in seven wells in the Northwest Reams Field. The Spiro has been interpreted as a "fluvial dominated channel deposit" in some areas (Houseknecht, 1986a). Alternatively, the unit has been mapped as a tide-dominated delta in Latimer County, Oklahoma (McGilvery, 1986a). The Spiro was not mapped in this study.

Cromwell and Spiro production in this area is related to the fault system in T. 7N., R. 14-15E. These normal faults indicate a structural trapping mechanism. The majority of production occurs on the upthrown side of the faults, but two wells on the downthrown block also produce gas. Gas production on the downthrown side may indicate some type of seal related to the fault plane. The field has produced more than 19 BCFG since the first well went on line.

Southeast Reams Field

The Southeast Reams Field (Plate XIII) is not completely

contained within the study area. The field is located in T. 6N., R. 15E., Pittsburg County. The field was developed in the early 1940's. No information was available regarding the discovery well.

Production is from the Lower Hartshorne Sandstone, which ranges from 36 to 114 feet thick within the area. The sand body is an east-west trending distributary channel. The channel is situated across the crest of the Flowery Mound Anticline. This forms an obvious combination trap. The Hartshorne channel representing the stratigraphic component, and the anticline being the structural component. Within the study area the field has produced more than 12 BCFG.

South Ulan Field

The South Ulan Field (Plate XIII) is located in parts of T. 6N., R. 13-14E., and T. 5N., R. 13-14E., Pittsburg County. The discovery well was the No. 1 Finamore, which was drilled by KWB Oil Property Management Company in 1974.

The No. 1 Finamore is located in the C of the W/2 SW NE of Sec. 32 T. 7N., R. 14E. The well produces from Spiro Sand perforations at 6692-6700 feet, and from Cromwell Sand perforations at 7065-7089 feet. The Spiro IPF was gauged at 1.717 MMCFPD through a 1/2" choke. Flow casing pressure was measured at 205 psi, and shut-in casing pressure was 1665 psi. The Cromwell IPF was gauged at 2,352 MMCFGPD through a 1/2" choke. Flowing casing pressure was measured at 305 psi, and shut-in casing pressure was 1595 psi. This well is now considered inactive, with a cumulative production of 274.6 MMCFG (Dwight's Production Data, 1986).

The majority of production in the South Ulan Field is from the Cromwell Sandstone. A major Cromwell distributary trends northeast-southwest across the field. The channel bifurcates allowing for two trends of Cromwell production (Plates IX, XIII). The Cromwell channels are cut by two normal faults, which trend north-south (Plate IV). In addition, a small structural high noses into the area from the north. Production occurs on all fault blocks, suggesting some type of seal against the fault plane. The trapping mechanisms are considered to be structural. The South Ulan Field has produced more than 9 BCFG.

Northwest Scipio Field

The Northwest Scipio Field (Plate XIII) is located in T. 7N., R. 12E., Pittsburg County. The discovery well was the No. 1 Gilcrease, drilled by the Otha H. Grimes Company in 1951.

The No. 1 Gilcrease is located in the SW SE SE of Sec. 16, T. 7N., R. 12E. The well produces from the Lower Hartshorne Sandstone at 2480-2635 feet (log depth) with no treatment. The well flowed 310 MCFGPD during a drill stem test of the Lower Hartshorne zone. Shut-in bore hole pressure was measured at 610 psi after 10 minutes. This well is considered inactive, with a final cumulative production of 259.3 MMCFG (Dwight's Production Data, 1986).

In the Northwest Scipio Field, gas production is from the Lower Booch Sandstone and Lower Hartshorne Sandstone. The Hartshorne sand body trends east-west, and attains at thickness of 30 feet in the area. The Hartshorne deposit is interpreted as a crevasse splay. The Booch channel is a small bifurcation that connects two north-south

trending distributaries. The Booch sand body is also 30 feet thick.

The trapping mechanism appears to be an up-dip stratigraphic pinchout. A small structural high is located north of the field (Plate V). This structure may provide the dip component. If so, the trapping mechanism could be classified as a combination trap. Total production from this field exceeds 5 BCFG.

Ulan Field

The Ulan Field (Plate XIII) is located in T. 7N., R. 13E., Pittsburg County. The discovery well was the No. 1 Graham, which was drilled by Brewer Oil and Gas Company in 1967.

The No. 1 Graham is located in the C of the SE SE of Sec. 22, T. 7N., R. 13E. The well produces from Upper Booch Sand perforations at 2056-2066 feet and Savanna Sand perforations at 1877-1896 feet. The Booch IPCOF was 536 MCFGPD, and the Savanna IPCOF was 1.450 MMCFGPD. This well has produced more than 670 MMCFG (Dwight's Production Data, 1986).

The Ulan Field produces from Booch and Hartshorne sands. The Hartshorne and Booch range from 20 to 30 feet thick in the area. The Hartshorne sand body appears to be a crevasse splay trending east-west across the field. The Booch channel is very narrow, and trends north-south. Some of the gas production in this field is from the Upper Booch Sandstone. The Upper Booch is relatively thin in this area, averaging 20 feet in thickness.

The trapping mechanism is structural. The Booch and Hartshorne channels are coincident with a small subsurface high that apparently has some closure. The Ulan Field has produced more than 6 BCFG.

Other Local Fields

Several other small fields have been developed within the study area. Most of these smaller fields have produced less than 1 BCFG.

The Northwest Cabaniss Field (Plate XIII) has produced 656.3 MMCFG from the Lower Hartshorne Sandstone. The trapping mechanism is an up-dip stratigraphic pinchout of a crevasse splay.

The Stuart Field (Plate XIII) produces from the Boggy, Booch and Hartshorne Sands. This small field has produced more than 1 BCFG from all three units combined. The trapping mechanism appears to be structural. The field is located on a small structural high, which noses into the study area from the west.

The West McAlester Field (Plate XIII) has produced 421 MMCFG from the Hartshorne and Cromwell Sands. Hartshorne production is the result of a combination trap. A Hartshorne channel trends east-west across the west end of the McAlester Anticline. Cromwell production occurs on the upthrown side of two deep-seated normal faults.

The Northeast Savanna Field (Plate XIII) is a combination trap. A Lower Hartshorne channel trends northeast-southwest across the Savanna Anticline forming the trap. The field has produced 5 MMCFG from the Lower Hartshorne Sandstone.

The Southeast McAlester Field (Plate XIII) has produced 982 MMCFG from the Red Oak Sandstone. The trapping mechanism appears to be an up-dip pinchout of the Red Oak along the south flank of the Adamson Anticline. The Red Oak Sandstone was not mapped in this study.

Prospecting for Natural Gas

Introduction

Obviously, this area of northwestern Pittsburg County is in the late mature stage of development. All of the prominent structures have been developed and the major sand bodies have been delineated by extensive drilling.

Future exploration efforts must include a detailed facies analysis of any prospective reservoir and a clear understanding of the structural framework of the area. With this in mind, a few considerations regarding the Cromwell, Hartshorne and Booch Sandstones will now be presented.

Cromwell Sandstone

The field histories presented in the previous section demonstrated the tendency for the Cromwell to produce only on structure. This appears to be the case in other areas, also. Withrow, (1969) noted that Cromwell production in the Jesse and Fitts fields of Coal County was related to faulting. Anderson (1975) recognized a similar relationship between Cromwell production and normal faulting in the Centrahoma Field of Coal County. In light of these examples, the conclusion that prolific Cromwell reservoirs are typically associated with structural traps, seems legitimate.

Prospect C-1 (Plates V,IX) is an example of a Cromwell prospect that includes the necessary structural element. This prospect is located in the center of the NW NW of Sec. 19, T 7N., R. 15E., Pittsburg County, Oklahoma. This prospect is located on the upthrown

side of the northeast-southwest normal fault system, and is within the limits of an established Cromwell production trend. The mapped thickness of the Cromwell is 100 feet at this location.

Hartshorne Sandstones

Within the study area, the Hartshorne reservoir sands are usually associated with stratigraphic and combination type trapping mechanisms. This is the result of lateral facies variation, as well as the close proximity of Hartshorne channels to structural highs. A clear understanding of the distributary facies must be incorporated with basic exploration techniques to define a Hartshorne prospect.

Prospect H-1 (Plates IV, X) is an example of a Lower Hartshorne Sandstone prospect. This prospect is located in the C of the SE SE SE of Sec. 34, T. 5N., R. 14E., Pittsburg County, Oklahoma. This prospect is located in the established Hartshorne production trend of the Northeast Savanna Field. The thickness of the Lower Hartshorne Sandstone at this location is approximately 55 feet. A combination trap is created with the Savanna Anticline.

Another attractive location is in the SW NW of Sec. 35, T. 7N., R. 14E., Pittsburg County, Oklahoma. Prospect H-2 (Plates IV, X) is a second example of a Lower Hartshorne Sandstone prospect. At this location the sand is approximately 100 feet thick. The combination trap is formed by a Lower Hartshorne channel trending east-west across the Lake McAlester Anticline.

Lower Booch Sandstone

The Lower Booch Sandstone typically produces from combination

type traps within the area of this study. The requirements for a purely stratigraphic trap seem to be present, but exploration thus far has not confirmed this theory. Because this area is the distal part of the Booch delta, careful attention must be given to electric log profiles. Delta-front sandstones typically are the best reservoir rock in a deltaic complex, but log profiles in this area indicate a rather high silt content in the delta-front facies.

Prospect B-1 (Plate IV, XII) is one example of a Lower Booch prospect. This prospect is located in the C of the NW of Sec. 6, T. 6N., R. 15E., Pittsburg County, Oklahoma. This prospect demonstrates a stratigraphic trap. The Lower Booch Sandstone is approximately 45 feet thick at this location. An up-dip pinchout, or lateral interfingering of the distributary facies with the prodelta and delta plain facies, would provide the trap.

To summarize, future exploration efforts for Cromwell, Hartshorne and Booch reservoir sands would profit from the construction of net sandstone isolith maps and detailed structure maps. Seismic data would be particularly valuable in delineating structural traps for the Cromwell Sand. Porosity maps would be helpful in determining possible Booch Sand traps, particularly in this area, where the sand appears to be increasing in silt content.

CHAPTER VIII

PETROLOGY AND DIAGENESIS

Upper Hartshorne Sandstone

Composition

Detrital Constituents. The detrital composition of the Hartshorne cores used in this study exhibit some variation due to the environment of deposition. The No. 1 Hunt-Garret core is a typical Upper Hartshorne Sandstone, which is characteristic of a distributary channel deposit. The petrographic data from this core indicate a fairly uniform petrology.

The No. 1 Finch core represents an alternating sequence of sandstones and shale-arenites deposited in a series of crevasse splays. Table III lists the average detrital composition of Upper Hartshorne Sands from the two cores.

Monocrystalline quartz is the most abundant detrital constituent. Monocrystalline grains appear to be subangular and range from very fine to fine in grain size. The original subrounded grain shape is commonly observed due to the presence of illite dust rims.

Polycrystalline quartz grains comprise 1% to 3% of the detrital composition in most thin section samples. Polycrystalline quartz appears as composite grains with strong undulose extinction and may reflect a metamorphic provenance.

TABLE III
AVERAGE DETRITAL COMPOSITION OF THE
UPPER HARTSHORNE SANDSTONE

Constituent	Avg. Percentage (%)
Quartz	76.0%
Rock Fragments	8.0%
Feldspar	1.5%
Detrital Matrix	2.0%
Organic Matter	less than 1.0%
Muscovite	1.0%
Tourmaline	Trace %
Zircon	Trace %

Feldspar is not abundant and constitutes 1.5% of the average detrital composition. Feldspars include plagioclase (albite), orthoclase, and traces of microcline. Albite is the most common feldspar and is recognized by twinning. Albite grains typically exhibit the effects of partial dissolution. Orthoclase grains usually appear pitted and cloudy. Traces of microcline are present in a few thin section samples and are distinguished by twinning.

Rock fragments include shale clasts, metamorphic rock fragments, organic rich illitic mudstone, and chert grains. Shale clasts are ordinarily granule to cobble size; they consist of laminated black carbonaceous shale. Shale clasts are abundant within individual sandstone units and appear to have been ripped up and rapidly deposited. Metamorphic rock fragments appear as composite grains consisting of stretched quartz grains and muscovite flakes. Organic rich illitic mudstone grains contain silt sized quartz. Siderite cement is commonly associated with illitic mudstone grains in thin section samples. Chert grains occur in most thin section samples, but are not abundant.

Detrital muscovite flakes are also a common detrital constituent. Muscovite appears as high birefringent flakes and display evidence of mechanical compaction.

Detrital matrix includes illite, chlorite, and organics. Illite and chlorite are observed forming squeezed pseudomatrix between adjacent detrital framework grains. Organics occur as laminae within illitic mudstone grains, or independently occupy pore spaces.

A variety of trace minerals occur including glauconite, biotite, zircon, tourmaline, leucoxene, and magnetite. Glauconite is not

abundant, and is seen in only a few thin section samples. Biotite is usually chloritized and displays anomalous purple and blue colors. The heavy minerals are very minor constituents, but are seen in most samples.

Folk's (1974) sandstone classification system was used to illustrate the compositional plot of each Upper Hartshorne sample (Figure 28). Samples plotted as sublitharenites, quartz-arenites, and shale arenites based upon the relative abundance of quartz, feldspar, and rock fragments. Sixteen samples plotted as sublitharenites due to metamorphic rock fragments and illitic mudstone grains. Fourteen samples plotted as quartz-arenites. Four samples plotted as shale-arenites due to the abundance of shale clasts in specific intervals.

Authigenic Constituents. Table IV is a list of the authigenic constituents. Quartz overgrowths are the major cementing agent in most thin section samples (Figure 29). Pressure solution can be observed in several samples, and appears as sutured detrital quartz grains (Figure 30).

Siderite is present and occurs in the form of flattened rhombic crystals and spherulitic cement (Figure 31). Siderite typically accounts for 1% to 2% of the total composition in most samples. One sample from the base of the No. 1 Hunt-Garret core contained 19% siderite. Siderite preserves original quartz grain shapes, when found in localized masses. Siderite is associated with calcite and dolomite in a few thin sections.

Calcite was seen replacing grains and as pore filling cement (Figure 32). Ferroan dolomite is distinguished by a light blue color after staining with potassium ferricyanide solution. Ferroan dolomite

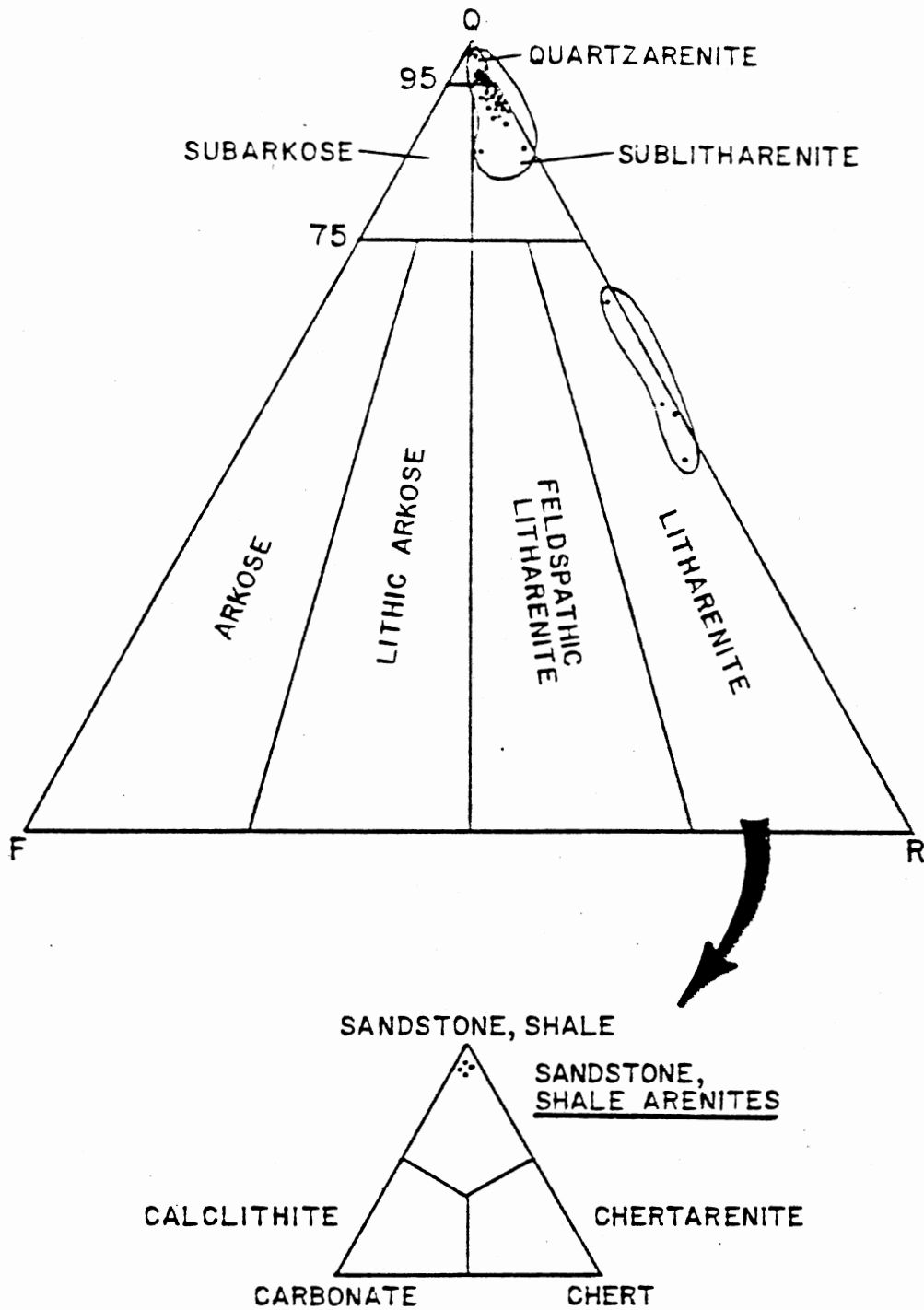


Figure 28. Classification of the Upper Hartshorne Sandstone.

TABLE IV
AVERAGE AUTHIGENIC COMPOSITION OF THE UPPER
HARTSHORNE SANDSTONE

Constituent	Avg. Percentage (%)
Quartz Overgrowths	3.0%
Siderite	2.0%
Calcite	less than 1.0%
Ferroan Dolomite	less than 1.0%
Kaolinite	2.0%
Illite	1.0%
Chlorite	less than 1.0%
Hematite	Trace %
Pyrite	Trace %

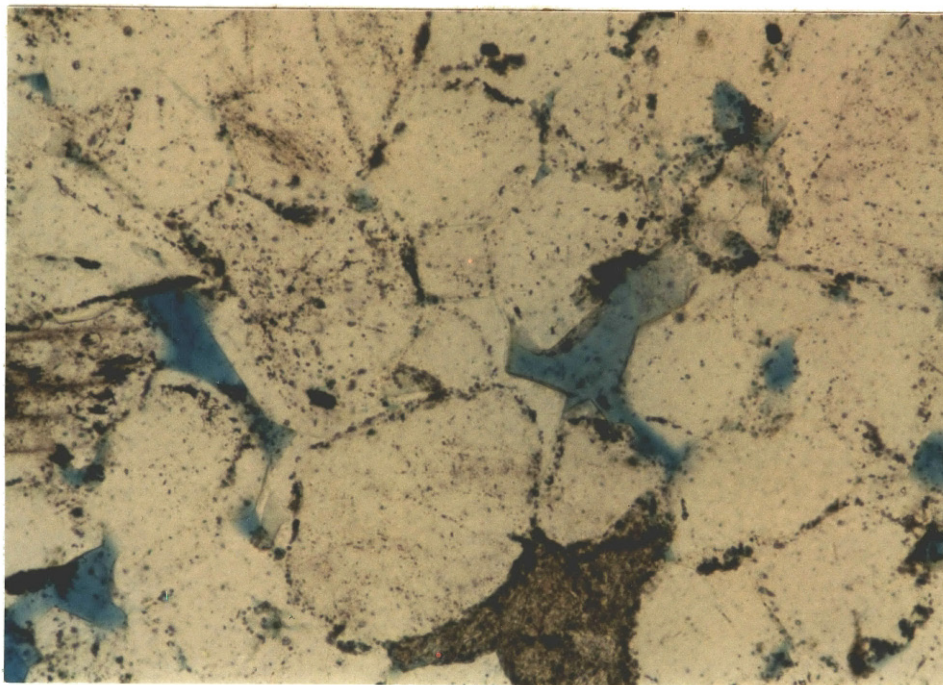


Figure 29. Photomicrograph of Quartz Overgrowth Cementation in Upper Hartshorne Sandstone (KMF-2136, 100X, PPL).

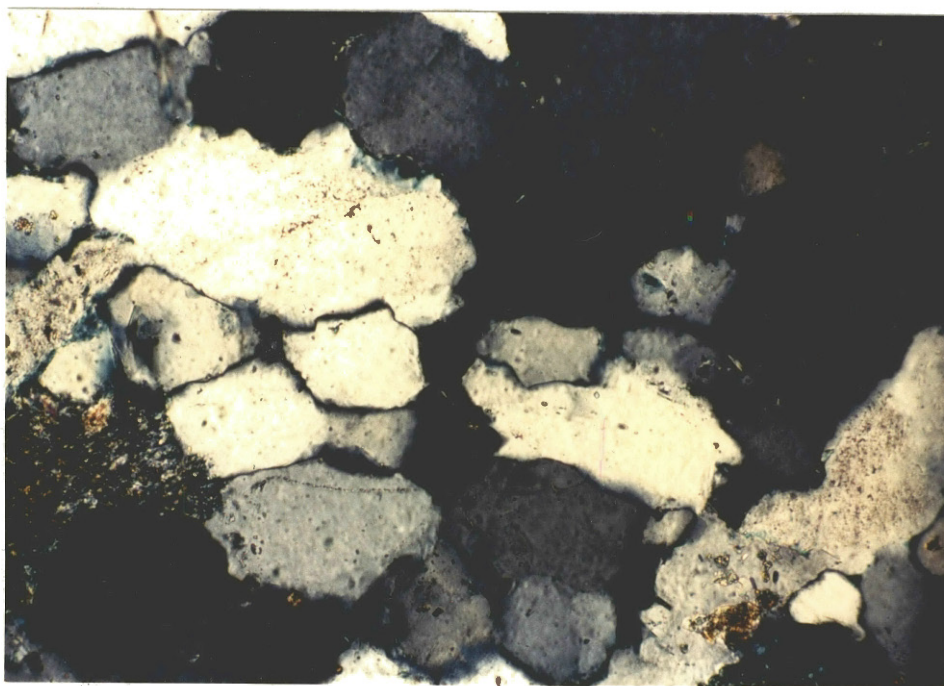


Figure 30. Photomicrograph of Detrital Grains Affected by Pressure Solution (HG-3578, 100X, XN).

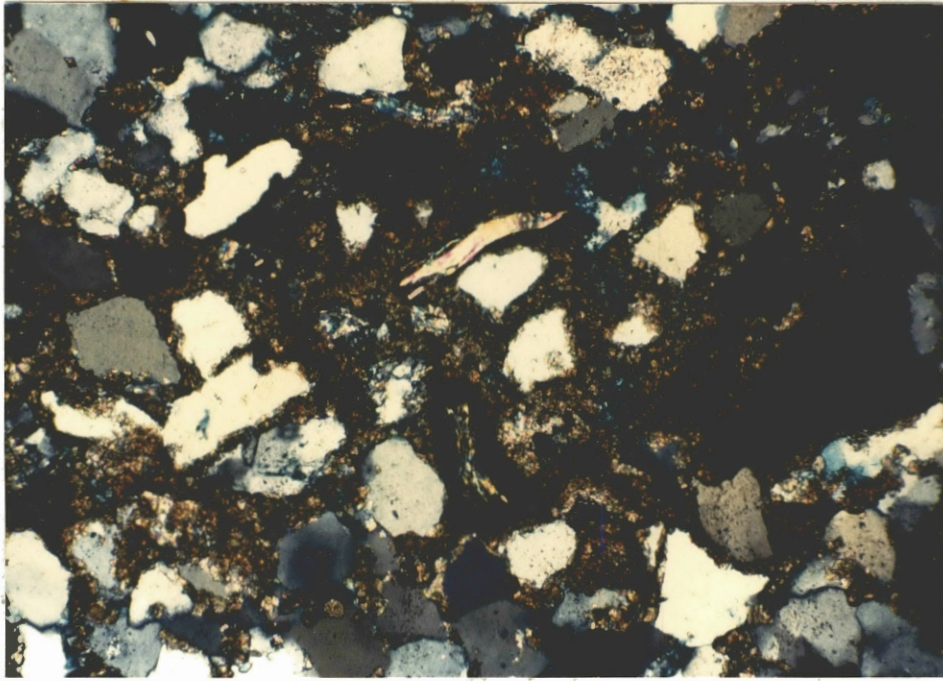


Figure 31. Photomicrograph of Siderite Cement in the Upper Hartshorne Sandstone (HG-3572, 40X, XN).

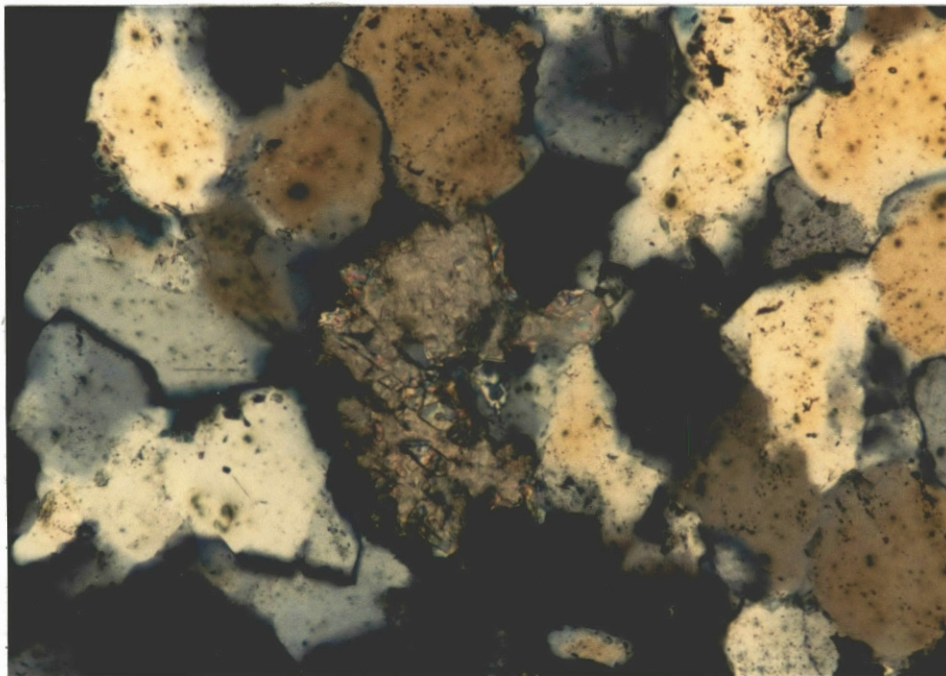


Figure 32. Photomicrograph of Calcite Cement Replacing Quartz (KMF-2094, 100X, XN).

is not abundant in these sands, and occurs as localized patches and as a grain replacement mineral (Figure 33). Authigenic quartz is commonly replaced by dolomite and calcite cements.

Authigenic clays include kaolinite, illite, and chlorite. Kaolinite is the major authigenic clay; it is usually more abundant in samples with less than 1% siderite cement. Kaolinite is seen as low birefringent pore-filling booklets (Figure 34). Illite forms as grain rimming and pore lining lathes and commonly occurs as dust rims. Sericite (a coarse variety of illite) partially replaces quartz grains and metamorphic rock fragments. Minor authigenic chlorite is seen in a few samples and forms the typical edge to face crystal morphology in pore throats.

Authigenic trace minerals include pyrite and hematite. Pyrite is usually associated with organic matter. Traces of hematite are probably an alteration product of siderite and appear reddish-brown under reflected light.

Porosity

The most important primary porosity texture is reduced intergranular (Figure 35). This texture is common due to the abundance of quartz overgrowth cementation. The formation of reduced intergranular porosity resulted from mechanical compaction, fringing carbonate cement, and quartz overgrowth (Schmidt and McDonald, 1979b).

Regular intergranular porosity is another important texture in thin section samples. Dissolution of detrital matrix and carbonate cement create regular intergranular texture (Schmidt and McDonald, 1979b). The dissolution of illite and chlorite detrital matrix,

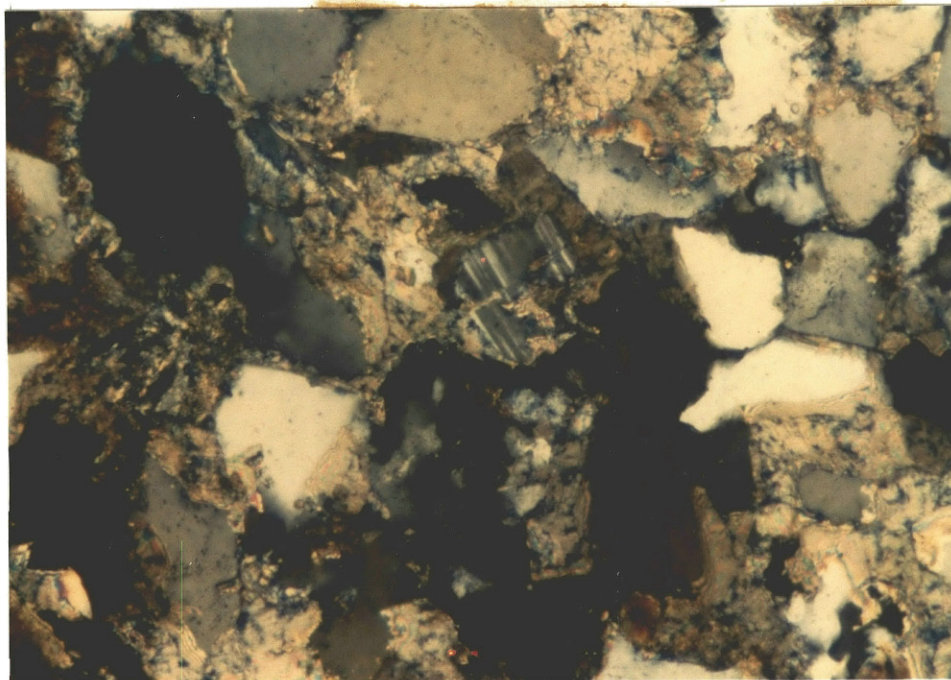


Figure 33. Photomicrograph of Ferroan Dolomite Cement in the Upper Hartshorne Sandstone (HG-3600, 100X, XN).

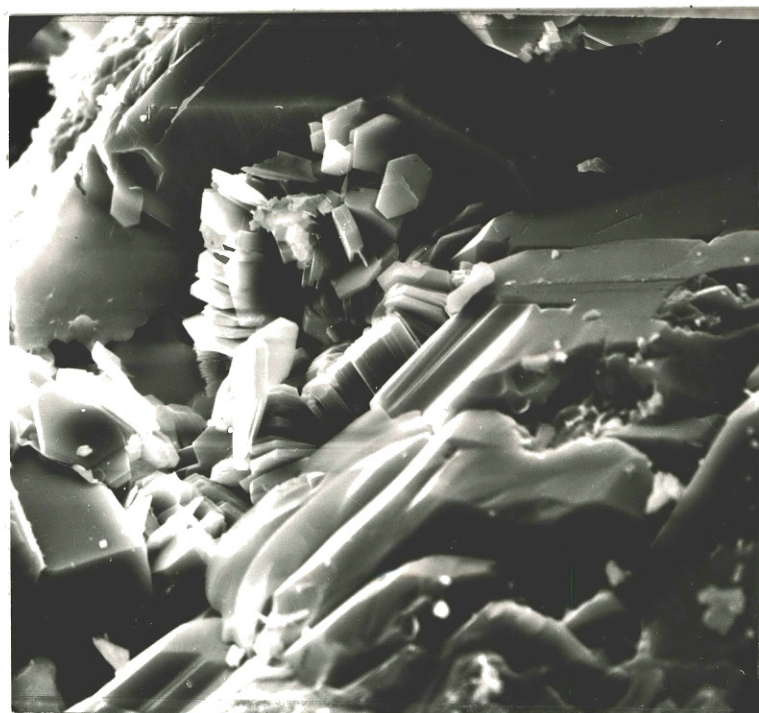


Figure 34. SEM Image of Authigenic Kaolinite Filling a Pore Throat (KMF-2131, 1200X).

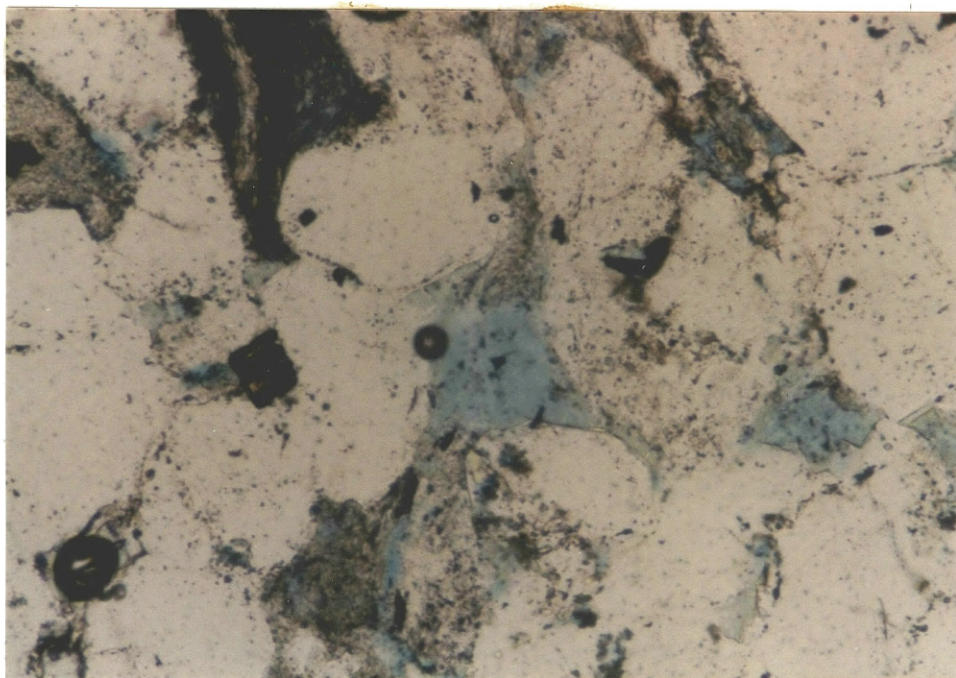


Figure 35. Photomicrograph of Reduced Intergranular Porosity in the Upper Hartshorne Sandstone (KMF-2131, 100X, PPL).

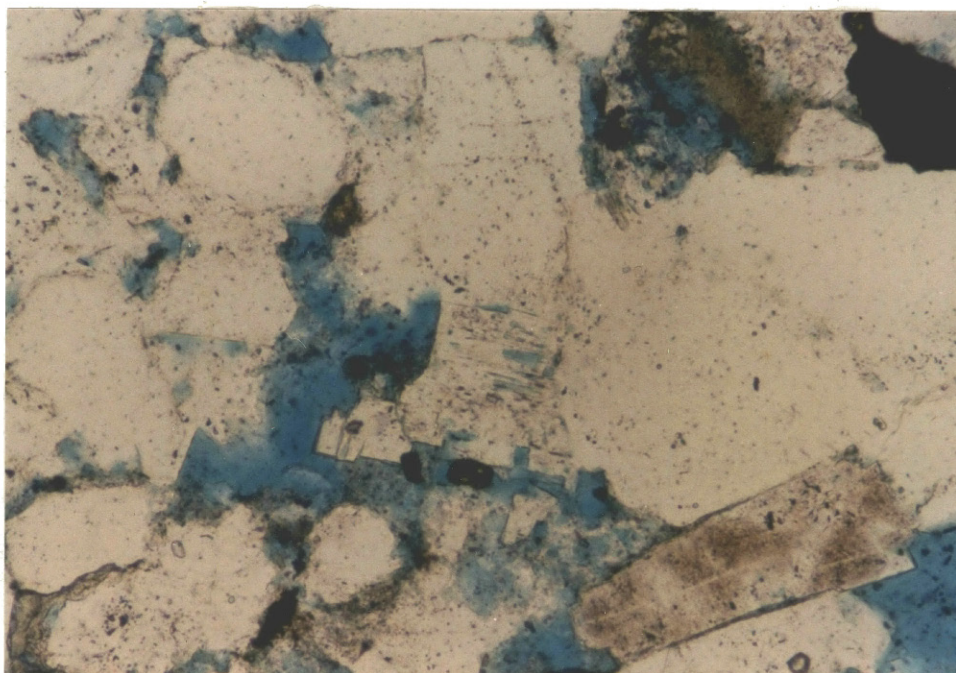


Figure 36. Photomicrograph of Secondary Porosity Resulting from Hybrid Pores (KMF-2176, 100X, PPL).

siderite, and calcite are the major factors contributing to the development of regular intergranular texture in the Upper Hartshorne Sands.

Secondary porosity also occurs in the form of hybrid pores (Figure 36). Typically, this type of porosity results from the dissolution of detrital and authigenic constituents. The hybrid pores seen in Upper Hartshorne Sand are of complex, diagenetic origin and are formed by a combination of the following: (1) reduction in porosity due to quartz overgrowths; (2) dissolution of quartz, rock fragments, and feldspar grains; (3) dissolution of detrital matrix; and (4) dissolution of carbonate cements (Schmidt and McDonald, 1979b).

Several other secondary porosity textures, as described by Schmidt and McDonald (1979b), are seen in thin section samples, but do not significantly contribute to the total volume of porosity. These textures include: oversized pore texture, moldic pore texture, intra-matrix pore texture, and intra-cement pore texture.

A variety of "petrographic criteria" typical of secondary porosity textures are observed in Upper Hartshorne thin sections (Schmidt and McDonald, 1979b). These consist of partial dissolution, grain molds, inhomogeneity of packing, oversized pores, and honeycombed grains (Figures 37 and 38). Partial dissolution is seen as the incomplete removal of authigenic cements, detrital grains, and detrital matrix. Grain molds occur where an entire detrital framework grain was removed. Inhomogeneity of packing and oversized pores are seen where local patches of carbonate cements have been dissolved.

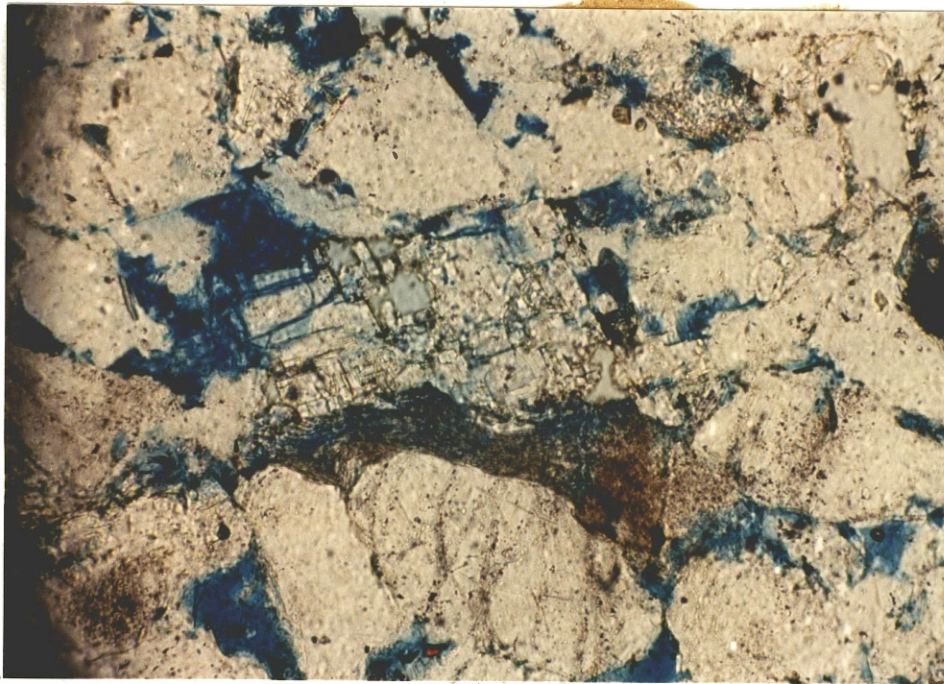


Figure 37. Photomicrograph of Honeycombed Feldspar Grain (HG-3588, 100X, PPL).

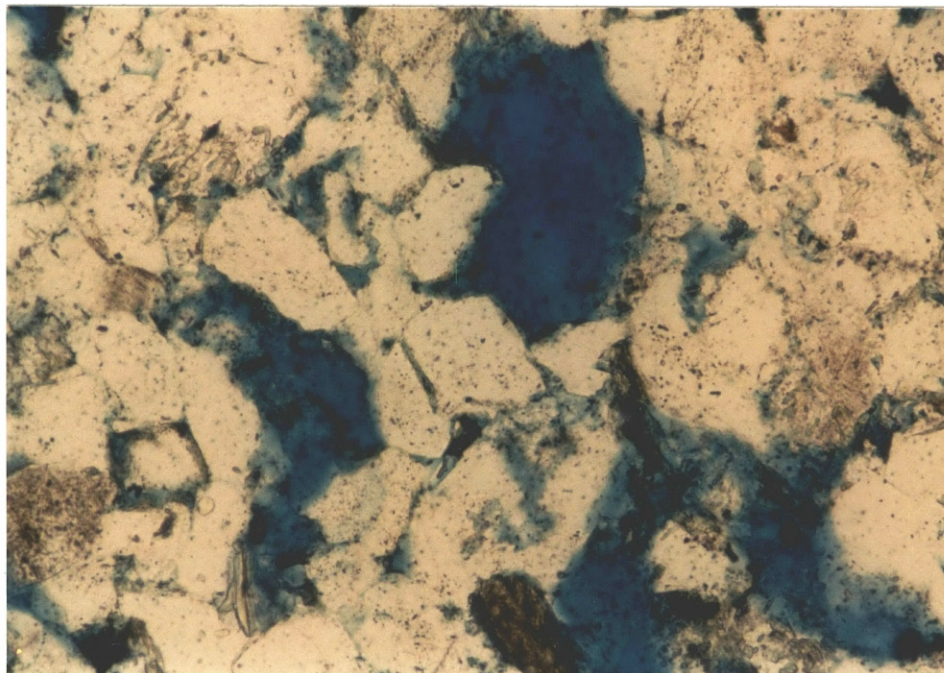


Figure 38. Photomicrograph Illustrating "Petrographic Criteria" for Secondary Porosity Including: Grain Mold, Top Center, Dissolution of Quartz, Bottom Center, and Dissolution of Detrital Matrix, Left (KMF-3572, 100X, PPL).

Feldspar grains that are pitted or dissolved along cleavage planes are seen as honeycombed grains.

Primary porosity was reduced by mechanical compaction, early siderite cement, and calcite cement. Secondary porosity resulted from dissolution of detrital grains and authigenic cements. This porosity was occluded by authigenic clays and late stage dolomite cementation. The total porosity volume of the two cores ranges from 2 to 9%.

The development of porosity in Upper Hartshorne Sands results from the dissolution of feldspar grains, rock fragments, detrital matrix, siderite, and calcite cements. The highest volume of porosity is associated with very fine to fine-grained quartz-arenites. Therefore, Hartshorne sands, that are considered to be channel deposits, should be of reservoir quality.

Diagenetic History

Figure 39 illustrates the probable paragenetic sequence for the Upper Hartshorne Sandstone. The sequence of diagenetic events was determined by the application of cross-cutting relationships in thin section samples.

Siderite is observed in association with organic-rich illitic mudstone grains localized along stylolites. These mudstone grains may have originally been iron-rich carbonaceous mud that altered to siderite shortly after deposition. Alternatively, original detrital grains could have been deposited with a thin outer coating of iron (Maynard, 1983). The requirements for the precipitation of siderite are low sulfide activity, low Eh, and high carbonate activity (Curtis and Spears, 1975). These conditions are all satisfied in a deltaic

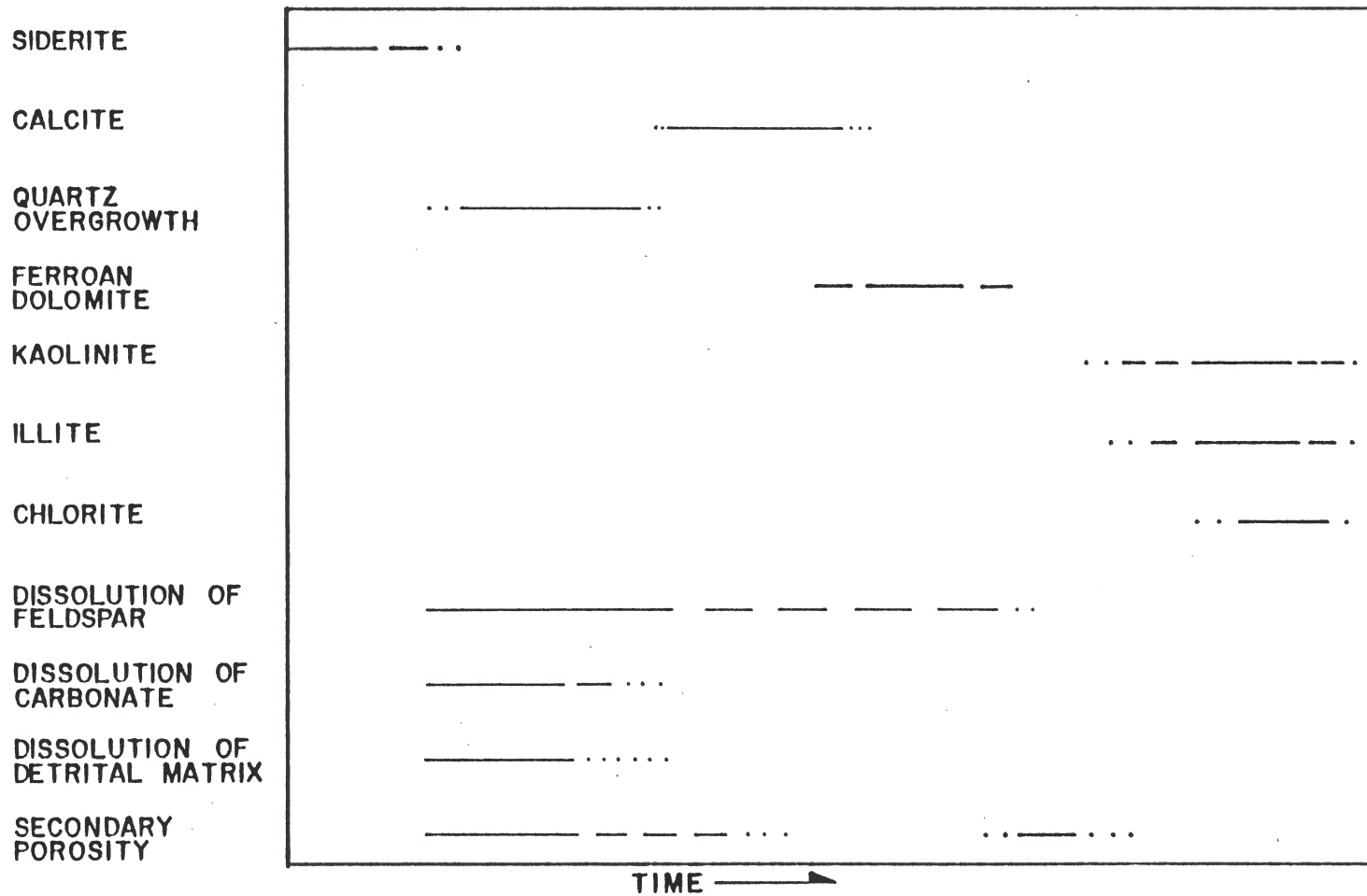


Figure 39. Paragenetic Sequence for the Upper Hartshorne Sandstone.

system (Bissell, 1984). Siderite is observed as spherulitic grains and rhombic crystals surrounding detrital grains. In most samples, siderite appears to precede authigenic quartz overgrowths.

A change in pH to a more acidic level facilitated the precipitation of quartz overgrowths. At the same time, precipitation of siderite would have slowed down or possibly halted. As the pore waters became more acidic, dissolution of feldspars, early carbonate cements, and detrital matrix would have proceeded.

Authigenic quartz overgrowths appear to have precipitated coeval with the waning stages of early carbonatization (Schmidt and McDonald, 1979a). Consequently, siderite occurs surrounding quartz grains with and without overgrowths. Siderite usually forms at shallow depth and may be related to methane-diagenesis (Al-Shaieb, 1987).

Calcite is an early authigenic cement and is more abundant in deeper thin section samples. Mechanical compaction of the Atoka Shale is the most likely source of carbonate. The release of carbonate ions into solution would have allowed for carbonate precipitation in Hartshorne Sands. Calcite cement replaces detrital grains and quartz overgrowths, and occurs in localized patches. Calcite is seen preserving original quartz grains and quartz grains with overgrowths.

Ferroan dolomite cement occurs as euhedral rhombic crystals and as a grain replacement mineral. Dolomite cement appears to have formed after the development of quartz overgrowths. Dolomite formation is considered to be a later diagenetic event and may be a replacement of calcite cement. Temperature and depth of burial are important factors influencing dolomite formation. The Hartshorne

Sands were never subjected to deep burial, but temperatures in the basin were elevated by tectonic activity in adjacent areas.

Dissolution of feldspar was probably an on-going process during early carbonatization. The dissolution of feldspars was a precursor to authigenic clay precipitation (Al-Shaieb and Shelton, 1981).

Kaolinite was observed as pore-filling booklets. Illite occurs as laths lining pores and bridging pore throats. Minor amounts of chlorite formed as a later precipitant, which lined pore throats.

Lower Booch Sandstone

Composition

Detrital Constituents. The most common detrital grains observed in the No. "A"-1 Mason core were quartz, feldspar, rock fragments, and detrital matrix. Bissell (1984) indicated that detrital composition within the Booch Sands was relatively constant and variations were due to grain size differences. This is consistent with the observations made in this study of the Lower Booch Sandstone. Table V lists the average percentage of each detrital constituent.

The most abundant detrital constituent is monocrystalline quartz. Quartz grains are commonly subangular to angular. The original subrounded grain shape is commonly preserved by illite dust rims. Grain size ranges from fine to medium in most thin section samples. The majority of grains exhibit complete extinction with stage rotation. Polycrystalline grains are common but not abundant and occur as composite grains exhibiting undulose extinction.

Feldspars include albite plagioclase, orthoclase, and traces of microcline. Albite is the most common feldspar and is easily

TABLE V
AVERAGE DETRITAL COMPOSITION OF THE
LOWER BOOCH SANDSTONE

Constituent	Avg. Percentage (%)
Quartz	70.3%
Feldspar	2.0%
Rock Fragments	3.0%
Detrital Matrix	2.8%
Organic Matter	1.0%
Muscovite	less than 1.0%
Biotite	Trace %
Tourmaline	Trace %
Zircon	Trace %

recognized on the basis of twinning. Orthoclase is typically pitted and cloudy in appearance. Individual grains of microcline exhibit twinning in two samples.

Rock fragments include metamorphic, organic rich illitic mudstone, and chert grains. Metamorphic rock fragments consist of stretched quartz grains and abundant muscovite flakes. Individual grains of illitic mudstone rich in organics commonly show signs of plastic deformation. Siderite cement typically replaces the edges of illitic mud grains. Chert grains occur in trace amounts in all thin section samples.

Detrital matrix consists of illite and chlorite. Clay matrix is ordinarily deformed and squeezed between adjacent framework grains.

Detrital accessory grains accounting for a trace percentage of the detrital composition include muscovite, biotite, leucoxene, zircon, tourmaline, and organics. Muscovite and biotite occur in all samples and usually show the effects of compaction. Heavy minerals include tourmaline, zircon, and leucoxene. Trace amounts of organics are common to all samples and are usually associated with silt rich illitic mud grains.

Figure 40 is a compositional plot of each sample according to Folk's (1974) sandstone classification system. This method of classification relies on the normalized percentage of quartz, feldspar and rock fragments in order to distinguish different types of sandstone. All of the thin section samples plotted as sublitharenites.

Authigenic Constituents. Table VI lists the average percentage of each authigenic constituent. Silica cement in the form of quartz

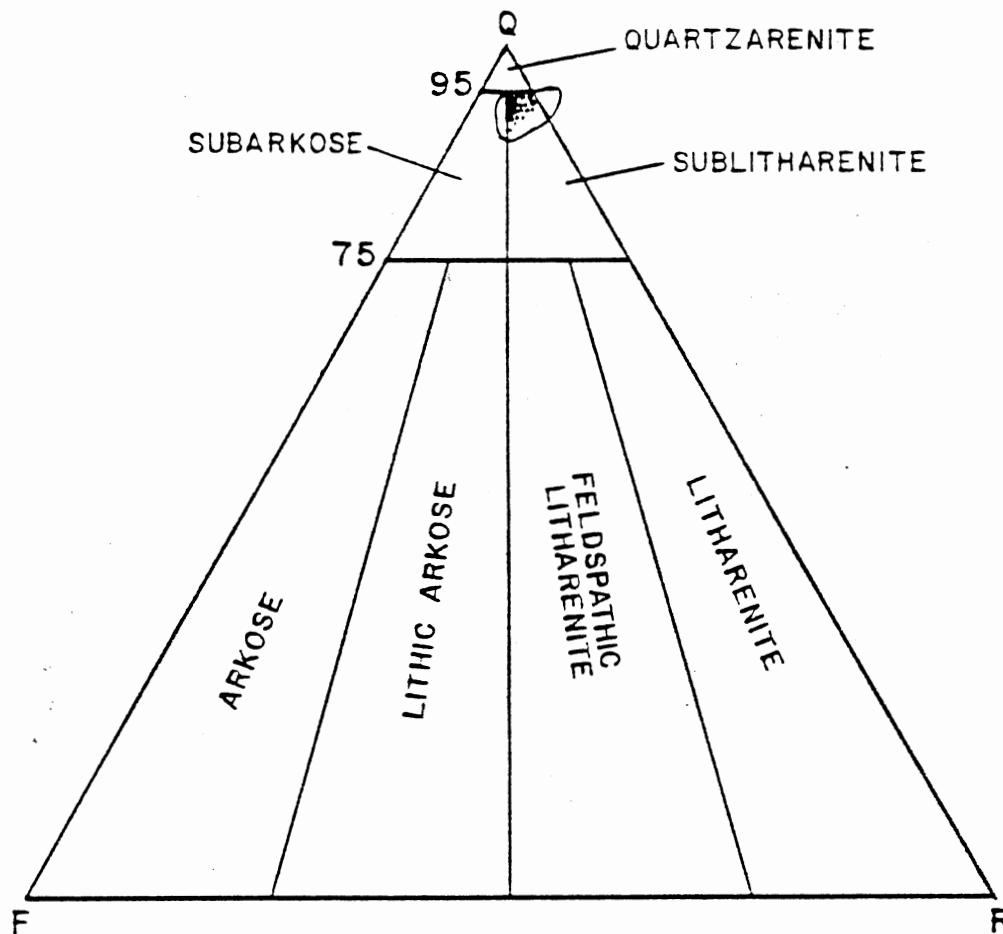


Figure 40. Classification of Lower Booch Sandstone.

TABLE VI
AVERAGE AUTHIGENIC COMPOSITION OF THE
LOWER BOOCH SANDSTONE

Constituent	Avg. Percentage (%)
Quartz Overgrowths	2.0%
Early Siderite	3.4%
Calcite	1.0%
Dolomite	less than 1.0%
Kaolinite	1.5%
Illite	2.0%
Chlorite	less than 1.0%
Hematite	Trace %
Pyrite	Trace %

overgrowths is the most common diagenetic constituent in samples, where early carbonates are not abundant (Figure 41). Quartz overgrowths are typically sutured. The effects of pressure solution were observed in several thin sections (Figure 42).

Early siderite cement appears as spherulitic grains and localized masses of flattened rhombic crystals (Figures 43 and 44). The spherulitic variety is typically observed surrounding quartz grains. Rhombic crystals regularly occur in open pore spaces and pore throats.

Curtis and Spears (1975) gave the requirements for the precipitation of early diagenetic siderite. These requirements include: low Eh, low sulfide activity, high carbonate activity, and restricted pore-water circulation. All of these requirements are satisfied just below the sediment/water interface in a deltaic environment. The precipitation of quartz overgrowths is locally restricted by siderite (Figures 43 and 44).

Siderite cement is commonly observed replacing quartz and feldspar grains and creating solution embayments. Calcite and dolomite cements are associated with siderite in a few samples.

Calcite occurs as local patches of poikilotopic cement and fills pore spaces between adjacent detrital grains (Figure 45). Calcite cement preserves original quartz grain shapes, and it is also present around quartz grains with overgrowths (Figures 45 and 46). Partial replacement of quartz and feldspar grains is common (Figure 45).

Dolomite cement is present in four samples and accounts for less than one percent of the total authigenic composition of this sandstone. Dolomite cement appears as euhedral rhombic crystals partially filling pore spaces (Figure 47).

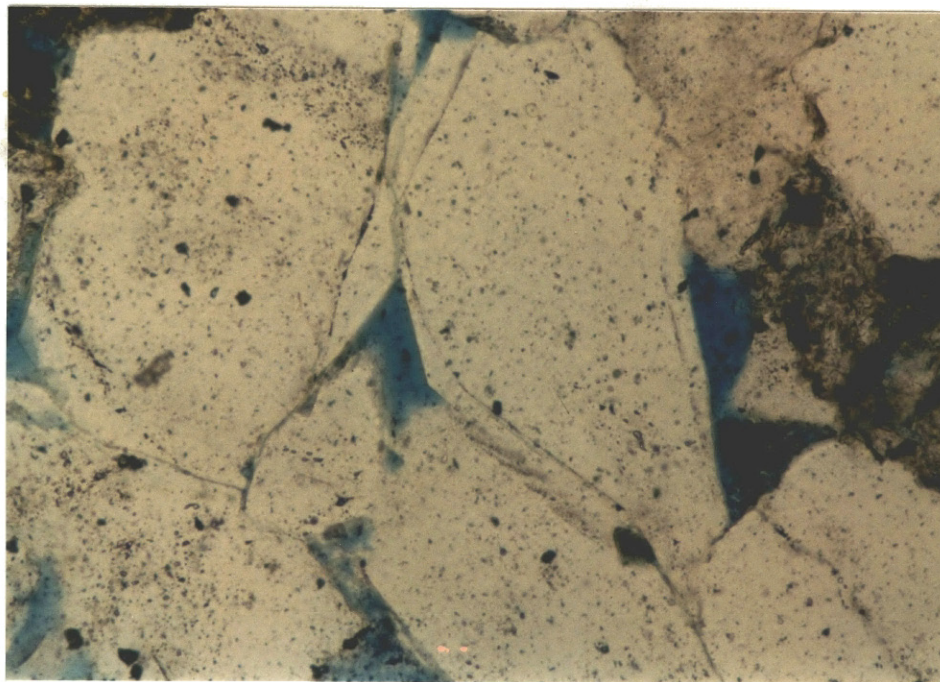


Figure 41. Photomicrograph of Typical Quartz Overgrowth
in the Lower Booch Sandstone (CSM-1370,
100X, PPL).

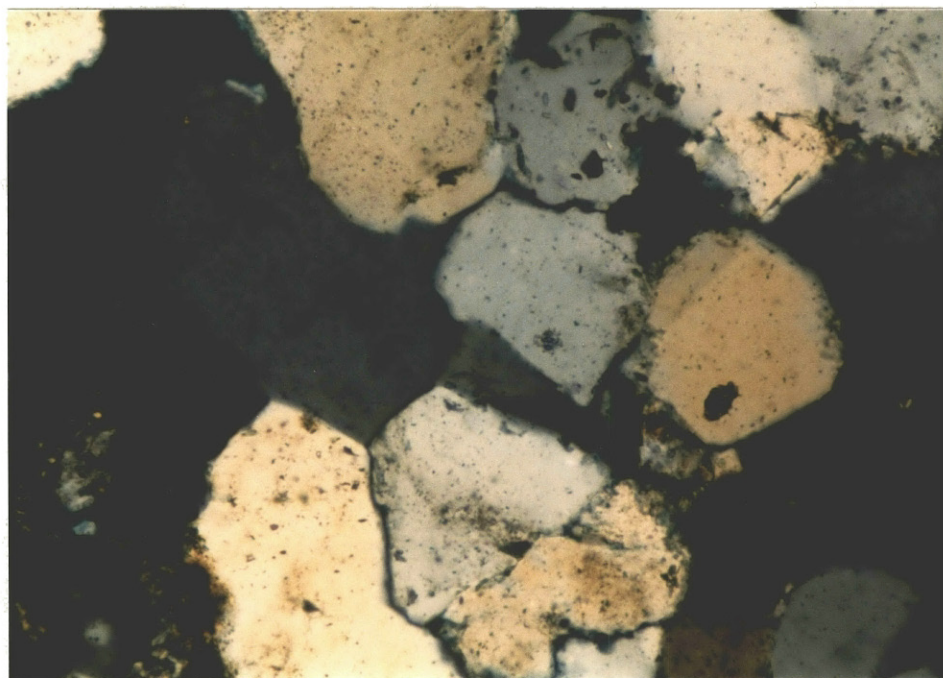


Figure 42. Photomicrograph of Quartz Overgrowths
and the Effects of Pressure Solution
(CSM-1479, 100X, XN).

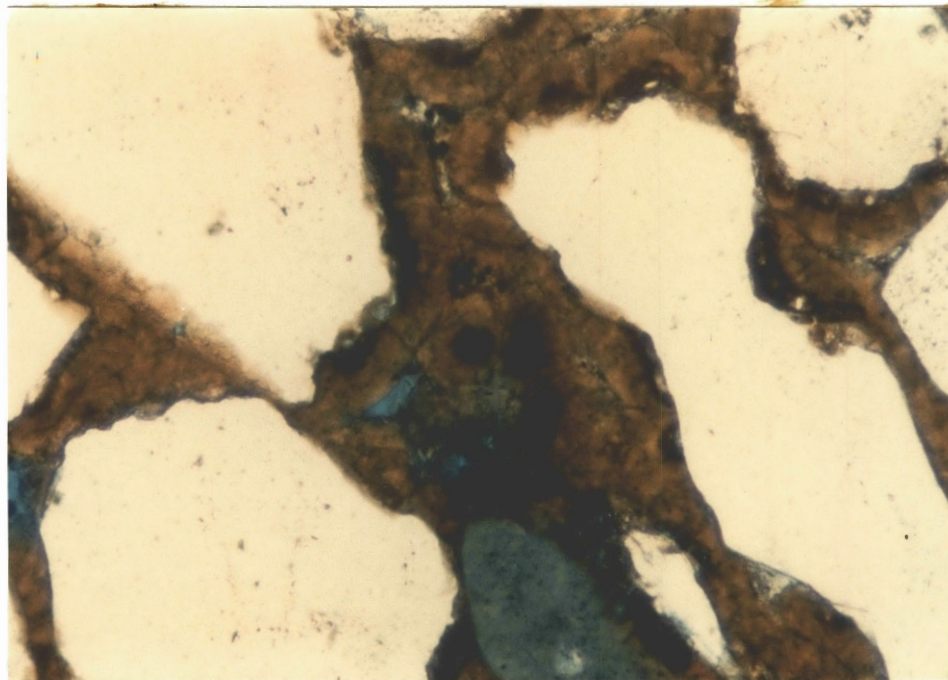


Figure 43. Photomicrograph of Spherulitic Siderite Cement (CSM-1498, 100X, PPL).

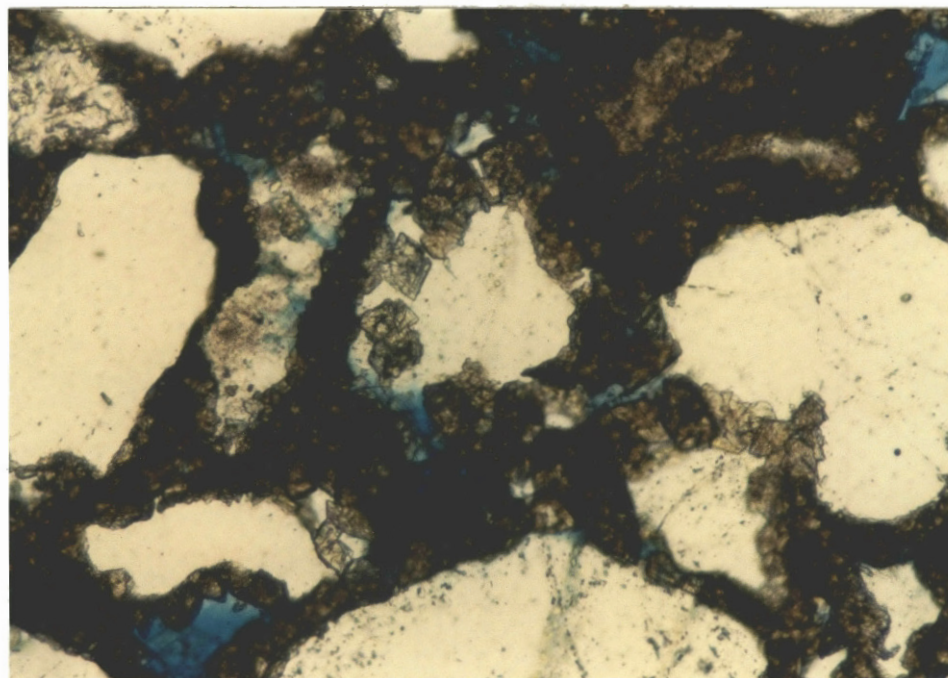


Figure 44. Photomicrograph of Flattened Rhombic Crystals of Siderite Cement (CSM-1452, 100X, PPL).

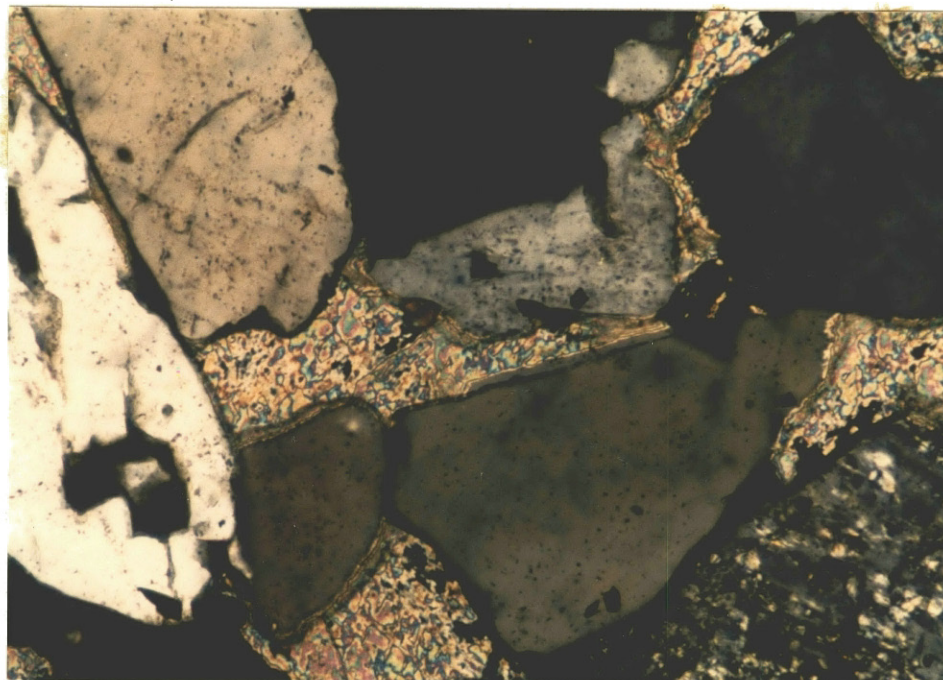


Figure 45. Photomicrograph of Calcite Cement Filling Pore Space, Preserving Original Quartz Grain Shape, and Partial Replacement of a Feldspar Grain (CSM-1498, 100X, XN).

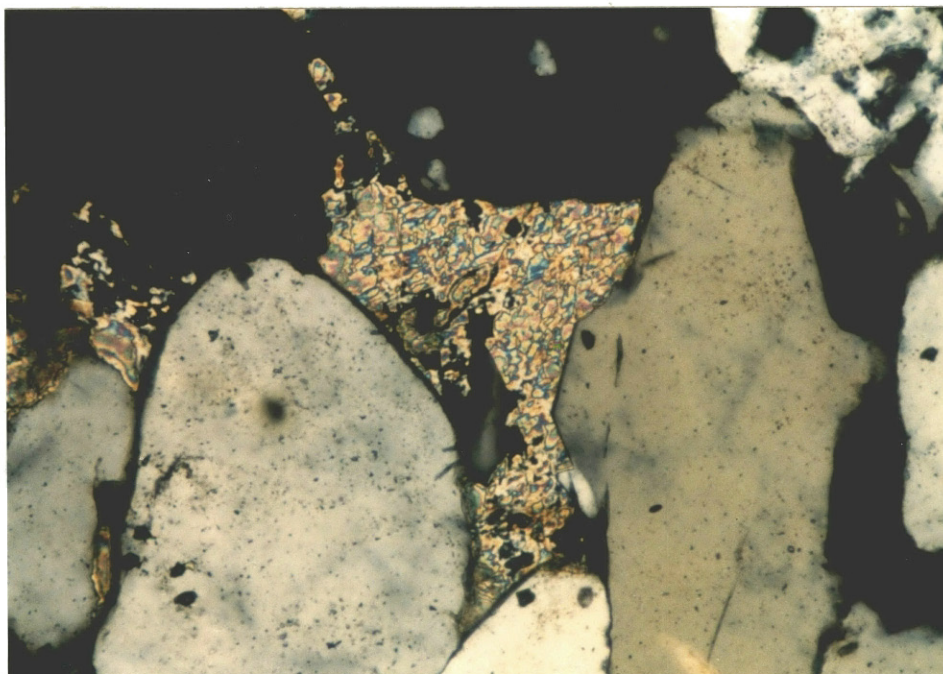


Figure 46. Photomicrograph of Calcite Cement Following Quartz Overgrowth (CSM-1498, 100X, XN).

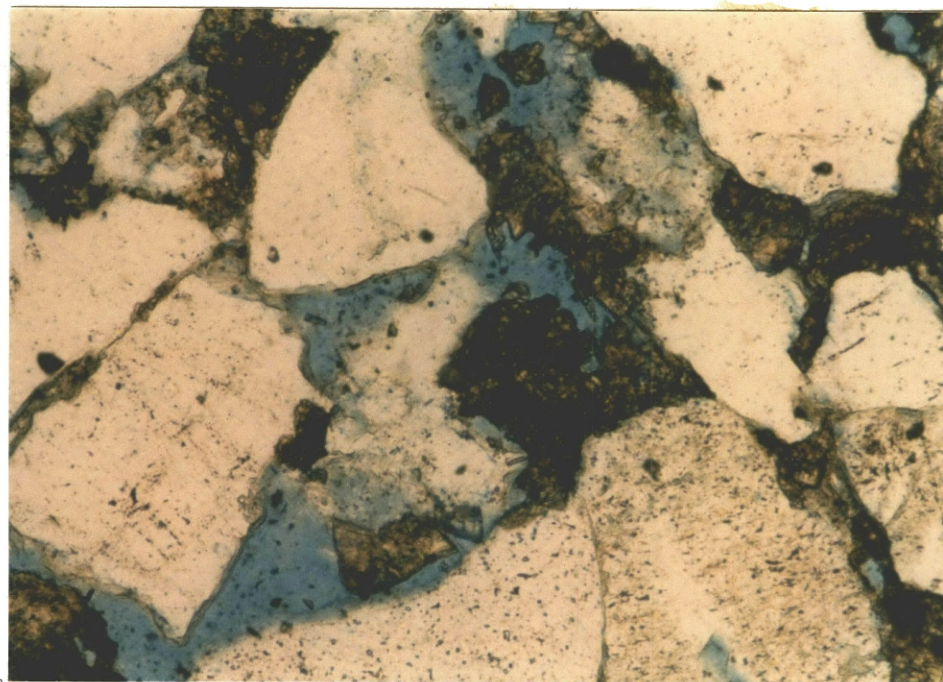


Figure 47. Photomicrograph of Euhedral Rhombic Crystals of Dolomite Cement (CSM-1404, 100X, PPL).

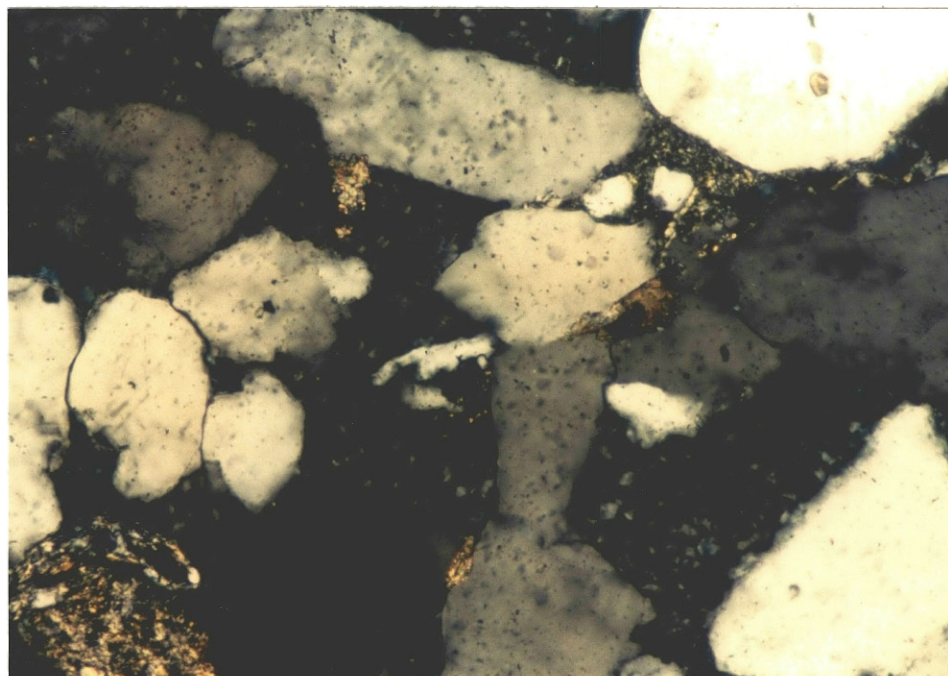


Figure 48. Photomicrograph of Pore-Filling Kaolinite Booklets (CSM-1383, 100X, XN).

A potassium ferricyanide solution was used on three separate occasions to determine the relative ferroan content of the dolomite cement. The result of these staining attempts was negligible, suggesting a minimum ferroan content or the absence of iron.

Authigenic clays present in most samples include kaolinite, illite, and chlorite. Kaolinite occurs as pore-filling booklets (Figures 48 and 49). Kaolinite is common in all samples and seems to be more abundant in samples with a medium grain size (Bissell, 1984). Illite typically occurs as high birefringent pore-lining laths (Figure 50). Illite is the most common clay in all samples and is usually more abundant than kaolinite. Sericite (coarse illite) is present in several thin section samples and is regularly seen as altered muscovite flakes in metamorphic rock fragments.

Chlorite was not observed in thin sections due to the "low relief, birefringence and pale color" of crystals (Wilson and Pittman, 1977). X-ray diffraction also failed to indicate the presence of chlorite. Bissell (1984) reported similar difficulties in recognizing chlorite in the Lower Booch Sandstone.

Chlorite was identified in several Lower Booch samples using the SEM (Figure 51). Chlorite crystals appeared in the typical cardhouse or edge to face orientation. In all samples, chlorite comprised less than one percent of the total authigenic composition.

Trace amounts of hematite and pyrite are present in several samples. Hematite is associated with siderite and exhibits a reddish-brown color under reflected light. Pyrite appears gold under reflected light and is ordinarily associated with organic matter.



Figure 49. SEM Image of Pore-Filling Kaolinite (CSM-1452, 2000X).

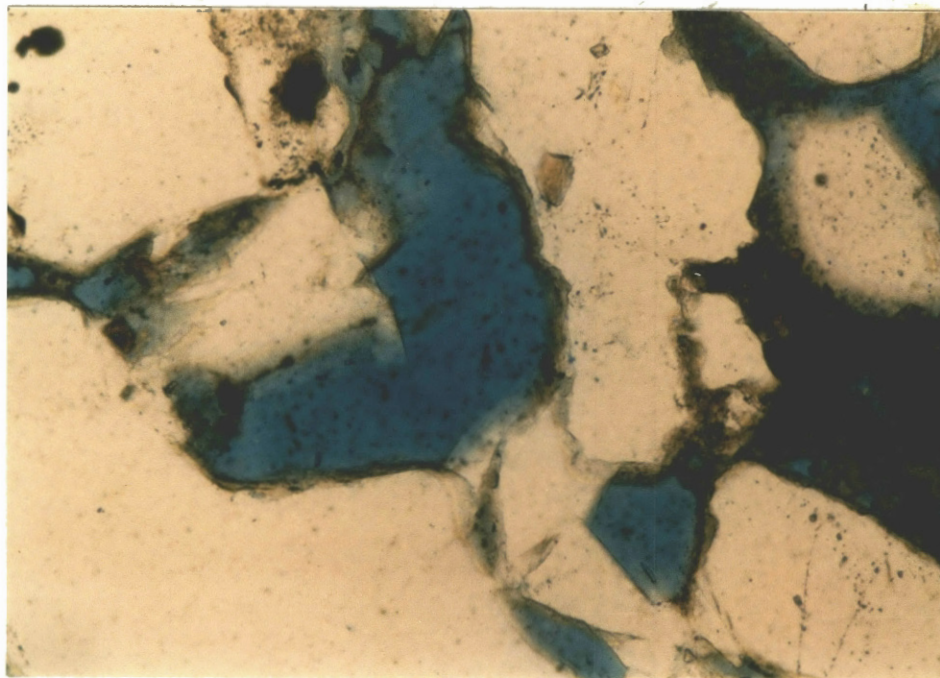


Figure 50. Photomicrograph of Pore-Lining Illite in the Lower Booch Sandstone (CSM-1498, 100X, PPL).

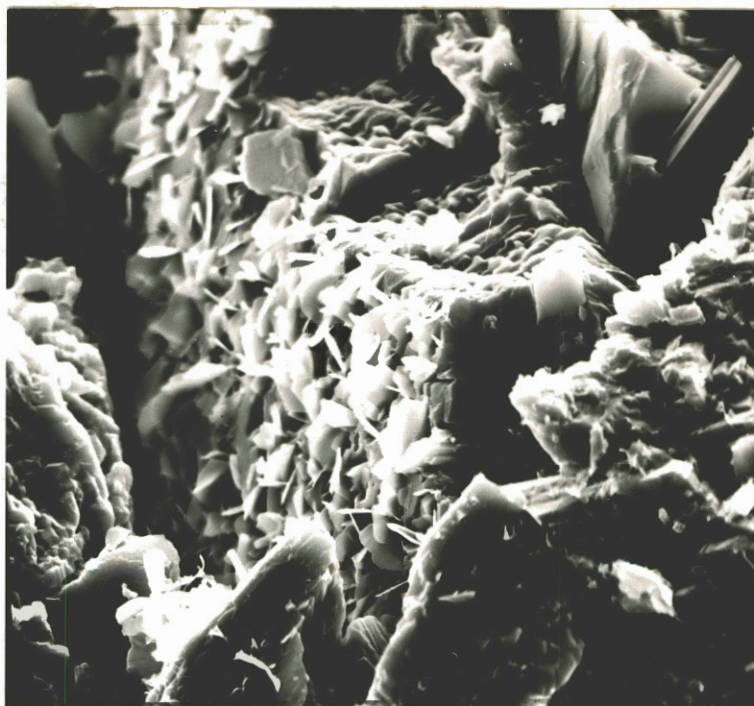


Figure 51. SEM Image of Typical Edge to Face Orientation of Authigenic Chlorite Crystals (CSM-1452, 2400X).

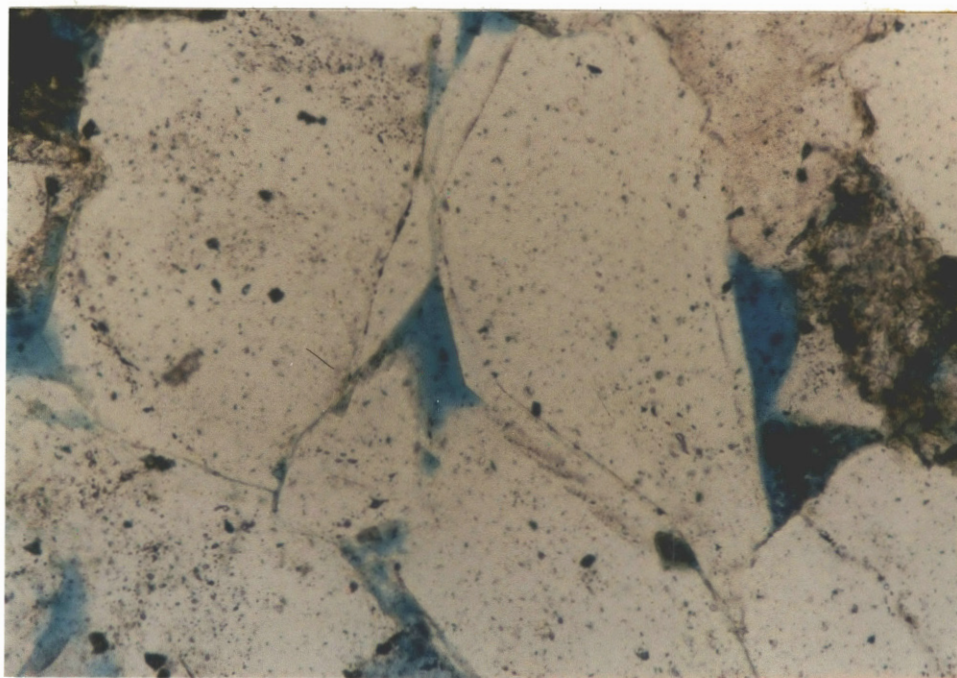


Figure 52. Photomicrograph of Reduced Intergranular Porosity Texture Due to Quartz Overgrowths (CSM-1370, 100X, PPL).

Porosity

Several types of secondary porosity occur in the Lower Booch Sandstone. Reduced intergranular texture is important in all samples (Figure 52). This type of texture results from quartz overgrowth cementation of grain edges (Schmidt and McDonald, 1979b). Regular intergranular texture is also common in all samples and results from the dissolution of detrital matrix and the dissolution of authigenic carbonate cements (Schmidt and McDonald, 1979b).

Hybrid porosity characterizes pores of complicated diagenetic origin (Schmidt and McDonald, 1979b). In the Lower Booch sands hybrid pores seem to result from the following: (1) partial reduction in porosity due to quartz overgrowths; (2) partial dissolution of quartz, rock fragments, and feldspar grains; (3) dissolution of detrital matrix; and (4) dissolution of authigenic carbonate cements (Schmidt and McDonald, 1979b) (Figure 53). Hybrid porosity is common to all samples with well developed porosity.

An abundance of "petrographic criteria" exist, which are typical of secondary porosity textures in Lower Booch Sands (Schmidt and McDonald, 1979b). These criteria include grain molds, partial dissolution, inhomogeneity of packing, oversized pores, and honeycombed grains (Figures 54 and 55). Grain molds, partial dissolution, and honeycombed grains result from the partial or complete dissolution of detrital grains and detrital matrix. Inhomogeneity of packing and oversized pores are probably due to the dissolution of authigenic carbonate cements.

A small percentage of secondary porosity is attributed to

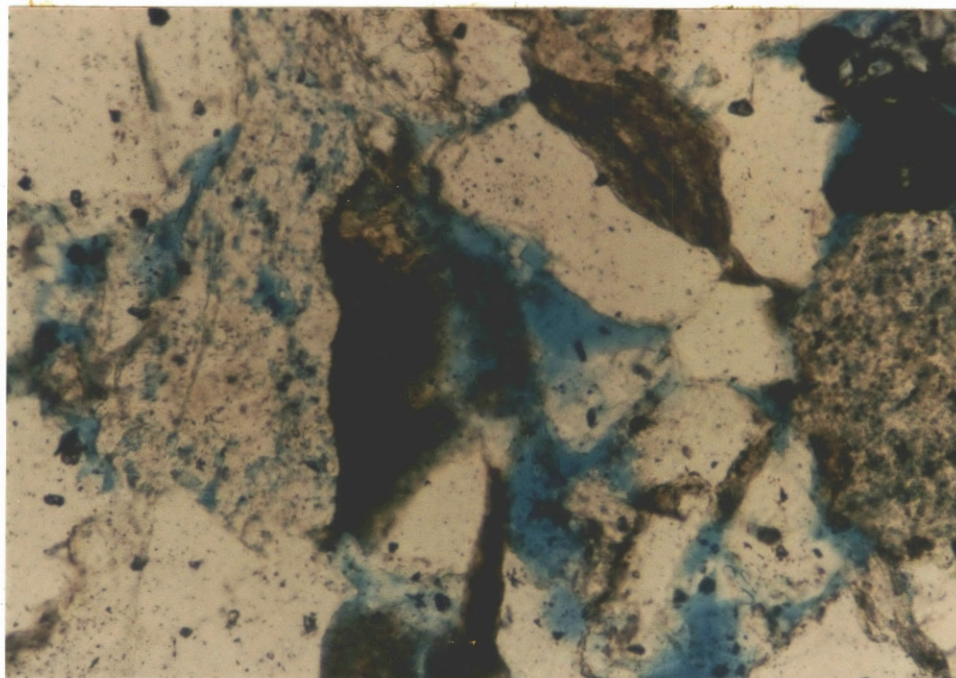


Figure 53. Photomicrograph of Hybrid Pores of Complex Diagenetic Origin (CSM-1370, 100X, PPL).

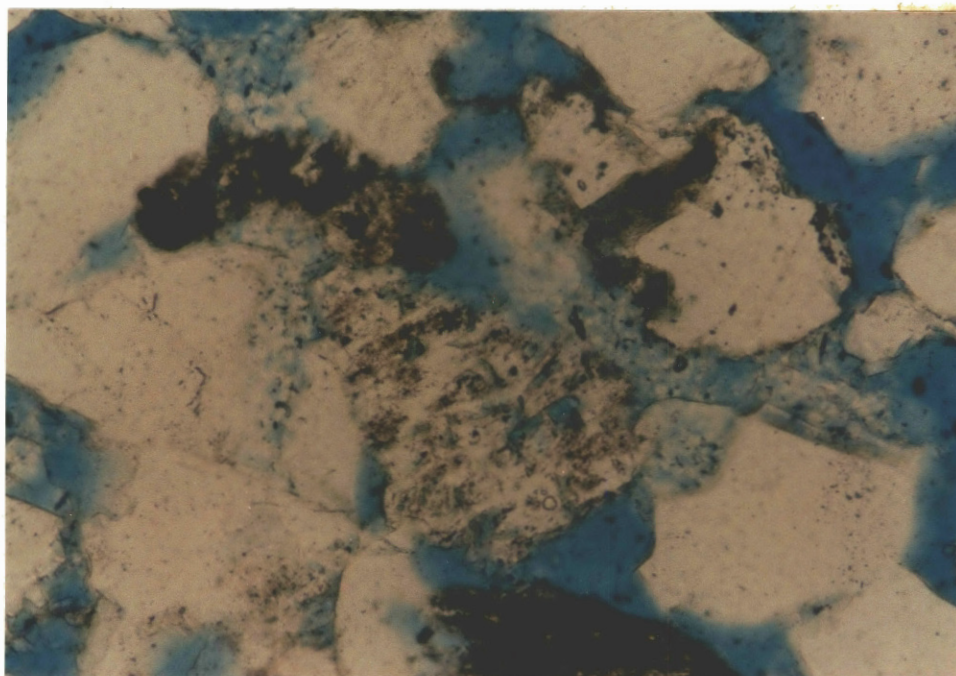


Figure 54. Photomicrograph of a Honeycombed Feldspar Grain (CSM-1383, 100X, PPL).

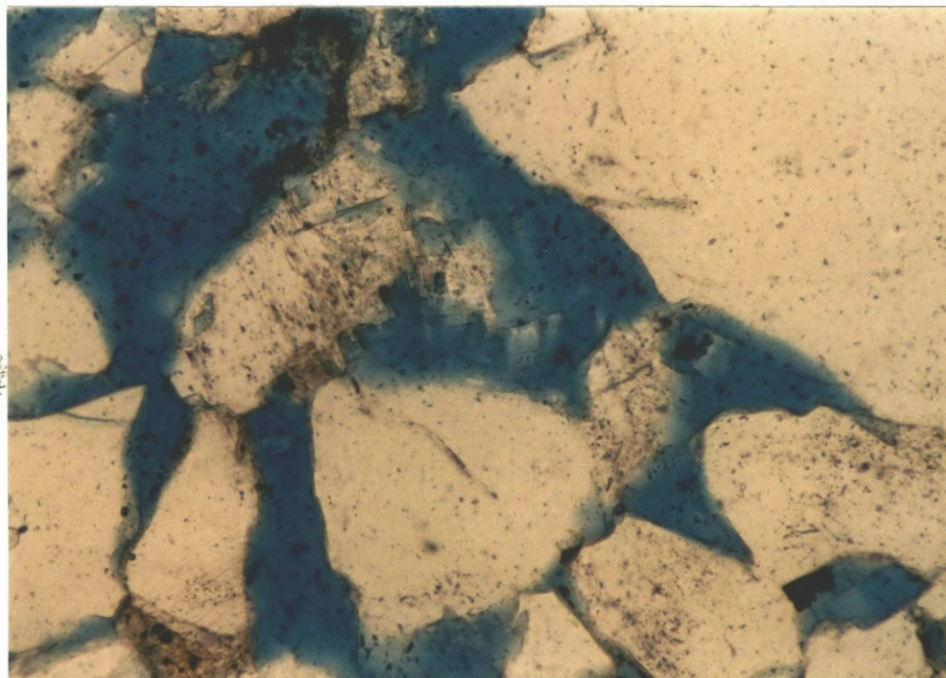


Figure 55. Photomicrograph of Apparent Inhomogeneity of Packing (CSM-1391, 100X, PPL).

authigenic kaolinite. Pore spaces occluded by kaolinite typically exhibit "micro-porosity" due to the small spaces between individual clay crystals.

The development of secondary porosity in Lower Booch Sands is in part a function of grain size variation (Bissell, 1984). In samples where very fine to fine-grained sand dominates, porosity generally ranges from 4% to 10%. In samples with fine to medium-grained sand, porosity ranges from 10% to 20%. Although grain size appears to be a major factor in the development of secondary porosity, the original detrital composition with respect to feldspars and detrital matrix is also an important consideration. Samples with a higher percentage of porosity usually contained smaller percentages of feldspars and detrital matrix or exhibited a higher degree of dissolution of detrital and authigenic constituents.

Primary porosity in the Lower Booch Sandstone was reduced by early siderite cement, quartz overgrowths, mechanical compaction, and calcite cement. Secondary porosity was created by dissolution of detrital and authigenic constituents. Secondary porosity was obstructed by authigenic clays and cements. Porosity values from thin section analysis range from 4% to 23%. The range in porosity is attributed to the dissolution of detrital framework grains, detrital matrix, and authigenic cements. The degree of dissolution is possibly a function of grain size variation as suggested by Bissell (1984). Alternatively, porosity may be a function of the original detrital composition of coarser sands.

Diagenetic History

The diagenetic events of the Lower Booch Sandstone were determined using grain cross-cutting relationships observed in thin sections. The proposed paragenetic sequence for this sandstone is illustrated in Figure 56.

Siderite is considered to be the earliest authigenic cement. Siderite cement is most abundant in deeper samples. Siderite cement may have originated as "colloidal iron compounds", which allowed precipitation of the cement following deposition (Bissell, 1984). Another possible origin for siderite is an iron rich grain coating on detrital grains, which would allow siderite precipitation shortly after deposition (Maynard, 1983). In either case, siderite precipitation only occurs when there is high carbonate activity, low Eh, and no sulfide activity (Curtis and Spears, 1975). A high constructive delta satisfies the requirements for early siderite precipitation (Bissell, 1984). The presence of siderite in dust rims, and the preservation of original quartz grain shapes are additional indications of an early diagenetic origin.

Early carbonatization ceased as pore waters became more acidic and quartz overgrowths began to precipitate. Quartz overgrowths reduced porosity in pore spaces that were not dominated by early carbonate cements. Partial dissolution of early carbonate cements, feldspars, and detrital matrix also proceeded while acidic conditions prevailed.

Calcite cement is most abundant in the deeper samples but is common in several thin section samples. Calcite cement preserves original quartz grain shapes in local poikilotopic patches and occurs

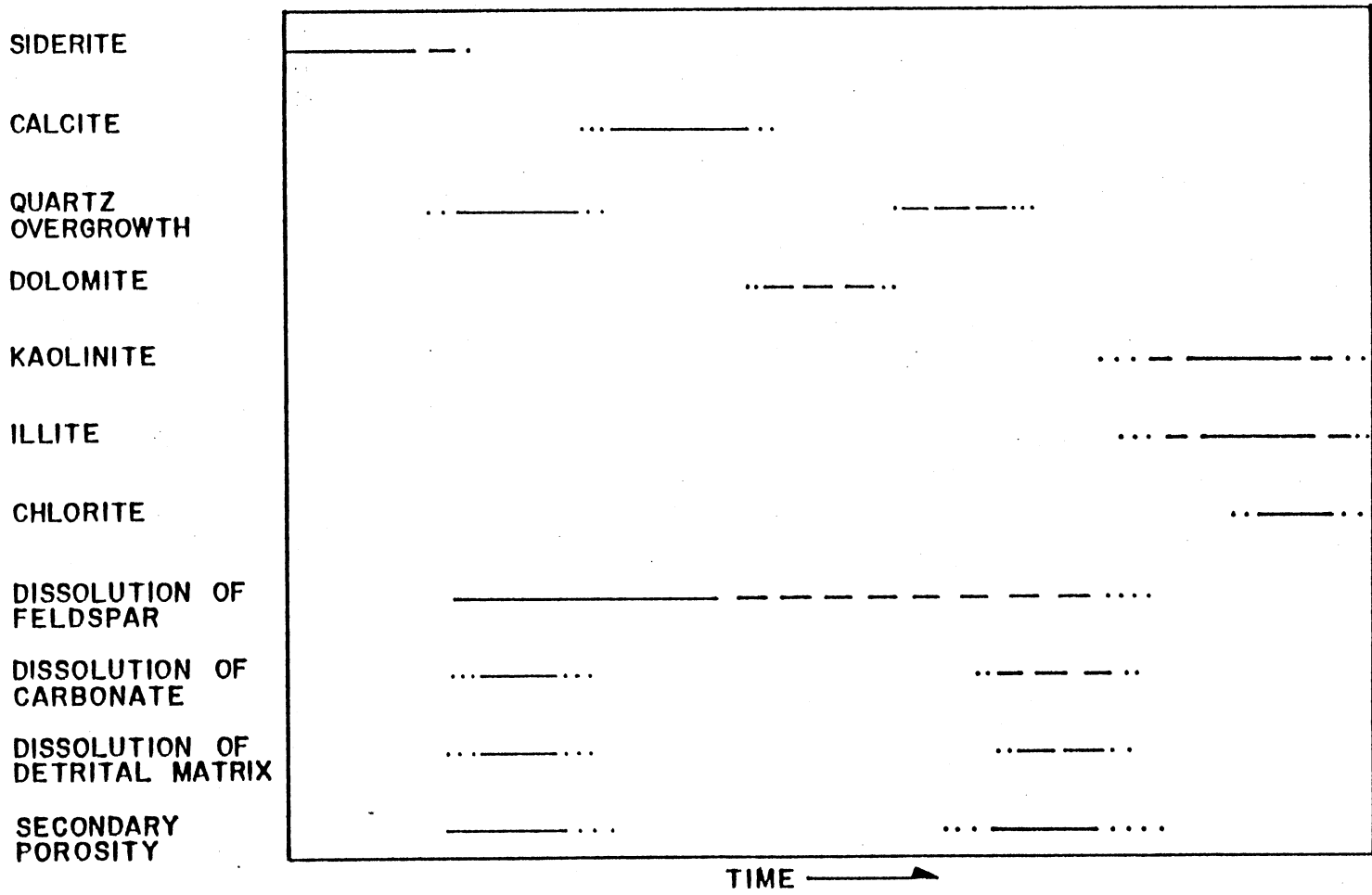


Figure 56. Paragenetic Sequence for the Lower Booch Sandstone.

in pore spaces reduced by quartz overgrowths. The proximity of samples with abundant calcite cement to the underlying shale section may indicate the source of carbonate. Compaction of underlying shale may have provided carbonate in solution to the overlying Booch Sands.

Dolomite cement occurs as euhedral rhombic crystals in open pore spaces, and is considered a late diagenetic event.

The precipitation of authigenic kaolinite and illite was associated with the dissolution of feldspars (Al-Shaieb and Shelton, 1981). The dissolution of feldspar grains started after the first carbonatization event; the precipitation of kaolinite and illite followed. Minor amounts of chlorite formed during the later stages of authigenic clay precipitation.

CHAPTER IX

SUMMARY AND CONCLUSIONS

The Lower Morrowan Union Valley Formation is divided into the Cromwell Sandstone member and the Union Valley Limestone member, in ascending order. The Cromwell Sandstone represents an episode of regressive sedimentation followed by a transgressive sedimentation episode, which is represented by the Union Valley Limestone.

The Lower Desmoinesian Hartshorne Formation is divided into four named members. In ascending order these members are the Lower Hartshorne Sandstone, Lower Hartshorne Coal, Upper Hartshorne Sandstone, and Upper Hartshorne Coal. The sandstones and coals of this formation represent two episodes of regressive sedimentation.

The Lower Desmoinesian McAlester Formation contains the Lower Booch (Warner) Sandstone member. This sandstone member represents one complete episode of regressive sedimentation.

Regressive episodes of sedimentation in the Cromwell, Hartshorne and Booch Sandstones are related to deltaic sedimentation in the Arkoma Basin. The Cromwell and Hartshorne Sandstones were derived primarily from northern and eastern source areas. The Lower Booch Sandstone was derived from a northern source area.

Depositional environments in the Hartshorne and Booch delta systems can be identified in cores. The depositional environments may represent one or more facies, which are associated with the

high-constructive, elongate delta systems of the Hartshorne Formation and Lower Booch Sandstone.

Subsurface mapping of the Cromwell, Hartshorne and Lower Booch Sandstones demonstrates the sand body geometry of these units. The sand body geometry of the Cromwell Sandstone suggests a high constructive, lobate delta system. Net sandstone isolith maps of the Upper and Lower Hartshorne Sandstones represent a high constructive, elongate geometry for this deltaic system; this is consistent with the depositional environment suggested by McDaniel (1968) and Houseknecht (1983). The sand body geometry of the Lower Booch Sandstone represents a high constructive, elongate delta system which agrees with the findings of Busch (1953), Fisk (1961), Brown (1979) and Bissell (1984).

Net sandstone isolith maps, structure maps, and a production map demonstrate the presence of three types of petroleum trapping mechanisms. These petroleum traps are stratigraphic, structural, and combination. Gas production from the Cromwell Sandstone is specifically associated with structural type traps. The Hartshorne Sandstones produce gas from stratigraphic and combination type traps. Combination traps are responsible for all of the Booch gas production in the study area.

The most prolific gas production from the Cromwell, Hartshorne and Booch Sandstones is associated with the distributary channel facies. The fine-grained quartz-arenites and sublitharenites of the Hartshorne distributaries are of reservoir quality. Porosity in the Hartshorne is a result of the dissolution of detrital and authigenic constituents. Booch Sandstones are fine to medium-grained

sublitharenites with substantial porosity, which was created by the dissolution of detrital matrix, feldspars, rock fragments and carbonate cements. A paragenetic sequence of events can be demonstrated based upon relationships between detrital and authigenic constituents.

The major conclusions of this study are as follows:

1. All of the Lower and Middle Pennsylvanian section, from the top of the Springer Shale to the top of the McAlester Formation, can be correlated in the subsurface across the entire study area.
2. Evidence from subsurface mapping and cores indicates that the Hartshorne Formation represents a high constructive, elongate delta as does the Lower Booch Sandstone. The Cromwell Sandstone represents a high constructive, lobate delta.
3. The structural deformation in the study area began in early Desmoinesian time and continued until middle Desmoinesian time. The result of this deformation includes the development of a northeast to southwest series of synclines and anticlines, thrust faulting across the crest of the McAlester and Adamson anticlines, and normal faulting in the northern part of the study area.
4. The Cromwell and Hartshorne Sandstones are the most prolific gas reservoirs within the study area. Current production from the Cromwell Sandstone is exclusively from structural type traps. The majority of gas production from the Hartshorne Sands is from stratigraphic traps.
5. The Upper Hartshorne is typically a fine-grained sublitharenite or quartz-arenite. The development of porosity was a result of

the dissolution of detrital matrix, feldspar grains, rock fragments, and authigenic carbonate cements. The Lower Booch is a fine to medium-grained sublitharenite. Porosity developed from the dissolution of detrital grains and early authigenic cements. In both the Upper Hartshorne Sandstone and the Lower Booch Sandstone, the volume of porosity is reduced by kaolinite, illite, chlorite and authigenic cements.

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APPENDIX A

CORE DESCRIPTIONS

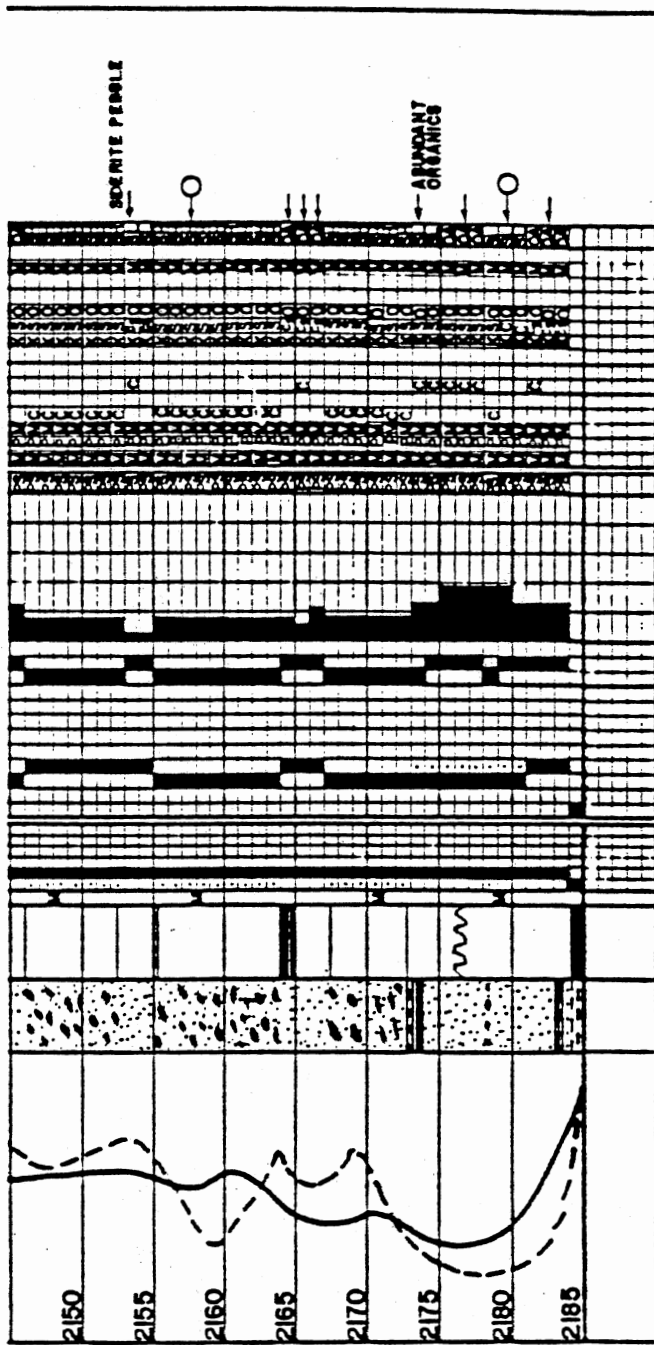
<h3>Lithology</h3> <ul style="list-style-type: none"> CLAY/CLAYSTONE SILTY CLAYSTONE/MUDSTONE SILT/SILTSTONE SAND/SANDSTONE INTERBEDDED SANDSTONE/MUDSTONE MUDDY SANDSTONE CONGLOMERATE LIMESTONE MARL DOLOMITE DOLOMITIC ROCK GYPSUM/ANHYDRITE GYPSIFEROUS ROCK HALITE 	<ul style="list-style-type: none"> CHERT CHERTY ROCKS COAL/LIGNITE VOLCANIC ROCKS INTRUSIVE ROCKS METAMORPHIC ROCKS <h3>Bedding (B)-Laminae (L)</h3> <ul style="list-style-type: none"> MASSIVE HORIZONTAL INITIAL SLOPE/DIP GRADED CROSS BEDDING (DUNES WAVES) THROUGH P-FL. SAND <h3>Surface Features</h3> <p>Surface Related</p>	<ul style="list-style-type: none"> RIPPLE LAMINAR FLOWAGE (F), FAULTED (F), LOAD (L) WATER ESCAPE DISRUPTED <h3>Deformed Features</h3> <ul style="list-style-type: none"> BURROW TRACE FOSSILS DISTURBED ROOT TRACES <h3>Chemical</h3> <ul style="list-style-type: none"> CONCRETIONS STYLOLITES 	<h3>Constituents</h3> <h4>QUARTZ</h4> <ul style="list-style-type: none"> M Monocrystalline P Polycrystalline C Chert O Other <h4>FELDSPAR</h4> <ul style="list-style-type: none"> K Feldspar P Plagioclase O Other <h4>ROCK FRAGMENTS</h4> <ul style="list-style-type: none"> M Metamorphic I Intrusive V Volcanic <h4>CLAY & CARBONATE</h4> <ul style="list-style-type: none"> C Clay C Carbonate <h4>FOSSILS</h4> <ul style="list-style-type: none"> P Plant C Carbonaceous Material W Carbonized Wood <h4>INVERTEBRATES & ALGAE</h4> <ul style="list-style-type: none"> A Algae B Brachiopods B Bryozoa C Cephalopods C Corals S Sponges F Forams G Gastropods P Pelecypods S Sponges 	<h3>Porosity Types</h3> <h4>CLAY MINERALS</h4> <ul style="list-style-type: none"> C Chlorite M Malleolite I Illite S Smectite M Mixed Layer O Other <h4>CARBONATES</h4> <ul style="list-style-type: none"> C Calcite F Ferrous Calcite D Dolomite I Ferrous Dolomite S Siderite O Other <h4>SILICA</h4> <ul style="list-style-type: none"> O Quartz Overgrowth M Micro Quartz C Chalcedony <h4>SULFIDES</h4> <ul style="list-style-type: none"> P Pyrite O Other <h4>SULFATES</h4> <ul style="list-style-type: none"> G Gypsum A Anhydrite B Barite O Other <h4>MICA</h4> <ul style="list-style-type: none"> M Muscovite B Biotite O Other 	<h3>Contacts of Strata</h3> <ul style="list-style-type: none"> ABRUPT TRANSITIONAL EROSIONAL GRADED DISRUPTED <h3>Cores</h3> <ul style="list-style-type: none"> CORE INTERVAL AND CORE NUMBER RECOVERED NO RECOVERY <h3>Miscellaneous</h3> <ul style="list-style-type: none"> THIN SECTION P & P ANALYZED SILT <h3>Rock Classification</h3>
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Petrologic Log

Company KERR-McGEE CORP. No. J. FINCH

Well Location C. SW Sec. 24, T. 8N., R. 17E.

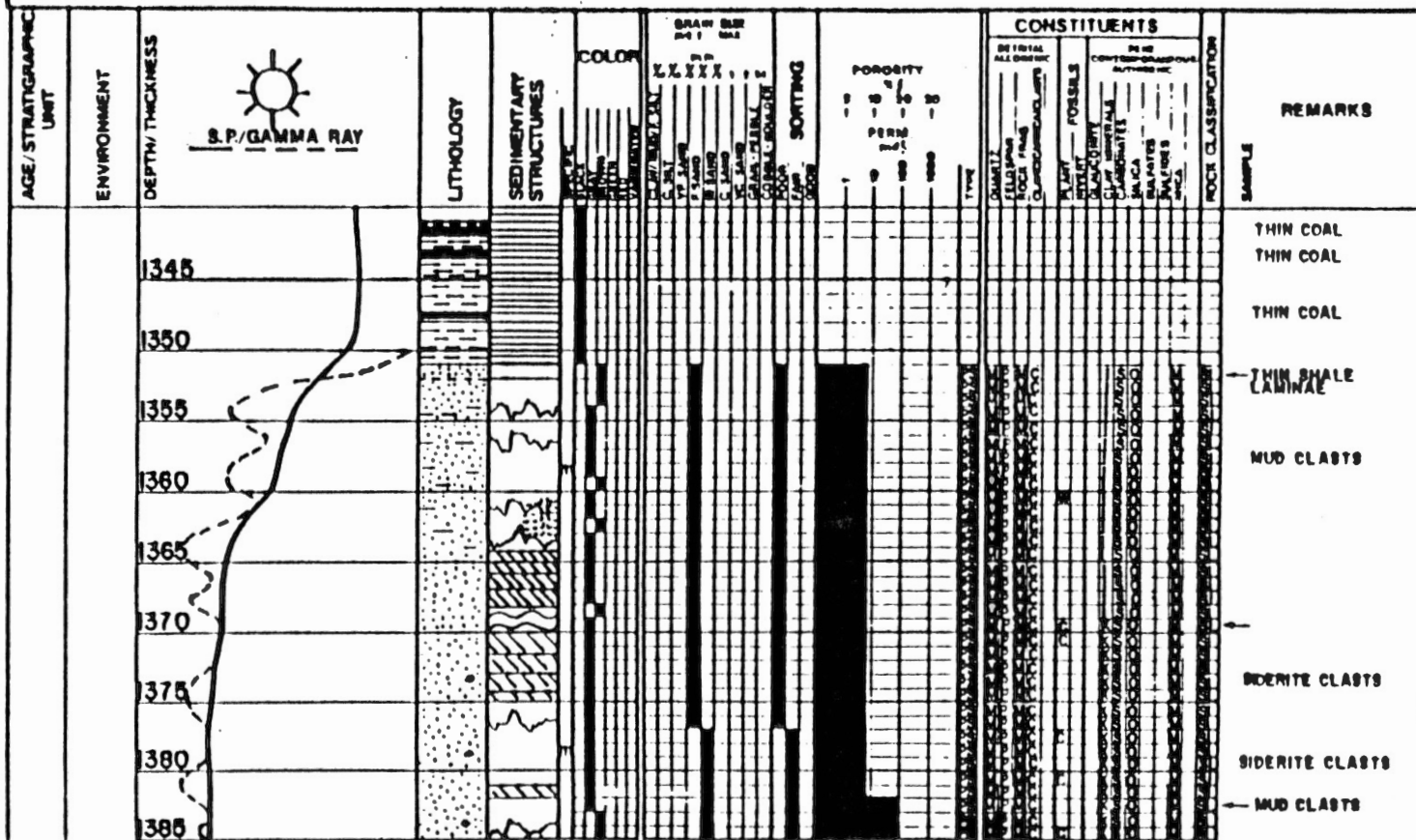
AGE/STRATIGRAPHIC UNIT	ENVIRONMENT	DEPTH/THICKNESS	S.P./GAMMA RAY	LITHOLOGY	SEDIMENTARY STRUCTURES	COLOR	GRAIN SIZE	SORTING	POROSITY	CONSTITUENTS	ROCK CLASSIFICATION	REMARKS
 S.P./GAMMA RAY		2105	—	[Lithology pattern]	[Structure pattern]	[Color pattern]	[Grain size pattern]	[Sorting pattern]	[Porosity pattern]	[Constituents pattern]	[Rock classification pattern]	
		2110	—	[Lithology pattern]	[Structure pattern]	[Color pattern]	[Grain size pattern]	[Sorting pattern]	[Porosity pattern]	[Constituents pattern]	[Rock classification pattern]	
		2115	—	[Lithology pattern]	[Structure pattern]	[Color pattern]	[Grain size pattern]	[Sorting pattern]	[Porosity pattern]	[Constituents pattern]	[Rock classification pattern]	
		2120	—	[Lithology pattern]	[Structure pattern]	[Color pattern]	[Grain size pattern]	[Sorting pattern]	[Porosity pattern]	[Constituents pattern]	[Rock classification pattern]	
		2125	—	[Lithology pattern]	[Structure pattern]	[Color pattern]	[Grain size pattern]	[Sorting pattern]	[Porosity pattern]	[Constituents pattern]	[Rock classification pattern]	
		2130	—	[Lithology pattern]	[Structure pattern]	[Color pattern]	[Grain size pattern]	[Sorting pattern]	[Porosity pattern]	[Constituents pattern]	[Rock classification pattern]	
		2135	—	[Lithology pattern]	[Structure pattern]	[Color pattern]	[Grain size pattern]	[Sorting pattern]	[Porosity pattern]	[Constituents pattern]	[Rock classification pattern]	
		2140	—	[Lithology pattern]	[Structure pattern]	[Color pattern]	[Grain size pattern]	[Sorting pattern]	[Porosity pattern]	[Constituents pattern]	[Rock classification pattern]	
		2145	—	[Lithology pattern]	[Structure pattern]	[Color pattern]	[Grain size pattern]	[Sorting pattern]	[Porosity pattern]	[Constituents pattern]	[Rock classification pattern]	
	TORN SANDSTONE											

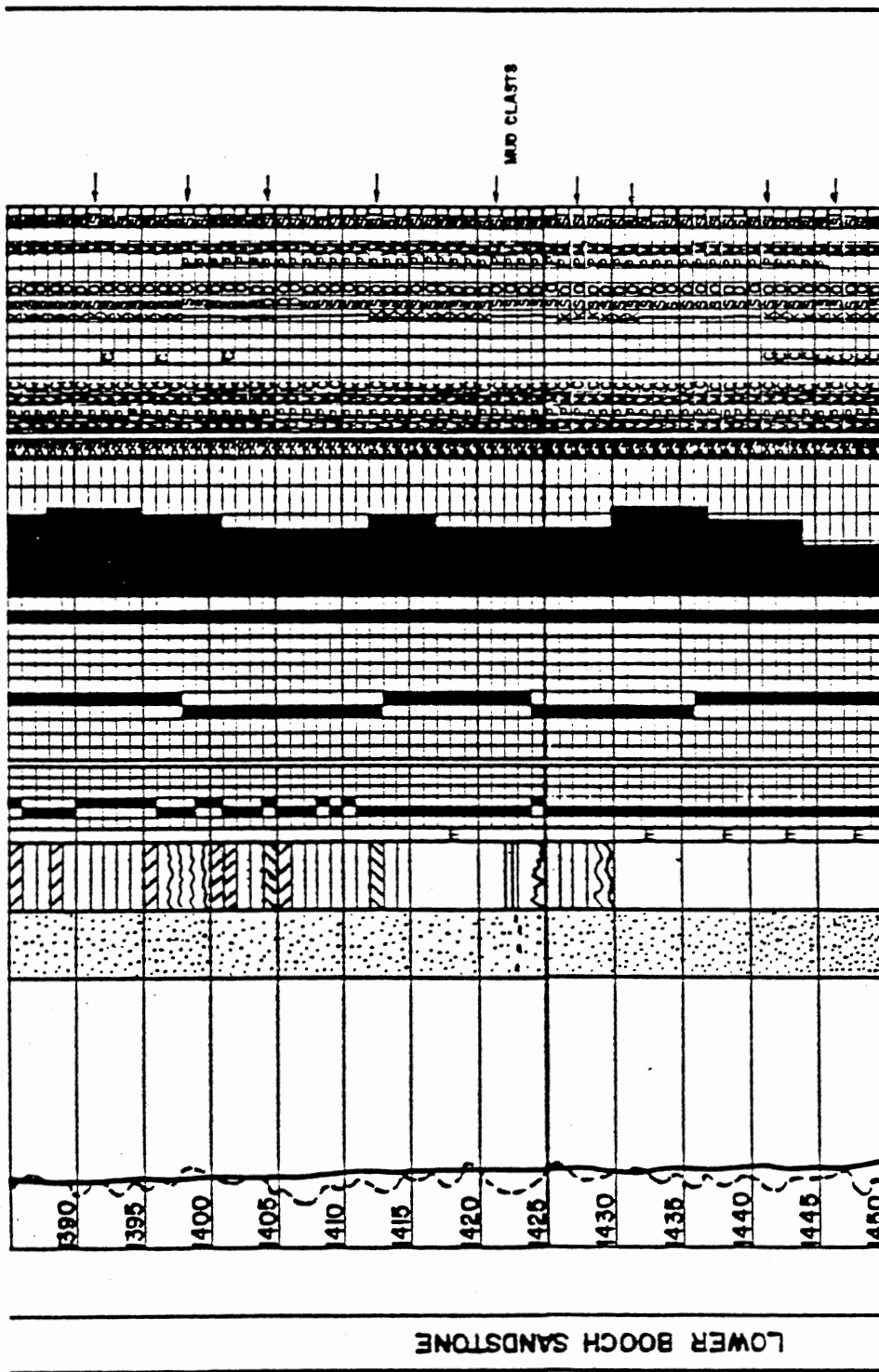


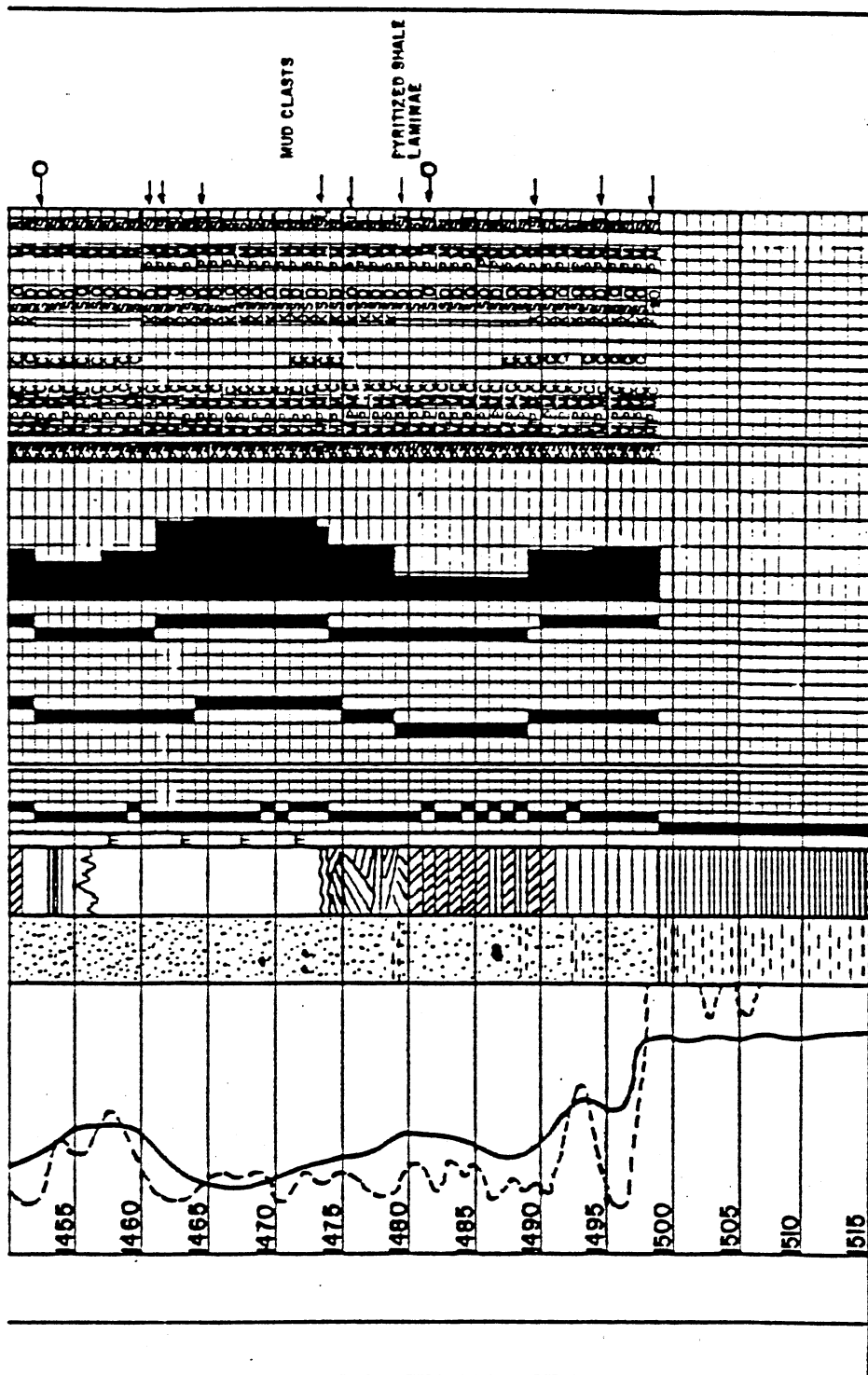
UPPER HARTSI

Company CITIES SERVICE COMPANY No. "A"-1 MASON
 Well Location SW SW Sec. 31, T. 10N., R. 18E.

Petrologic Log





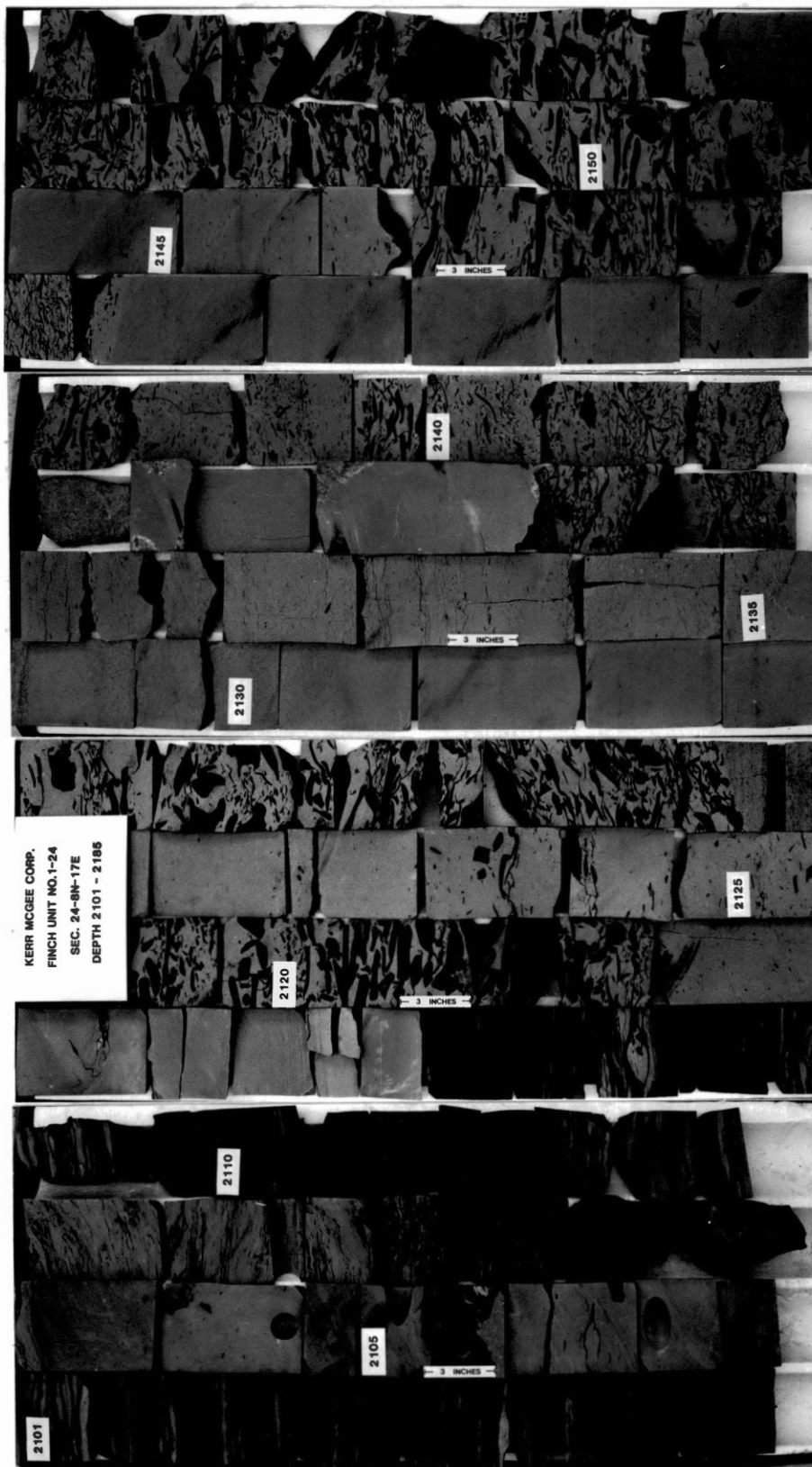


APPENDIX B

COMPOSITE CORE PHOTOGRAPHS

KERR-McGEE CORPORATION

NO. 1 FINCH CORE



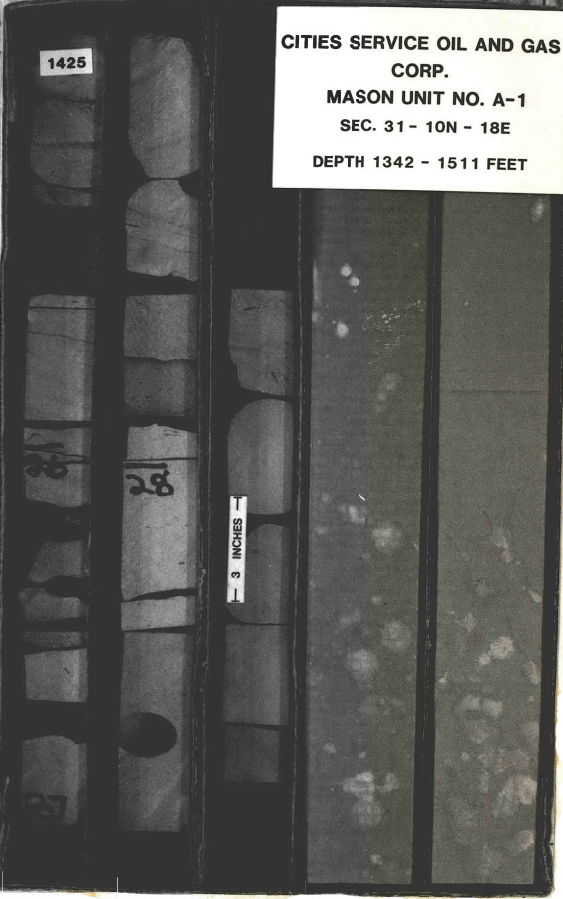
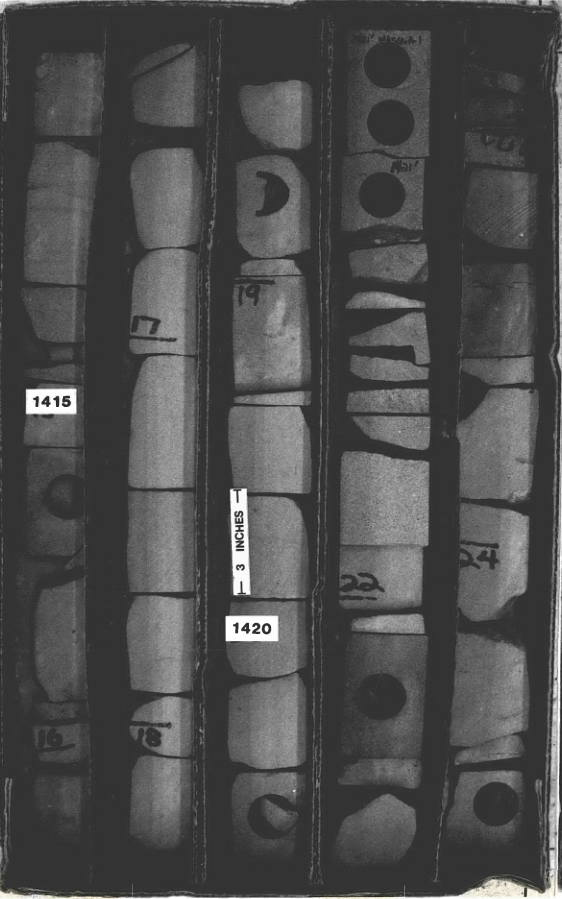
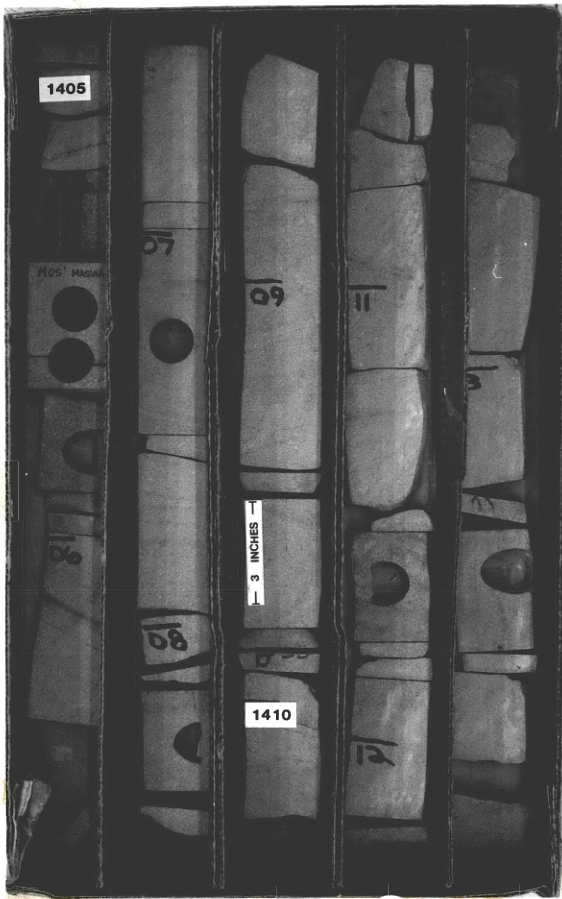


CITIES SERVICE OIL AND GAS CORPORATION

NO. "A"-1 MASON CORE







CITIES SERVICE OIL AND GAS
CORP.
MASON UNIT NO. A-1
SEC. 31 - 10N - 18E
DEPTH 1342 - 1511 FEET

CITIES SERVICE OIL AND GAS
CORP.
MASON UNIT NO. A-1
SEC. 31 - 10N - 18E
DEPTH 1342 - 1511 FEET

1430

3 INCHES

1435

1440

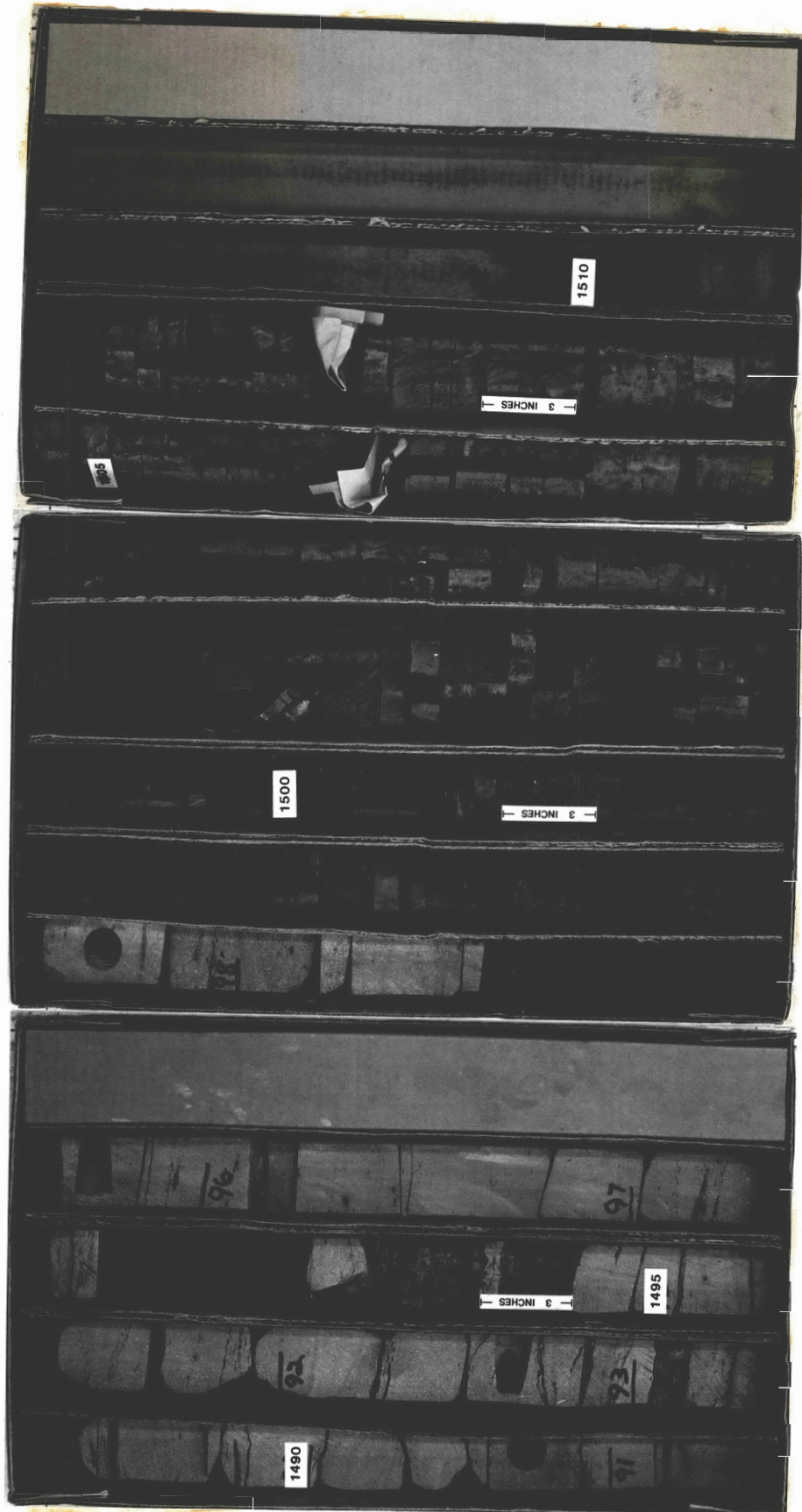
3 INCHES

1445

1455

1460





2
VITA

Perry Merle Fields, III

Candidate for the Degree of

Master of Science

Thesis: SUBSURFACE GEOLOGY OF THE MORROWAN LOWER DORNICK HILLS
(CROMWELL SANDSTONE) AND THE DESMOINESIAN KREBS (HARTSHORNE)
AND LOWER BOOCH SANDSTONES) IN NORTHERN PITTSBURG COUNTY,
OKLAHOMA.

Major Field: Geology

Biographical:

Personal Data: Born in Oklahoma City, Oklahoma, June 26, 1962,
the son of Mr. and Mrs. Perry M. Fields, Jr.

Education: Graduated from Putnam City West High School, Oklahoma
City, Oklahoma, in May, 1980; received the Bachelor of
Science degree in Geology from Oklahoma State University in
December, 1984; completed requirements for the Master of
Science degree at Oklahoma State University in May, 1987,
with a major in Geology.

Professional Experience: Teaching Assistant, Department of
Geology, Oklahoma State University, August, 1986 to
December, 1986. Junior Member of the American Association
of Petroleum Geologists; Member of the Oklahoma City
Geological Society.

2
 OTHA GIMES
 GILCREASE No. 1
 16 - 7N - 12E
 SW SE NW

3
 REGAL PETROLEUM
 STACY No. 1
 35 - 7N - 12E
 NW SE NW

4
 ARKLA EXPLORATION CO.
 HENRY No. 1
 18 - 6N - 13E
 SE NW SE

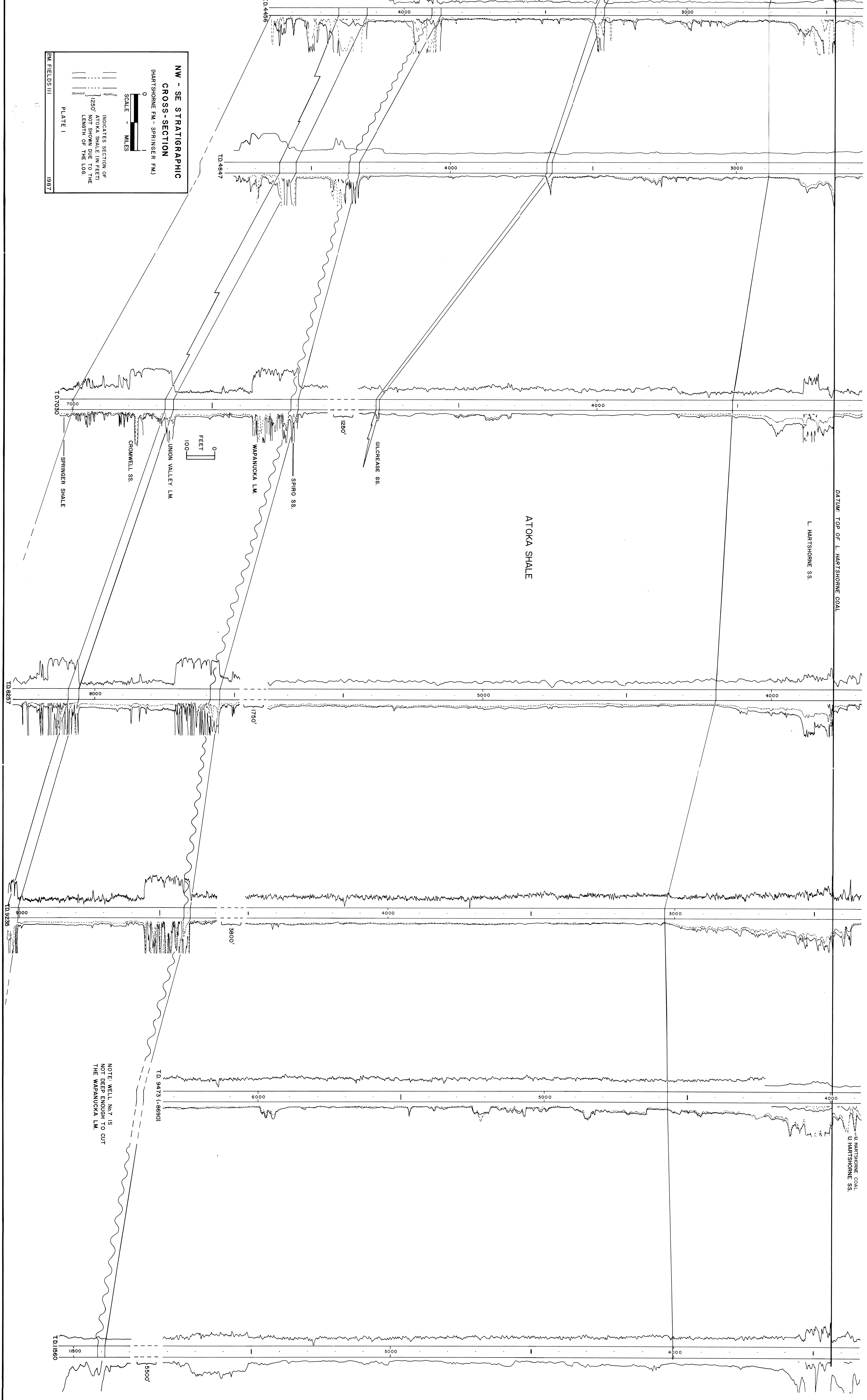
5
 DYCO PETROLEUM CORP
 ENGLEMAN No. 1-36
 36 - 6N - 13E
 NW NW

6
 GULF OIL CORP
 CHOCTAW STATE No. 1-4
 4 - 5N - 14E
 SE

7
 MONSANTO CO.
 SHUMAN No. 1
 23 - 5N - 14E
 SW NE

8
 ARACHE CORP
 GERMAN No. 1
 23 - 5N - 15E
 SW NE

**NW - SE STRATIGRAPHIC
 CROSS-SECTION**
 (HARTSHORNE FM. - SPRINGER FM.)
 SCALE - MILES
 0 1 2
 INDICATES SECTION OF
 WELL NOT SHOWN DUE TO THE
 LENGTH OF THE LOG.
 PLATE I
 RM FIELDS III 1987



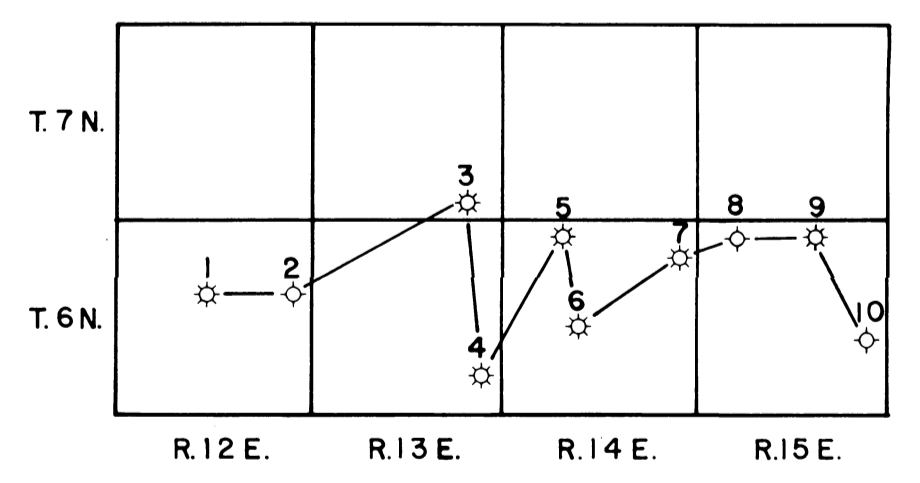
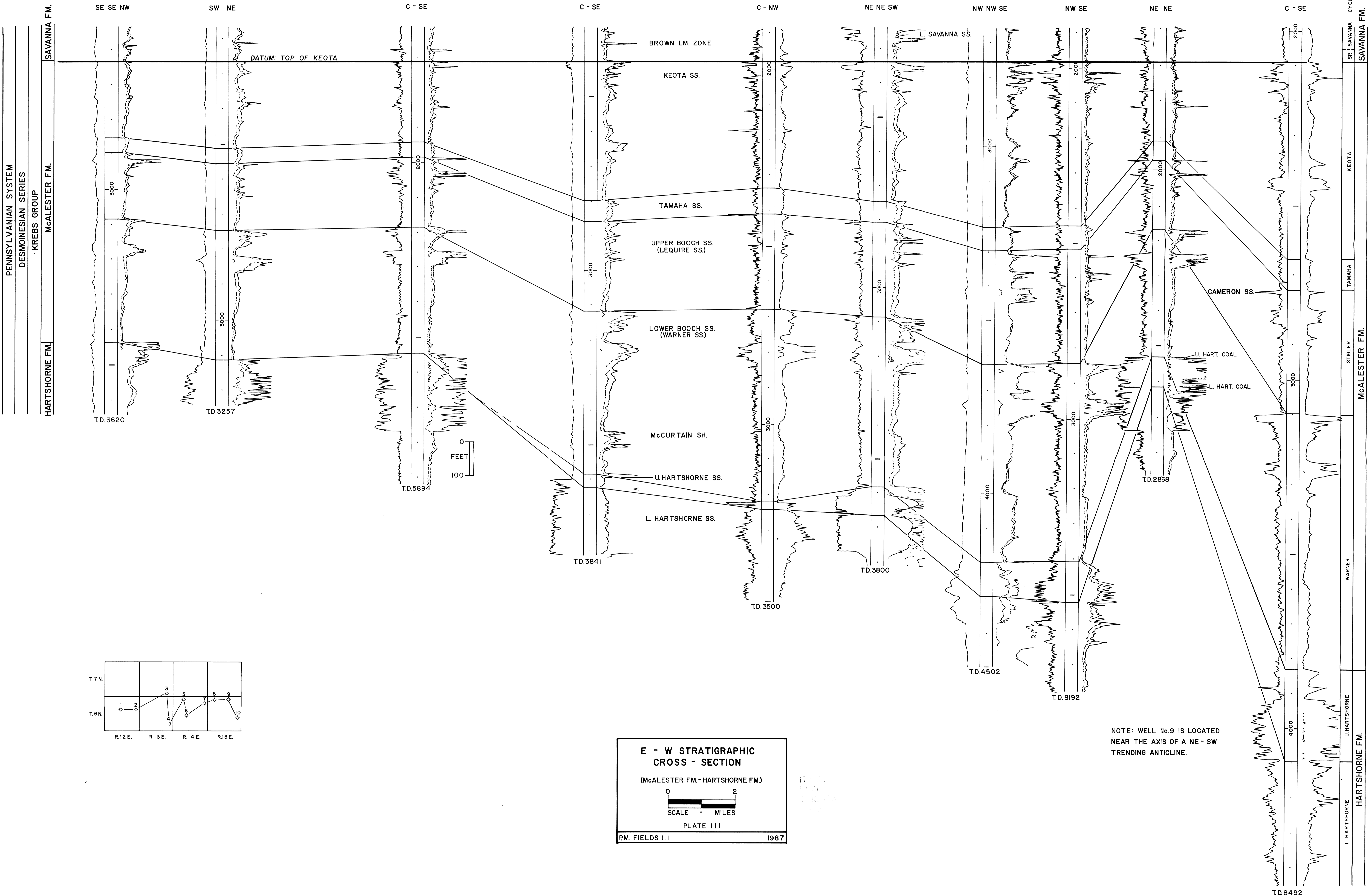
WAPANUCKA FM.	ATOKA FM.	HARTSHORNE FM.
L. DORNICK HILLS GROUP	U. DORNICK HILLS GROUP	KREBS GROUP
MORROWAN SERIES	ATOKA SERIES	DESMOINESIAN SERIES
PENNSYLVANIAN SYSTEM		

SE

W

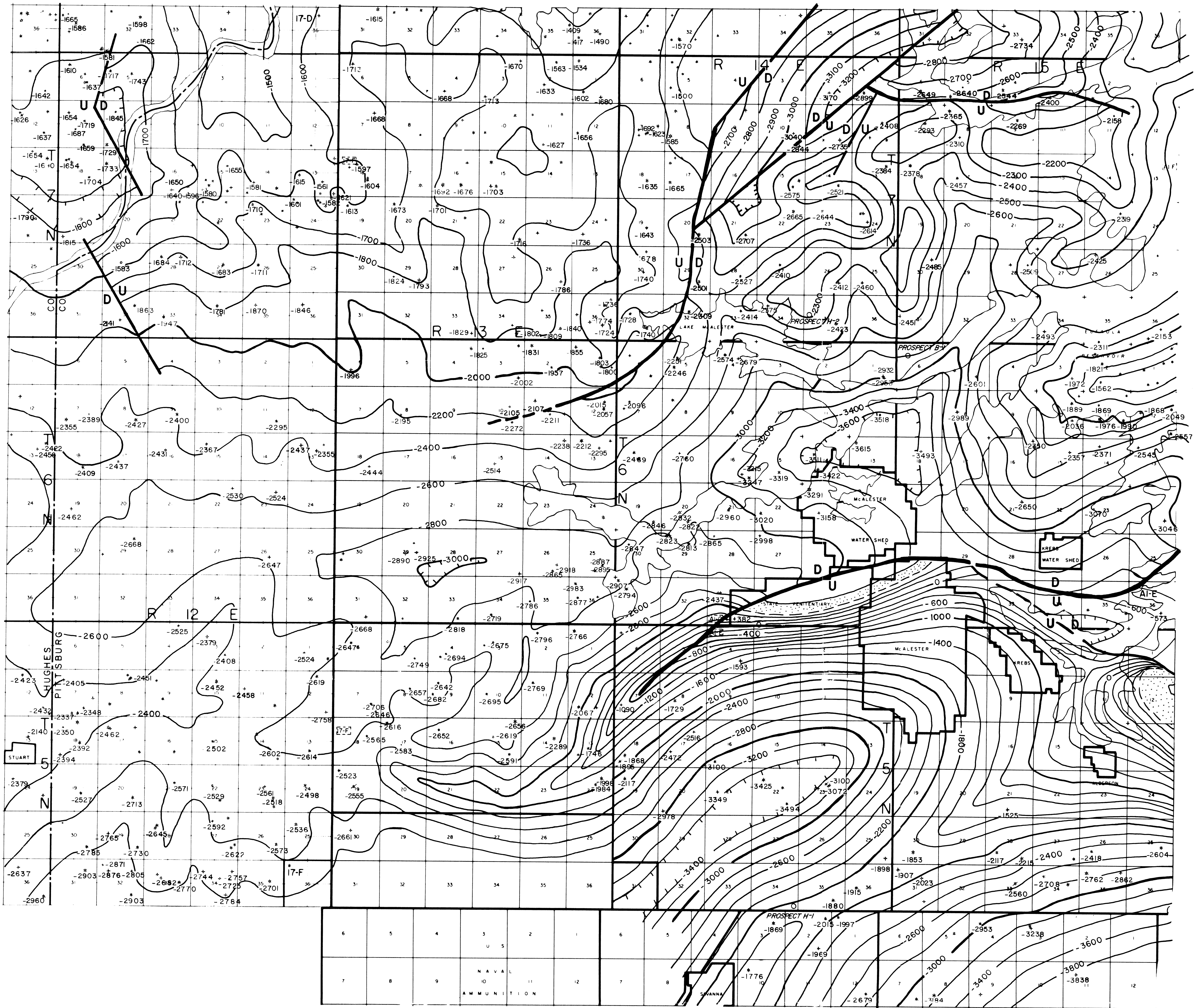
E

- | | | | | | | | | | |
|--|---|--|---|---|--|---|---|--|---|
| 1
REGAL PETROLEUM
HILSWECK No.1
16 - 6N - 12E
SE SE NW | 2
HUMBLE OIL
LEE No.1
13 - 6N - 12E
SW NE | 3
CHEYENNE PETROLEUM CO.
STATE No.1
35 - 7N - 13E
C - SE | 4
NATOL PETR. & SAMEDAN OIL
BLEVINS No.1
25 - 6N - 13E
C - SE | 5
GEODYNE RESOURCES, INC.
WILSON No.1
4 - 6N - 14E
C - NW | 6
SKELLY OIL
COMPELUBE No.1
21 - 6N - 14E
NE NE SW | 7
LEBEN DRLG.
BULLARD No.1
12 - 6N - 14E
NW NW SE | 8
ARKLA EXPL. CO.
BULLARD No.1
5 - 6N - 15E
NW SE | 9
TXO PRCD. CORP.
HOLT 'J' No.1
3 - 6N - 15E
NE NE | 10
OXLEY PETROLEUM CO.
GALLOWAY No.1
24 - 6N - 15E
C - SE |
|--|---|--|---|---|--|---|---|--|---|

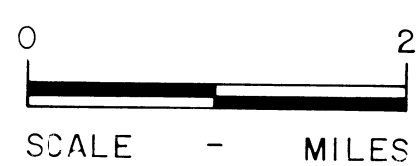


**E - W STRATIGRAPHIC
CROSS - SECTION**
(McALESTER FM. - HARTSHORNE FM.)
SCALE - MILES
PLATE III
P.M. FIELDS III 1987

NOTE: WELL No.9 IS LOCATED
NEAR THE AXIS OF A NE - SW
TRENDING ANTICLINE.



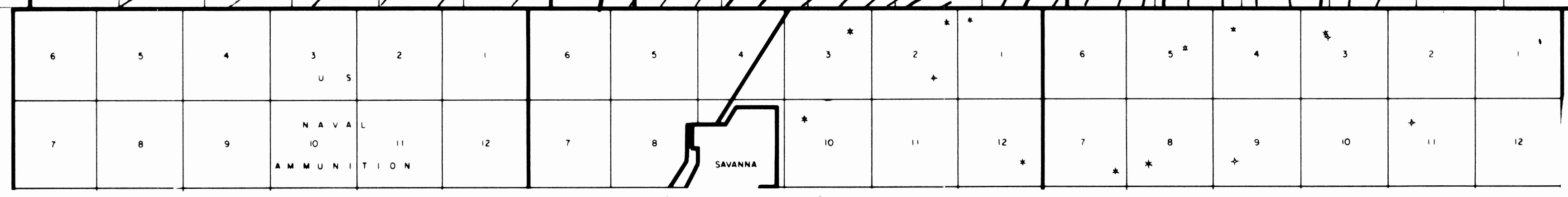
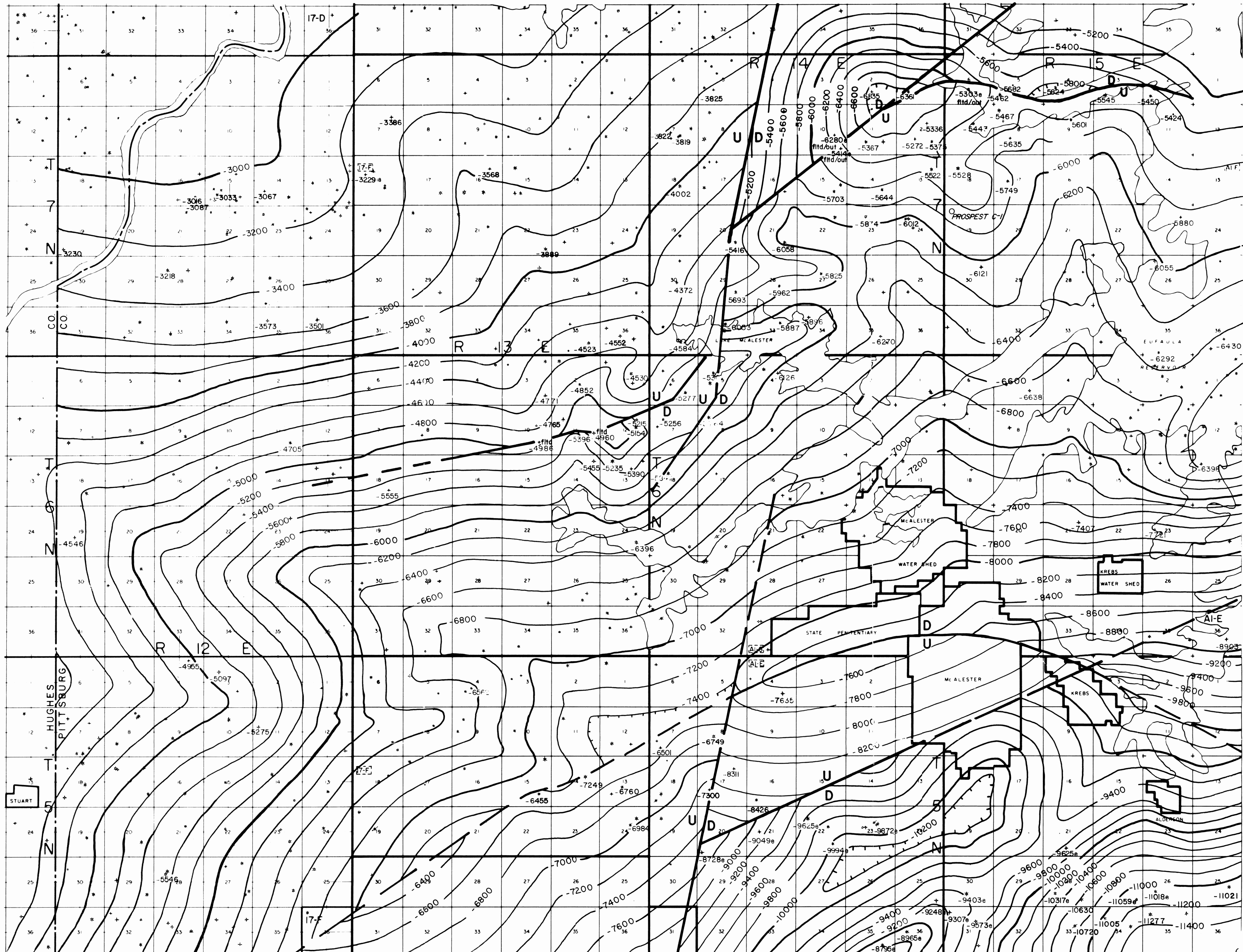
STRUCTURE MAP
ON TOP OF
LOWER HARTSHORNE COAL



C.I. = 200'
C.I. = 100' IN NORTHERN TOWNSHIPS

HARTSHORNE FM. OUTCROP

PLATE IV



STRUCTURE MAP
ON TOP OF
WAPANUCKA LIMESTONE

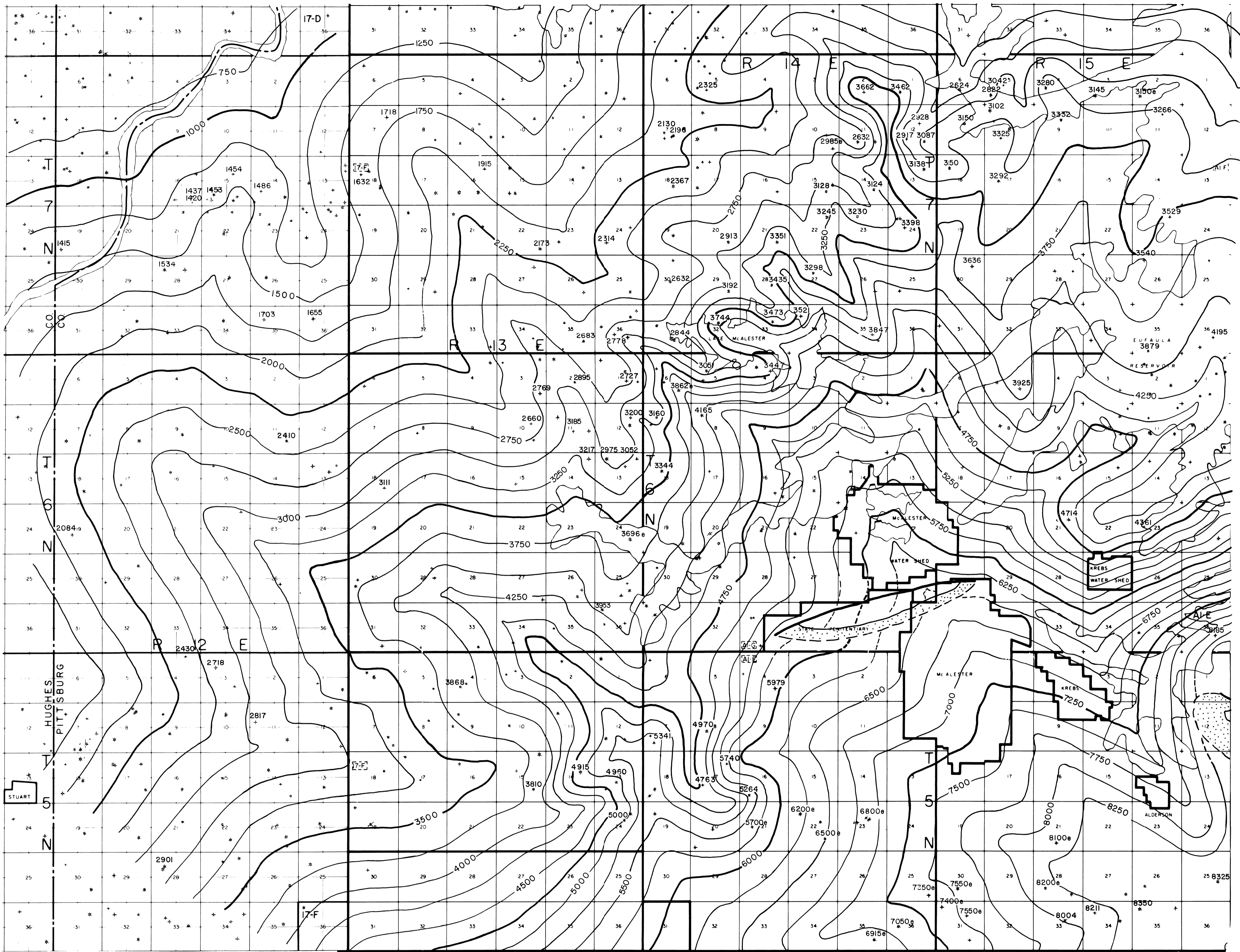
0 2
SCALE - MILES

CI. = 200'

flt'd - WAPANUCKA LIME CUT BY FAULT
e - ESTIMATED STRUCTURE VALUE

PLATE V

PM.FIELDSIII 1987



6	5	4	3	2	1	6	5	4	3	2	1	6	5	4	3	2	1
7	8	9	10	11	12	7	8	9	10	11	12	7	8	9	10	11	12

ISOPACH MAP
OF THE
HARTSHORNE FM. - ATOKA FM.

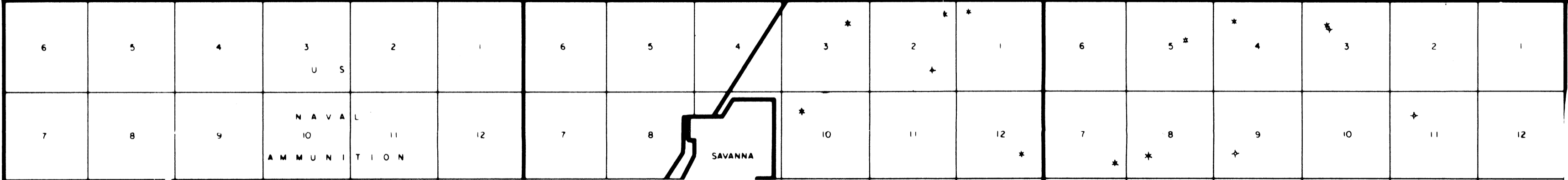
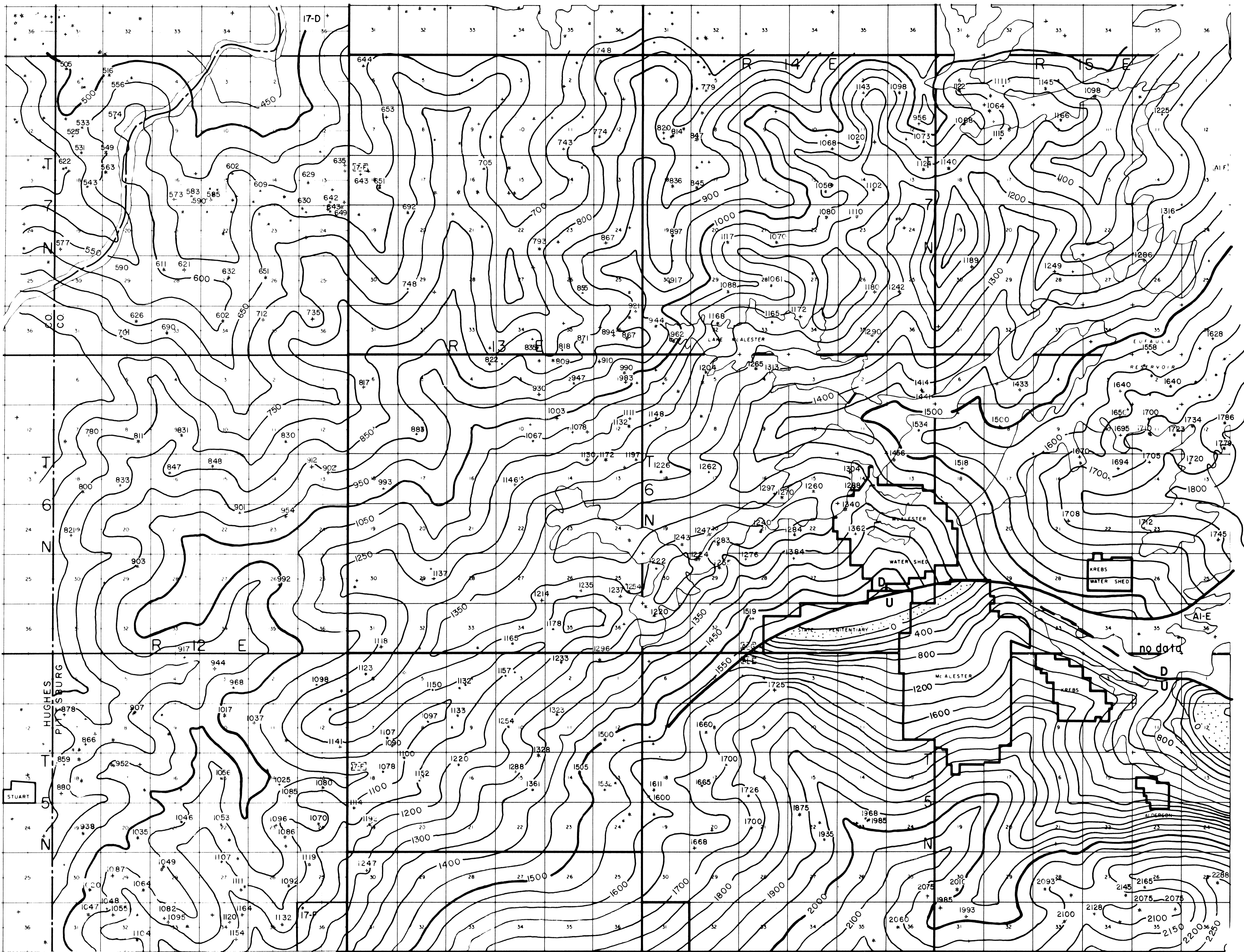
0 2
SCALE - MILES

C.I. = 250'

HARTSHORNE FM. OUTCROP

PLATE VI

PM. FIELDS III 1987



ISOPACH MAP
OF THE
McALESTER FORMATION

0 2
SCALE - MILES

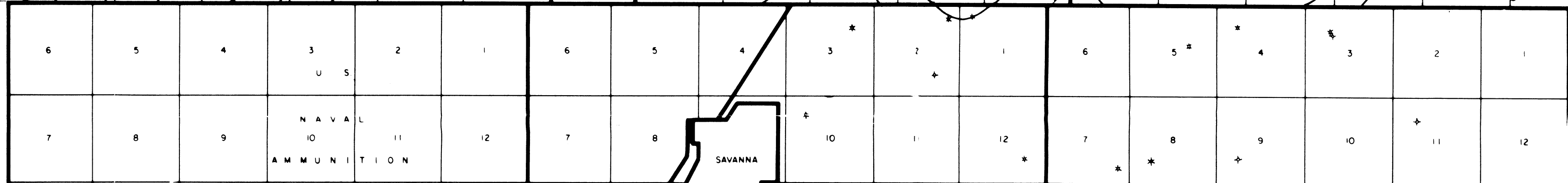
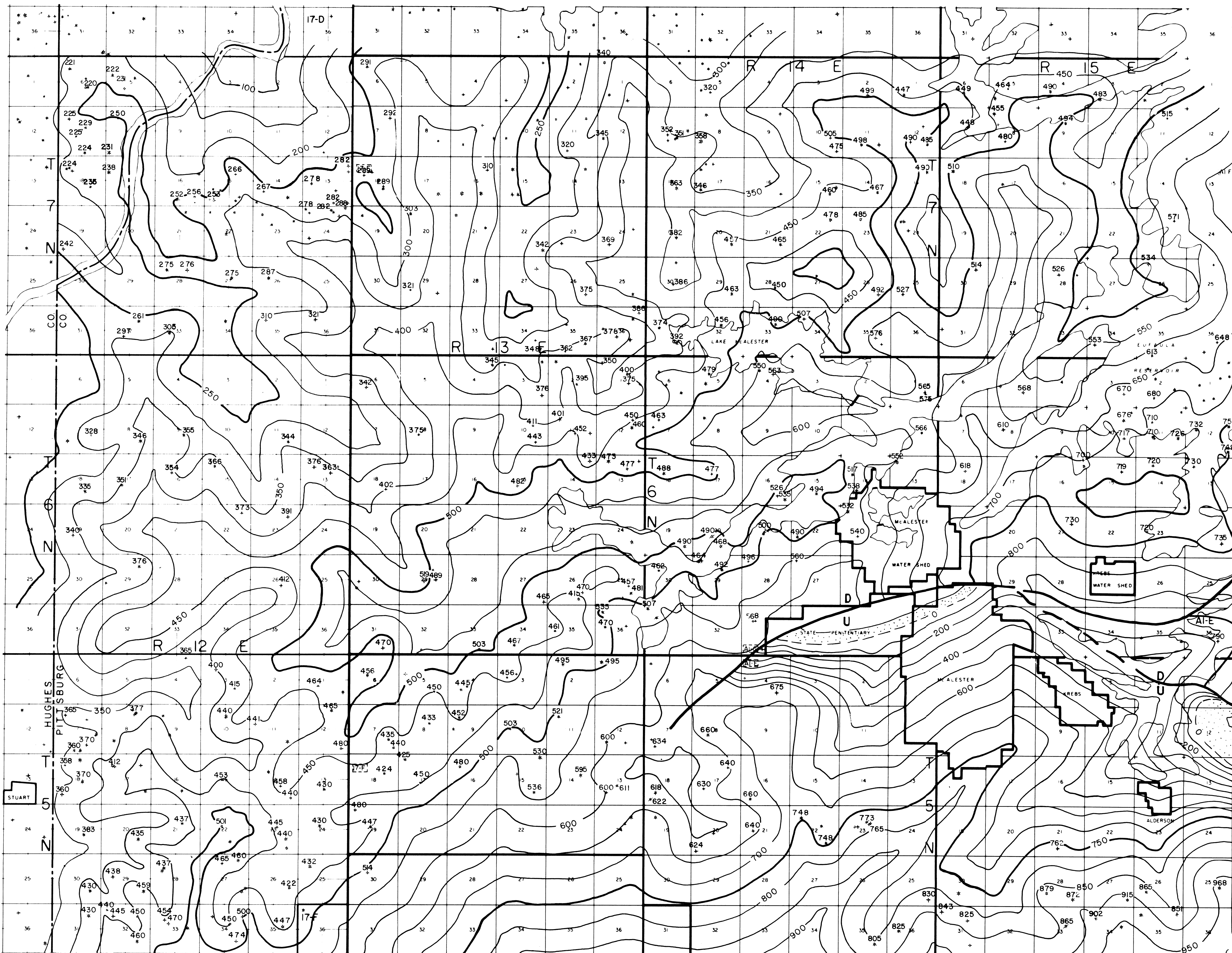
C.I. = 50'
C.I. = 200' BETWEEN 0' AND 1600'
ON THE SOUTH SIDE OF THE
PENITENTIARY FAULT

HARTSHORNE FM. OUTCROP

PLATE VII

PM.FIELDS III 1987

The
11
1420
0.0



ISOPACH MAP
OF THE
WARNER COAL CYCLE

0 2
SCALE - MILES

C.I. = 50'

C.I. = 100' BETWEEN 0' AND 600'

ON THE SOUTH SIDE OF THE
PENITENTIARY FAULT

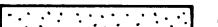
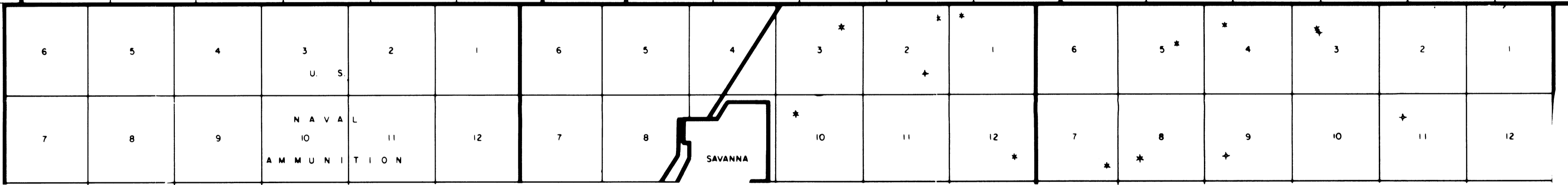
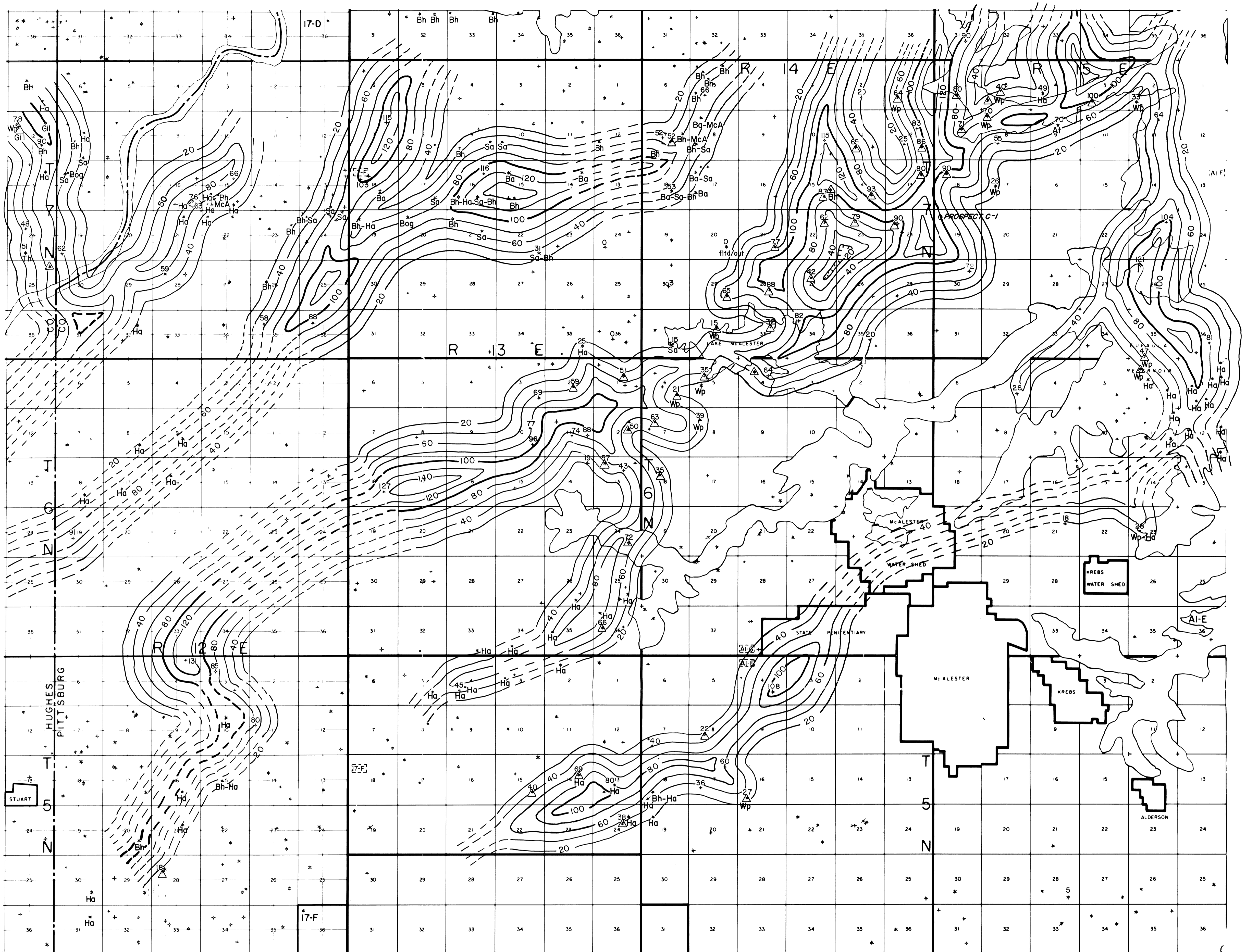
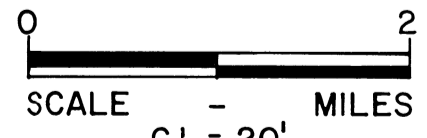
 HARTSHORNE FM. OUTCROP

PLATE VIII

P.M. FIELDS II 1987



**NET SANDSTONE ISOLITH MAP
CROMWELL SANDSTONE**



C.I. = 20'
CONTOUR LINES DASHED WHERE SAND THICKNESS IS INFERRED

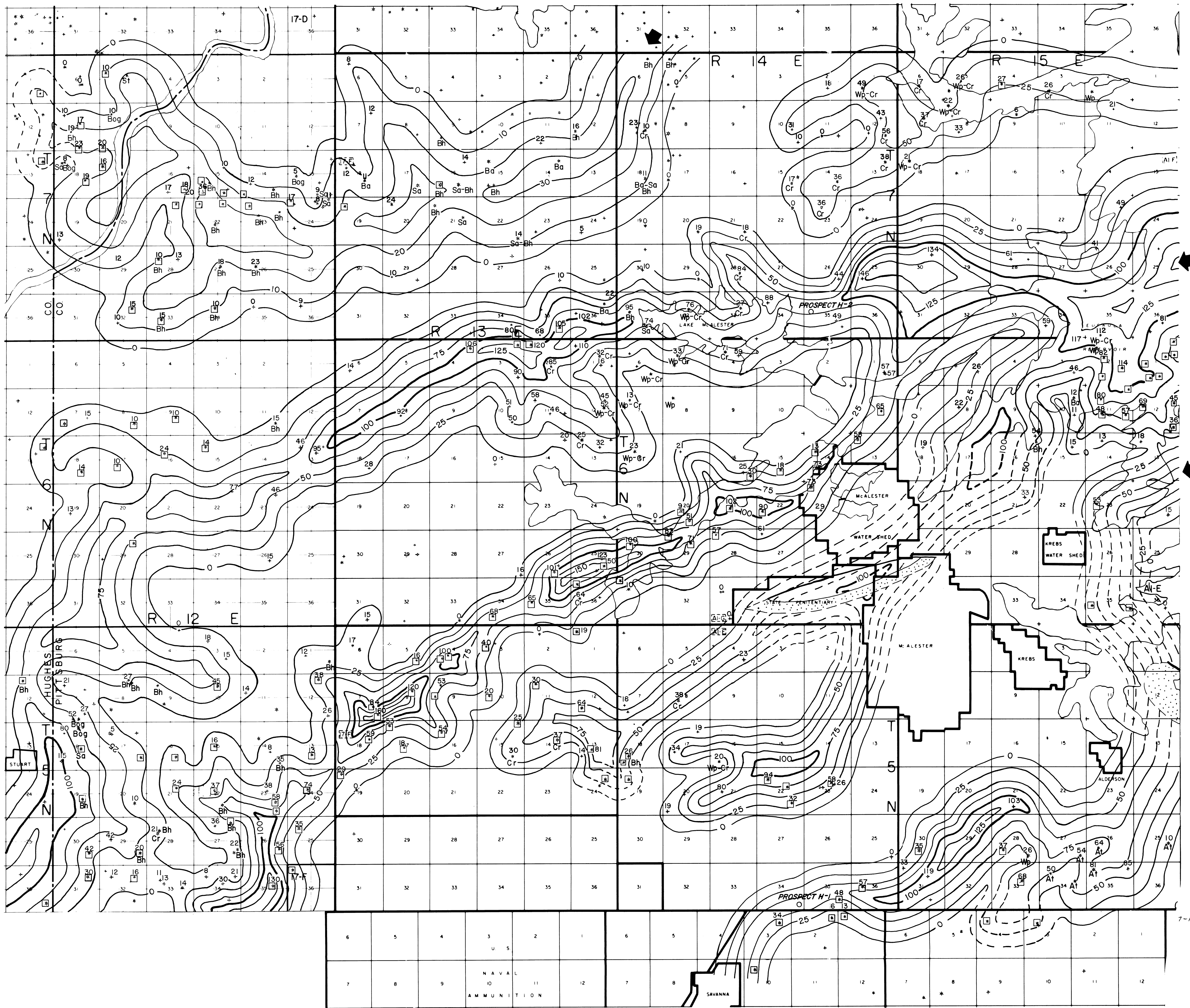
THURMAN -	Th	BOOCH -	Bh
BOGGY -	Bog	HARTSHORNE -	Ha
BARTLESVILLE -	Ba	ATOKA -	At
SAVANNA -	Sa	GILCREASE -	Gil
McALESTER	McA	WAPANUCKA -	Wp
		CROMWELL -	Cr

PLATE IX

P.M. FIELDSIII

1987

Handwritten notes:
M-1
F402
COP 2



NET SANDSTONE ISOLITH MAP
LOWER HARTSHORNE SANDSTONE

0 2
SCALE - MILES

*Thesis
with
figures
cp. 2*

C.I. = 25'
CONTOUR LINES DASHED WHERE SAND THICKNESS IS INFERRED

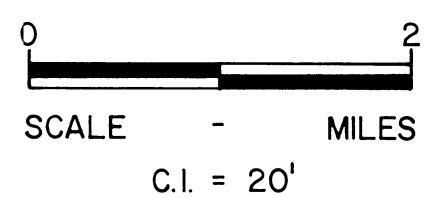
PRODUCTION
BOGGY - Bog L. HARTSHORNE SS. - □
BARTLESVILLE - Ba ATOKA - At
SAVANNA - Sa WAPANUCKA - Wp
BOOCH - Bh CROMWELL - Cr

HARTSHORNE FM. OUTCROP

PLATE X



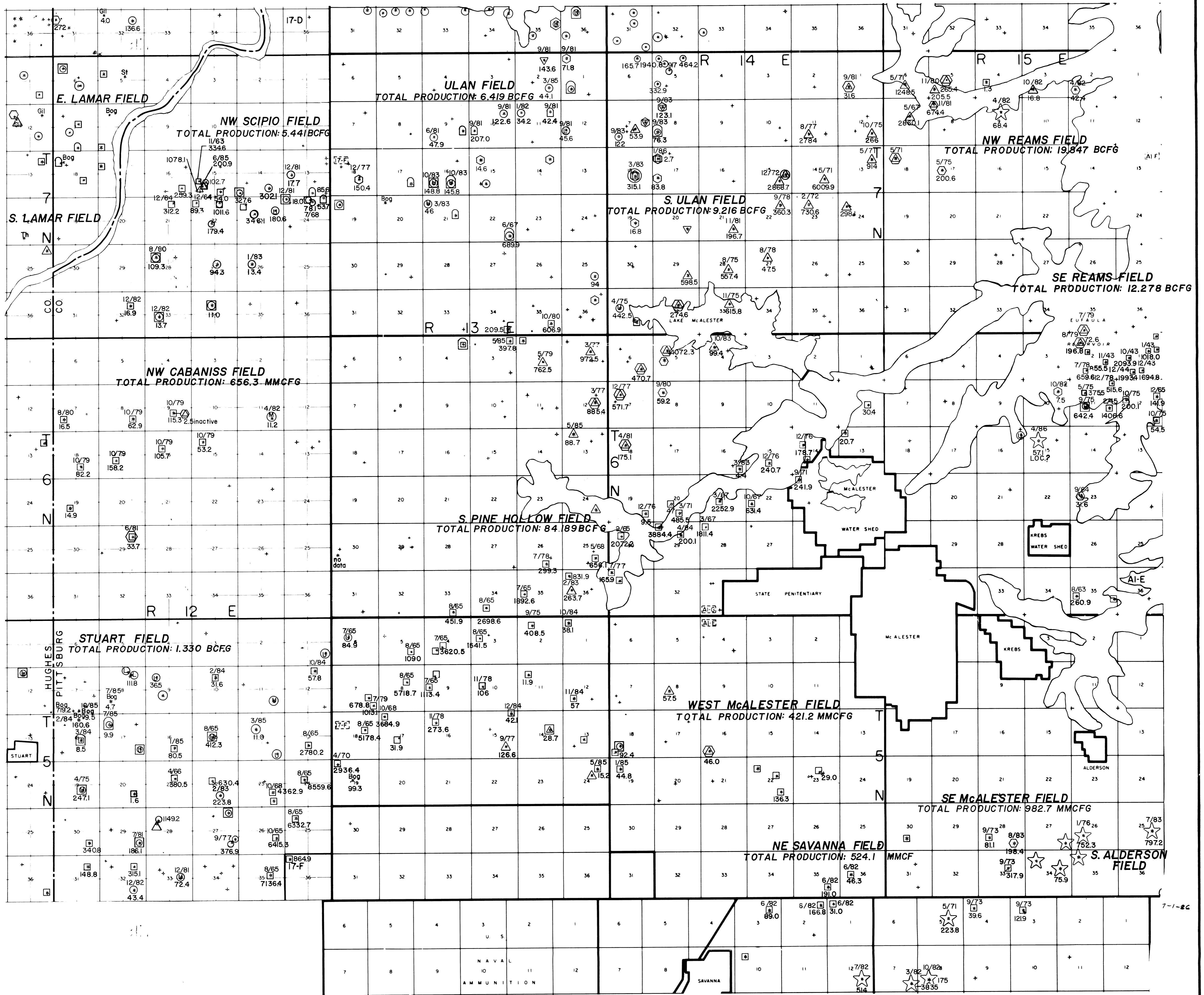
NET SANDSTONE ISOLITH MAP
UPPER HARTSHORNE SANDSTONE



*THIS IS
H31
IN THE
COPY*

BOGGY-	Bog	L. HARTSHORNE SS. -	L.Ha
BARTLESVILLE-	Ba	ATOKA -	At
BOOCH-	Bh	WAPANUCKA -	Wp
U. HARTSHORNE SS. -	□	CROMWELL -	Cr
	▨	HARTSHORNE FM. OUTCROP	

PLATE XI



GAS PRODUCTION
CUMULATIVE PRODUCTION IN MMCF AS OF 6-1-86

STUART - St	HARTSHORNE - □
THURMAN - Th	ATOKA - ☆
BOGGY - Bog	GILCREASE - Gil
BARTLESVILLE - B	SPIRO - } ○
SAVANNA - S	WAPANUCKA - } ○
BOOCH - O	CROMWELL - △

DATE OF FIRST PRODUCTION GIVEN FOR ACTIVE WELLS

0 2
SCALE - MILES
PLATE XIII

PM. FIELDS III 1987