SUBSURFACE GEOLOGY OF THE MORROWAN LOWER DORNICK HILLS (CROMWELL SANDSTONE) IN SOUTHERN HUGHES COUNTY, OKLAHOMA

By

REX DAVID STOUT

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DORNICK HILLS (CROMWELL SANDSTONE)

IN SOUTHERN HUGHES

COUNTY, OKLAHOMA

Thesis Approved:

Arthur W. Cleaves, II

Thesis Advisor

Dean of the Graduate College

Thomas C. Collins

PREFACE

This thesis is a study of the subsurface geology of the Morrowan Lower Dornick Hills (Cromwell Sandstone) in six townships of southern Hughes County, Oklahoma.

Dr. Arthur Cleaves served as thesis advisor. I am grateful to the committee members, Dr. Zuhair Al-Shaieb and Dr. Gary F. Stewart for their sincere interest, encouragement, and invaluable guidance and suggestions during the course of this work.

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Appreciation is expressed to the following individuals: Mr. Lanny Woods of Samson Resources Company, for providing information on Hughes County, Oklahoma and interpretations of structural geology; Mr. Jeff Miller of Mitchell Energy Corporation, for providing interpretations of structural geology; and Dr. John Shelton of Masera Corporation, for assisting in interpretation of cores.

Special thanks are due my parents, Mr. and Mrs. Ira L. Stout, for their undivided interest, understanding, and support throughout all my endeavors.

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CHAPTER I

ABSTRACT

In the subsurface of the Arkoma basin of southern Hughes County, Oklahoma, the Morrowan Union Valley Formation consists of two formal members; in ascending order these are the Cromwell Sandstone Member and the Union Valley Limestone Member. Locally, an informal member is present, the Jefferson Sandstone. In the area investigated, the Union Valley Formation mostly is composed of sandstones of the Cromwell Member.

Stratigraphic cross-sections, cores, thin sections, isopach maps, and isolith maps were employed to map the distribution of the formation and to reconstruct the depositional setting.

The Union Valley accumulated in shallow marine environments on the Arkoma shelf. Depositional patterns appear to have been influenced by syndepositional tectonism.

The Union Valley Formation produces oil and gas primarily from structural traps developed on anticlines and fault blocks, and from structural-stratigraphic traps.

CHAPTER II

INTRODUCTION

Location of Study

The Cromwell Sandstone Member of the Morrowan Union Valley Formation is a major source of hydrocarbons in the Arkoma Basin. In the course of this study, subsurface geology of the Union Valley Formation was examined in part of the Arkoma Basin, Oklahoma. The area of investigation is in southern Hughes County, Oklahoma; it includes six townships (T. 4-5 N., R. 9-11 E.), an area of about 216 square miles (Figure 1).

Objectives

The principal objectives of this study included:

1. Division and correlation of Upper Mississippian and Lower Pennsylvanian strata by means of stratigraphic electric-log cross-sections.
2. Recognition of major depositional enviroments of the Union Valley Formation, as made evident from examination of cores and from sand-body geometry, the

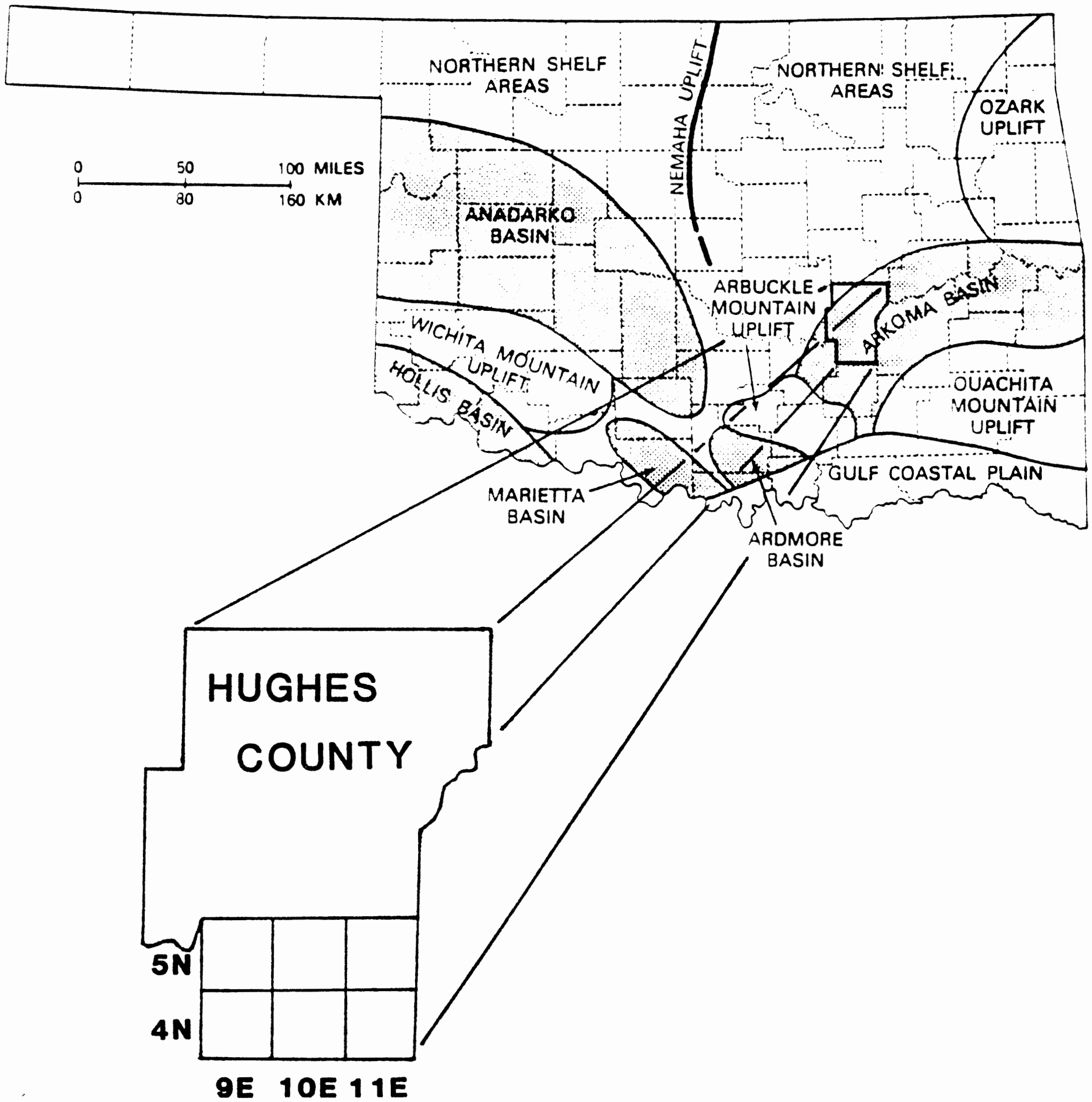


Figure 1. Location Map of Study Area.

latter illustrated by subsurface maps and cross-sections.

3. Reconstruction and integration of regional tectonic and depositional histories of the western Arkoma Basin.
4. Preparation of a structural contour map of the top of the Wapanucka Limestone, to demonstrate local folds and faults.
5. Documentation of hydrocarbon-trapping mechanisms, and productivity of Union Valley-Cromwell oil and gas fields within the study area.
6. Description of the general diagenetic overprints as shown by thin sections of the Union Valley Formation, obtained from conventional whole cores.

Methods of Investigation

Subsurface information was obtained from electrical well logs, compensated neutron-formation density logs, gamma ray logs, sonic logs, thermal neutron decay logs, scout tickets, Herndon Maps, and proprietary seismic data.

Seven stratigraphic electric log cross-sections were constructed to illustrate vertical and lateral facies relationships of Upper Mississippian through Lower Pennsylvanian strata (Plates 3,4, and 5). A structural contour map (Plate 1) was prepared of the top of the Wapanucka Limestone, a regional marker horizon, to illustrate subsurface structural features in the study area.

The stratigraphic section of principal interest in this study was divided into three format units for correlation and mapping. Regional stratigraphy of Upper Mississippian through Lower Pennsylvanian strata is illustrated in Figure 2. Format units, as defined in the subsurface of the study area are illustrated with the aid of a 'type' electric log (Figure 3). One interval isopach map (Plate 6) illustrates variation in thickness of the Union Valley format unit. A gross sandstone isolith map of the Union Valley Limestone-Cromwell Sandstone interval (Plate 7) demonstrates interval geometry. This map also aided in interpretation of a paleodepositional setting and entrapment of petroleum. Because most wells were drilled under influence of local structural geology, the irregular distribution of records hampers the mapping of individual sandstone bodies at numerous places.

Six cores from the Union Valley Formation were examined for description of sedimentary structures, texture, and lithology. Cores were calibrated with applicable geophysical logs where possible and were described on petrologic log forms (Appendix A). Each core was sampled for thin-section and x-ray diffraction analysis.

Thirty thin sections were examined for varieties and relative amounts of detrital and authigenic constituents, and types of porosity. Standard petrographic methods and criteria were employed in delination of paragenetic histories.

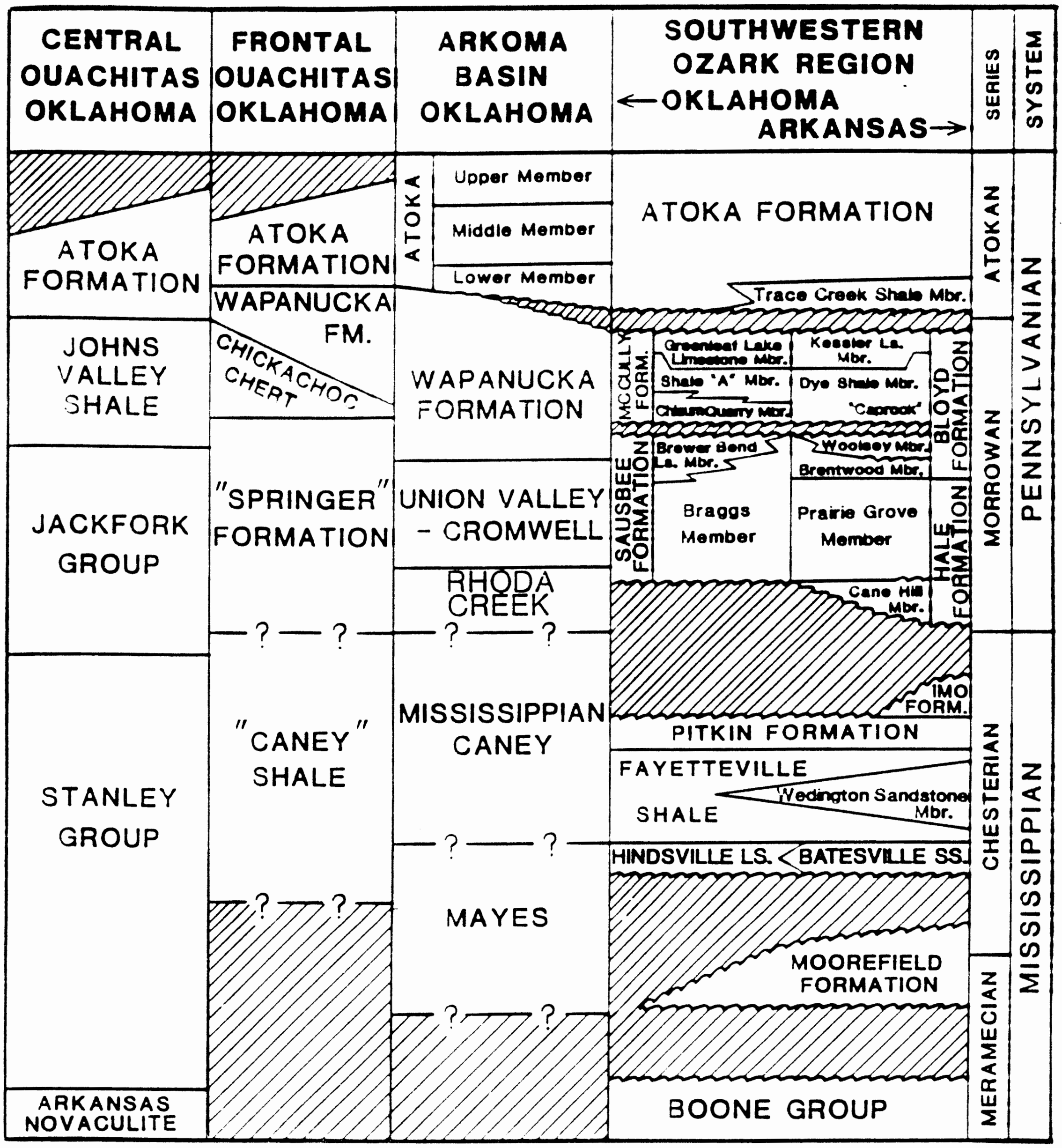


Figure 2. Regional Upper Mississippian and Lower Pennsylvanian Stratigraphy (modified from Sutherland, 1988b, p.333).

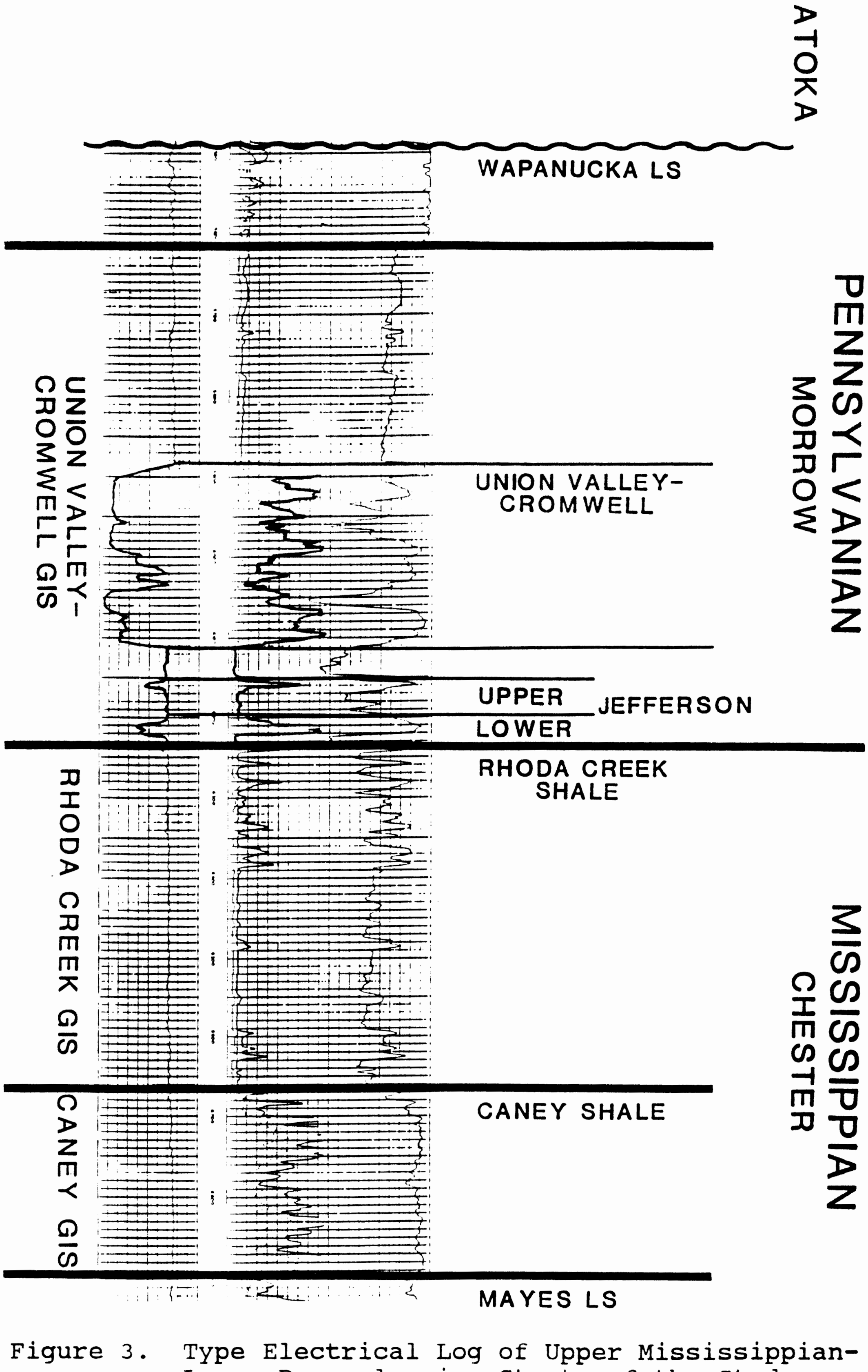


Figure 3. Type Electrical Log of Upper Mississippian-Lower Pennsylvanian Strata of the Study Area.

Thin sections were stained with Alizarin Red to aid in differentiation between calcite and dolomite cements. X-ray diffraction was performed on powdered rock samples from rocks where thin-section samples were collected. Diffraction analysis from 2-35 degrees 2θ was conducted in order to supplement thin section mineral identification. Clay fractions of selected samples were analysed in natural, heated, and glycolated states from 2-15 degrees 2θ.

The petroleum geology of the Union Valley Formation was investigated in part with the preparation of a production code map (Plate 8). Production statistics were obtained from Petroleum Information and Dwights production reports. Probable trapping mechanisms in fields where the Union Valley produces were described. Structural contour and cross-sections assisted in evaluation of trapping mechanisms in the Union Valley. Additional stratigraphic cross-sections were useful in delination of syndepositional tectonic events and reservoir distribution.

Previous Investigations

Several studies in the south-central and Arkoma Basin regions of Oklahoma have concerned regional stratigraphy of Paleozoic strata, specifically Upper Mississippian and Pennsylvanian rocks. The primary focus of early studies concerned coal bed stratigraphy of the McAlester Coal Basin.

Among these are works by Drake (1897), Taff and Adams (1900), and Taff (1901). Shannon and Trout (1915) conducted one of the earliest studies concerning petroleum geology.

The first published comprehensive analysis of Pennsylvanian stratigraphy in the Arkoma Basin was that of Hendricks and others (1936). Harlton (1938) discussed the stratigraphy of "Bendian" rocks of the Oklahoma portion of the Ouachita Mountains and their correlation with age equivalent rock units in other states. Dott (1941) wrote about regional stratigraphy of the Mid-Continent region. Barker (1951) examined Upper Mississippian through Lower Pennsylvanian strata exposed on the Lawrence Uplift in Pontotoc County, Oklahoma. Elias (1956) studied the stratigraphy of Upper Mississippian and Lower Pennsylvanian sedimentary rocks in south-central Oklahoma. Elias' study is significant in view of his revision of stratigraphic nomenclature.

Kuhleman (1951) examined the surface exposures of Mississippian-and Pennsylvanian-aged strata in the Stonewall and Atoka Quadrangles of south-central Oklahoma. Laudon (1958) described the subsurface geology of Upper Mississippian and Lower Pennsylvanian rocks in the McAlester (Arkoma) Basin of Oklahoma. Laudon utilized wells located in the present study area for the construction of regional cross-sections in addition to regional isopach and structure maps.

Bellis (1961) studied the general stratigraphy of pre-Desmoinesian rocks of south-central Oklahoma. The Arkoma Basin Study Group (i.e. Tulsa Geological Society) published a comprehensive account of the Arkoma Basin, the Albert Nelson Murray Memorial Volume, in 1961. Frezon (1962) examined Paleozoic rocks in the Arkoma Basin, illustrated by means of a stratigraphic cross-section, including some wells in the current study area, in a regional study extending from Coal County, Oklahoma eastward to Sebastian County, Arkansas.

Visher and others (1971) employed the concept of format units in subdivision of Mississippian and Pennsylvanian strata in eastern Oklahoma. A stratigraphic cross-section ("Cherokee Group Cross-section") illustrating these format units extends into the study area. This cross-section, in conjunction with the cross-sections of Laudon (1958) and Frezon (1962), provided a basis for the initial subdivision of the subsurface stratigraphic section of interest in the study area. Frezon and Dixon (1975) investigated the Pennsylvanian System as a part of a regional paleotectonic analysis throughout the Oklahoma and Texas Panhandle regions. This study included subcrop, whole-interval-isopach, and lithofacies maps. Sutherland and Henry (1979) examined Morrowan strata in northeast Oklahoma and suggested that the rocks represented various shallow marine environments of depositon.

Fay et al. (1979) conducted a regional study of the Mississippian and Pennsylvanian Systems in Oklahoma. Sutherland and Manger (1979) examined the broad shelf-to-basin transition from the Ozark to Ouachita regions. Frezon and Jordan (1979) examined the Mississippian System throughout Oklahoma.

Sutherland and others (1982) described exposures of Morrowan and Atokan strata in the Arbuckle Mountain area. Houseknecht (1983) published a concise discussion of the tectonic and stratigraphic framework of the Arkoma Basin. Rascoe and Adler (1983) documented the regional occurrence of hydrocarbons, as well as the Late Paleozoic structural-stratigraphic framework, of the Mid-continent region. Sutherland (1988a, 1988b) investigated the Late Mississippian and Pennsylvanian tectono-depositional evolution of the Arkoma Basin. Grayson (1990) described conodont successions of Upper Devonian-through Pennsylvanian strata exposed in Pontotoc County.

Studies of the Union Valley Formation in Hughes County are sparse, with the majority of studies to date concentrating on Morrowan rocks of the region located in Pontotoc, Seminole, and Okfuskee Counties. Hollingsworth (1933) conducted an examination of surface exposures in Ponotoc County. Miller and Owen (1944) described the cephalopod fauna of the Union Valley Formation on the Lawrence Uplift. Fitts (1951) and Duck (1959) described Cromwell Sandstone occurrences in Seminole County. Quinn

(1962) investigated the Union Valley cephalopod fauna. Withrow (1968) documented the subsurface geology of the Cromwell in the Franks Graben of Pontotoc and Coal Counties. Wilshire (1971) conducted a field study of the Cromwell in the Northwest Citra Field, in the present study area. Anderson (1975) documented the petroleum geology of the Cromwell Sandstone in the Centrahoma Field, Coal County. Cockrell (1985) examined the subsurface geology of the Union Valley in portions of Okfuskee and Seminole Counties. Jefferies (1982) examined the stratigraphy and geometry of the Union Valley over a large area of the Arkoma Basin in eastern Oklahoma. Busby (1983, 1986) described stratigraphic relationships of the Union Valley in the subsurface in portions of Okfuskee County. Fields (1987) examined the geometry and petroleum geology of the Cromwell in Pittsburg County.

CHAPTER III

STRATIGRAPHY

Introduction

Upper Mississippian strata in the Oklahoma portion of the Arkoma Basin are included in the Chesteran Series with the Lower and Middle Pennsylvanian strata divided into the Morrowan, Atokan, and Desmoinesian Series (Table 1). This study examines the stratigraphy of the Union Valley Formation, deposited during the Early Pennsylvanian, and its relationship with the underlying Mississippian strata.

Upper Mississippian Series

Chester Series

A consensus regarding the subsurface relationship of Lower Pennsylvanian sedimentary rocks with those of the underlying Mississippian is not discernible in the geologic literature about the Arkoma Basin. An understanding of past and current ideas regarding this relation should provide valuable insight into the delineation and examination of

TABLE I

UPPER MISSISSIPPIAN AND LOWER PENNSYLVANIAN STRATIGRAPHY

Atokan Series	U. Dornick Hills Group	Atoka Fm.
Morrowan Series	L. Dornick Hills Group	Wapanucka Fm. Union Valley Fm.
Chesterian Series		Rhoda Creek Fm. Caney Sh.

basal Pennsylvanian sedimentary rocks in the study area. Upper Mississippian strata in the basin include the Caney Shale and the Rhoda Creek Formation of the Chesteran Series.

The Chesteran Series underlies the Pennsylvanian System throughout southern Hughes County, as demonstrated in Figure 4. Chesteran strata in the study area can be characterized as carbonate rocks in the lower portions and silty shales and sandy shale in the upper portions. The Meramecian Mayes Limestone is gradational with the overlying Chesteran Caney Shale (Levorsen, 1930; Boyd, 1938). Selk (1949) described the Mayes as brown silty limestone.

<u>Caney Shale</u>

By the mid 1920's it was realized that the Caney Shale as defined by Taff (1901), comprised a sequence of shales which contained fauna of both Mississippian and Pennsylvanian affinities. Subsequently, numerous modifications of varying merit have been made regarding classification of this stratigraphic interval. The informal designations of "Penn Caney" and "Mississippian Caney" arose in reference to the upper and lower portions of the Caney Shale, as originally defined by Taff (Elias and Branson, 1959). This informal subdivision somewhat alleviated the problems inherent within the original designation.

General usage has resulted in the restriction of the term "Caney" to those shales referred to as "Mississippian

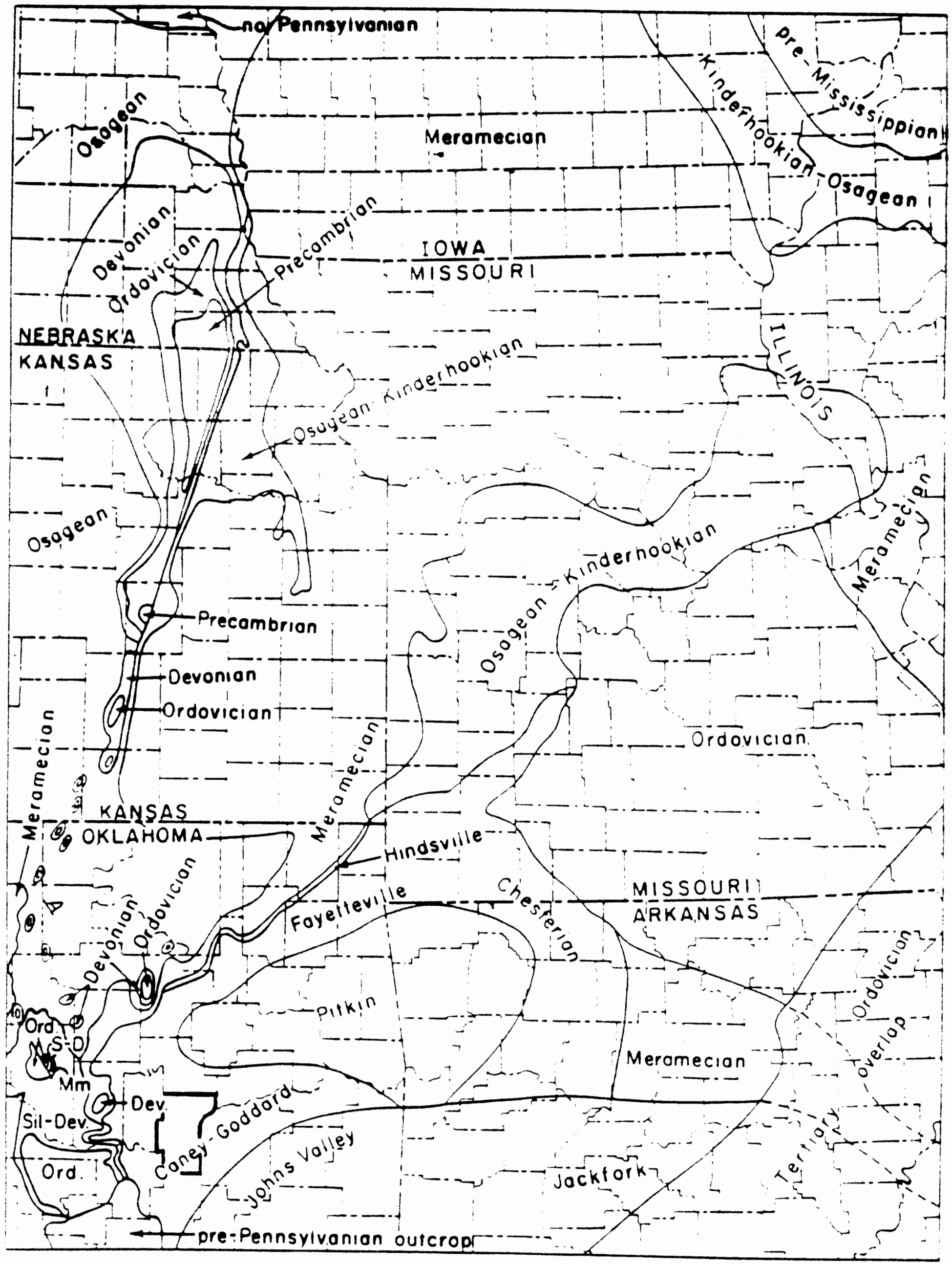


Figure 4. Regional Pre-Pennsylvanian Subcrop Map (modified from Branson, 1961a, p.181).

Caney," as proposed by Ulrich (1927), Miser (1934), and Westheimer (1956). The Caney Shale of this study is equivalent to those shales referred to as "Mississppian Caney". Elias (1956) divided the Caney Shale into three members, the Ahlosa, Delaware, and Sand Branch, based on exposures in the Lawrence Uplift. Westheimer (1956) correlated the upper portions of the Caney with those of the Goddard Shale of Johnston County, Oklahoma.

The Caney Shale is generally brown to black, blocky, and it is increasingly calcareous as it grades into the underlying Mayes Limestone (Dannenburg, 1952). Boyd (1938) noted that the top of the Caney is marked by a glauconite-rich stratum and that it is unsuited for use as a structural horizon. Because the Caney is calcareous, a high-resistivity wireline-log response is characteristic (Westheimer, 1956). This diagnostic log response was utilized by Frezon (1962) in the delination of the lithic boundary of the Caney Shale with that of overlying strata in the Arkoma Basin. The contact of the Caney and the overlying Rhoda Creek Formation has no time-stratigraphic connotations; it is a practical means of dividing the Chesteran stratigraphic succession of the Arkoma Basin.

Rhoda Creek Formation

The Rhoda Creek Formation was defined by Elias (1956) as including shales previously referred to as "Penn Caney" or "Springer" and was included in the Springeran Series. The Springer Formation was defined by Goldston (1922); the type locality is in Carter County and it contains the Mississippian-Pennsylvanian boundary, as noted by Frezon and Dixon (1975).

Laudon (1958) proposed to replace the term "Penn Caney" with that of the Goddard Shale. Laudon considered the Goddard and "Penn Caney" to constitute a single formation, with the Goddard being similar in both lithology and stratigraphic position to the "Penn Caney". The term "Goddard" has not gained widespread acceptance among geologists.

Saunders (1973) determined that Springer terminology should be restricted to the type locality, as it partially replicated designated Chester and Morrowan type sections. Grayson (1990, p.89) stated "Extension of Springer from its type area (Ardmore Basin) to the Arkoma Basin is not accepted, owing to marked lithologic differences in the local successions and indeterminable lack of lateral continuity", nonetheless Springer terminology remains in widespread use.

The Rhoda Creek Formation has undergone modification from Elias' original designation. As originally defined, the Rhoda Creek was a formation in the Springeran Series, and was separated from the overlying Morrowan Series by an unnamed shale interval and from the underlying Caney Shale by an unconformity (Elias, 1956). Work by Saunders (1973) extended the Rhoda Creek boundary upward to the base of the Union Valley Formation, thereby including the previously unnamed shale interval. The underlying Caney Shale was determined to be conformable with the Rhoda Creek.

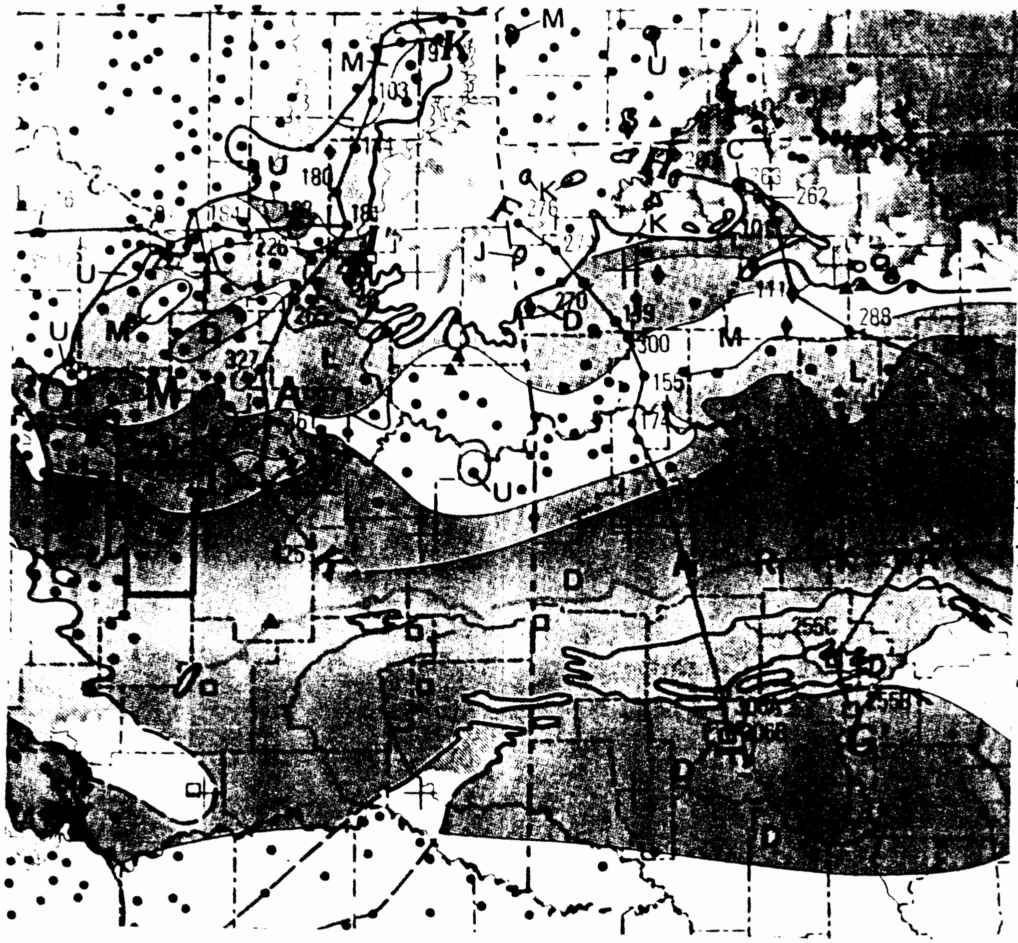
The Rhoda Creek was originally regarded as Pennsylvanian, but examination of the Rhoda Creek goniatite fauna indicated a Mississippian age (McCaleb and others, 1964). Grayson (1990), utilizing conodont biostratigraphy, determined that the Rhoda Creek contains the Mississippian-Pennsylvanian boundary. Thus the younger portions of the Rhoda Creek are considered to be Morrowan. Grayson (1990) also reported that the Mississippian-Pennsylvanian boundary is conformable, coincident with a lithologic change and the previously documented geochemical anomaly of Orth and others (1986, 1988). As recognized in this study the Rhoda Creek is that of Grayson (1990) and is essentially equivalent to those shales variously referred to as "Penn Caney" or Springer in the Arkoma Basin.

Previous descriptions of the subsurface Rhoda Creek Formation generally have utilized "Penn Caney" or Springer terminology. In discussion of the Rhoda Creek in central Hughes County, Harvey (1960, 1961) referred to it as "Springer Shale," observed the Rhoda Creek as being gray to black, splintery, containing a few thin beds of limestone and sandy in certain locales. In a study of lithofacies of shales referred to as "Springer" in the Arkoma Basin, Frezon and Dixon (1975) determined that the Rhoda Creek is mostly shale in the study area (Figure 5). The Rhoda Creek generally is noncalcareous shale that shows a low-resistivity wireline-log response. Similar observations were made by Laudon (1958) and Frezon (1962) in studies of Springer and Goddard shales respectively.

Presence or absence of the Rhoda Creek in the study area has been a point of controversy in the literature. Weaver (1954) and Branan (1961) concluded that the Rhoda Creek is absent due to onlap. More recent correlations, specificaly those by Harvey (1960, 1961), Bellis (1961), and Frezon and Dixon (1975) demonstrate the presence of the Rhoda Creek Formation in the immediate study area. Huffman (1959) determined Rhoda Creek aged strata reaches a maximum of 500 feet in the Arkoma basin. The Rhoda Creek exhibits a general increase in thickness from 290 feet in the northwest, to 420 feet in the southeast portions of the study area. The Rhoda Creek Formation is overlain by the Morrowan Union Valley Formation in all areas of the current study.

Mississippian-Pennsylvanian Boundary

The Late Mississippian was characterized by regressive conditions in the southern Mid-continent region. The resultant progressive truncation of the Chesteran Series, evident in exposures in northeastern Oklahoma and Arkansas, in conjunction with apparent continous sedimentation in



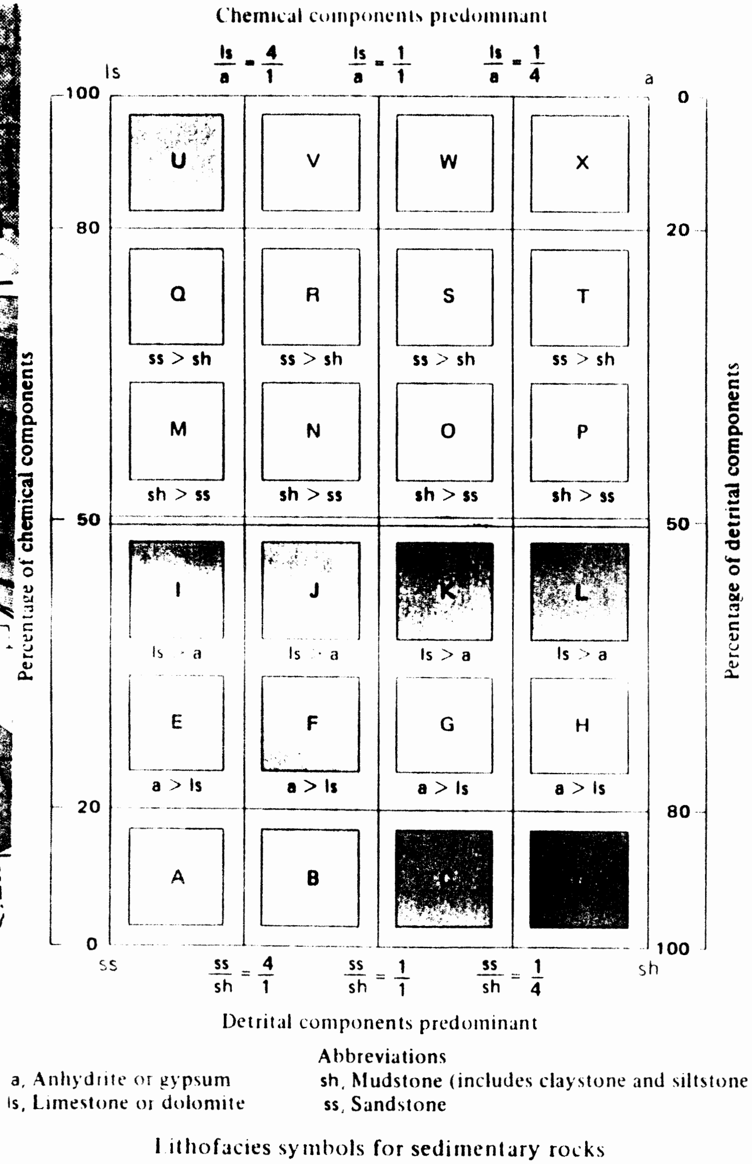


Figure 5. Lithofacies of the Chesterian Series (modified from U.S. Geol. Survey Professional Paper 1010, Plate 6-B).

basinal areas to the south, has combined to create much disagreement regarding the nature of this systemic boundary in the Arkoma Basin.

Cockrell (1985) and Busby (1986) determined that the Union Valley Formation is unconformable on Chesteran shales in areas north of the study area. Boyle (1930) and Weaver (1954) concluded that an angular unconformity is between the Cromwell Sandstone and shales correlated as Caney, in Hughes County. Studies of regional extent include those of Harlton (1938), Laudon (1959), Jackson (1949), Branan (1961), Rascoe and Adler (1983), and Sutherland (1988a,1988b), all of which also recorded the existence of a basal Morrowan unconformity. Palynological studies by Wilson (1966) in the Arbuckle region suggest an unconformity between the Springeran and Morrowan Series.

Investigations to the south of the study area, particularly those by Barker (1951), Kuhleman (1951), Mann (1957,1958), Withrow (1968), and Grayson (1990), determined the systemic boundary to be within a gradational sequence of strata. Branan (1961), Frezon (1962), Visher and others (1971), and Ethington and others (1989), showed evidence of regional conformity in the Arkoma Basin. Other studies in areas immediately north and east of the present study area include those of Harvey (1960,1961) and Fields (1987) which reported conformable boundaries between Chesterian and Morrowan strata.

As the Rhoda Creek Formation contains the Mississippian-Pennsylvanian boundary by definition (Grayson, 1990), and is present in southern Hughes County, the boundary is regarded as conformable in the present study. Local unconformities associated with an individual Morrowan depositional event may be present, but a widespread unconformity is not belived present in the study area. Barrett (1960) determined the absence of Rhoda Creek sands does not imply erosional truncation in the Arkoma.

Pennsylvanian System

Morrowan Series

The Morrowan Series in the Arkoma basin is composed of shales, siltstones, sandstones, and shelf carbonates. Prehaps the Morrowan Lower Dornick Hills Group (LDHG) oversteps the underlying Rhoda Creek Formation northward in the study area, but apparently sedimentation was continuous in southern areas. The Wapanucka Formation is overstepped northward by the Atokan Series.

Lower Dornick Hills Group

Union Valley Formation. The Union Valley Formation is the lowest formation of the LDHG; it contains two members: the upper Union Valley Limestone and underlying Union Valley

Sandstone (Barker, 1951). The Union Valley Formation was named for exposures near the Union Valley schoolhouse located on the Lawrence Uplift in Pontotoc County. Originally included within the Wapanucka Formation by Taff (1901), the Union Valley was elevated to member status by Hollingsworth (1933,1934). The Union Valley received formation status by Hyatt (1936).

The Union Valley was correlated with the Hale Formation of northwest Arkansas, where the type section of the Morrow Series was established by Roth in 1929 (Barker, 1951). The Hale Formation is composed of two members, a lower sandstone, the Cane Hill Member, which is unconformably overlain by a sandy limestone, the Prarie Grove Member. Bennison (1956) correlated the Union Valley Limestone and Sandstone (Cromwell) with the Prairie Grove and Cane Hill members of the Hale Formation, respectively. The Hale Formation unconformably overlies the Chesterian Pitkin Limestone. The Pitkin is not in the study area, but grades into the Caney Shale north of Hughes County (Boyle, 1930).

Union Valley Formation equivalents of the Ardmore Basin include the Primrose and Overbrook Sandstones. The Union Valley Limestone was correlated by Dott (1941) with the Primrose and the Union Valley Sandstone was correlated by Tomlinson (1959) with the Overbrook Sandstone. The Overbrook is considered to be a member of the Springer Series in the Ardmore Basin. Coeval sediments of the Ouachita Mountains are assigned to the "Springer Shale".

The Union Valley Sandstone has been correlated with the Cromwell sandstone of the subsurface. The Cromwell sandstone was named in honor of Joe Cromwell, whose oil discovery in Seminole County resulted in the opening of the giant Cromwell Field. Numerous other informal subsurface names have been applied to the Union Valley Sandstone, among them are: "Black and Simons, Papoose, Lyons-Quinn, First Cromwell-Smith, Second Cromwell-Sykes, Lyons, Jefferson, Konawa, Ingram" (Jordan, 1957). Although originally designated as an interval in the Cromwell, many operators currently regard sands correlated as Jefferson in the study area as Rhoda Creek ("Penn Caney"-"Springer") in age. Jordan (1957) recommended discontinuation of Jefferson sand terminology with reference to sands correlated as Rhoda Creek in age. The Jefferson sand(s), as recognized in this study, are those sands in the lower portions of the Union Valley Formation below the Cromwell Sandstone and are consequently regarded as Morrowan in age. Wilshire (1971) determined the Jefferson sand(s) of southern Hughes County to comprise a portion of the Union Valley facies tract, implying a genetic relationship.

The Cromwell Sandstone and overlying Union Valley Limestone exhibit a complex stratigraphic relationship. Locally the Union Valley Limestone is absent, separated by a thin shale break, or it shows a gradational contact with the Cromwell. As a result, the Union Valley Limestone as used by most subsurface workers in the study area, may refer to any number of calcareous horizons which typically develop on the upper surface of the multiple Cromwell sands. The Union Valley Limestone is not regarded in a time stratigraphic manner in this study.

Sample and insoluble residue studies conducted by Jackson (1949) and Barker (1951) indicate upward-increasing carbonate content in the Cromwell, suggesting that a gradational contact exists with the limestone member. Hamric (1961) describes similar vertical gradations in areas to the northeast of the current study area. Langworthy (1929) and Cutolo-Lozano (1969) discussed lateral facies gradations of the Cromwell sand to the northwest of the study area in Seminole County, Oklahoma. Instances in which a gradational contact exists commonly result in a degree of uncertainty in differentiation of the Union Valley Limestone and Cromwell Sandstone on electrical well logs. As a result, the two members are regarded as congruous, with the limestone being regarded as a calcareous facies of the Cromwell in this study, similar methods were employed by Jackson (1949).

The Union Valley Limestone is gray to brown, fine to coarsely crystalline, fossiliferous, siliceous, and glauconitic. It ranges from 0 to 40 feet thick in the study area. The Cromwell Sandstone is gray to brown, fine to medium-grained, subangular to subrounded, calcareous, glauconitic, fossiliferous, and commonly bioturbated. Locally the Cromwell consists of multiple strata of sandstone, interbedded with dark-gray to black marine shales. The discontinous nature of individual Cromwell sands results in difficult regional correlation (Arkoma Basin Study Group, 1961, and Sutherland, 1988a, 1988b). The Cromwell Sandstone ranges from 0 to approximately 300 feet thick in the study area. The underlying Jefferson sand(s) are lithologically similar to the Cromwell but typically are thinner and more consistent laterally.

Wapanucka Formation. The Upper Morrowan Wapanucka Formation, described first by Taff (1901), is the upper formation of the Lower Dornick Hills Group. The Wapanucka conformably overlies the Union Valley Formation and is overstepped by the Atokan Series. The Wapanucka Formation contains an unnamed lower shale and and upper limestone member.

Commonly referred to as "Limestone Gap" or "Wapanucka Shale," the lower shale of the Wapanucka interfingers with the underlying Union Valley Formation. The shale is gray to black and contains thin beds of limestone and sandstone of localized extent. Conductivity responses on electrical logs typically are lower than those shown by shale interbeds of the Union Valley Formation (see Figure 3, type electrical log).

The upper limestone member for which the formation is named is brown to gray and commonly sandy and/or oolitic. The Wapanucka is an easily recognized marker horizon on electrical logs and can be correlated across the entire study area. Thickness of the Wapanucka Limestone ranges from 45 feet in the northwest to 130 feet in the southeast.

Atokan Series

The Atokan Series is represented by the Upper Dornick Hills Group in the Arkoma Basin. The Atokan is composed of alternating shales and sandstones deposited in non-marine, shallow marine, and deep marine environments (Houseknecht, 1983). A significant angular unconformity is between the Atokan Series and the underlying Morrowan Series. Atokan rocks are overlain by the Desmoinesian Series.

Upper Dornick Hills Group

Atoka Formation. The Atoka Formation of the Upper Dornick Hills Group was named for exposures near Atoka, Oklahoma (Taff, 1900). The Atoka Formation thickenss across numerous faults in the basin, generally becoming thicker southeastward. In the upper to middle portions of the Atoka Formation are several lenticular sandstones known as the Gilcrease sandstones. Dickey and Rohn (1955), described a deltaic orgin for the Gilcrease. Gilcrease sandstones are fine to medium-grained (Mann, 1957). Atokan shales are gray to black, locally silty and/or calcareous, and slightly glauconitic (Jackson, 1949).

Format Intervals

Introduction

The Upper Mississippian (Chesterian) through Middle Pennsylvanian (Atokan) stratigraphic section has been divided into three informal marker-defined genetic increments of strata in the study area. Format units were used to divide the subsurface stratigraphic section of the area by Frezon (1962) and by Visher and others (1971). The utilization of informal marker-defined units in subsurface studies is an aid in the reconstruction of paleodepositional environments.

Genetic Intervals

As defined by Busch (1974), "genetic increment of strata" (GIS) consists of a "vertical sequence of strata in which each lithologic component is related genetically to all the others". Genetic increments of strata can be defined in the subsurface section based on marker beds. As utilized in this study, marker-defined increments of strata employ boundaries that are recognizable on geophysical logs. Marker horizons must satisfy essential criteria: the upper marker bed must be of a "lithologic-time" nature; the lower marker may be of a "lithologic-time" variety, an unconformity, or a facies variation from "marine to non-marine" Busch (1974).

Visher and others (1971) subdivided the Upper Mississippian and Lower through Middle Pennsylvanian stratigraphic section in the study area into informal format units of "time-stratigraphic" significance. The format units of interest consist of the Mayes Format, defined as the stratigraphic interval extending from the "top of the Mayes limestone to the top of the Boone Chert," and the Wapanucka-Cromwell Format as "the top of the Wapanucka Limestone to the top of the Caney Shale" (Visher and others, 1971). The format units used by Visher and others (1971) are somewhat analogous to the genetic increments utilized in this study.

As an aid in interpretation of paleoenvironments, the following GIS units are defined, in ascending order: the Caney GIS - extending from the top of the Mayes Limestone to the top of the Caney Shale; the Rhoda Creek GIS - from the top of the Caney Shale to the base of the Union Valley Formation; the Union Valley GIS - from the base of the lowermost Jefferson sandstone present to the base of the Wapanucka Limestone (see Figure 3, Type Log). The Caney GIS is comparable to the previously discussed Mayes Format of Visher and others (1971); the Rhoda Creek and Union Valley GIS's are similar to the aforementioned Wapanucka-Cromwell Format.

The top of the Rhoda Creek GIS is interpretive in areas where a conformable relationship exists with the overlying Union Valley GIS and is defined by an unconformity surface elsewhere. Where the Rhoda Creek Formation is overlain unconformably by the Union Valley, the Rhoda Creek GIS is not a GIS in the strict sense, but the interval remains a mappable entity. The use of the base of the Wapanucka Limestone as the upper marker horizon of the Union Valley GIS precludes similar dilemmas, because of the regional unconformity between the Wapanucka and basal Atokan rocks.

CHAPTER IV

STRUCTURAL FRAMEWORK

Introduction

The Arkoma Basin is bordered by a number of significant geologic features, each of which have had varying degrees of influence regarding basin evolution. A general understanding of the regional tectonic history of the Arkoma basin may allow placement of the local structural-stratigraphic features into a regional context. This synopsis of evolution of the basin records the development of a deformed foreland basin from a passive continental margin.

Regional Tectonic History

Before the Late Precambrian, the North American craton was sutured to a large landmass, the supercontinent, "proto-Pangea" (Walper, 1977). Rifting along the southern margin of North America resulted in opening of the proto-Atlantic (Ouachita) ocean basin (Figure 6-A) and development of numerous rift basins along the southern continental margin

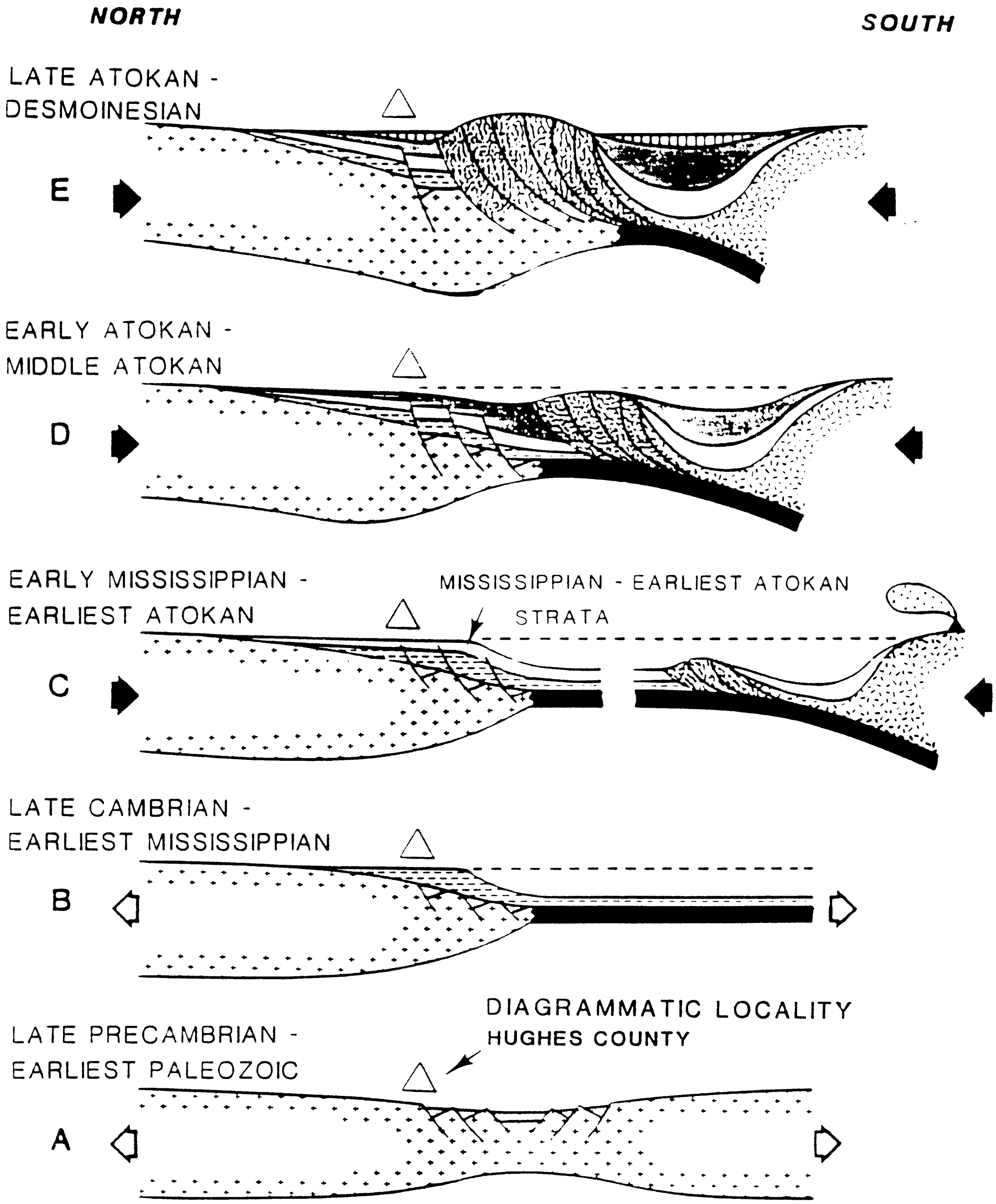


Figure 6. Diagramatic Evolution of the Southern Margin of North America (modified from Houseknecht,1983, p.15).

(Figure 7). Rifting of "proto-Pangea" has been described as having occurred during the Late Precambrian (Keller and Cebull, 1973) and Late Cambrian (Dickinson, 1981). Continued rifting resulted in a divergent plate margin along the southern boundary of North America.

Subsidence and deposition of typical "shelf-slope-rise" strata along the passive southern margin of North America (Figure 6-B) occurred during the Late Cambrian through Devonian (Houseknecht, 1983). Recent work by Lowe (1985) suggests that the rifted Ouachita trough was 'relatively' narrow during this interval. In the latter part of the Devonian the Ouachita Geosyncline developed to the south of the passive continental margin, named the Arkoma Shelf by Sutherland (1988a). During early Mississippian time the northern margin of the geosyncline became more active tectonically and a southward-dipping subduction complex evolved to the south (Figure 6-C). Progressive destruction of the Ouachita Ocean Basin followed, as indicated by the occurrence of tuffaceous sediment in the Stanley Group and increased sedimentation rates (Figure 8).

During the remainder of the Mississippian, subduction continued, and the eugeosyncline migrated northward. Near the close of the Mississippian (Chester) major changes took place in the geosyncline; the trough became better defined and was realigned in a northeastward trend (Frezon and Jordan, 1979). Increased orogeny and epeirogeny accompanied development of the Ozark Uplift (Glick, 1979), and the

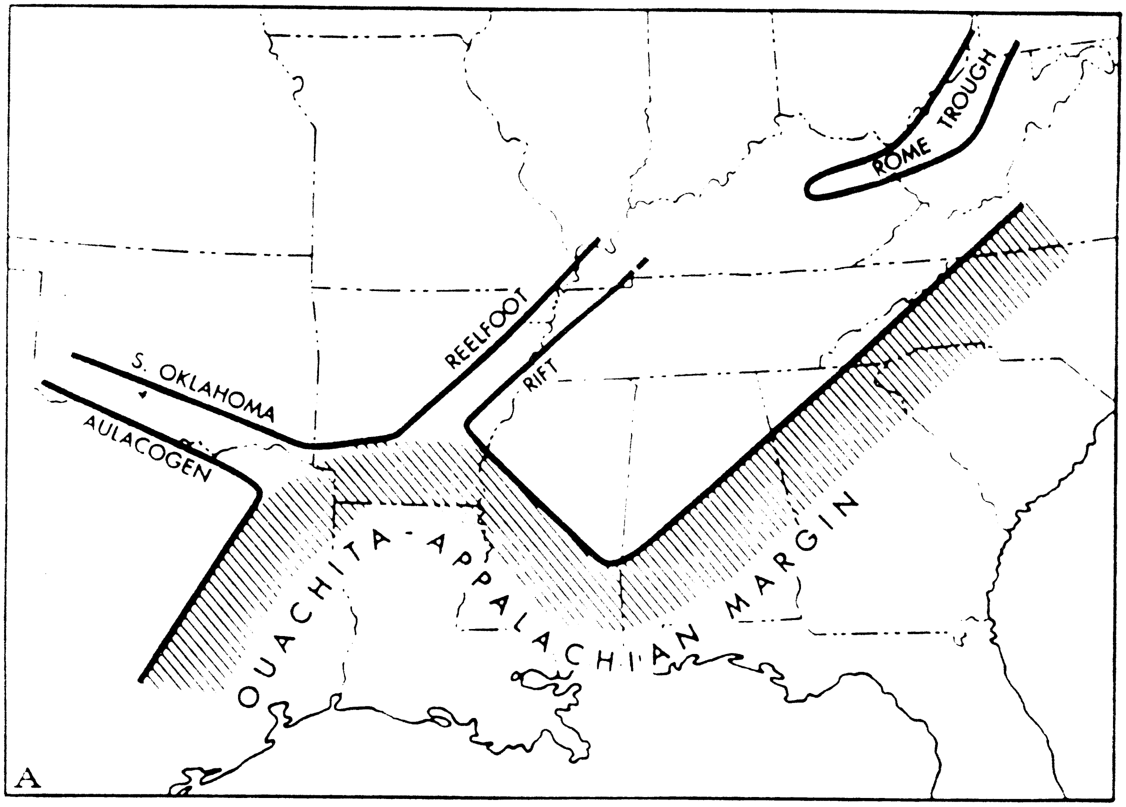


Figure 7. Diagramatic Interpretation of Rifted Continental Margin (from Lowe, 1985, p. 793).

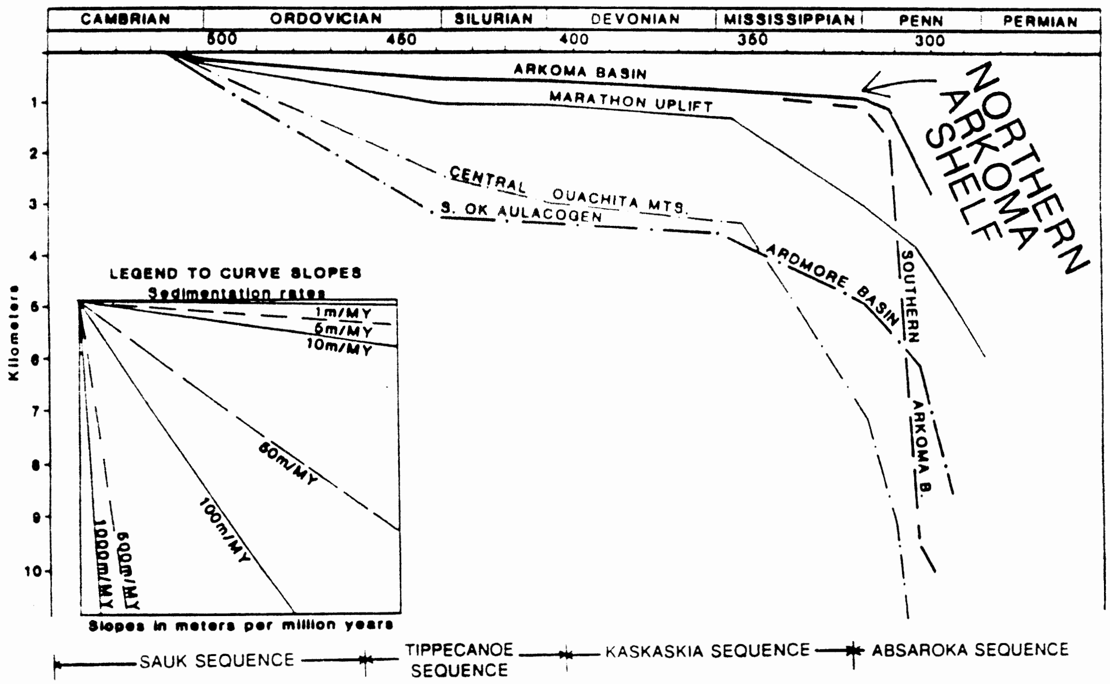


Figure 8. Sedimentation Rates of Ouachita System and Adjacent Arkoma Foreland Basin (modified from Viele and Thomas, 1989, p. 698, after Arbenz, 1989, p.379)

development of a southward extension of the Appalachian geosyncline linking with the Ouachita geosyncline (Craig and Vernes, 1979). Major faults were established or rejuvenated in the Hunton Arch region (Fitts, 1951). The Caney and Rhoda Creek Formations were deposited across the Arkoma Shelf with carbonate sediments to the north and continued flysch to the south (Figure 9). The initial pulse of the Wichita Orogeny is recorded in the very young Mississippian rocks (Johnson, 1988), which created the "pre-Pennsylvanian unconformity" of northern Mid-Continent areas (van Waterschoot van der Gracht, 1931).

During the early Morrowan the southern portions of the Arkoma Shelf were unstable; and subsided more than shelf areas to the north (Sutherland and Henry, 1977). Large-scale faulting took place during early Morrowan time between the Ozark shelf and basinal areas to the south in Oklahoma (Branan, 1968) and western Arkansas (Glick, 1975). Eustatic sea-level fluctations, in conjunction with epeirogenic movements, resulted in cannibalization of Upper Mississippian sediments from northern shelf areas. "Continuous" sedimentation occurred to the south, with progressive onlap of Morrowan and younger strata northward. The Arkoma Shelf and Anadarko basin were connected by a westward axis of deposition during the Morrowan Epoch (Frezon and Jordan, 1979).

Structural features to the north of the subsiding shelf were being expressed in a positive manner during the early

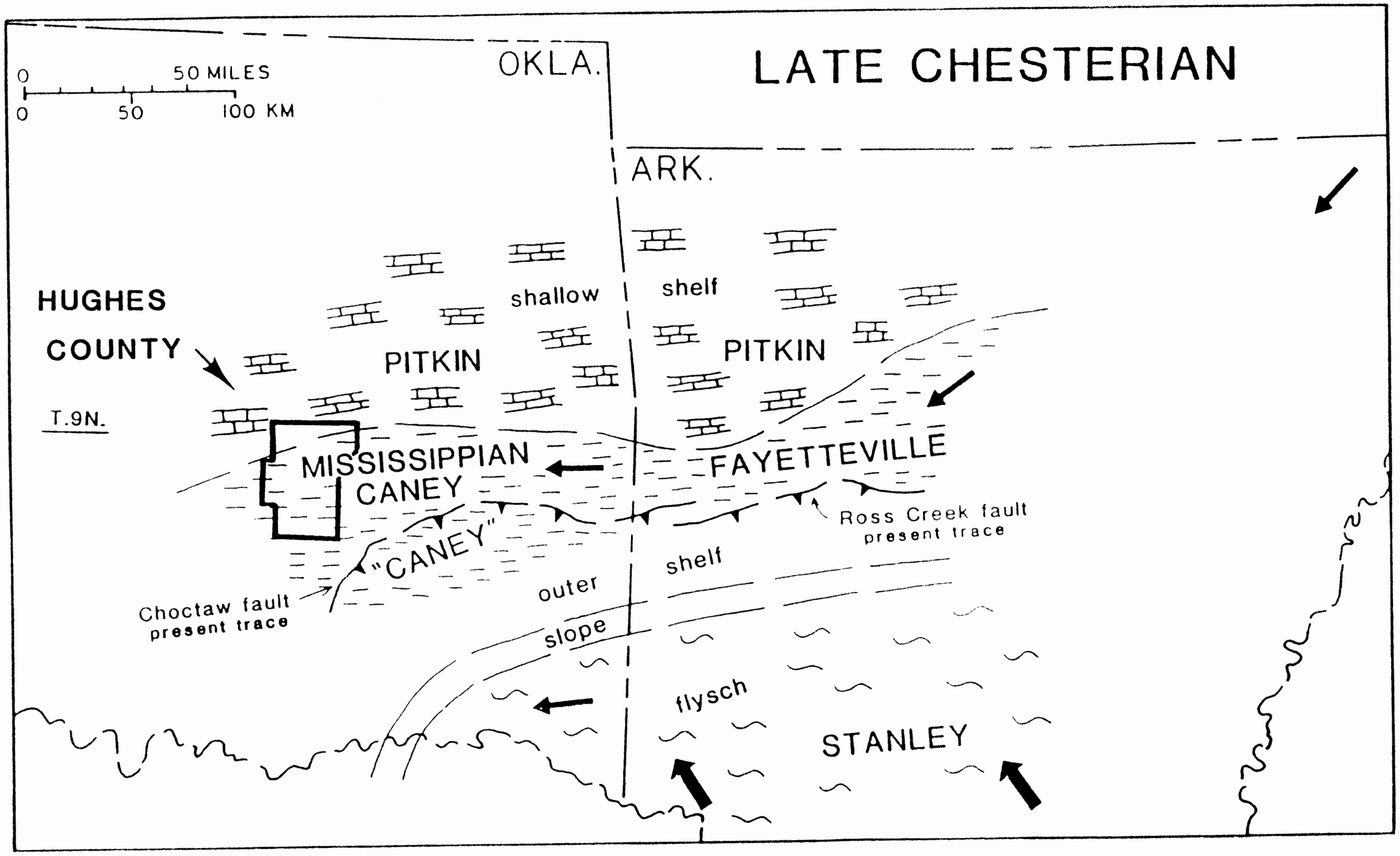


Figure 9. Late Chesteran Paleogeography (modified from Sutherland, 1988a, p.1792).

Morrowan. Among the major features were the Siouxia highland, Cambridge arch, Central Kansas uplift, Ozark dome, and Nemaha ridge. H.A. Ley (1926)(in van Waterschoot van der Gracht, 1931) determined the Nemaha may possibly have been uplifted at least 1000 feet. Jefferies (1982) suggested the existence of a broad paleouplift that extended southward from the Ozark uplift across the southern shelf. Early Morrowan paleogeography is illustrated in Figure 10.

The Union Valley Formation was deposited during the early Morrowan as the lateral equivalent of carbonate facies; the carbonate rocks are the Braggs and Prairie Grove Members of the Sausbee and Hale Formations, in the southern Ozark region. Eastward into Arkansas, Union Valley equivalents are the Cane Hill and Prairie Grove Members of the Hale Formation, which were deposited in a wave-dominated, transgressive shallow marine setting (Henbest, 1953). Morrowan strata in Arkansas contain possible hummocky cross-bedding and an abundant marine fauna with associated bioturbation structures (Ballard, 1957). In regions to the south, equivalent outer-shelf shales and flysch sediments of the Jackfork Group were deposited.

The middle Morrow was marked by regressive sedimentation with nonmarine conditions having existed in northwestern Arkansas (Glick, 1975, Figure 11). Sutherland and Henry (1977) have documented evidence of shallow marine conditions and associated carbonate strata in northeastern Oklahoma. Basinward, the lower shales of the Wapanucka

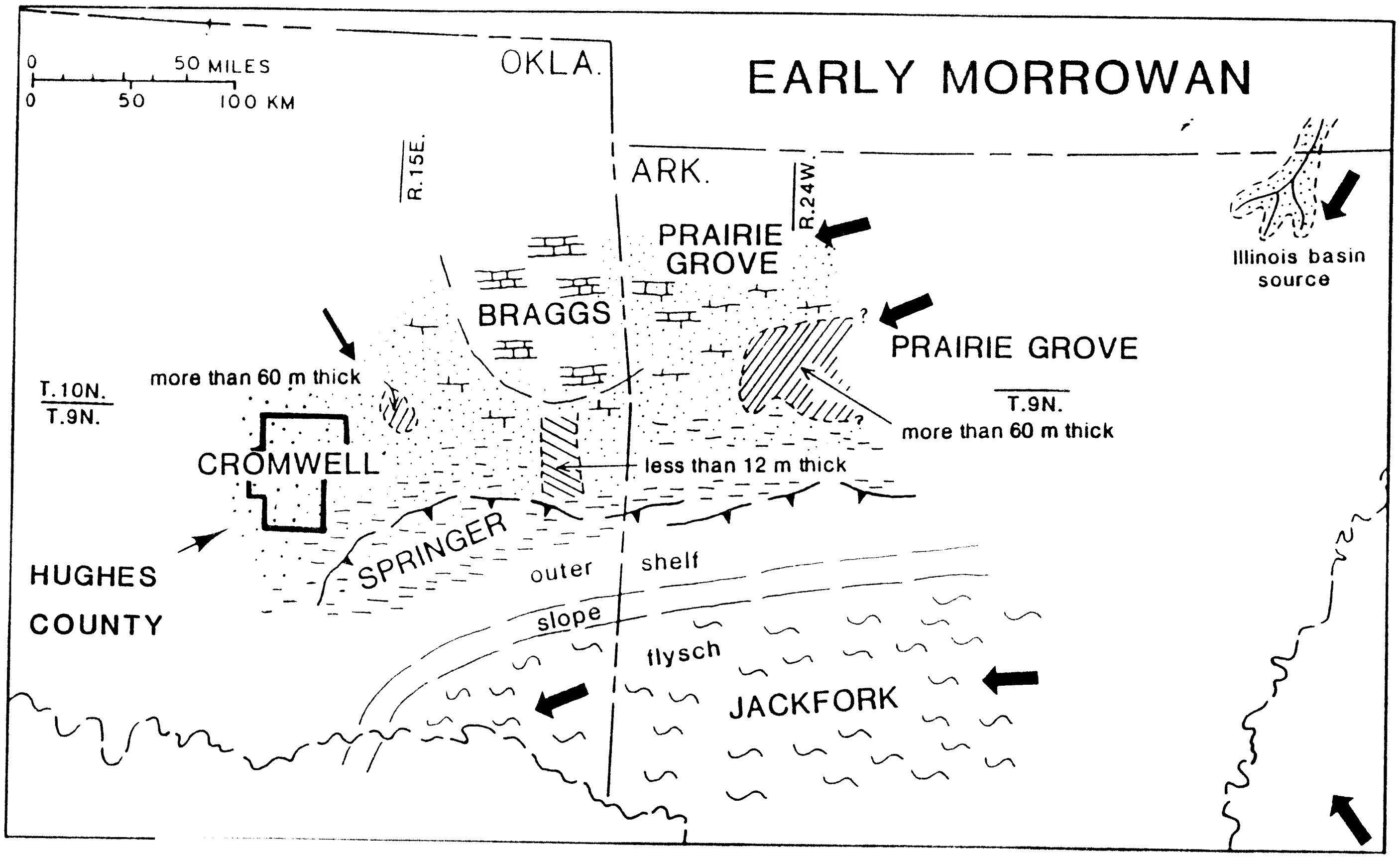


Figure 10. Early Morrowan Paleogeography (modified from Sutherland, 1988a, p. 1793).

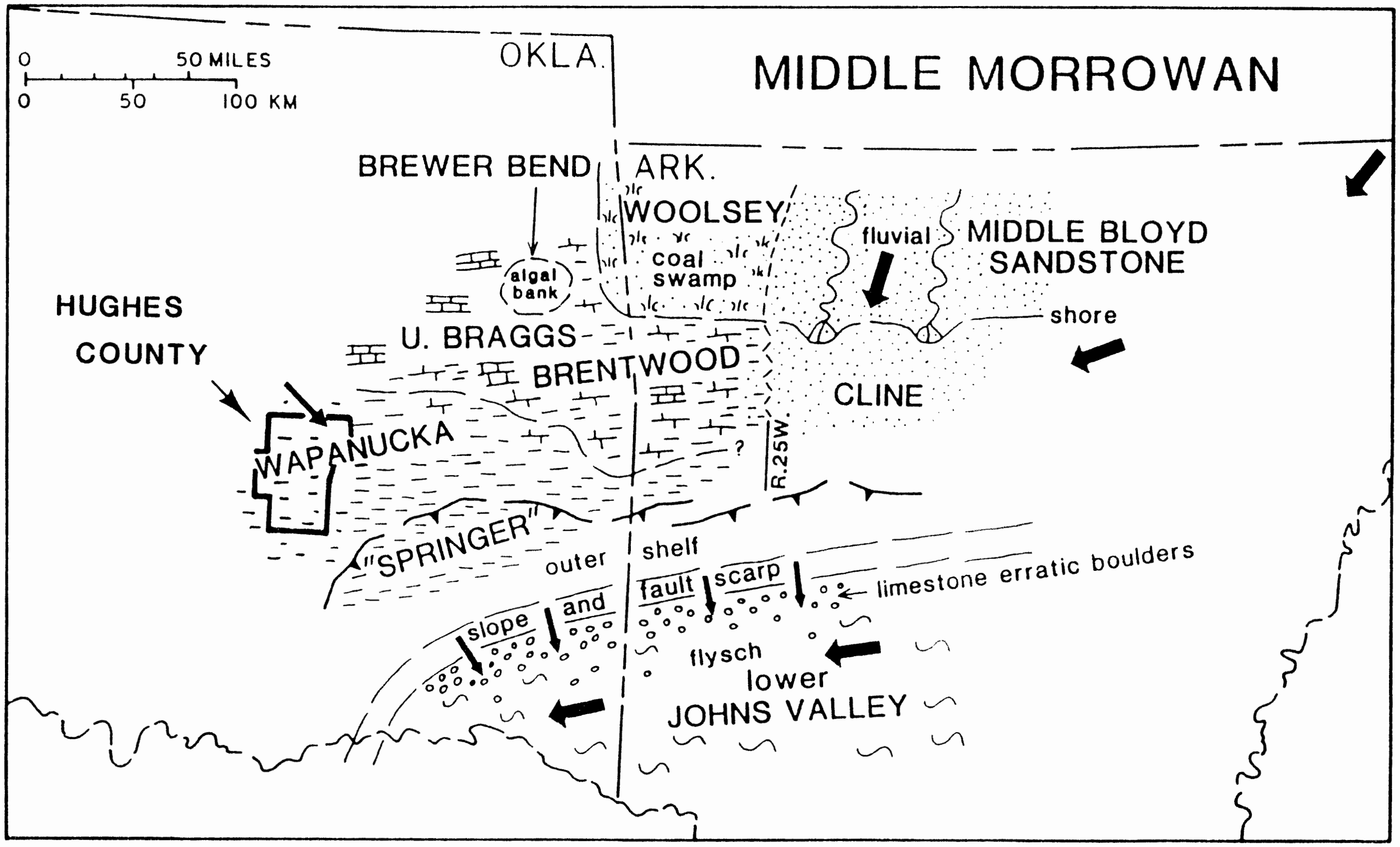


Figure 11. Middle Morrowan Paleogeography (modified from Sutherland, 1988a, p.1794).

Formation and the equivalent "Springer" shales of the outer shelf were deposited during middle Morrowan time (Sutherland, 1988a). Further regression led to deposition of the regionally persistent Wapanucka Limestone during the late Morrowan (Figure 12). The close of the Morrow records the second pulse of the Wichita orogeny.

Continued subduction resulted in closure of the Ouachita ocean basin by early Atokan time. The upper portions of the Wapanucka Limestone and the shallow marine Foster and Spiro sandstones were deposited on the southern Arkoma shelf during this time (Figure 13), whereas in regions to the north the Atoka Formation unconformably overlies truncated strata. To the south, the margin of the North American continent was partially drawn into the southward-dipping subduction complex (Figure 6-D) allowing vertical loading and "flexural bending" of the previously rifted continental margin (Dickinson, 1974, 1976; Houseknecht, 1983). In this resultant breakdown of the continental margin, the shelf-slope-rise configuration of the Arkoma Shelf was replaced during development of the Arkoma foreland basin.

Breakdown of the continental margin was initiated by a series of step-like normal faults that extended into the basement; some were faults associated with the earlier rifting of "Proto-Pangea" (Houseknecht, 1983). Koinm and Dickey (1967) described the significant increase in thickness of lower through middle Atokan strata across these

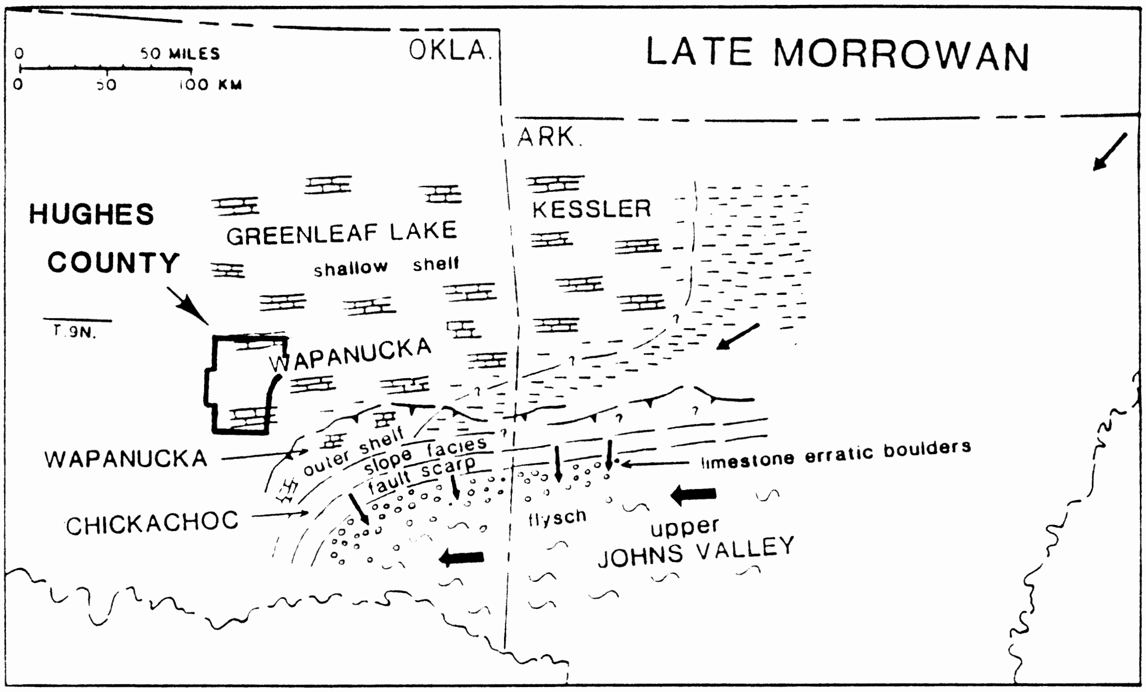


Figure 12. Late Morrown Paleogeography (modified from Sutherland, 1988a, p.1795).

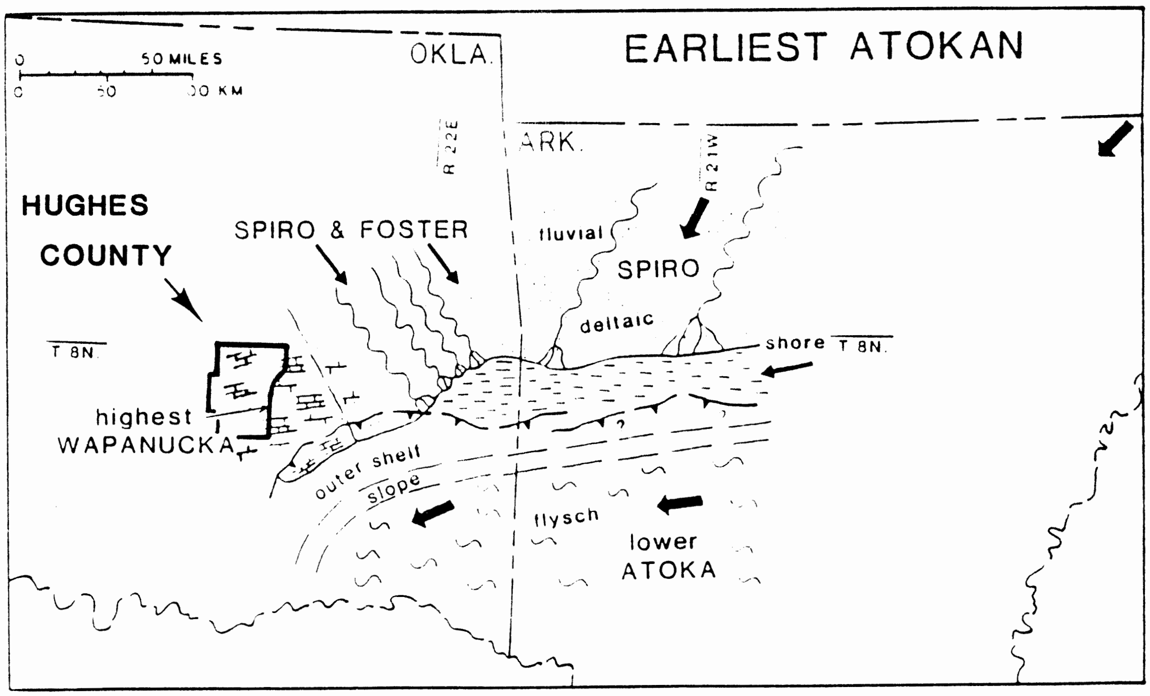


Figure 13. Earliest Atokan Paleogeography (modified from Sutherland, 1988a, p. 1795).

faults, although in some instances earlier periods of syndepositional movement is suggested. Lower through middle Atokan paleogeography is illustrated in Figure 14. Sutherland (1988a) documented movement on the Hunton Arch during this time, the evidence of which is Wapanucka Limestone detritus in strata deposited during early Atokan time.

By late Atokan time (Figure 6-E), the most intense collisional events had occurred, with the subduction complex having been uplifted as the Ouachita Mountains (Houseknecht, 1983). The Ouachita orogenic complex formed a portion of the Hercynian System along which Laurasia and Gondwanaland formed the Pangea supercontinent (Dickinson, 1981). Sutherland (1988a) indicated that upper Atokan strata are not displaced by lower through middle Atokan syndepositional faults. Underwood and others (1988) reported that Desmoinesian strata were affected by compressive forces in a manner similar to compression of Atokan strata.

During early Desmoinesian time, continued compressional events produced major de'collement thrusts, many of which ramped on the existing extensional syndepositional fault planes primarily of Atokan age. Hardie (1988) determined that major thrusts developed by forward propagation. By middle Desmoinesian time, deposition of chert pebbles from the Ouachita orogenic belt northward into the basin began, in addition to sediment being introduced from the Appalachian Mountains, Ozark Uplift, and Hunton Arch. The

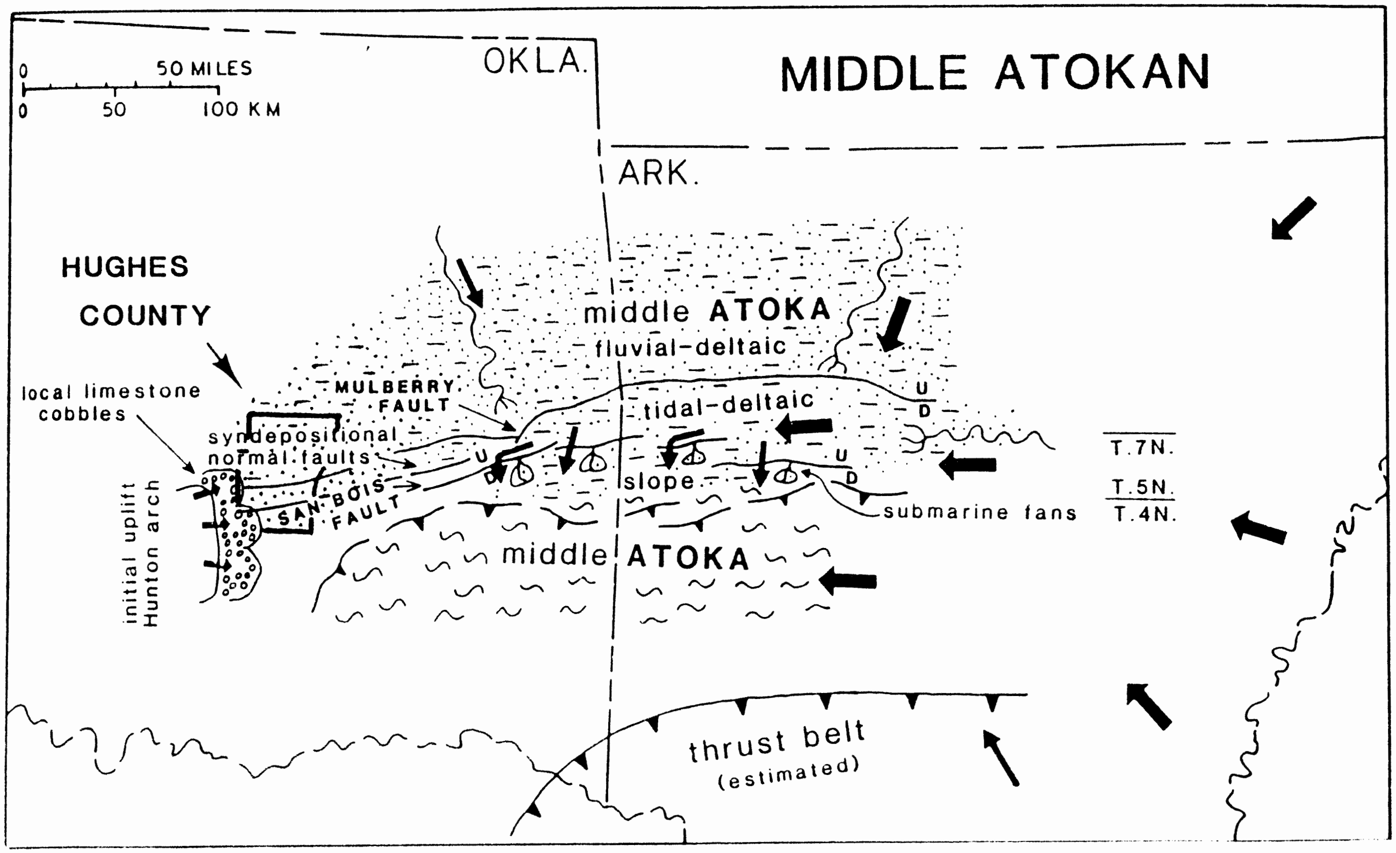


Figure 14. Middle Atokan Paleogeography (modified from Sutherland, 1988a, p. 1797).

northern margin of the basin migrated northward through the Desmoinesian (Weirich, 1953). Reduced intensity of tectonic events associated with the Ouachita Mountains continued until Late Permian. The last orogeny of consequence to affect the region during the Pennsylvanian was the Arbuckle disturbance of Virgilian age.

Regional Structural Setting

The Arkoma Basin is an east trending foreland basin in south-central Oklahoma and central Arkansas. The basin is bordered by the Ozark Uplift to the north, the Central Oklahoma Platform to the northwest, the Arbuckle Uplift to the southwest, and the Ouachita Uplift to the south (Figure 15). The trace of the Choctaw fault traditionally is regarded as the boundary between the Arkoma Basin and the complexly deformed Ouachita orogenic belt to the south, although recent work suggests that the boundary is transitional and may represent an incipient triangle zone (Hardie, 1988).

The Arkoma Basin has been described as an assymetric "arcuate synclinorium" (Houseknecht, 1983). The basin is characterized by extensional and compressional structural features. Extensional features consist primarily of basement-involved down-to-the-south syndepositional faults, with compressional features represented by folds with associated northward verging overthrust belts (Schramm and

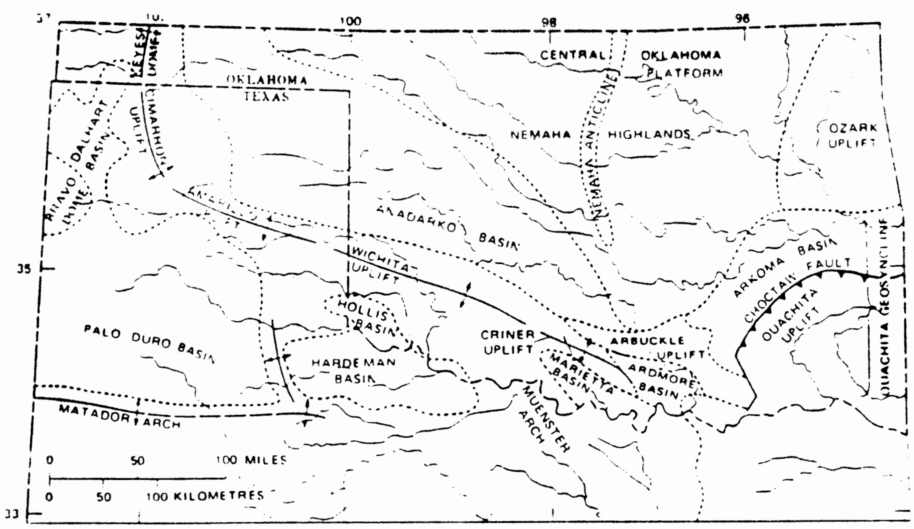


Figure 15. Regional Geologic Setting of Arkoma Basin and Ouachita Foldbelt (from Frezon and Dixon,1975, p. 179).

Caplan, 1971; Berry and Trumbly, 1968). Buckner (1972) and Fritz (1978) noted regional structural patterns in the basin are reflected by salinity gradient anomalies (Figure 16).

Syndepositional faults are younger northward, generally trend east-west, and record the evolution of a foredeep with basinal sedimentation from the previous shallow shelf sedimentation that previously was typical of the Arkoma Shelf. Other faults trend northeast to north-northeast. Compressional anticlines with associated thrust faults along their axes commonly are more tightly folded and asymmetric southward toward the Ouachita orogenic belt.

Local Structural Features

The structural configuration of the study area was evaluated on the basis of a structural contour map constructed of the top of the regionally persistent Wapanucka Limestone (Plate 1). The study area is divided into northern and southern areas by an east trending, down-to-the-south syndepositional fault, herein referred to as the Allen Fault (Plate 1). The Allen Fault is semi-parallel with the township line separating Townships 4 and 5 north. Displacement on the Allen Fault at the Wapanucka level ranges from approximately 600 to 1400 feet. Branan (1968) determined that major east trending faults in the Arkoma Basin are related to tensional relief associated with rapid subsidence.

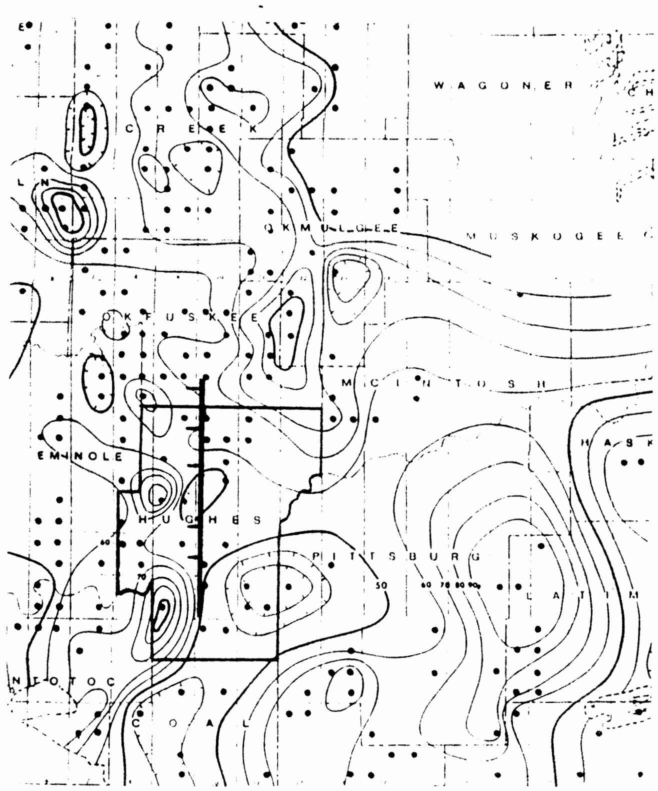


Figure 16. Regional Salinity Map, Permian-Pennsylvanian Strata (modified from Buckner, 1972, figure 17).

South of the Allen Fault, regional dip is to the northeast, ranging from 200 to 300 feet per mile (Plate 1). A series of northeast-trending normal faults extends across this area, with interpretation of throws based in part on well control and seismic interpretations provided by Miller (1989) and Woods (1990). These faults apparently are splays of the down-to-the-north Ahloso Fault (Plate 1). The Ahloso fault extends eastward from Seminole County into Coal County, then northward into Hughes County (Plate 1). Closure is evident along the Citra and East Gerty Faults and the fault in T.4N., R.11E (Plate 1). Additional areas of anticlinal closure may exist along these faults, with current well control insufficient for justification at this time. South of the Allen Fault, primarily in the northern portions of T.4N., R.9E., a down-to-the-north fault system results in a westward-narrowing graben, which apparently terminates eastward against the East Gerty Fault (Plate 1). The positioning of these faults is somewhat interpretative.

North of the Allen Fault, regional dip is to the east-southeast at approximately 200 feet per mile (Plate 1). This portion of the study area is bisected by a major north-trending down-to-the-west normal fault, the Holdenville Fault. This fault extends northward from the study area, across northern Hughes County, into Okfuskee County. Associated with the Holdenville Fault are many well known subsurface structures. Closure against the fault plane on both downthrown and upthrown sides of the Holdenville Fault is evident (Plate 1).

The Southwest Calvin Anticline strikes northeastward from the Holdenville Fault, at approximately 40 degrees. The Southwest Calvin Anticline is breached by several normal faults of relatively small displacement (Plate 1). The Southwest Calvin Anticline is similar to another well known structural feature in central Hughes County, the Horns Corner Anticline. The gross geometrical relationship of the Holdenville Fault and the Southwest Calvin Anticline is suggestive of some degree of left-lateral strike-slip movement. Woods (1990) suggested that seismic data is indicative of wrench movement across the Holdenville Fault. Buckner (1972) documented salinity-gradient differences in Pennsylvanian-Permian rocks in eastern and southern Hughes County (see Figure 16), the terrains of which are approximately bisected by the Holdenville Fault.

Eastward from the Southwest Calvin Anticline in T.5 N.,R.11 E. intersecting faults of northeast-southwest orientations form a complex pattern (Plate 1). A series of structural closures is associated with these faults; apperantly the anticlines are westward extensions of the McAlester Anticline. The McAlester Anticline was described by Colton (1935). Woods (1990) aided in the interpretation of these intricate fault patterns.

CHAPTER V

DEPOSITIONAL FRAMEWORK

Introduction

The Union Valley Formation is interpreted as having been deposited in shallow marine waters. Evidence obtained from examination of cores, cross sections, isopach maps, and isolith maps clearly demonstrates criteria generally accepted for identification of facies deposited on a shallow, subaqueous marine shelf.

Evidence of Ancient Shallow Marine Deposits

Criteria commonly utilized to recognize ancient shallow marine deposits include specific authigenic minerals, faunal content, trace-fossil assemblages, sedimentary structures, and vertical facies associations. Heckel (1972) provided a comprehensive account of these criteria.

Specific authigenic minerals, most notably glauconite and chamosite, are indicative of shallow marine deposits. Glauconite is most commonly associated with calcareous sandstones and silicous carbonate rocks deposited in a shallow marine depositional setting. Takahashi (1939) suggested that glauconite forms under marine conditions of normal salinity. Shallow to moderate depths in association with relatively slow depositional rates characterize marine enviroments conducive to formation of glauconite (Kuenen, 1950). Cloud (1955) determined that a lack of "intrinsic" amounts of water turbulence is required for glauconite formation, but noted a predisposition for slightly reducing conditions. Burst (1958) used compositional differences in glauconite as an aid in the interpretation of paleo-depositional environments. Selley (1978) discussed the use of glauconite as an environmental indicator, stating that it cannot be reworked.

Faunal content may provide insight in facies analysis, as most faunal assemblages are restricted to rather specific salinity conditions and water depths. The majority of major invertebrate faunal groups occur in normal marine salinities of 30-40 ppt (parts per thousand), as demonstrated in Figure 17, (Heckel, 1972). In the absence of other criteria the possibility of transportation of fossils, made evident by abrasion and fragmentation, may invalidate an interpretation of shallow marine conditions, although Merrett (1924)(in Heckel, 1972), determined that marine organisms are unlikely to be introduced into nonmarine environments through mechanical transport processes.

Precise paleoenviromental interpretations based on trace-fossil assemblages commonly demands the insight of

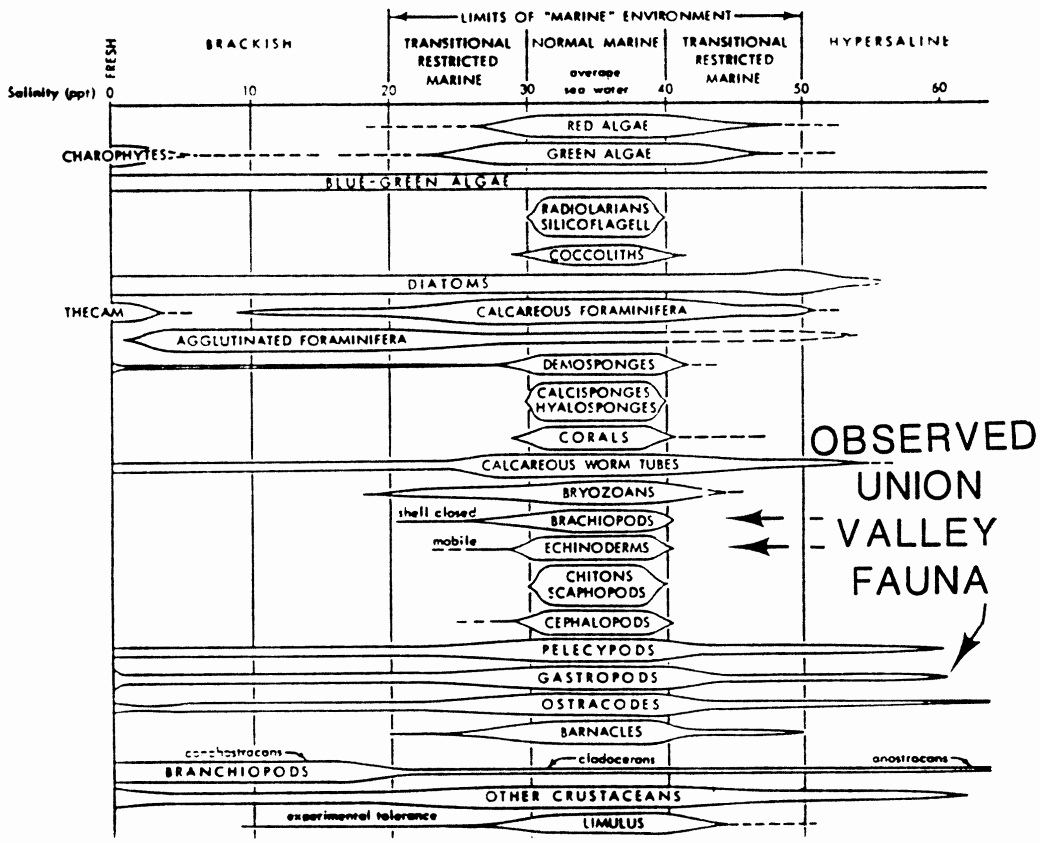


Figure 17. Distribution of Invertebrate Groups and Marine Salinity Contrasts (modified from Heckel, 1972, p. 234).

experts. Nevertheless, certain broad ichnofacies assemblages (Figure 18) are diagonostic of shallow marine environments. Trace fossils are unique in that they can not be transported or reworked, and they provide definitive evidence of paleoenviromental conditions. Goldring (1964) recognized two distinct ichnofacies assemblages common to shallow marine sediments.

Previous interpretations of paleodepositional environments of the Union Valley Formation, specifically of the Cromwell Sandstone, have attributed deposition of the sandstone to marine and (or) deltaic processes. Barker (1951) concluded that the sandstone "marks a nearshore deposit" of a transgressive sea, after examination of exposures on the Lawrence Uplift. Fitts (1951) believed that sands of the Union Valley in Seminole County were deposited as "bars and beaches". Bennison (1956) suggested that the Union Valley represents the initial deposits of cyclic shelf sedimentation of the northern shelf of the Ouachita geosyncline. Duck (1959) stated that the Cromwell of the Northwest Butner Pool, Seminole County, was deposited "by a readvancing sea."

Withrow (1968) studied the Cromwell in the Franks Graben, an extension of the Arkoma Basin. He determined that the sandstone was deposited by interaction of "river and ocean currents". A deltaic orgin was alluded to by Visher and others (1971) in an examination of Pennsylvanian strata in eastern Oklahoma. Deposition in a "marine-delta

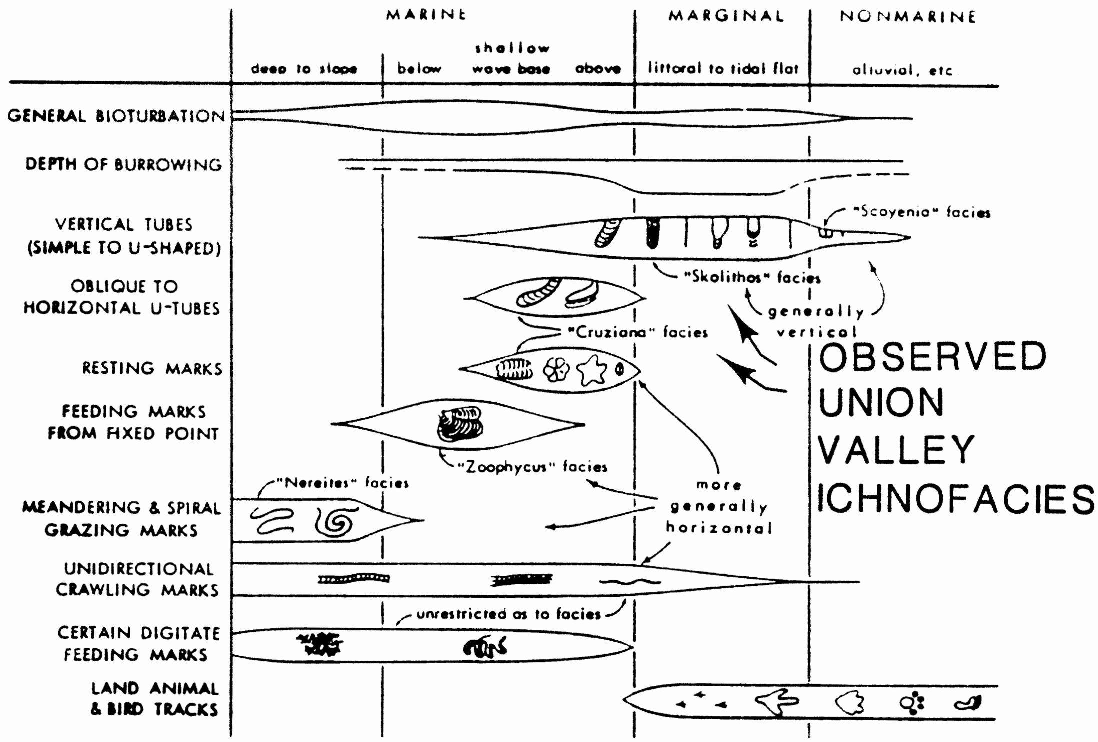


Figure 18. Ichnofacies Distribution Among Various Depositional Environments (modified from Heckel, 1972, p. 244).

complex" characterizes Cromwell facies in the Centrahoma Field in Coal County, as determined by Anderson (1975). Cockrell (1985) believed that the Cromwell was deposited in alluvial-deltaic through shallow marine enviroments in Okfuskee and Seminole Counties.

Jefferies (1982) was of the opinion that the Union Valley was deposited in a "near shore clastic environment" over a large area in the eastern Oklahoma portion of the Arkoma Basin. According to Rascoe and Adler (1983) the Union Valley and overlying Wapanucka Formation were deposited in shallow marine environments in the Arkoma Basin. Fields (1987) suggested that the Cromwell represents deltaic sedimentation in northern Pittsburg County. Sutherland (1988a) concluded that the Cromwell was deposited on the broad southward sloping Arkoma Shelf. Miller (1989) suggested that across Hughes County, the Cromwell represents "shingled" beach deposits. From examination of exposures in the Canyon Creek area in Pontotoc County, Grayson (1990) suggested that the Union Valley Formation may have accumulated as "laterally discontinous offshore bar and interbar" deposits on a shallow marine shelf.

Stratigraphic Cross-Sections

Six stratigraphic cross-sections are included in this study (Plates 3,4,and 5). The cross-sections are oriented north-south and east-west, forming a correlation network

(Plate 2). Wells utilized best illustrate local and regional facies relationships within the Union Valley Formation and adjacent strata. The base of the regionally persistent Wapanucka Limestone is the datum.

Published stratigraphic and structural cross-sections that included wells located in or adjacent to the present study area provided valuable insight into subdivision of the Chesterian and Morrowan strata. Among the more relavent works are those by Laudon (1958) and Visher and others (1971). Laudon correlated Chesterian and Morrowan strata across the eastern part of Hughes County (Figure 19). This section is significant because the Jefferson sandstone is classified in the Union Valley Formation, as opposed to inclusion in the underlying Rhoda Creek. The Cherokee Group cross-section of Visher and others (1971) extends southward into the present study area (Figure 20). This section was of great aid in division of the stratigraphic section into format intervals. Together, these sections provided a framework for the stratigraphic correlations set out in this study.

Cross-Section A-A'

Cross-section A-A' is a west-to-east section that extends from T.4 N.,R.9 E. to T.4 N.,R.11 E. (Plate 3). The Caney and Rhoda Creek Formations thicken eastward, the Union Valley interval also thickens eastward. The Lower Jefferson

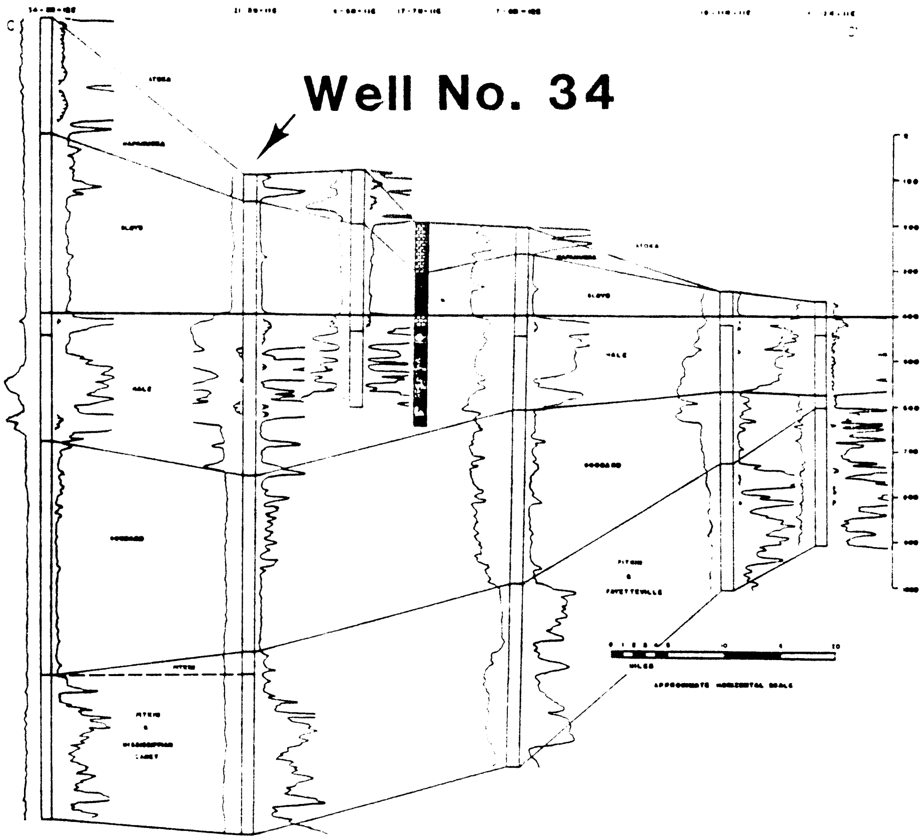


Figure 19. Regional Morrowan Cross Section (modified from Laudon, 1958, p. 27).

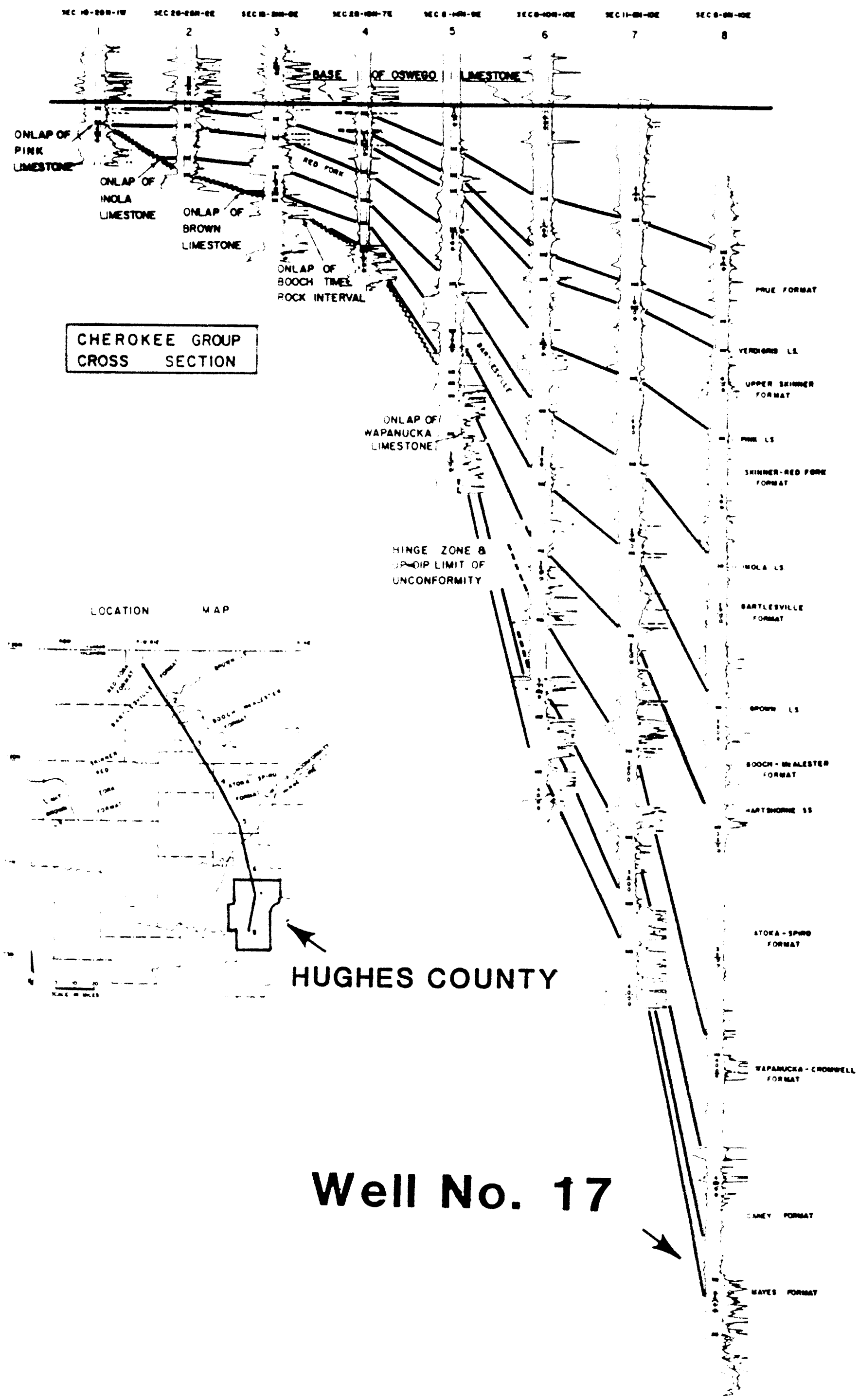


Figure 20. Cherokee Group Cross Section of Visher and Others (modified from Visher and Others, 1971, p. 1210-1211).

sandstones are fairly consistent in thickness. The Upper Jefferson sandstones and the base of the Union Valley-Cromwell section are subparallel with the underlying Rhoda Creek marker bed. The base of the Union Valley-Cromwell is abrupt to gradational with the underlying Jefferson facies. The Union Valley-Cromwell section thickens westward, principally with an accompaning thinning of the overlying shale. This thickening of Union Valley-Cromwell and thinning of overlying shale is particularly evident between wells in Sec. 11, T.4 N.,R.9 E.(well 3), and Sec.7, T.4 N.,R.11 E.(well 4). The Union Valley Limestone seems to be gradational with the underlying Cromwell Sandstone. The Wapanucka Limestone thickens eastward, reflecting the absence of the pre-Atokan unconformity basinward.

Cross-Section B-B'

Cross-section B-B' is a west-to-east section extending from T.5 N.,R.8 E., to T.5 N.,R.11 E. (Plate 3). This section incorporates the type log located in Sec. 29, T.5 N.,R.11 E. The Caney Shale is of relative constant thickness across the section. The Rhoda Creek is also of nearly consistent thickness, with some thinning evident near the western edge of the section. The Jefferson sands thicken and thin locally. The base of the Union Valley-Cromwell is abrupt to gradational, as in section A-A', and is subparallel with marker horizons in the Jefferson interval, Rhoda Creek, and Caney Shale. Where the Union Valley-Cromwell thickens, as does the Union Valley interval, but thickening predominatly is at the expense of overlying shales. Distribution of the Union Valley Limestone is erratic and appears related to Cromwell thickness, favoring thick sand development. Contact of the Union Valley Limestone with the Cromwell in Sec.29, T.5 N.,R.11 E.(well 13) seems to be gradational. The Cromwell is thick in this well and appears to consist of stacked sand bodies; the Union Valley Limestone apparently is not coeval with the upper calcareous portions of the Union Valley-Cromwell of wells in Sections 27 and 28, T.5 N.,R.10 E.(wells 12 and 13). Similar conditions are present westward along the section. The Wapanucka thickens eastward, in a pattern similar to that observed along section A-A'.

<u>Cross-Section C-C'</u>

Cross-section C-C', a west-to east section, extends from T.5 N.,R.9 E. to T.5 N.,R.11 E.(Plate 4). This section incorporates an electrical log of the Midwest No. 1 H. Pierce (well 16) a core from which was examined. Also in this section is the southernmost well (well 17) of Visher's and others' (1971) Cherokee Group cross-section. The Caney Shale and Rhoda Creek Formations gradually thicken eastward. The Union Valley interval thickens both eastward and westward from the No. 1 Pierce well. The Jefferson sands are more variable than in sections A-A', and B-B'(Plate 3); the Upper Jefferson sands are absent in the No. 1 Pierce (well 16). The base of the Union Valley-Cromwell is relatively sharp and subparallel with underlying marker horizons, particularly eastward. The Union Valley-Cromwell consists of numerous strata of sandstone, each of which appears to become calcareous in its upper portion. Absence of the Union Valley-Cromwell and Upper Jefferson sands in the No. 1 Pierce appears to be related to an apparent paleostructural "high," based on lateral and vertical facies relationships observed. The presence of this "high" is coincident with an anticlinal structure (Plate 1), and interval "thins" which will be discussed later. The Wapanucka Limestone increases in thickness eastward, as observed in previous sections.

<u>Cross-Section D-D'</u>

Cross-section D-D' is a south-to-north section that extends from T.4 N.,R.9 E. to T.6 N.,R.9 E. (Plate 4). This section also includes the No. 1 H. Pierce well. The Rhoda Creek and Caney Shale intervals are fairly consistent in thickness. The interval between the Lower Jefferson sand and Rhoda Creek marker shows local variations in thickness northward along the line of section. The Union Valley interval thickens southward with the base to the Union Valley-Cromwell and Jefferson sands being subparallel with the Rhoda Creek marker bed. As the Union Valley interval thins northward, progressively older sand bodies pinch out (for example, these depositional pinchouts are apparent in the Union Valley-Cromwell between wells 25 and 26). The Upper Jefferson demonstrates analogous behavior between wells 26 and 16. The Union Valley interval thickens significantly between wells 9 and 24 in the Union Valley-Cromwell zone, with the Jefferson sands maintaining a fairly consistent thickness. This abrupt increase of interval thickness is coincident with the down-to-the-south Allen Fault (Plate 1), a circumstance strongly suggestive of syndepositional tectonism. The Union Valley Limestone is sporadic along the line of section.

Cross-Section E-E'

Cross-section E-E' is a south-to-north section that extends from T.4 N., R10 E., to T.6 N.,R.10 E.(Plate 5). This section also includes an electrical log (well), common with Visher's and others' (1971) Cherokee Group cross-section. The Caney Shale is consistent in thickening with the Rhoda Creek Formation; both thicken southward. The Lower Jefferson sands vary locally, with the Upper Jefferson generally thinning northward. Part of this thinning may be due to truncation beneath the overlying Union Valley-Cromwell zone. The base of the Union Valley-Cromwell is relatively sharp and subparallel with the Rhoda Creek marker bed. The Union Valley-Cromwell thickens primarily at the expense of overlying shales in the southern portion of the section but at the expense of both underlying and overlying strata in northern portions. It should be noted that the northern portion of the section transverses the Calvin Anticline. The Wapanucka Limestone thins northward, reflecting the influence of the Atokan unconformity surface.

Cross-Section F-F'

Cross-section F-F' is a south-to-north section that extends from T.4 N., R.11 E. to T.5 N.,R.11 E. (Plate 5). This section includes the type log (well 13), and an electrical log (well 34) also common with Laudon's (1958) cross-section. Laudon did not recognize the faulted Wapanucka Limestone in this well. The Caney Shale and Rhoda Creek Formations are of fairly consistent thickness. The Union Valley interval also thickens southward. The base of the Union Valley-Cromwell is subparallel to marker beds in the underlying strata. The Union Valley-Cromwell consists of multiple stacked sand bodies, with the Union Valley Limestone gradational into the underlying Cromwell at some places. The Wapanucka Limestone thickens southward.

Geometries, Stratigraphic Cross-Sections

As illustrated by stratigraphic cross-sections, facies geometries typically have the following characteristics:

1. The Jefferson sands are latteraly extensive.
2. The Union Valley Limestone-Cromwell Sandstone thickens primarily at the expense of overlying shales.
3. The Union Valley Limestone is gradational with the underlying Cromwell Sandstone.
4. The evidence inspected led to the conclusion that sandstone bodies are enclosed in marine shales.

Descriptions of Cores

Six cores of the Union Valley Formation were examined for lithology, composition, and sedimentary structures. Two of the six cores were from wells in the study area; locations of wells are given in Table 2. Figure 21 is a map of cored-well localities in relation to the study area. Petrologic logs and composite core photos are in Appendices A and B respectively. Each of the cores examined contains diagnostic criteria that aided in the interpretation of paleoenvironments.

Austin and Emrick, No. 1 Steele

The Austin and Emrick, No. 1 Steele is in the SW NW SE, Sec. 30,T.9 N.,R.9 E., in the Adams Field, Hughes County. The interval cored was 3352-3411 feet, based on core-to-log calibrations. The condition of the core is excellent.

TABLE II

CORE LOCATIONS

Operator	Farm	Spot	Sec.,	Twn.,	Range
Austin and Emrick	No. 1 Steele	SW NW SE	30	9N.	9E.
Austin and Emrick	No. 2 Bunny Long	NE SW SE	30	9N.	9E.
Midwest	No. 1 H. Pierce	C NE NW	12	5N.	9E.
NCRA	No. 1 Johnson	SW SE	31	3N.	9E.
Pan American	No. 1 D. Roberts	E/2 NE SE	32	2N.	8E.
Delaney	No. 1 Foster	NW NE NE	17	5N.	10E.

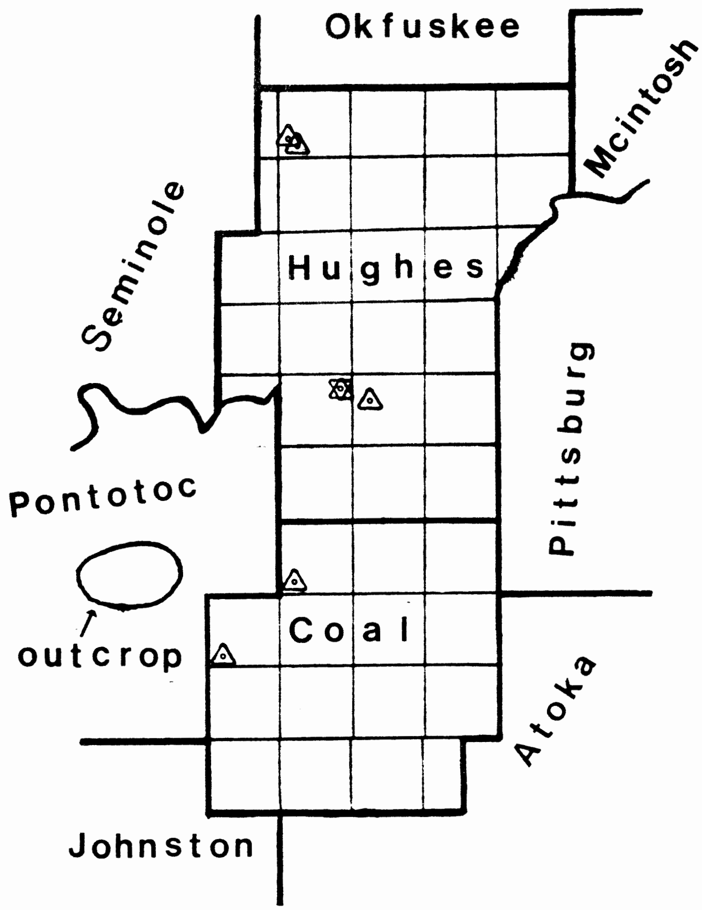


Figure 21. Union Valley Outcrop and Core Locality Map.

The Union Valley Limestone is not in the No. 1 Steele. The Cromwell Sandstone consists of three coarsening- upward sandstone units separated by marine shales. The Cromwell appears to be unconformable on the underlying Rhoda Creek Formation. The cored interval contains the uppermost sandstone body present, a shale, and the upper portions of the middle sandstone body.

The lowermost two feet of the core, 3409-3411 feet, are the uppermost part of the middle sand. Grain size decreases upward from medium- to fine-grained sand with a corresponding increase in evidence of bioturbation. Small-scale trough cross-bedding is in the lower one foot of this interval. Burrow types are diverse and consist of both vertical and horizontal morphologies. An excellent specimen of Chondrites is at 3409.2 feet (Figure 22).

A black marine shale between 3400 and 3409 feet separates the upper and lower sand bodies. Significant features of this interval include a pyritized gastropod in a vertical position and siderite clasts at 3406 feet (Figure 23). The shale is gradational with the overlying sand body.

Strata between 3380 and 3400 feet consist of a coarsening-upward interval of siltstone and very fine-grained to fine-grained sandstone. This strata are characterized a pervasively-bioturbated muddy sand to a moderately bioturbated sandstone (Figure 24). A rounded clay clast is at 3380.5 feet.

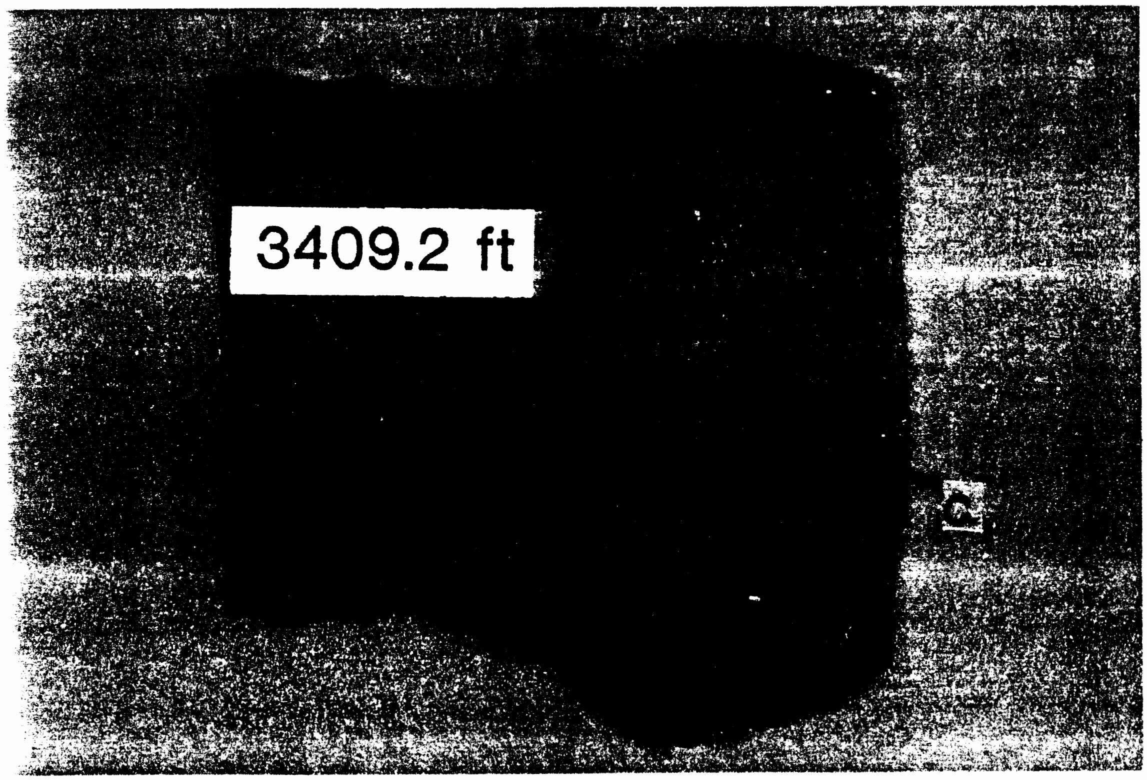


Figure 22. Occurrence of Chondrites (C), in the Austin and Emrick, No. 1 Steele.

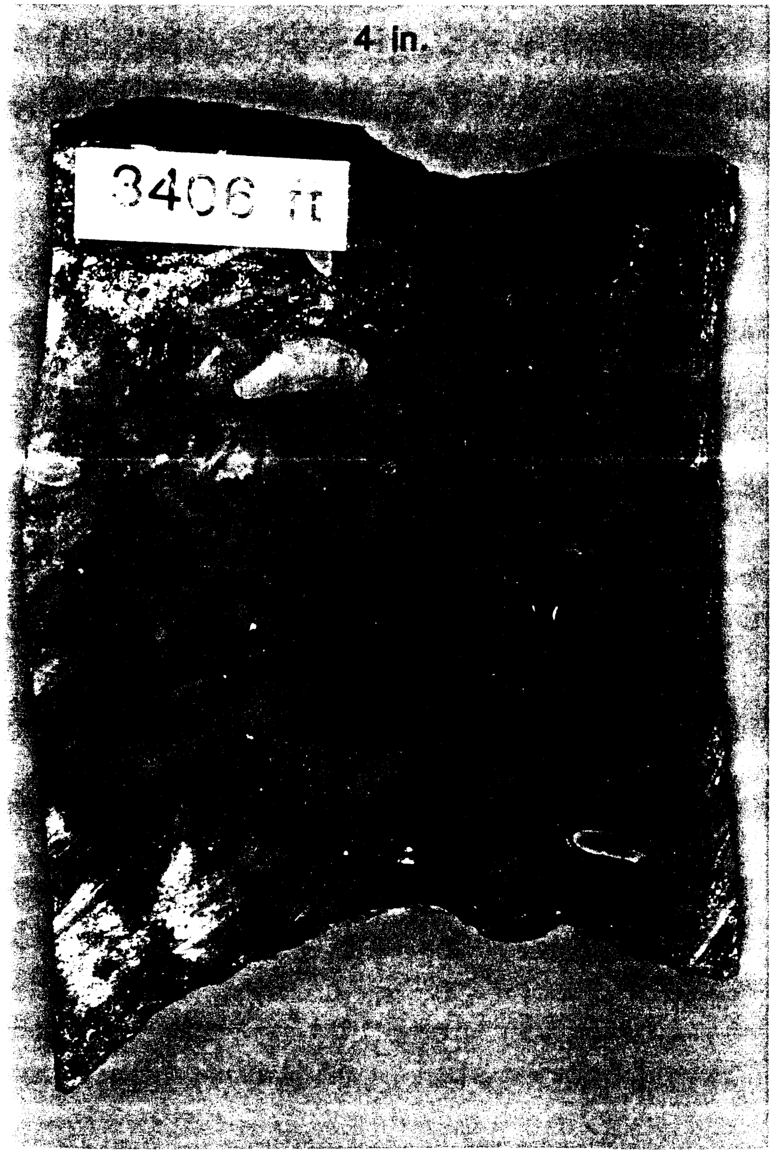


Figure 23. Siderite Clasts in Marine Shale, in the Austin and Emrick, No. 1 Steele.

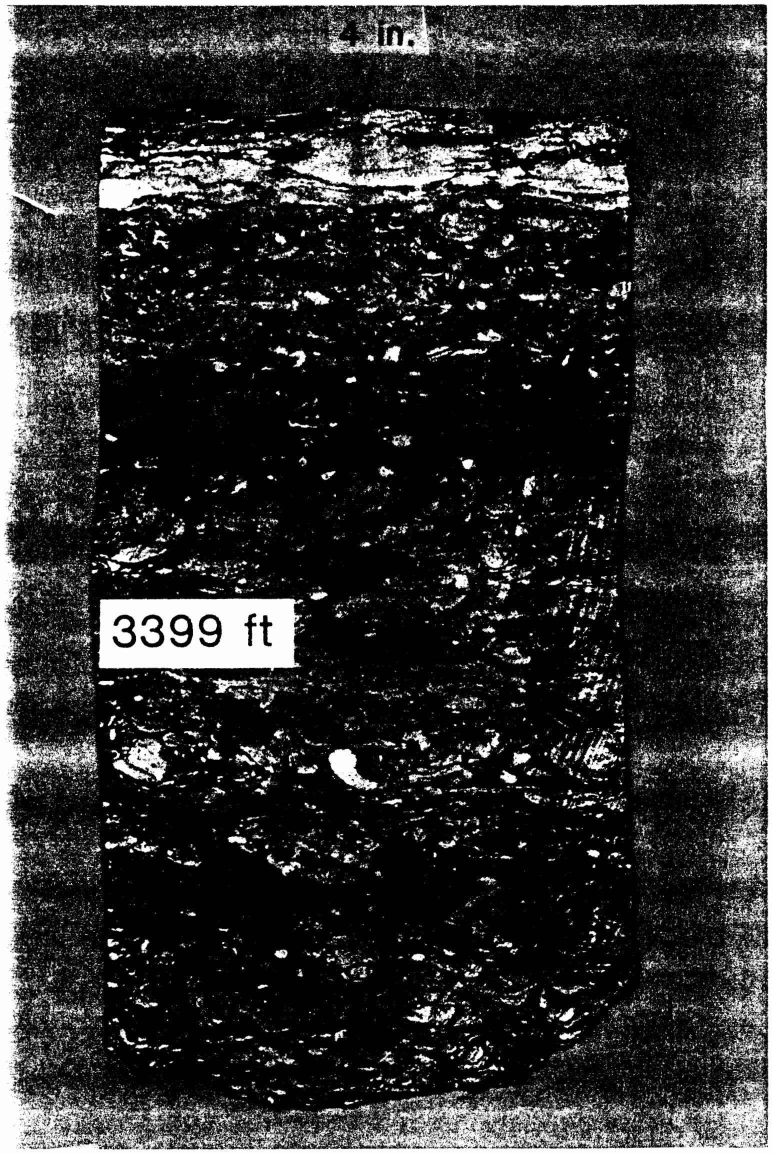


Figure 24. Pervasively Bioturbated Muddy Sandstone, in the Austin and Emrick, No. 1 Steele.

Strata between 3373 and 3380 feet are fine-grained, slightly to moderately bioturbated sandstone (Figure 25). Several oxidation bands are in this interval; they are interpreted as evidence of recent oxidation of unstable constituents rather than as evidence of subaerial exposure, as witnessed by their increase in abundance and areal extent after core slabbing operations were concluded.

Sedimentary structures generally are well preserved from 3352 to 3373 feet. Strata in this interval contain horizontal bedding, trough cross-bedding, fluid-escape structures, ripple lamination, and are dominantly non-bioturbated (Figure 26). Hummocky cross-bedding may also be present (Figure 27). Stylolites are associated with organic matter from 3361 to 3369 feet; in addition, from 3370-3371 feet color grades from gray sandstone below to brown sandstone above.

The No. 1 Steele core is interpreted to have been deposited in a shallow marine setting, possibly as a series of stacked ridge complexes. Significant paleoenviromental indicators include burrows/bioturbation, glauconite, and invertebrate fossils. A coarsening-upward sequence is evident from the core and electric-log sequences (Appendces A and B). The lower portion of the upper sand body may have originated as a bioturbated shelf facies that coarsened upward into inter-ridge, ridge margin, and central ridge facies, based on similar facies relationships observed by

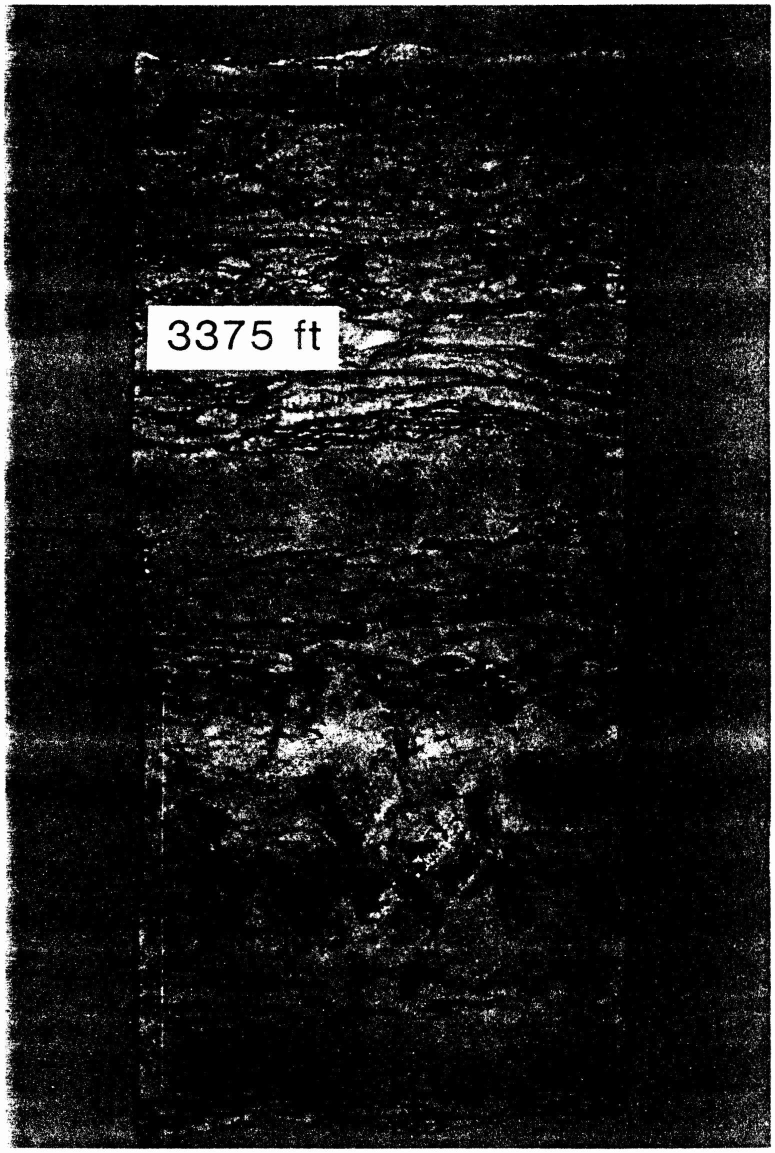


Figure 25. Burrowed Sandstone in the Austin and Emrick, No. 1 Steele.

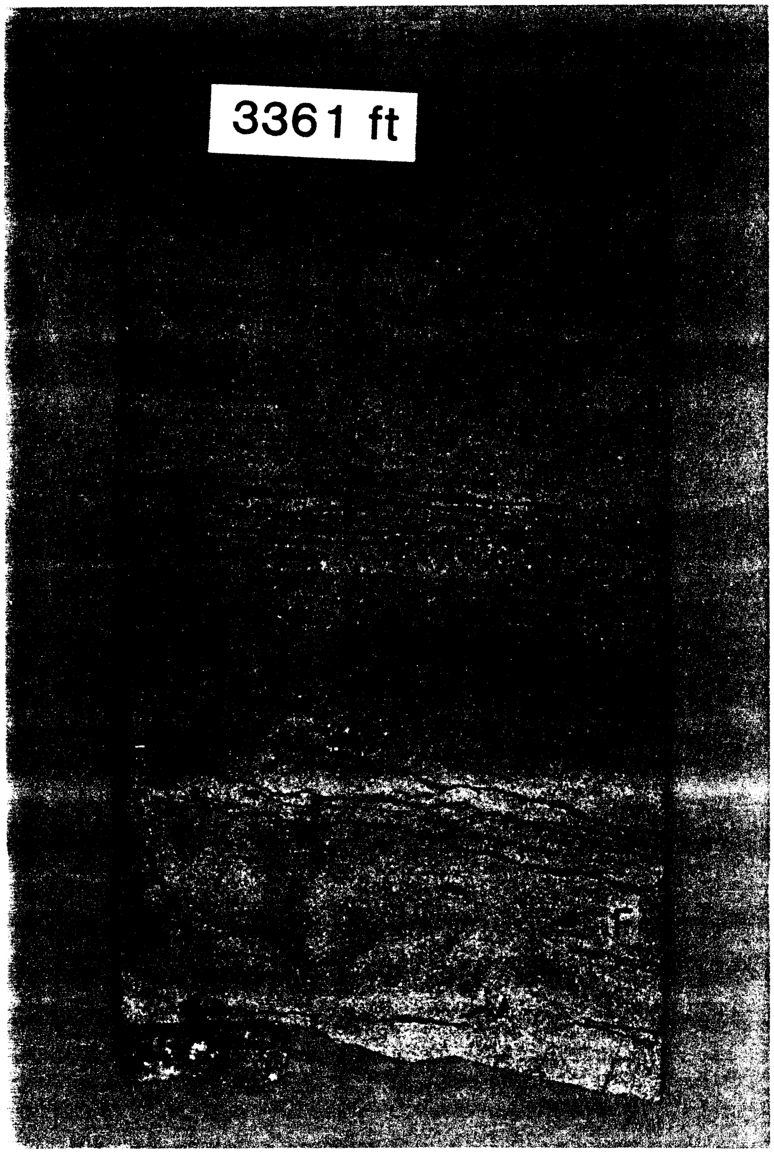


Figure 26. Ripple Lamination and Fluid Escape Structure (F), in the Austin and Emrick, No. 1 Steele.

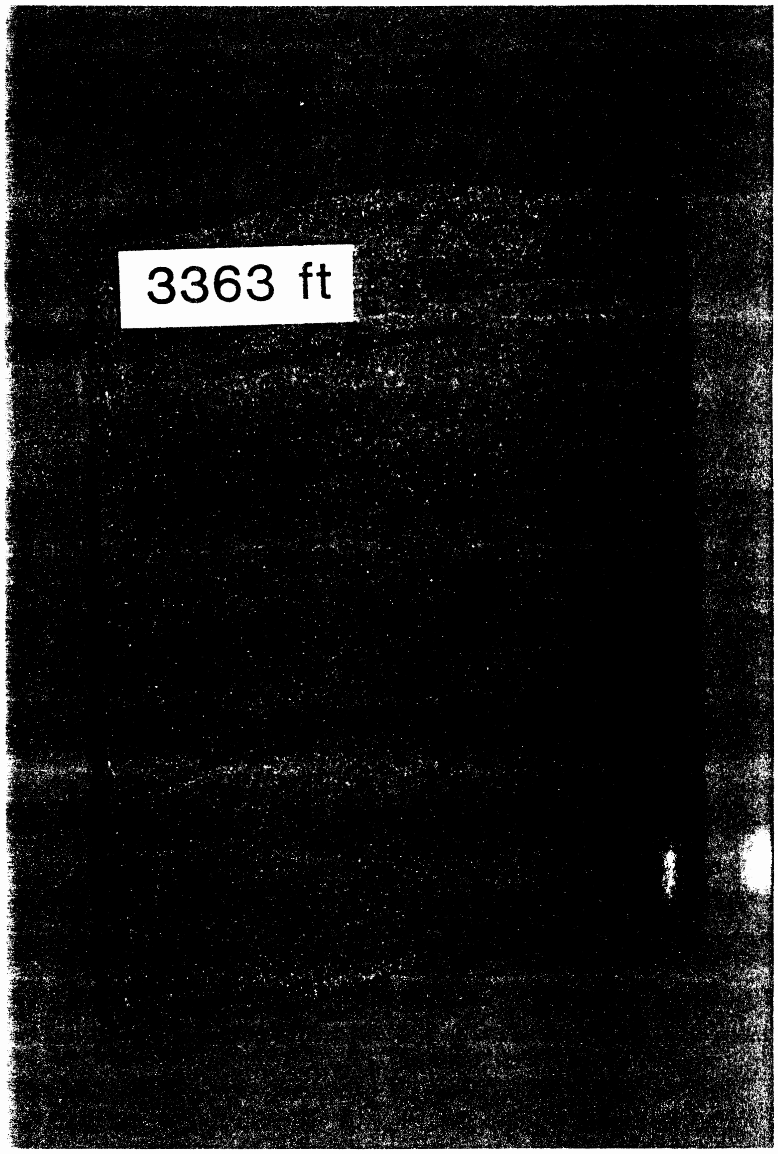


Figure 27. Possibe Hummocky Cross Stratification, in the Austin and Emrick, No. 1 Steele.

Tillman and Martinsen (1984) in the Shannon Sandstone of Wyoming.

Austin and Emrick, No. 2 Bunny Long

The Austin and Emrick, No. 2 Bunny Long is located in the NE SW SE, Sec. 30, T.9 N., R.9 E., in the Adams Field, Hughes County. The geophysical log was unavailable for core-to-log calibrations. Reported core depths are 3331-3373.5 feet; they are assumed to be correct. Based on comparative lithology, excellent correlation exists with the upper sandstone of the core from the Austin and Emrick, No. 1 Steele, described above.

Strata from 3358-3372 feet are brown, fine-grained sandstone with minor evidence of bioturbation. Sedimentary structures include planar bedding, massive bedding, small-scale trough crossbedding, and possibly hummocky crossbedding. Burrows are both horizontal and vertical (Figure 28).

Soft-sediment deformation of a flowage-like configuration extends from 3356.5-3358 feet (Figure 29). A large stylolite is located at 3356 feet. A fine-grained trough-crossbedded interval occurs from 3355 to 3356 feet. Burrows, most likely of the Skolithos ichnofacies are perpendicular to crossbedding surfaces (Figure 30).

Strata from 3331 to 3355 feet are coarsening-upward, fine-grained to medium-grained sandstone. Sedimentary

Figure 28. Vertical and Horizontal Burrow Morphologies, in the Austin and Emrick. No. 2 Bunny Long.

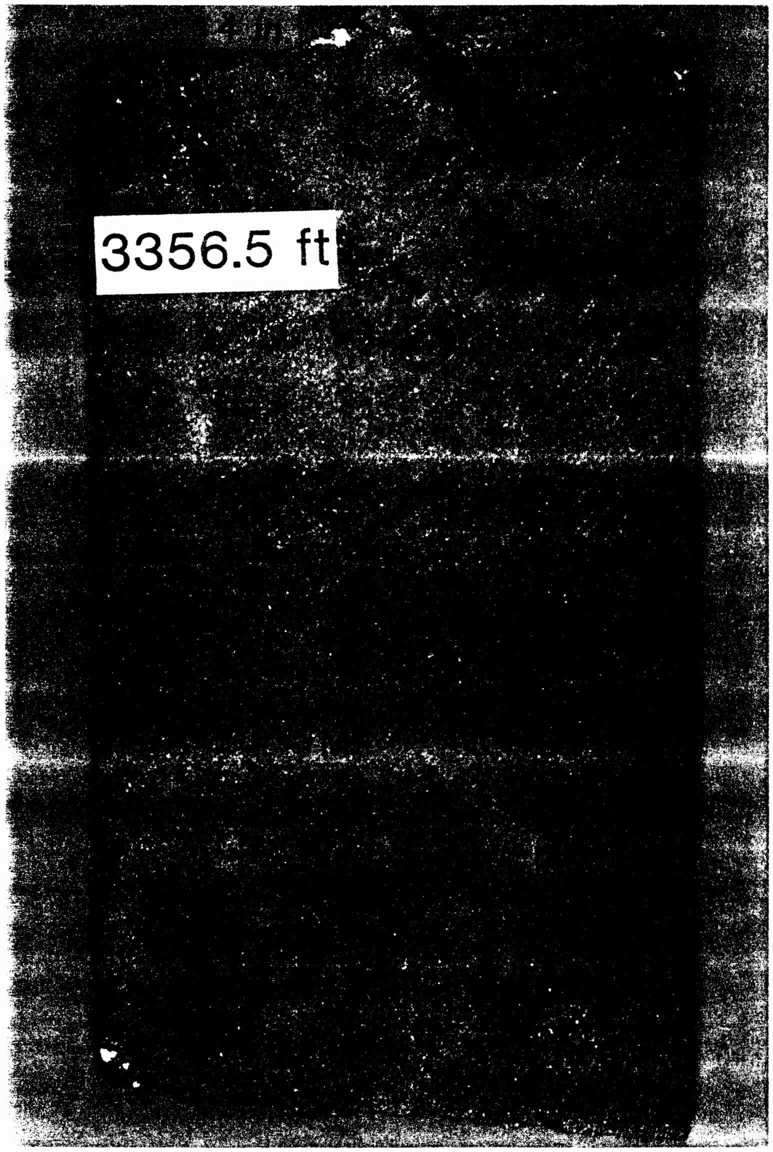


Figure 29. Soft Sediment Deformation and Motteling (M), in the Austin and Emrick, No. 2 Bunny Long.

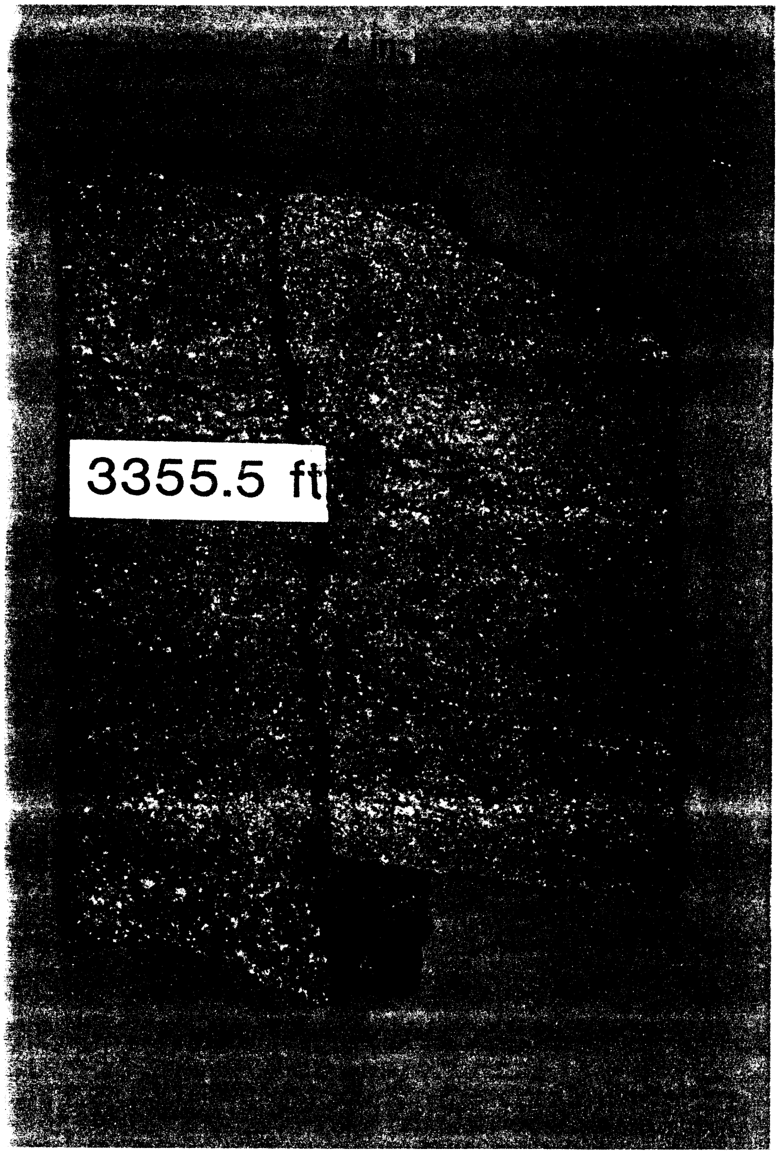


Figure 30. *Skolithos* Burrows Perpendicular to Cross Bedding Surface, in the Austin and Emrick, No. 2 Bunny Long.

structures include massive bedding, small-scale trough crossbedding, ripple lamination, and bioturbation structures (Figures 31 and 32). Shale clasts are in the sandstone from 3342 to 3344 feet, with a layer of shell hash containing crinoid stems and possibly brachiopods at 3341 feet. Color appears to be related to calcium-carbonate cement, with relatively heavily cemented intervals being gray and lightly cemented intervals appearing brown. The upper seven feet (3331-3338), is generally massive and extremely friable.

The Cromwell Sandstone in the No. 2 Bunny Long core is interpreted as having been deposited in a shallow marine, open-shelf setting. Supportive evidence includes burrows/bioturbation, glauconite, invertebrate marine fossils (echinoderm plates, crinoid stems, brachiopods, and gastropods), and possible hummocky cross-stratification. Isopachous radial-calcite cement, also suggestive of a marine depositional enviroment, is present in small amounts. Ridge-margin and central-ridge facies may compose the sandstone in the No. 2 Bunny Long, based on comparison with similar facies in the No. 1 Steele core.

Midwest Oil Corporation, No. 1 H. Pierce

The Midwest, No. 1 H. Pierce is in the C NE NW, Sec. 12, T.5 N., R.9 E., in the South Atwood Field, Hughes County. The No. 1 H. Pierce is a dry hole that was completed in June 1965. The interval cored was 4328-4339 feet;

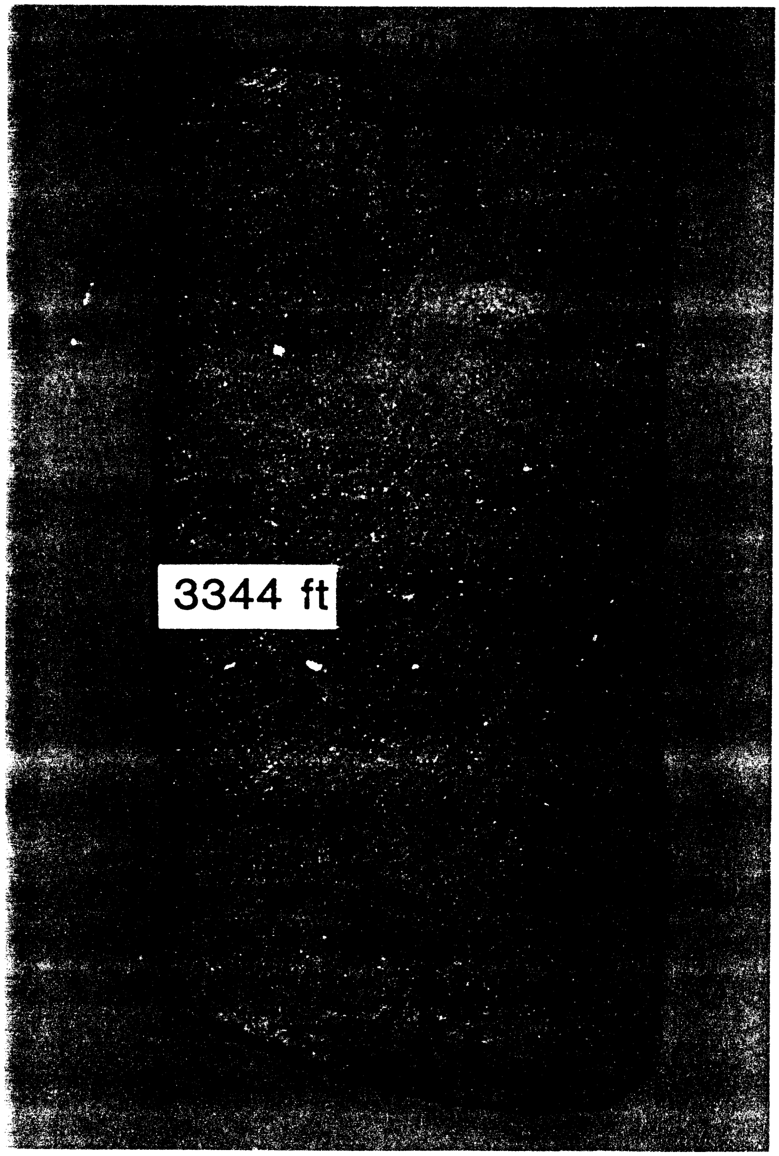


Figure 31. Shale Clasts and Drapes in the Austin and Emrick, No. 2 Bunny Long.

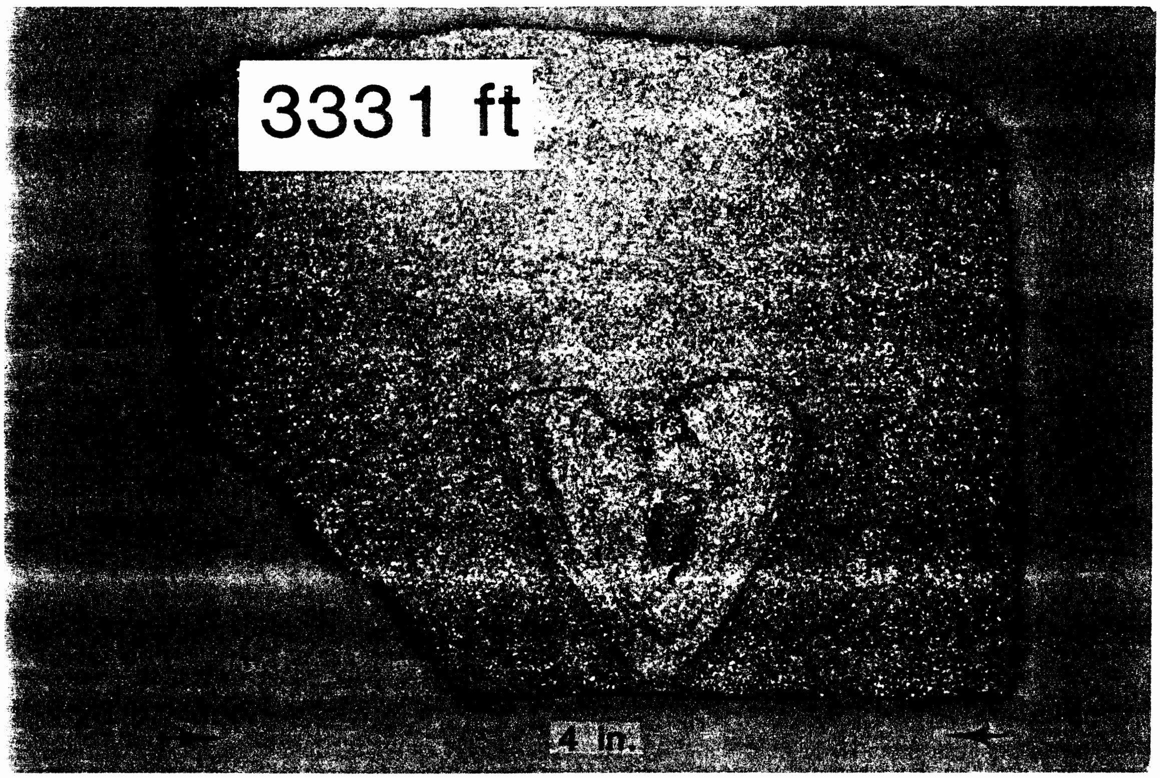


Figure 32. Plug Shaped Burrow (P), in the Austin and Emrick, No. 2 Bunny Long.

it consists of the Lower Jefferson zone of the Union Valley Formation. Although the sandstone was not mapped in this study, the electric log of the No. 1 H. Pierce was incorporated in stratigraphic cross-sections C-C'and D-D'.

The Lower Jefferson consists predominantly of gray, medium-grained sandstone containing abundant clasts of black shale. The lowermost foot of the core is black shale containing siderite concretions and plant remnants. Sedimentary structures in the sandstone primarily are of trough crossbedding with a notable lack of bioturbation structures. In addition to shale clasts, an abraded clast of tabulate coral is at 4334.5 feet (Figure 33)(Ritter, 1990).

Indicators of paleoenvironments are suggestive of deposition in a shallow marine setting, possibly associated with storm events. Although features attributable to burrowing were not observed, invertebrate faunal debris and glauconite are supportive of an interpretation of marine environment. The abraded coral clast and shale clasts imply that deposition was influenced strongly by processes of lateral mechanical transport. The open-hole geophysical log of the No. 1 H. Pierce (see Appendix A), suggests a relatively sharp base. Log signatures of this motif are generally regarded as being characteristic of high energy depositional events, similar to those proposed for the Pierce core.

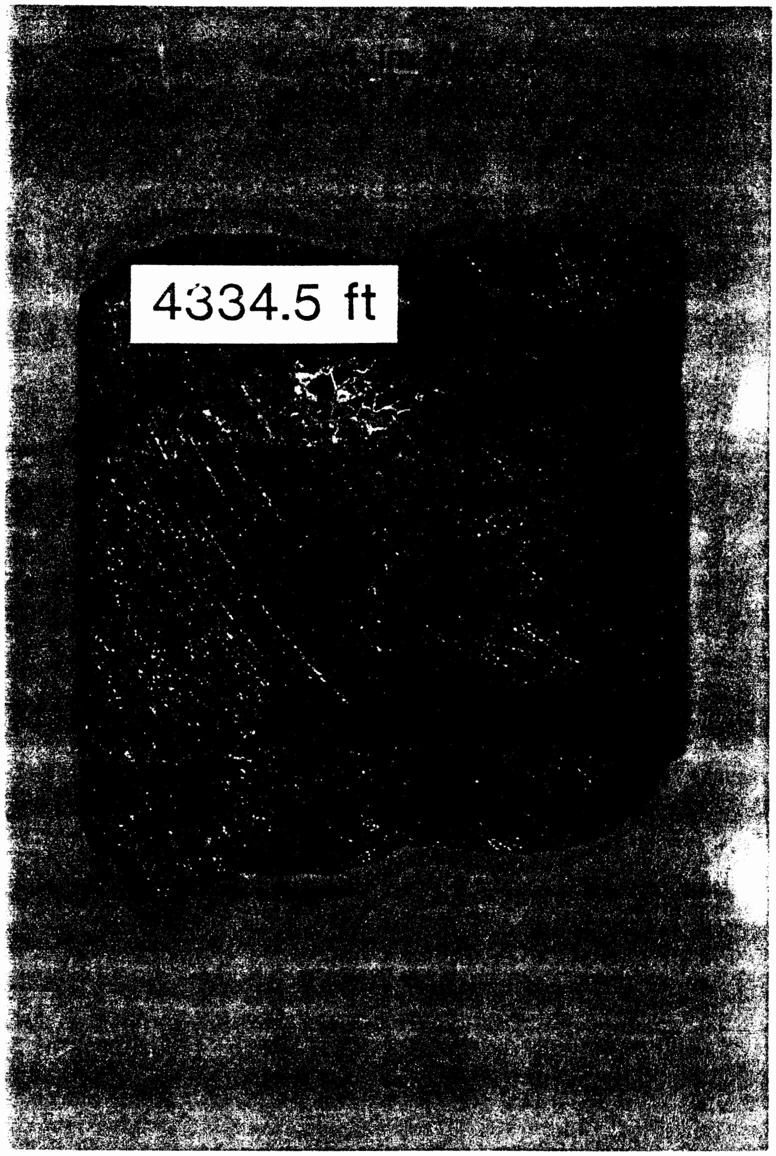


Figure 33. Shale Clasts and Abraded Coral Fragment (CF), in the Midwest, No. 1 H. Pierce.

National Cooperative Refinery Association, No. 1 Johnson

The NCRA, No. 1 Johnson is in the SW SE, Sec. 31, T.3 N., R.9 E., in the Southeast Lula Field, Coal County. The No. 1 Johnson was completed as a wildcat discovery in September, 1975, in the Cromwell Sandstone. The initial potential flow (IPF) of the well was 126 barrels of oil per day (BOPD) and 370 barrels of water per day (BWPD) from perforations at 3934-3978 feet. Flow tubing pressure was 100 psi (pounds per square inch) through a 22/64 inch choke.

The interval cored was 3955-4014 feet. The upper and lower contacts of the Union Valley Formation are not in the cored interval. The Union Valley Limestone is not in the No. 1 Johnson; only the Cromwell Sandstone is present.

Strata between 4003 and 4014 feet are bioturbated, slightly muddy, fine-grained sandstone. Chert nodules are particularly well developed at 4003.5 feet. The interval from 3991.5-4003 is made up of alternating irregular laminae of siltstone, fine-grained sandstone and dark shale; it also contains a four-foot interval of burrowed fine-grained sandstone (Figure 34). Burrows mostly are vertical or of the curving-tube morphology.

Strata between 3955 and 3991.5 feet consist primarily of fine- to medium-grained sandstone containing abundant bioturbation structures. Sedimentary structures generally are poorly preserved due to bioturbation, and they

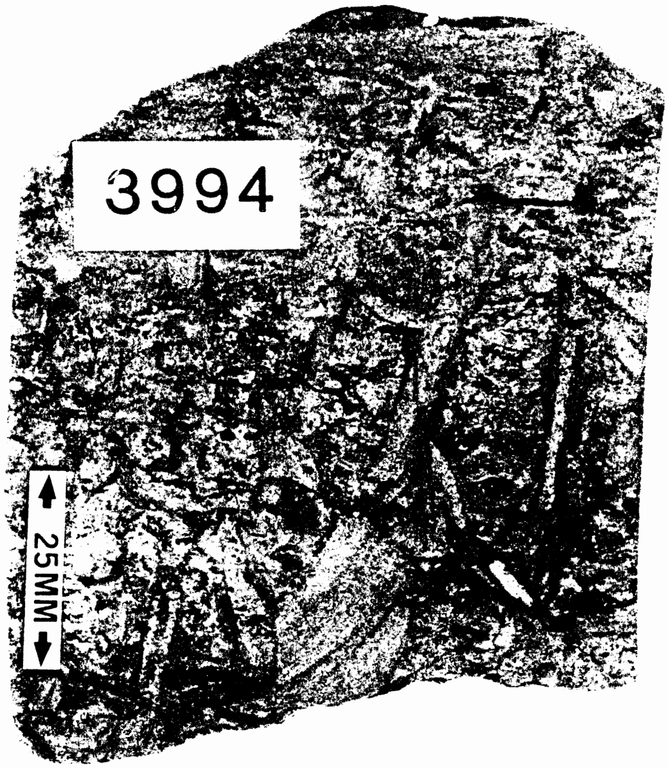


Figure 34. Burrowed Sandstone, in NCRA, No. 1 Johnson.

principally are small-scale trough crossbedding (Figure 35). Impressions of leaves are present at numerous places. Minor amounts of skeletal debris are also present. Faults are at 3980 feet (Figure 36), and 3984 feet. Shelton (1988) suggested that faulting occurred shortly after deposition and prior to significant lithification.

The No. 1 Johnson core is interpreted as having been deposited in a shallow marine setting. Criteria suggestive of marine conditions include glauconite, invertebrate marine fossils, and burrow/bioturbation features. Remnants of wood and plants are relatively common in comparison with previously discussed cores. Shelton (1973) documented the occurrence of plant material in a variety of shallow-marine settings.

Pan American Petroleum Corporation, No. 1 D. Roberts

The Pan American, No. 1 D. Roberts is in the C E 1/2 NE SE of Sec. 32, T.2 N., R.8 E., Coal County. The No. 1 D. Roberts is a 4503-foot dry hole completed in May, 1965. The cored interval was 4266-4417 feet, based on core-to-log calibrations. Completion attempts from 4403-4407 feet and 4364-4366 feet were uneconomic following treatments.

The interval from 4390-4417 feet is predominantly brown, muddy, bioturbated, fine-grained sandstone. Sedimentary structures are mostly trough cross-bedding, but

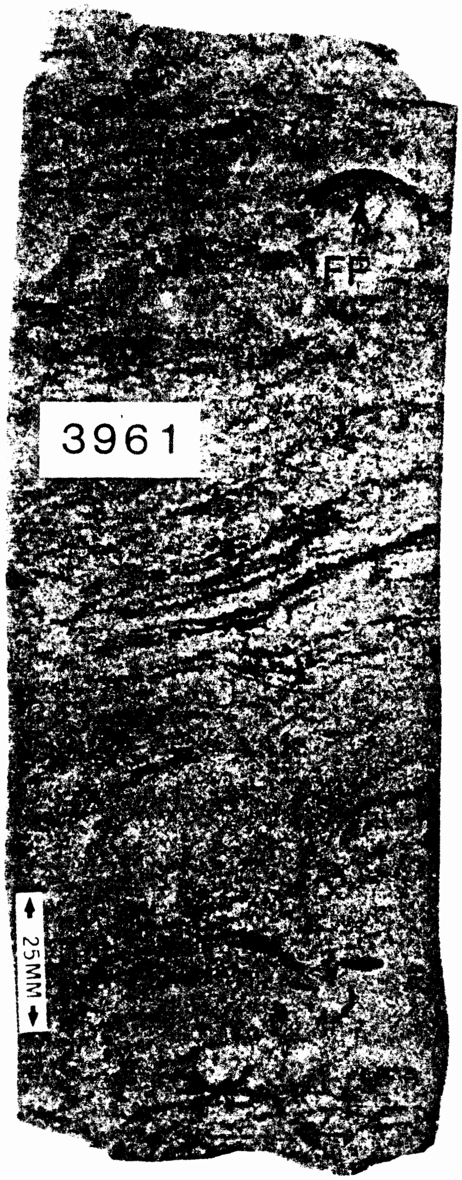


Figure 35. Small Scale Trough Crossbedding (T), in the NCRA, No. 1 Johnson. Also Note Inverted Fossil Fragment (FF).

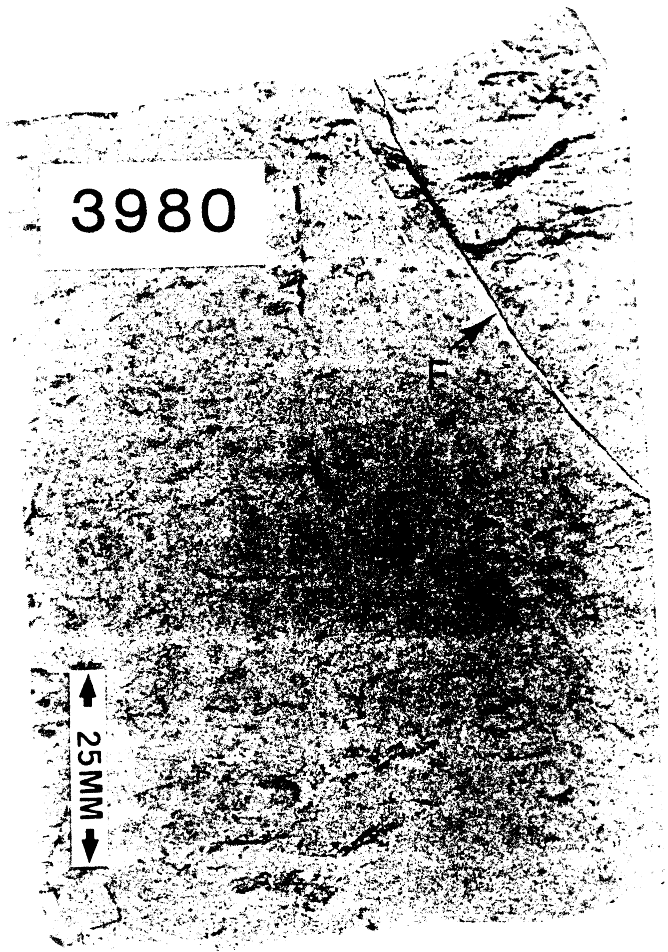


Figure 36. Possible Syndepositional
Fault (F), in the
NCRA, No. 1 Johnson.

generally have been modified by biological processes. Coal and woody fragments are throughout the interval.

A black shale extends from 4387.5-4390 feet. Strata from 4358-4387.5 feet are of muddy, bioturbated, very fine to fine-grained sandstone, containing a few intervals of thin black shale and interbedded sandstone and shale. Carbonaceous detritus is at selected localities, as illustrated in Figure 37. Fossiliferous black shale containing chert-filled gastropods makes up the section from 4349-4358 feet.

Strata from 4329-4349 feet are consistent with previously described sandstone intervals. Very fine-grained sandstone to siltstone interbedded with black shale characterize the interval from 4320.5-4329 feet. Small scale trough cross-bedding is in the coarser portions. Strata between 4298-4320.5 feet are similar to previously described bioturbated sandstones (Figure 38). A black silty shale containing coal-like material occurs from 4296.5-4298 feet. The upper portion of the core, 4266-4296.5 feet, consists of black calcareous shale with abundant crinoid stems.

The No. 1 D. Roberts core is interpreted as being representative of multistoried shallow marine sand bodies separated by deeper marine shales. The resistive calcareous shale overlying the bioturbated sands of the Cromwell may be a shaly facies of the Union Valley Limestone. Invertebrate fossils, glauconite (with minor amounts of isopachous

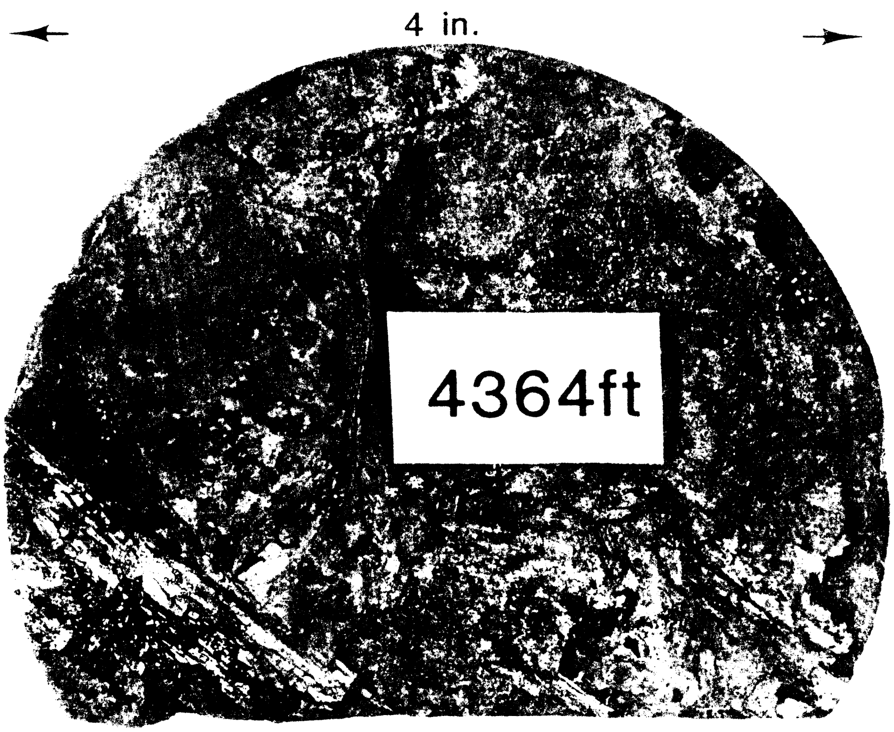


Figure 37. Carbonaceous Debris (C), in the Pan American, No. 1 Roberts

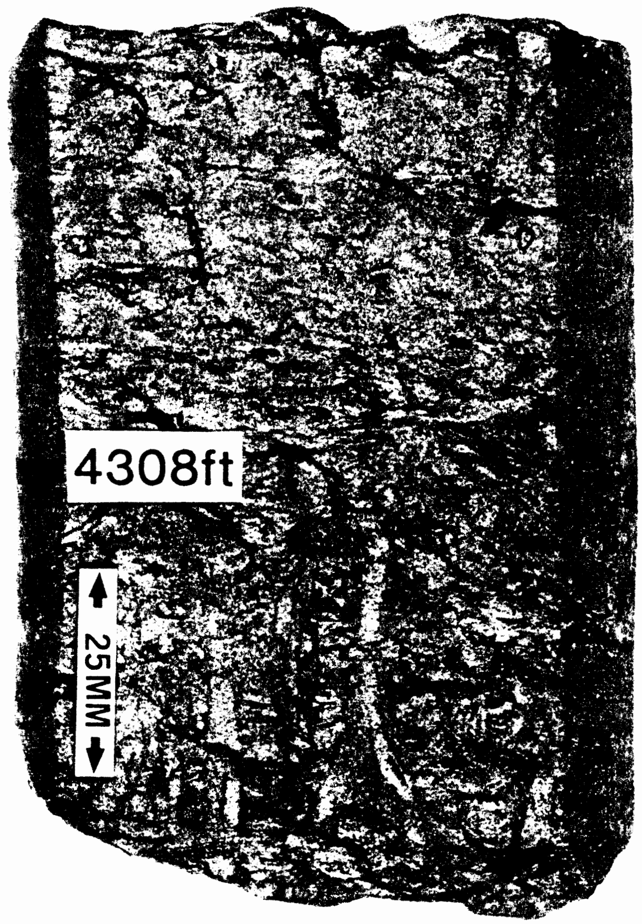


Figure 38. Muddy Burrowed Sandstone in the Pan American, No. 1 Roberts.

calcite cement and ooids observed in thin section) in conjunction with the gross facies relationships present are all indicative of deposition within a shallow-marine setting.

W.A. Delaney, No. 1 Foster

The Delaney, No. 1 Foster is in the NW NE NE, Sec. 17, T.5 N., R.10 E., Hughes County. The No. 1 Foster is a 4613 foot dry hole completed in July, 1939. An open hole geophysical log was not available; reported core depths were 4603-4613 feet. A drill-stem test of the cored interval reportedly recovered 150 feet of mud and 575 feet of salt water in 15 minutes. Additionally, the fresh core smelled like petroleum. The Cromwell reportedly was topped at 4600 feet. The cored interval is assumed to be the upper portions of the Union Valley Formation, based on the significant amounts of calcareous material (Figure 39).

Interval Isopach-Isolith Maps

Isopach Map, Union Valley GIS

A gross-interval isopach map of the Union Valley GIS was prepared (Plate 6). The gross-isopach map demonstrates that the Union Valley GIS is present over the entire study area, thickness ranges from 422 to 691 feet. Gross-isopach

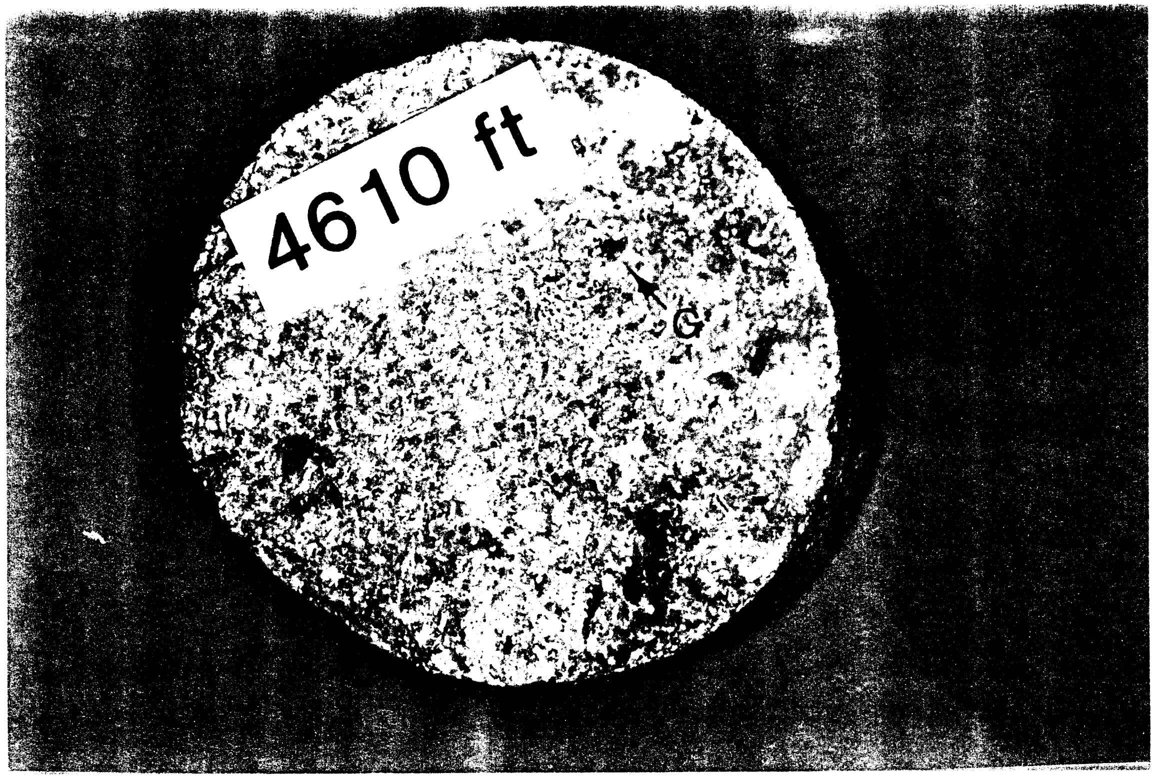


Figure 39. Glauconitic and Calcareous Sandstone, in the W.A. Delaney, No. 1 Foster.

contour lines generally are parallel to strike of the basin (NE-SW). The Union Valley interval is thin over many known anticlinal structural features. A syndepositional fault is inferred along the boundary of T.4 and 5 North. The position of this postulated growth fault corresponds to that of the previously described Allen Fault (see Plate 1). Possible movement has also occured along the Holdenville Fault.

Isolith Map, Union Valley Limestone and Cromwell Sandstone Interval

The gross isolith of the Union Valley-Cromwell (Plate 7) generally reflects patterns similar to those shown in Plate 6. Isolith trends are generally oriented NNE. The Union Valley-Cromwell interval is absent or thin over many documented anticlinal structural features. The uplifted areas along the northern portions of the Holdenville Fault are devoid of sandstone strata. Abrupt thickening in the region of the Allen Fault, reflects patterns shown in Plate 6 and cross-section D-D' (Plate 4). The patterns demonstrated by the Union Valley-Cromwell isolith map are suggestive of a shallow marine 'blanket' sandstone. Although evidence from cores suggests that some deposits may have originated in channels or have been related to storms, linear-bifurcating trends are not particularly evident. Shelton (1973) has documented similar isopach-isolith patterns (i.e. 'blanket') in the Cambrian Franconia Formation.

Interpretations of Paleoenvironments

Criteria diagonistic of shallow-marine shelf facies and processes clearly are present in cores and thin sections examined in this study. Facies geometries illustrated by stratigraphic cross-sections and isopach-isolith maps are less conclusive, but with integration with petropyhsical data, the weight of evidence suggests that the Union Valley Formation was deposited on a broad, tectonically active, subsiding shelf.

Evidence from cores and thin sections consisting of marine fauna, trace-fossil assemblages, sedimentary structures, and authigenic minerals are suggestive of deposition on a storm dominated shelf. Features characteristic of a tide-dominated setting, such as herringbone crossbedding, were not observed in this study. Sedimentation rates are interpreted as having been relatively slow as indicated by the rather large amounts of bioturbation and glauconite, but punctuated by events of rapid deposition, most likely associated with storms.

Facies geometries, as determined from stratigraphic cross-sections and isopach-isolith maps, are suggestive of laterally extensive 'blanket' or sheet-like deposits.

Geometries suggestive of channeling are generally absent, with sandstone bodies enclosed in marine shales.

CHAPTER VI

PETROLOGY AND DIAGENESIS

Introduction

Thirty thin sections obtained from the previously described cores of the Union Valley Formation were examined in this study. The primary purpose of thin-section analysis was to document evidence for aid in the interpretation of paleoenviroments. Discernment of diagenetic overprints was a secondary objective.

Sutherland (1988a) described the Cromwell as being primarily a quartz-arenite. In this study, sandstone facies of the Union Valley were determined to range from quartzarenite to quartz wacke. Thin sections obtained from the W.A. Delaney No. 1 Foster core contained a significant amount of faunal debris.

Composition

Detrital Constituents. Detrital constituents present in significant amounts include monocrystalline quartz, glauconite,fragments of invertebrate fossils, and clayey matrix.

Detrital constituents generally in trace amounts include ooids, polycrystalline quartz, zircon, tourmaline, rutile, leucoxene, plagioclase feldspar, chert, muscovite, and biotite. Detrital matrix prdominately is clayey, although minor amounts of silty matrix are present.

Monocrystalline quartz is the most abundant detrital constituent (greater than 70 percent average). Sphericity of quartz grains ranges from subangular to rounded. Grain size is from very fine to medium. Grain extinction is straight to slightly undulose, indicating a probable plutonic source. Rutile needle inclusions are common in many grains. Polycrystalline quartz is of minor amount in most thin sections. Polycrystalline quartz grains typically have relatively straight boundaries between subcrystals. Grain extinction generally is strongly undulose.

Glauconite is a significant constituent in many samples, being present in trace to 12 percent. Glauconite grains generally are pelletoid; they are interpreted as *in situ* fecal pellets. Granular texture and characteristic bright green color predominates, with some degree of alteration resulting in a brownish green tinge in some grains. Deformation of glauconite commonly results in formation of pseudomatrix (Figure 40).

Invertebrate-shell fragments range from trace to 13 percent. The fragments are of tabulate corals (Figure 41), echinoderms (Figure 42), gastropods (Figure 43), and

Figure 40. Photomicrograph of Glauconite Pseudomatrix (G),(XN, 4605 Ft., Delaney, No. 1 Foster).

Figure 41. Photomicrograph of Tabulate Coral Fragment (XN, 4338.10 Ft., Midwest, No. H. Pierce).

Figure 42. Photomicrograph of Glauconitic Echinoderm Fragment (XN, 3959 Ft., NCRA, No. 1, Johnson).

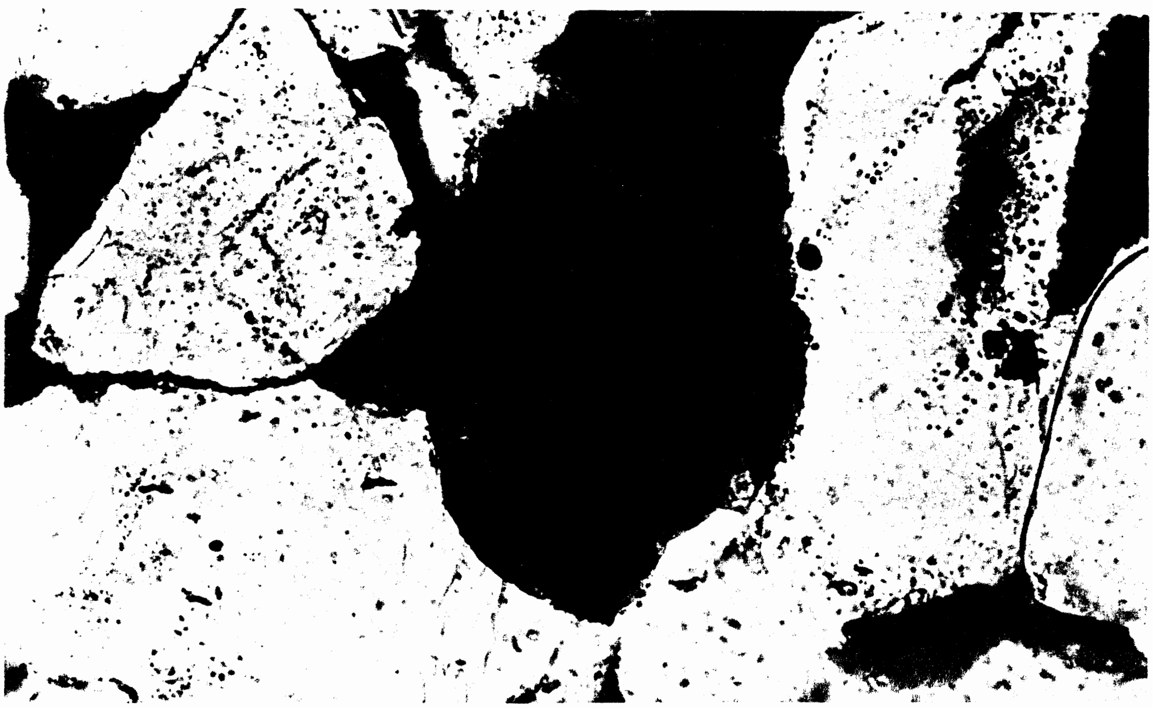


Figure 43. Photomicrograph of Phosphatic Gastropod (XN, 4329 Ft., Midwest, No. H. Pierce).

brachiopods. Shell fragments principally are carbonate, but minor amounts are phosphatic.

Detrital matrix ranges from trace to 24 percent, and is clay-dominated. Composition primarily is illitic, as determined by optical and x-ray diffraction methods. Evidence of recrystallization of illitic matrix to chlorite is common in many samples; the material is difficult to distinguish from glauconitic pseudomatrix. Silty matrix and organic matter are in lesser amounts. Organic material commonly is in laminae.

Authigenic Constituents: Most authigenic constituents are cements and clays. Cements are silicious and carbonate. Authigenic clays primarily are chlorite, illite, and kaolinite.

Silicous cements are chiefly syntaxial quartz overgrowths. Early, intermediate, and advanced stages of cementation by overgrowths were observed. Where advanced, quartz overgrowths resulted in a "welded" appearance (Figure 44), with the original grain texture difficult to differentiate. Original grain texture commonly is detectable from clay dust rims. A minor amount of chalcedony cement is also present. Carbonate cements include siderite (Figure 45), isopachous calcite (Figure 46), poikilotopic calcite (Figure 47), and ferroan dolomite.

Authigenic clays include chlorite, illite, and kaolinite. Chlorite is present in grain coating and pore

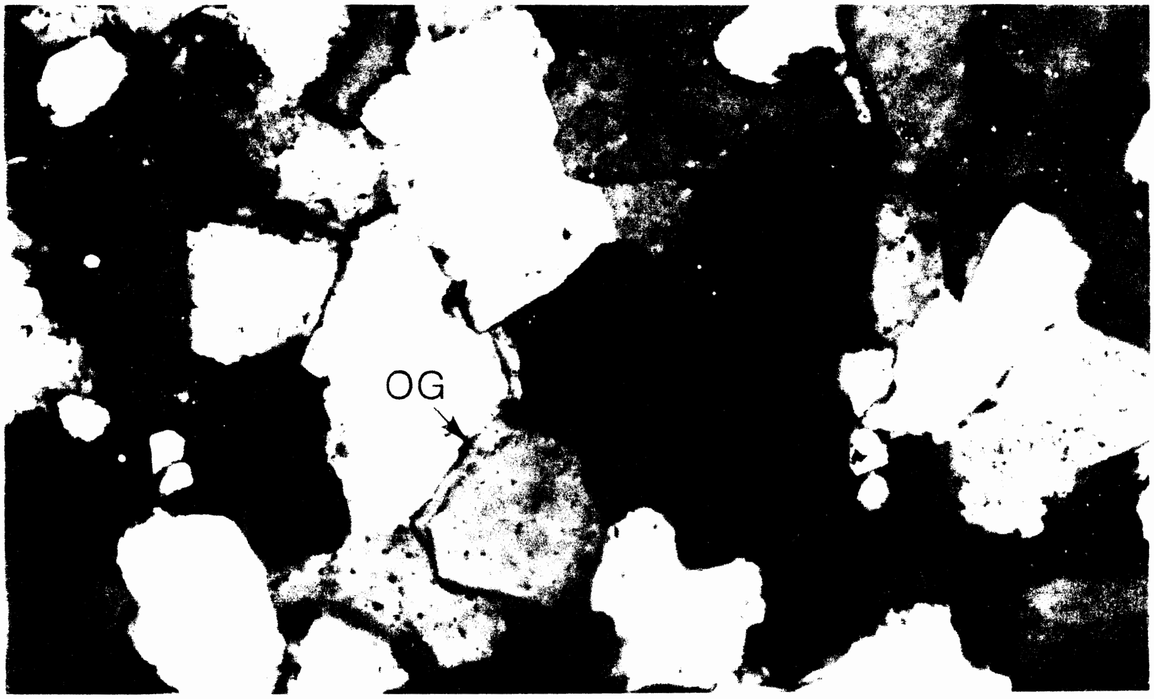


Figure 44. Photomicrograph of Advanced Quartz Overgrowth Cementation (XN, 4605 Ft., Delaney, No. 1 Foster).

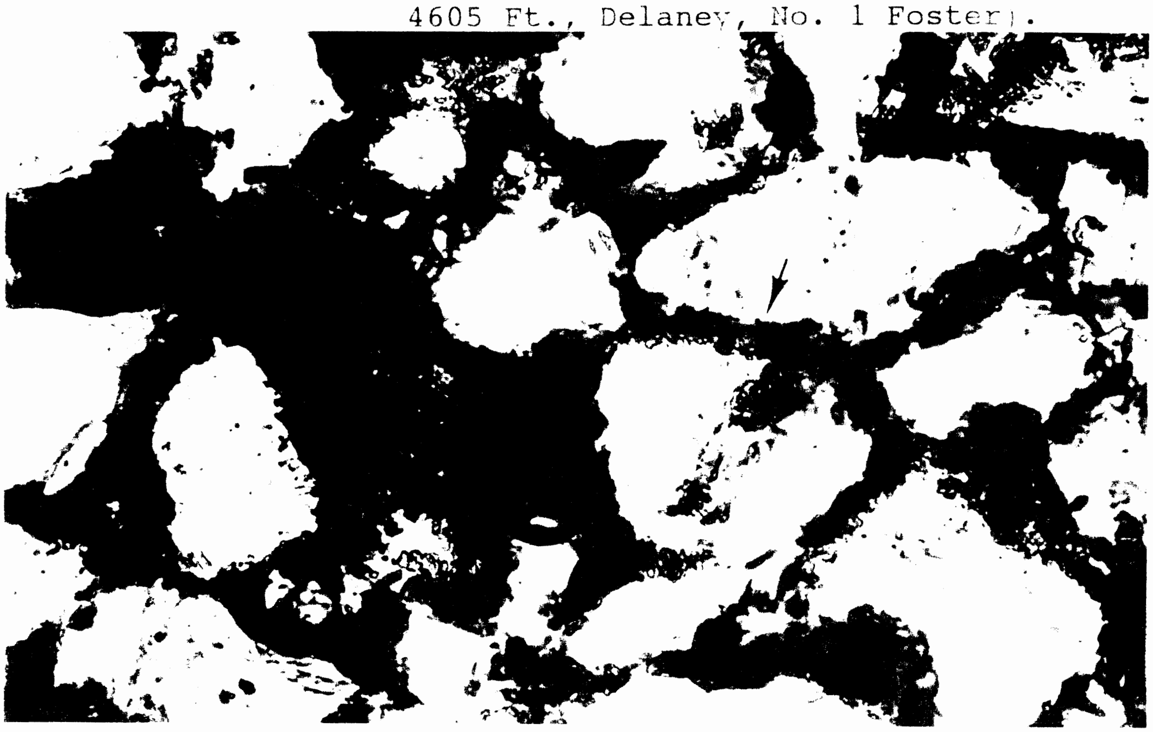


Figure 45. Photomicrograph of Siderite Cement (S), (PP, 3372 Ft., Austin and Emrick, No. 1 Steele).

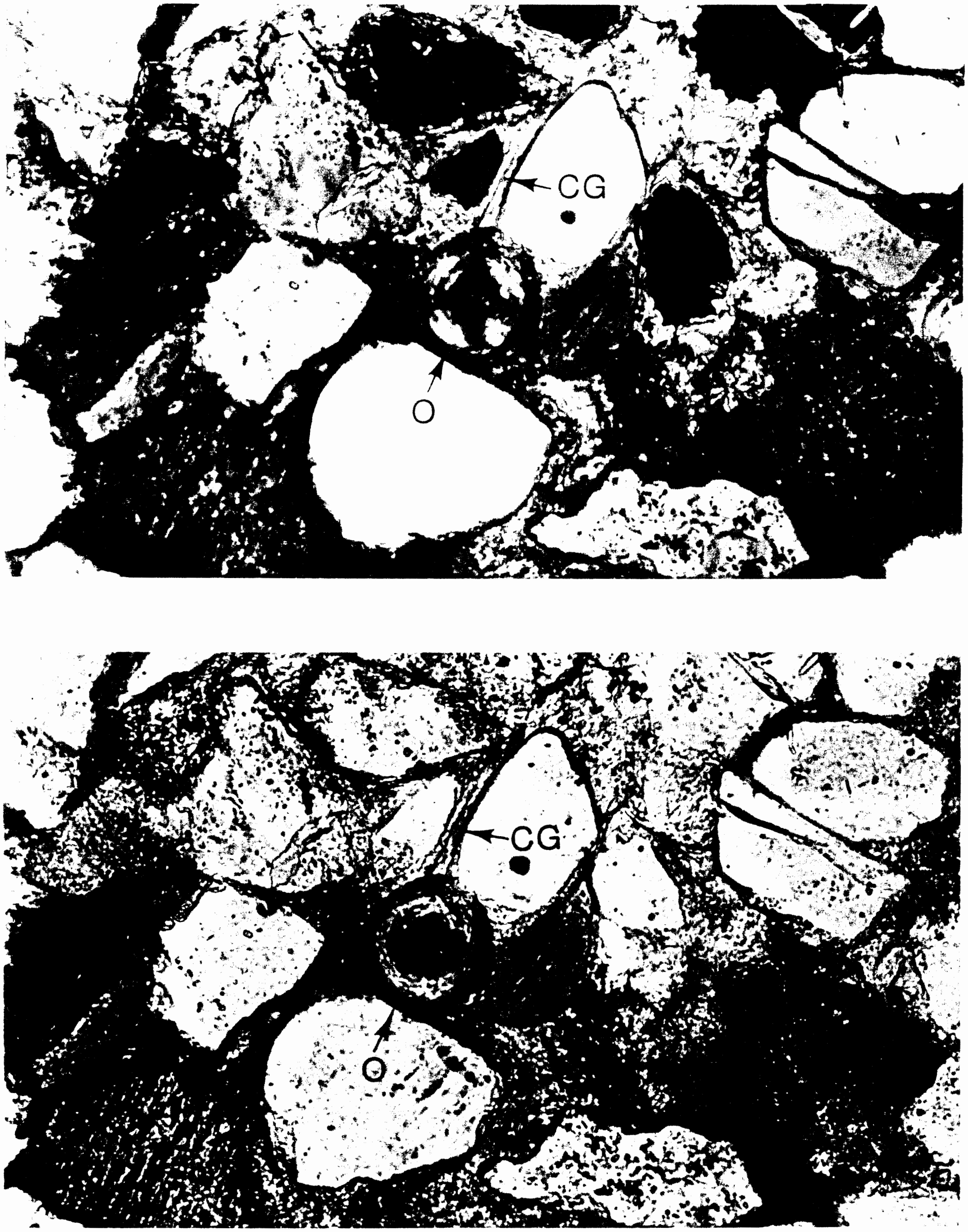


Figure 46. Photomicrograph of Poikilotopic Calcite Cement, Also Note Corroded Quartz Grain (CG) and Ooid (O), (XN upper, PP lower, 4300 Ft., Pan American, No. 1 Roberts).

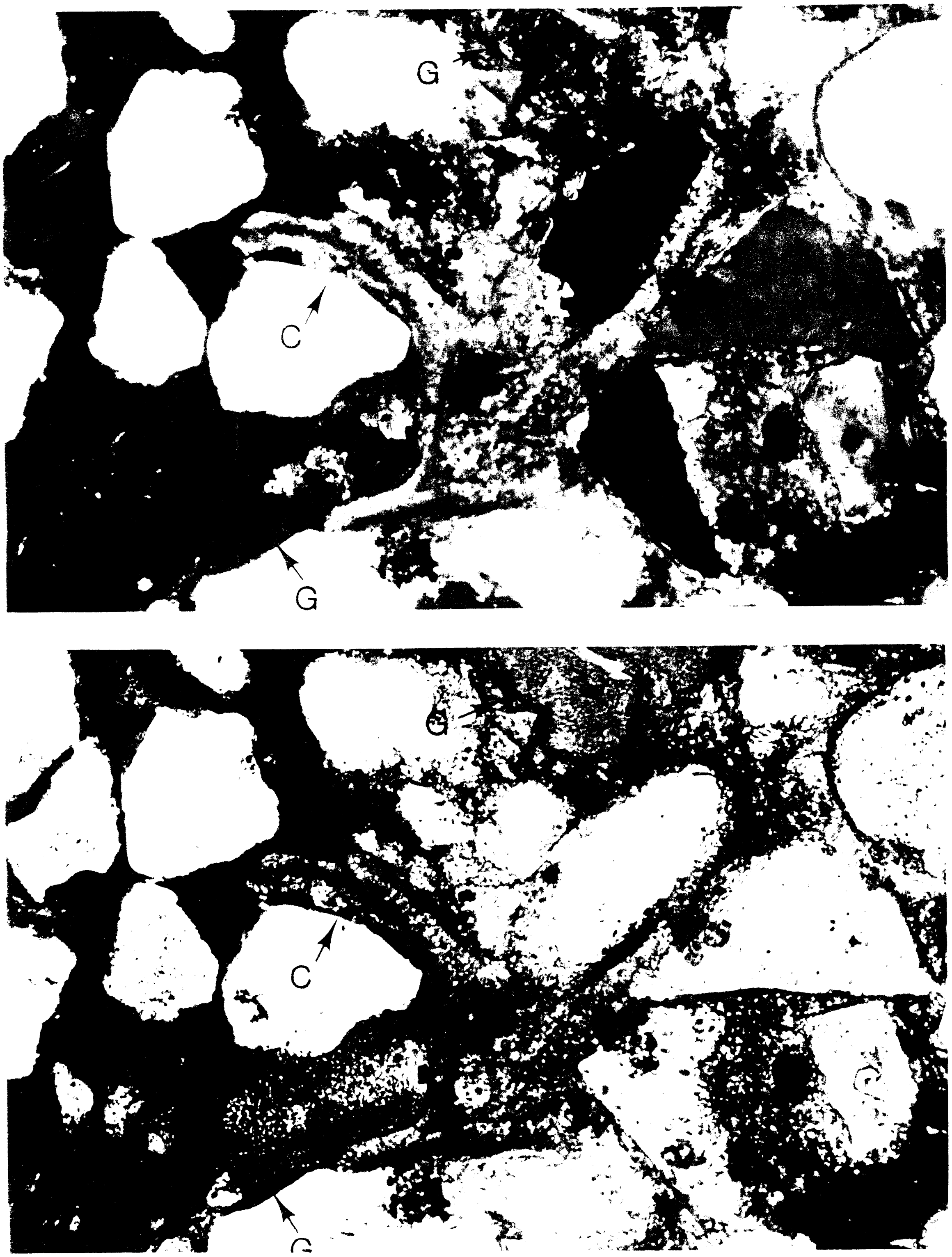


Figure 47. Photomicrograph of Isopachous Calcite Cement (C) and Glauconite (G), (XN upper, PP lower, 4300 Ft., Pan American, No. 1 Roberts)

filling occurrences. Illite commonly lines pores. Kaolinite is restricted to pore-filling positions (Figure 48).

Other authigenic minerals observed are phosphate and pyrite, these minerals occur in trace amounts, associated with pores.

Porosity: Porosity mostly is secondary, developed by dissolution of metastable constituents. Materials dissolved to create porosity were carbonate cements and grains, and detrital matrix. Some of the secondary porosity was owing to shrinkage of glauconite.

Criteria for recognition of secondary porosity include partial dissolution, inhomogeneity of packing, oversized pores, fractured grains, and the aspect of shrinkage. Partial dissolution is detected from remnants of authigenic cements and of detrital matrix. Inhomogeneity of packing and oversized pores are associated with dissolution of carbonate cement. Shrinkage is associated with glauconite. Schmidt and McDonald (1979) identified shrinkage porosity as a consequence of shallow burial.

Diagenetic History

Paragenetic events were determined on a relative basis by identifying cross-cutting relationships from thin sections. The probable paragenetic sequence is illustrated

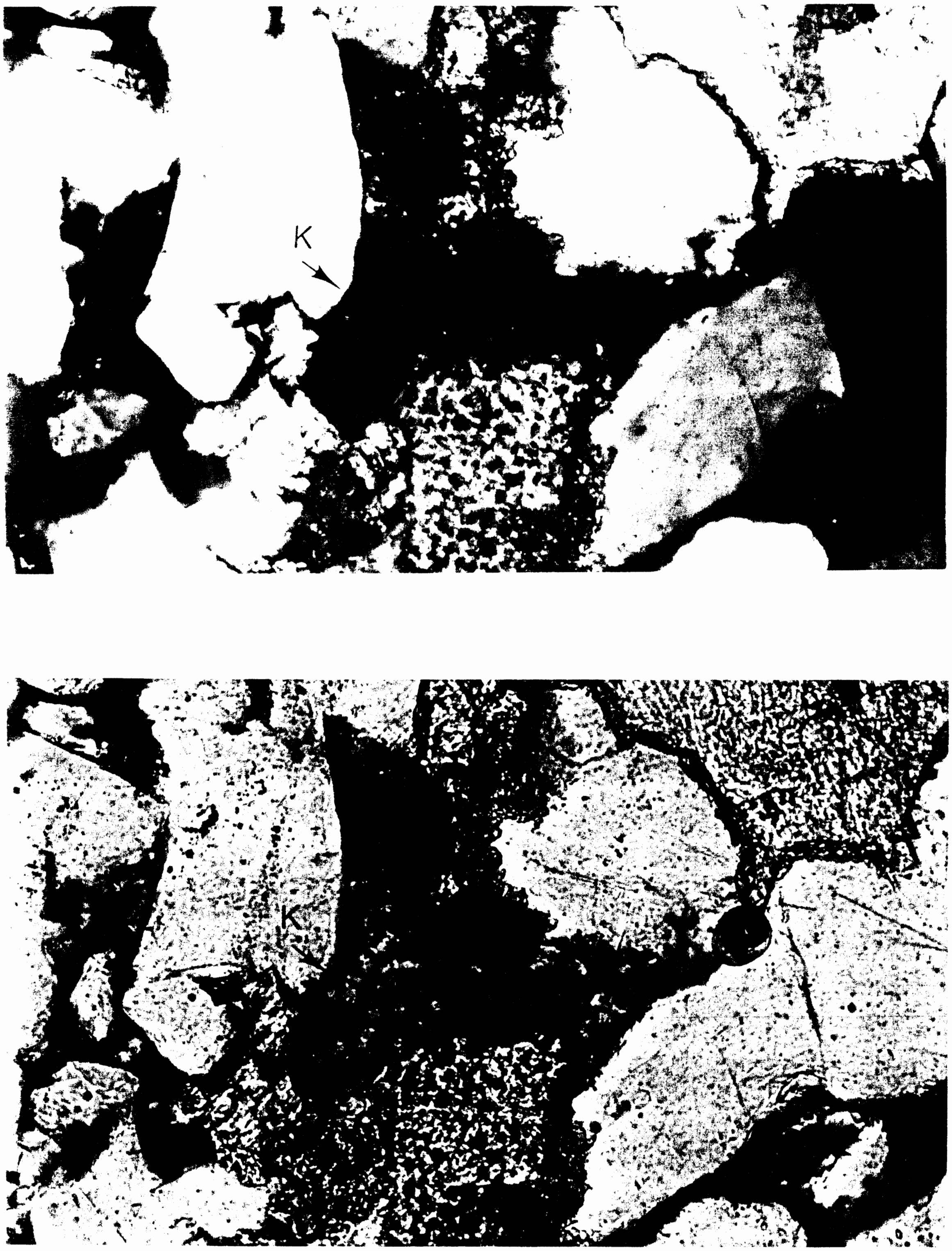


Figure 48. Photomicrograph of Porefilling Kaolinite (K), Also Note Echiniderm Fragment (F), (XN upper, PP lower, 3338 Ft., Austin and Emrick, No. 2 Bunny Long).

in Figure 49. Organics and clays concentrated along styolites served to seperate diagenetic regimes (Figure 50).

Early isopachous-calcite cementation is thought to have occurred as a syndepositional event. Following this early stage of calcite cementation was cementation by siderite. Siderite cementation is observed in many sandstones, it is believed to develop when sediments are buried at shallow depths. Following these early events of carbonate cementation, chlorite rims precipitated on detrital quartz grains. An increase in PH levels is indicated by the precipatation of quartz overgrowths. Further changes in PH are suggested by calcite cement.

Decarbonatization resulted in dissolution of metastable constituents and creation of secondary porosity. Secondary porosity was reduced by precipatation of ferroan dolomite and authigenic clays.

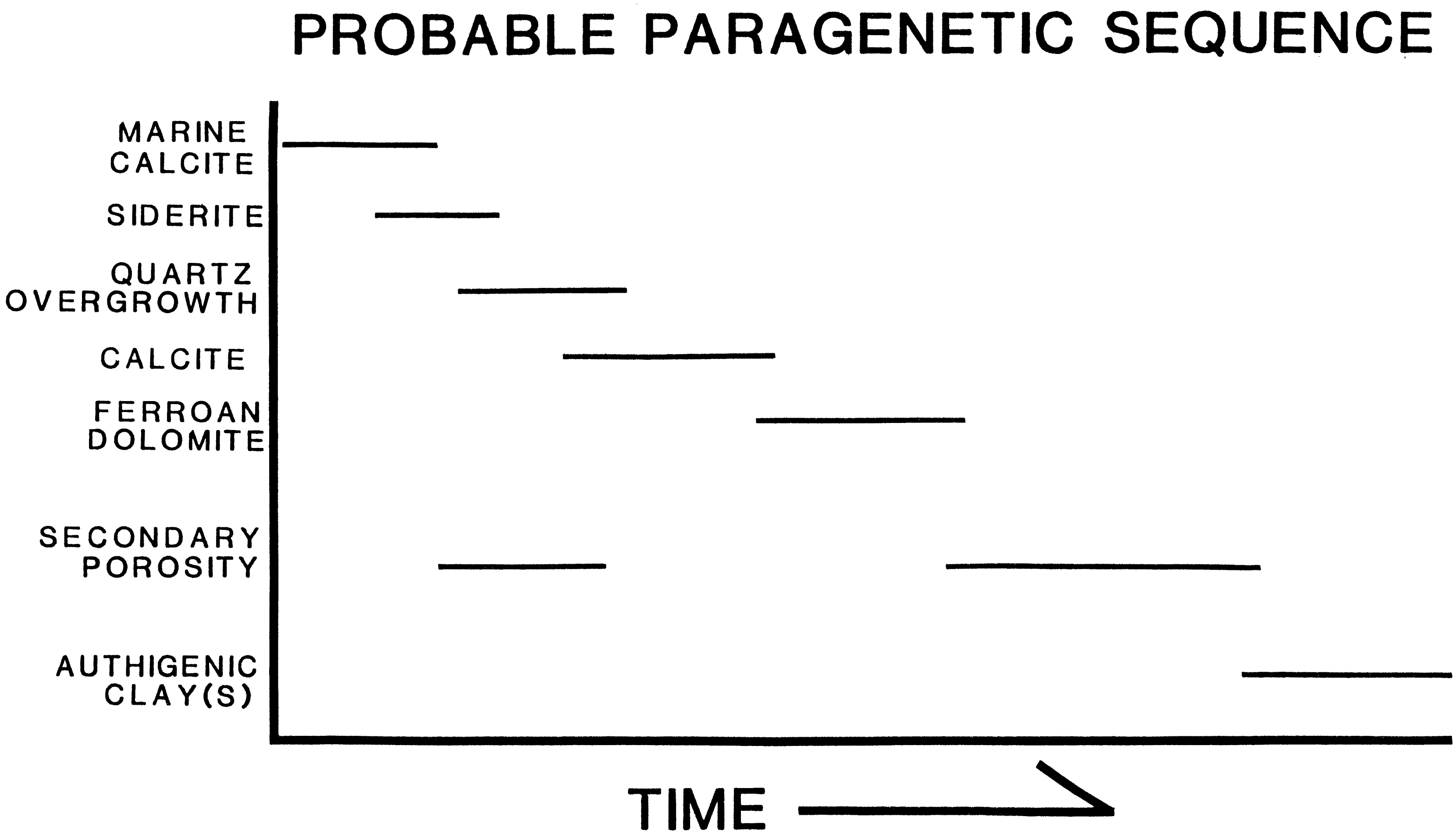


Figure 49. Probable Paragenetic Sequence

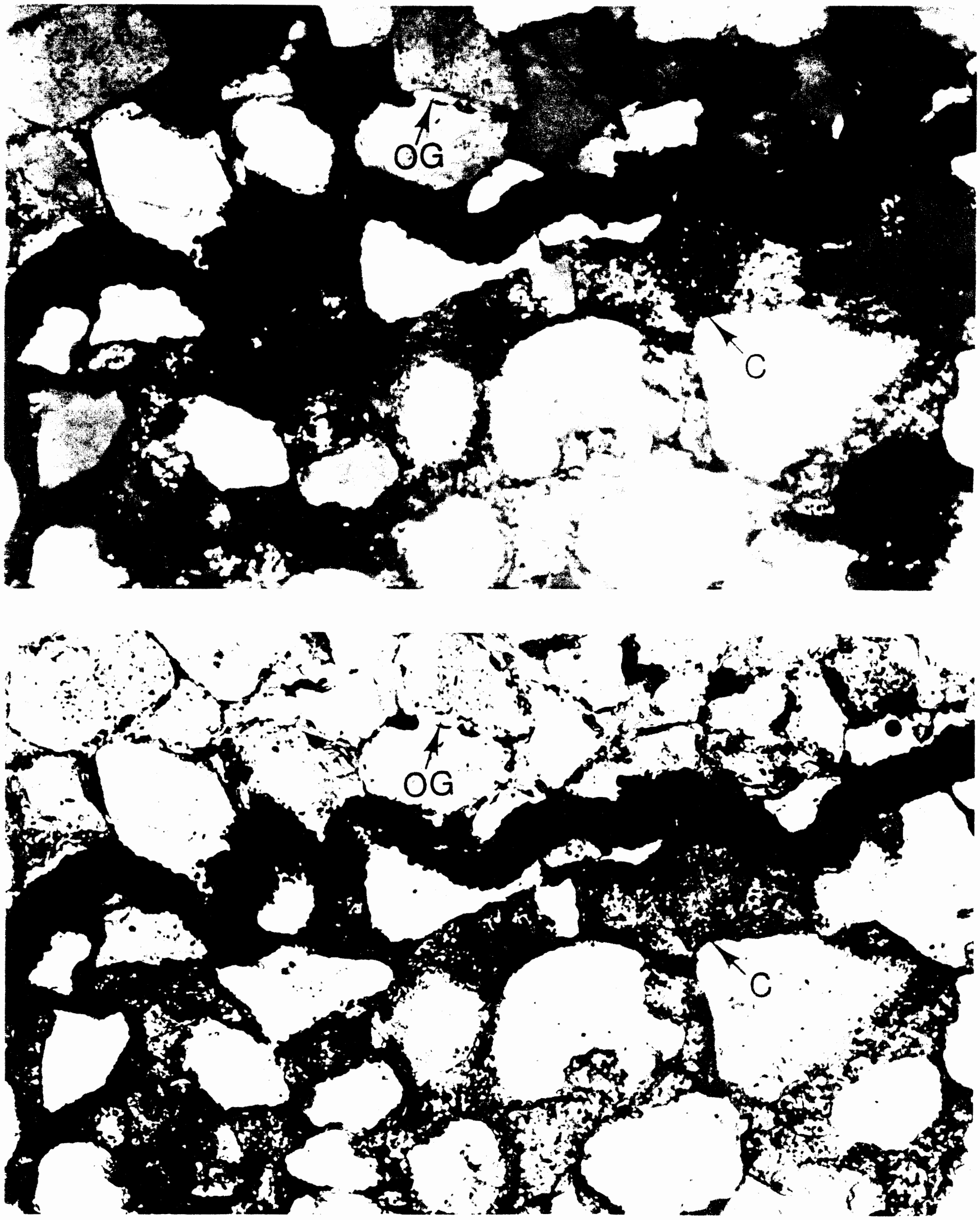


Figure 50. Diagenetic Regimes Seperated Along Stylolite, Note Quartz Overgrowth Cementation (OG) and Calcite Cementation (C), (XN upper, PP lower, 4335 Ft., Midwest, No. 1 H. Pierce).

CHAPTER VII

PETROLEUM GEOLOGY

Introduction

The Union Valley Formation produces commercial amounts of both oil and gas in the study area. Most oil-and-gas traps are controlled by structural geology. Stratigraphic-trapping components are also significant in many accumulations. Stratigraphic traps are underexploited in the study area; probably they hold the greatest potential for future discovery of petroleum in the Union Valley Formation.

Union Valley Fields

East Gerty Field: The East Gerty Field (Plate 8) is in T.4 N., R.10 E., Hughes County. The discovery well was the No. 1-9 Hightower, drilled by MGF Oil Corporation in September, 1982.

The No. 1-9 Hightower is in the NW NW SE NW of Section 9, T.4 N., R.10 E. The well was completed in the Cromwell Sand from perforations at 6000-6004 feet. The initial potential production was gauged at 9 BOPD. The No. 1-9 Hightower is now abandoned.

All established production to date in the East Gerty Field is from the Union Valley Formation. The principal trapping circumstance is a result of the westward pinchout of Cromwell Sandstone against regional dip to the northeast. The East Gerty Fault (Plate 1) separates the field into distinct reservoirs. The field has an established water contact.

Southwest Calvin Field: The southwest Calvin Field (Plate 8) is in T.5 N., R.10 E., Hughes County. The discovery well was the Phillips No. 1 Beeker, completed in January, 1938 at a total depth of 6286 feet.

The No. 1 Beeker is in the NE NW SW of Section 8, T.5 N.,R.10 E. Originally completed as a Viola oil well, the well was plugged back and completed as an oil well in the Cromwell Sandstone. Completed from perforations for 127 BOPD and 20,000,000 CFGPD, the well is now abandoned.

The Southwest Calvin Field is an anticlinal trap on the SW Calvin Anticline (see Plate 1). Production chiefly is from the Union Valley Formation with other production from the Boggy, Savanna, and McLish Formations.

Northwest Gerty Field: The Northwest Gerty Field (Plate

8), is in T.5 N., R.9 E., Hughes County. The discovery well was completed in 1954 in a shallow Pennsylvanian sand. The field produces from the Cromwell and Jefferson Sands.

The principal trapping mechanism in the Union Valley Formation is structural. The field is separated by the Holdenville Fault and other associated fault splays. The field limits are defined by water and by depositional pinchout of reservoir facies.

Hilltop and Southwest Hilltop Fields: The Hilltop Fields are in T.5 N., R.11 E., Hughes County. The discovery well for this area of Union Valley production was the Magnolia Petroleum Company No. 1 McCoy, completed in March 1941.

The No. 1 McCoy is in the SW SW SE of Section 16, T.5 N.,R.11 E. The well produced from the Cromwell Sandstone with top of pay reported at 5373 feet. The Cromwell IPF was 10,750,000 CFGPD. The well is now abandoned.

Union Valley production at Hilltop and Southwest Hilltop Fields appears to be structurally controlled, with porosity distribution of secondary importance. The importance of structural geology is demonstrated by the field's having been discovered and extended by seismic methods.

North Legal Field: The North Legal Field (Plate 8) is in T.4 N., R.11 E., Hughes County. The discovery well was the Hanover Management No. 1 Sutterfield, completed in March, 1978, and located in Section 10, T.4 N., R.11 E.

The North Legal Field produces exclusively from the Union Valley Formation. Structural closure against down-to-the-basin faults appears to be the principal trapping mechanism.

North Gerty Field: The North Gerty Field (Plate 8) is in T.5 N., R.10 E., Hughes County. The discovery well was the Graben Gas and Water Company No. 1 Hundley, completed in June, 1948 from an unnamed sand at 1756 feet.

Only one well currently produces from the Union Valley at North Gerty Field. Closure against a splay of the Allen Fault (Plate 1), appears to control production. Development potential in the Union Valley Formation appears to be seriously limited.

Northeast Citra Field: The Northeast Citra Field (Plate 8) is in T.4 N., R.9 E., Hughes County. The discovery well was the D & D Drilling No. 1 W.A. McDonnell, which was completed in August, 1955.

The No. 1 W.A. McDonnell is in the SW SW SW of Section 12, T.4 N., R.9 E. The well was completed in the Cromwell Sandstone from perforations at 5218-5230 feet, IPP was 5 BOPD.

Union Valley production at Northeast Citra is controlled primarily by structural geology. Closure against an east trending down-to-the-north fault is the principal trap. Production is limited by downdip water.

Citra Field: Citra Field (Plate 8) is in the southern half of T.4 N., R.9 E., Hughes County. The discovery well was the Carter Oil Company No. 1 Hamilton, in the W 1/2 of NE SW of Section 33, T.4 N., R.9 E. The well was completed in the Cromwell Sandstone for 29 MCFGPD, with top of pay reported at 4225 feet.

Structural geology is the primary trapping mechanism at Citra Field. Closure against the Citra Fault and downdip water apparently limit production.

CHAPTER VIII

EVIDENCE OF SYNDEPOSITIONAL TECTONISM

Normal faults that extend to the basement and that show thickening of early through middle Atokan strata across the downthrown side have been documented by several geologists (Koinm and Dickey, 1967; Buchanan and Johnson, 1968; Berry and Trumble, 1968). These faults generally have been attributed to flexure of the southern continental margin, due to interaction with the approaching subduction complex from the south. Based on detailed stratigraphic correlations, evidence suggests that many of the faults and associated structures in the study area demonstrate syndepositional Atokan movement, and that they also show evidence of similar relationships in the underlying Morrowan strata. Principal evidence includes thickening of depositional units across selected faults (see Plate 4, Section D-D') and downdip from associated structures (see Plates 6 and 7). Patterns of distribution of sandstone in the Union Valley GIS also suggest some syndepositional structural influence.

The evidence of syndepositional faulting in the study area, taken in conjunction with geometry of the Holdenville and Allen faults and their related structures (i.e., S.W. Calvin Anticline) is suggestive of left-lateral wrench faulting (Figure 51). Woods (1990) observed that the Holdenville fault shows wrench-like geometries in transverse seismic sections. Stewart (1990) suggested other large faults in the immediate study area (i.e. Allen and Ahloso faults) may also be related to wrench movements. The Holdenville fault is one of many well known subsurface faults that underlie normal faults arranged in an en-echelon pattern at the surface (Figure 52). The orgin of these faults has been debated for many years in the geologic literature, but has generally been attributed to rotational movement (Foley, 1926; Link, 1929; Melton, 1930; Walper, 1970). Cockrell (1985) suggested normal faults to the northwest of this study, in Seminole and Okfuskee Counties, may also have experienced periods of wrench movement.

Syndepositional movement on basement-involved normal faults in the western portions of the Arkoma basin has been documented as Atokan in age (Archinal, 1979). Movement in eastern portions of the basin has been documented as having been as early as Late Mississippian (Viele and Thomas, 1989). Morrowan movement in central portions of the Arkoma basin (Figure 53) has been described by Roberts (1987), and Schneider (1991). Based on evidence observed in this study area, syndepositional movement longer ago than Atokan is proposed for western portions of the basin. This possibility, may require revision of the model of east-to-

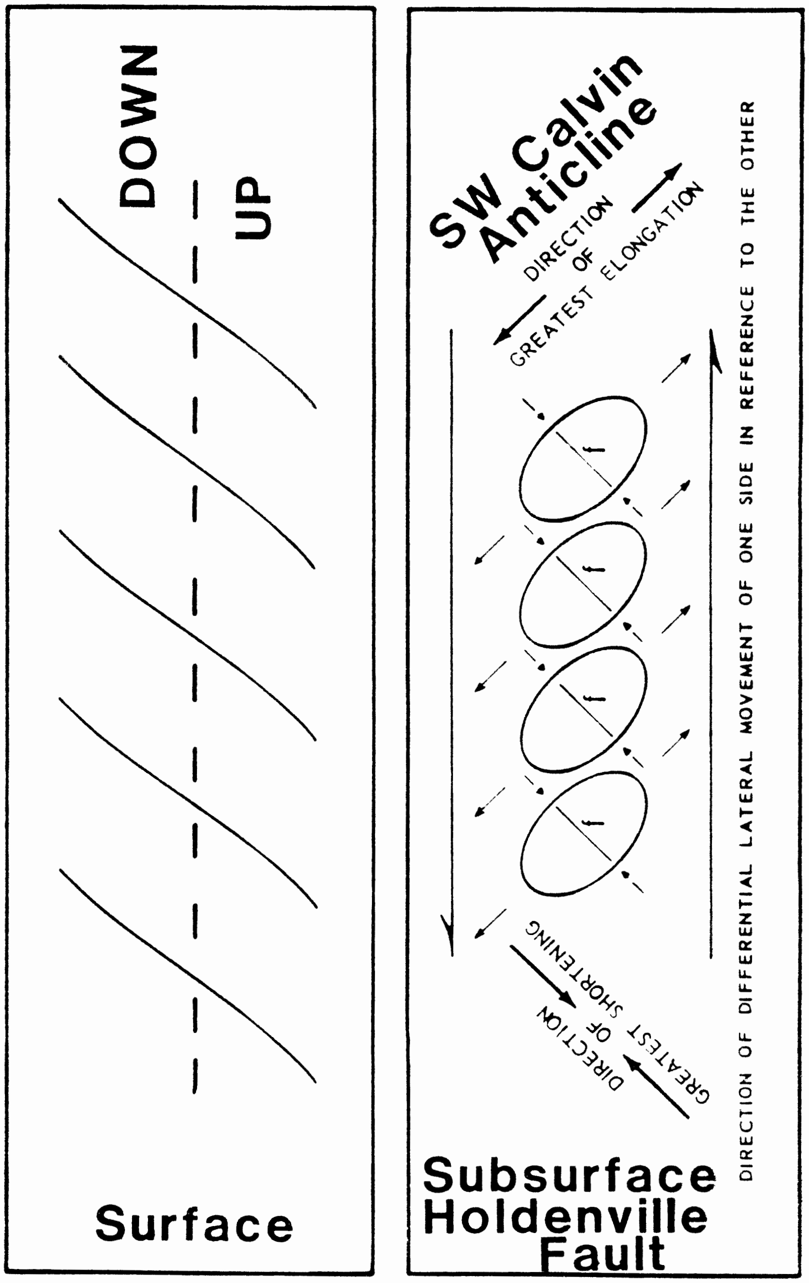


Figure 51. Proposed Geometry of Wrench Fault System in Southern Hughes County, Oklahoma (modified from Bucher and Hintze, p. 11).

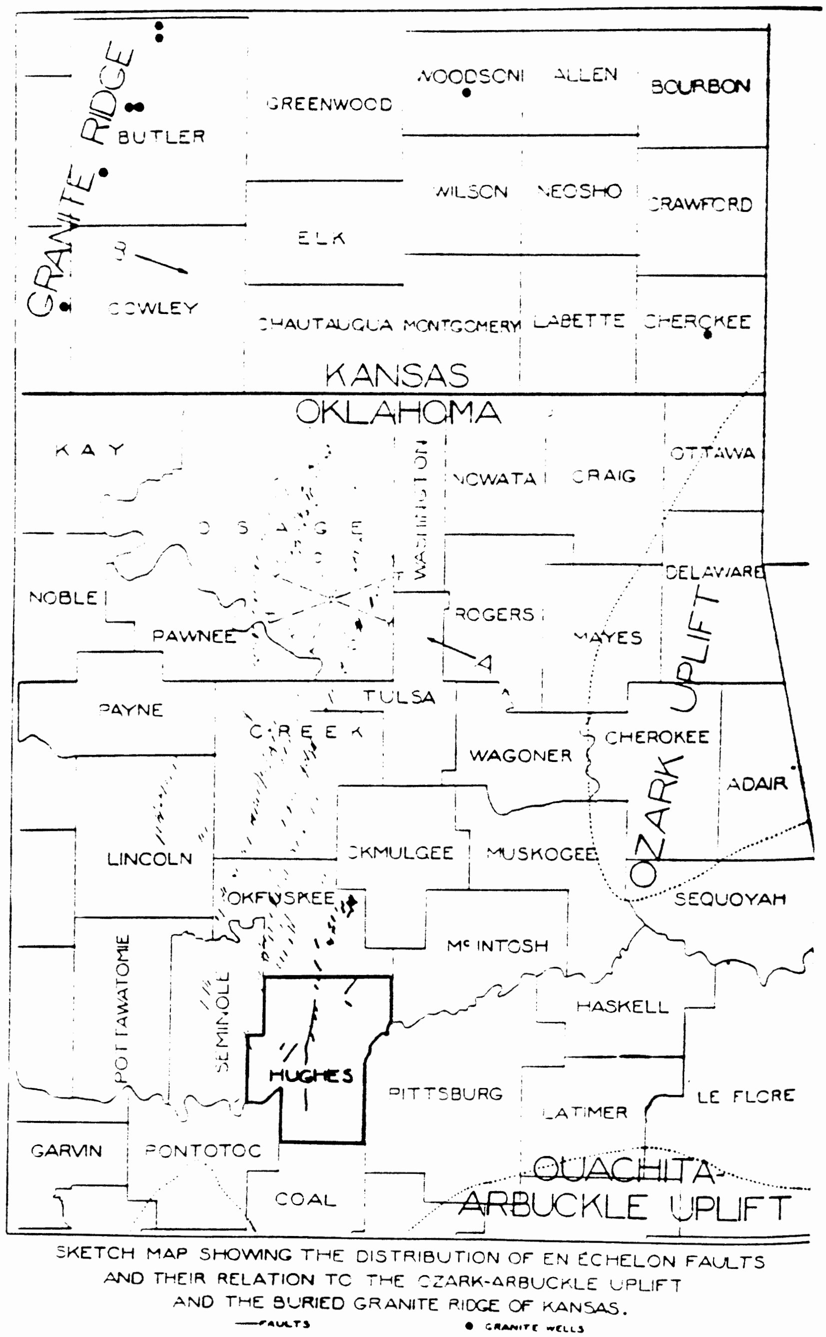


Figure 52. En-Echelon Faults at Surface, Overlying Subsurface Faults in Eastern Oklahoma (modified from Foley, 1926, p. 294).

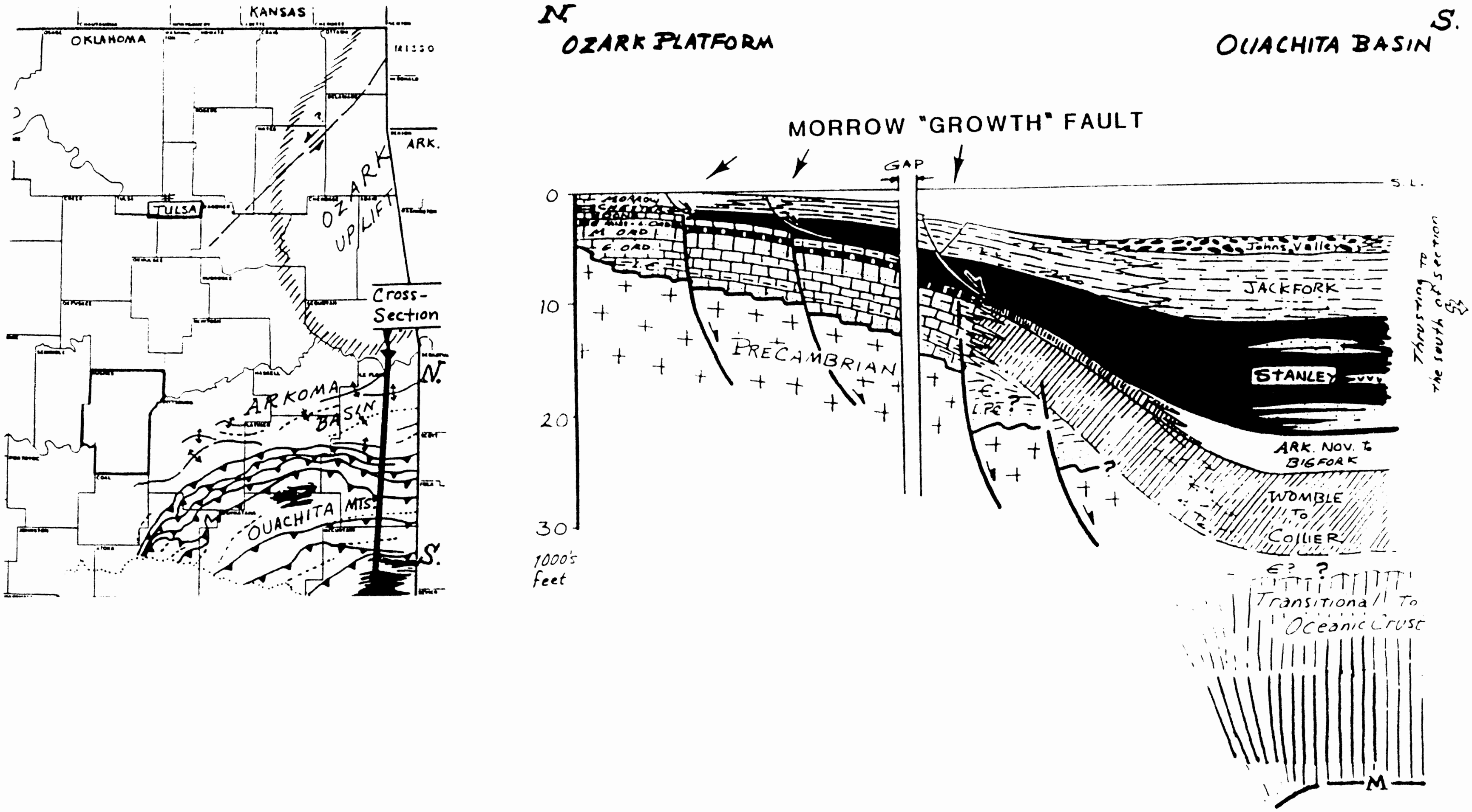


Figure 53. Diagrammatic Morrowan "Growth" Faults, Central Arkoma Basin (modified from Roberts, 1987, p. 3 and 14).

west migration of Carboniferous faulting in the basin as described by Grahm et al., (1975), Housknecht and Kacena, (1983), and Vanarsdale and Schweig (1990).

CHAPTER IX

SUMMARY

1. Upper Mississippian and Lower Pennsylvanian rocks can be correlated across the study area.
2. Facies of the Union Valley Formation as made evident from subsurface cross-sections, isopach maps, isolith maps, cores, and thin sections are indicative of shallow, subaqueous marine deposits.
3. Syndepositional tectonism may have influenced the depositional patterns of the Cromwell Sandstone.
4. The Cromwell Sandstone is typically a quartz arenite, commonly containing trace to moderate percentages of glauconite and marine invertebrate faunal debris.
5. Hydrocarbon production from the Union Valley Formation is primarily from structural traps developed on anticlinal structures.

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APPENDIX A

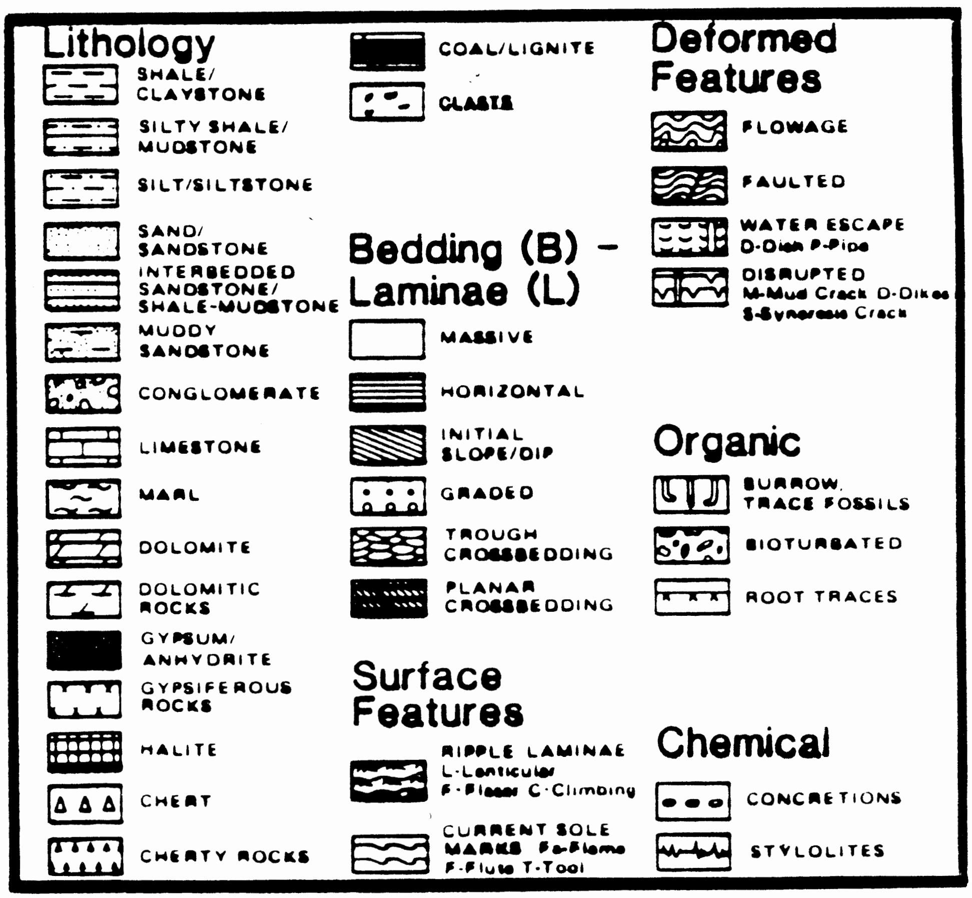
CORE DESCRIPTIONS

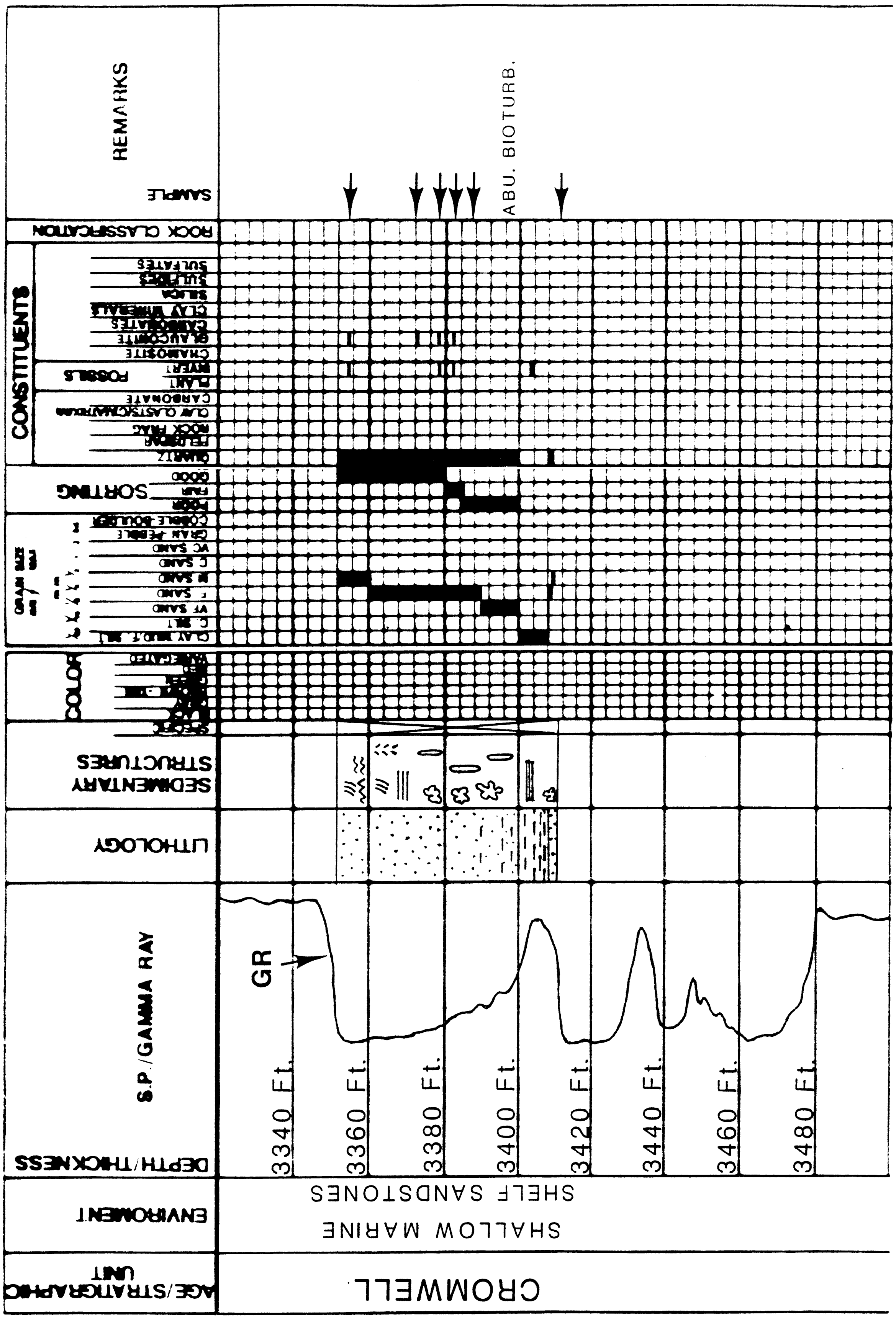
PETROLOGIC LOG

Well A&E No. 1 STEELE

Location SW NW SE Sec. 30 T. 9 N., R. 9 E

HUGHES Co., OKLA.



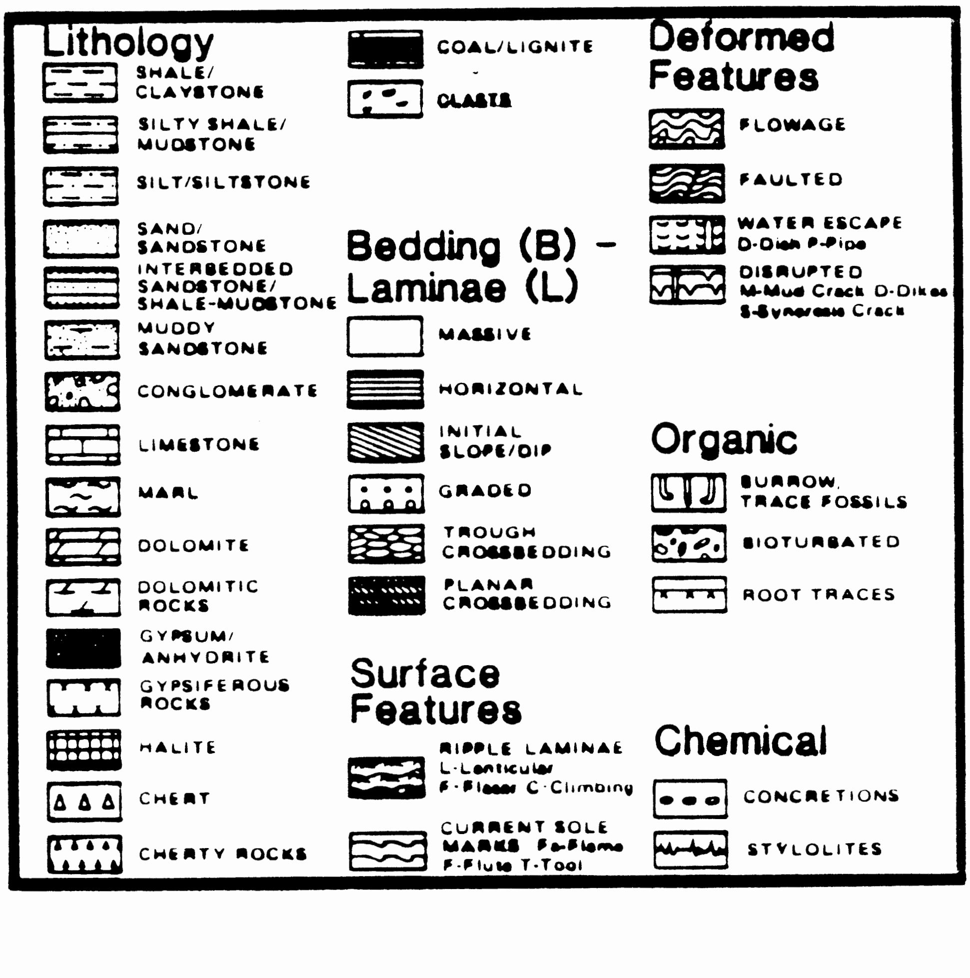

REMARKS
SAMPLE
ABU. BIOTURB.
ROCK CLASSIFICATION
CONSTITUENTS
FOSSILS
SORTING
GRAIN SIZE
COLOR
SEDIMENTARY STRUCTURES
LITHOLOGY
S.P./GAMMA RAY
GR
DEPTH/THICKNESS
3340 Ft.
3360 Ft.
3380 Ft.
3400 Ft.
3420 Ft.
3440 Ft.
3460 Ft.
3480 Ft.
ENVIRONMENT
SHELF SANDSTONES
SHALLOW MARINE
AGE/STRATIGRAPHIC UNIT
CROMWELL

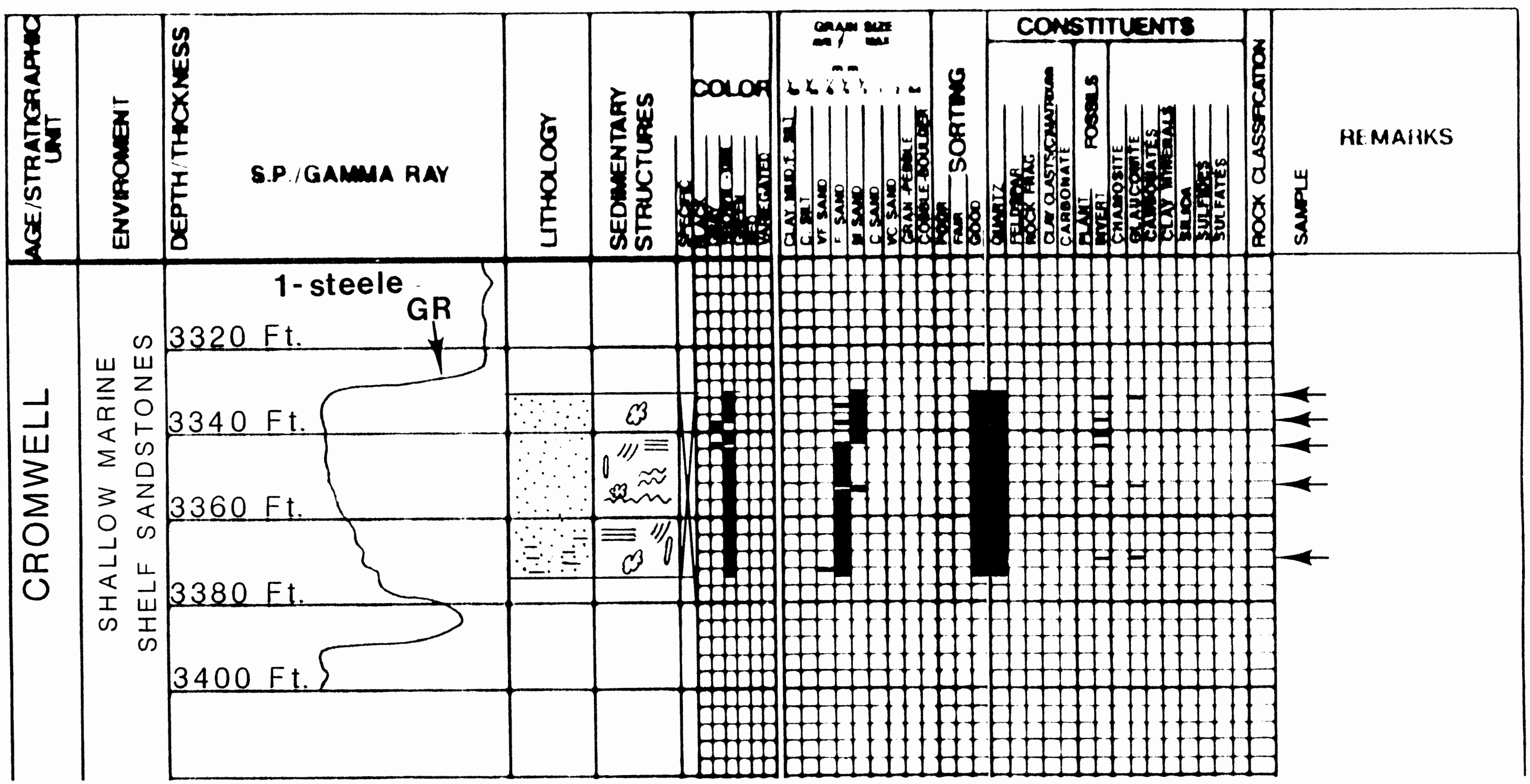
PETROLOGIC LOG

Well A&E No. 2 BUNNY LONG

Location NE SW SE Sec. 30 T. 9 N., R. 9 E

HUGHES Co., OKLA.



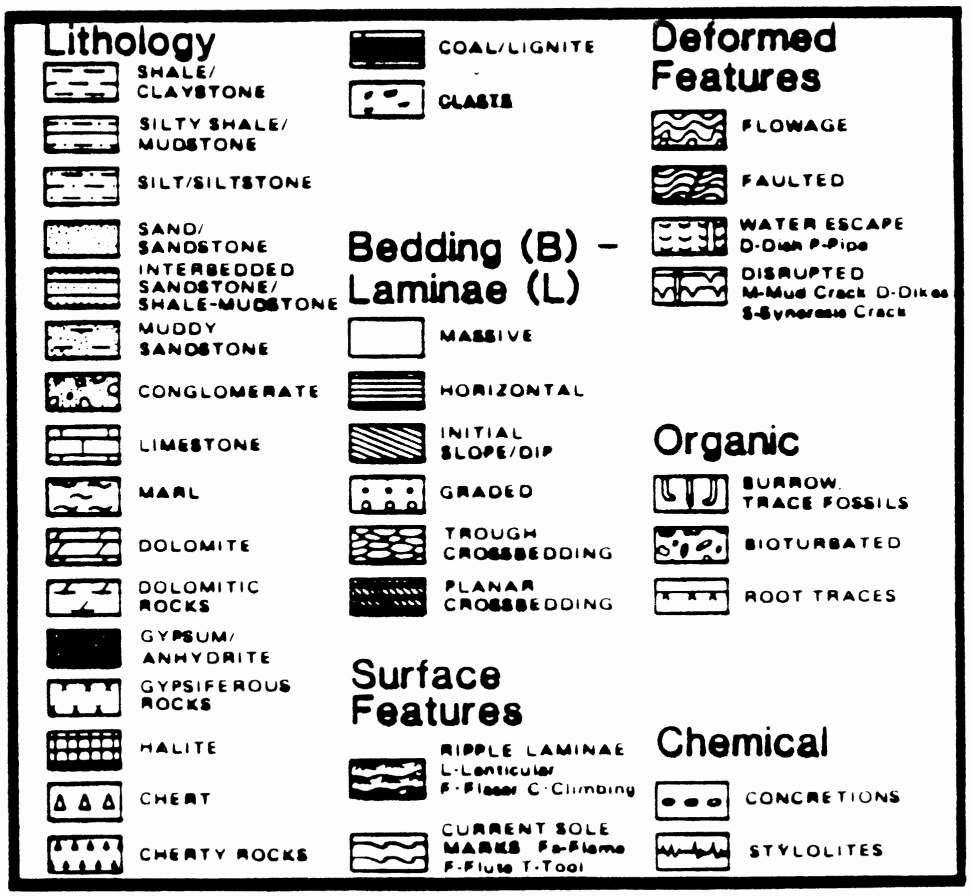

AGE/STRATIGRAPHIC UNIT
ENVIROMENT
DEPTH/THICKNESS
S.P./GAMMA RAY
LITHOLOGY
SEDIMENTARY STRUCTURES
COLOR
VARIEGATED
GRAIN SIZE
CLAY MUD F. SILT
C. SILT
VF SAND
F SAND
M SAND
C SAND
VC SAND
GRAN PEBBLE
COBBLE BOULDER
SORTING
POOR
FAIR
GOOD
CONSTITUENTS
QUARTZ
FELDSPAR
ROCK FRAG
CLAY CLASTS/CHANTRUM
CARBONATE
FOSSILS
PLANT
INVERT
CHAMOSITE
GLAUCONITE
CARBONATES
CLAY MINERALS
SILICA
SULFIDES
SULFATES
ROCK CLASSIFICATION
SAMPLE
REMARKS
CROMWELL
SHALLOW MARINE
SHELF SANDSTONES
1-steele
GR
3320 Ft.
3340 Ft.
3360 Ft.
3380 Ft.
3400 Ft.

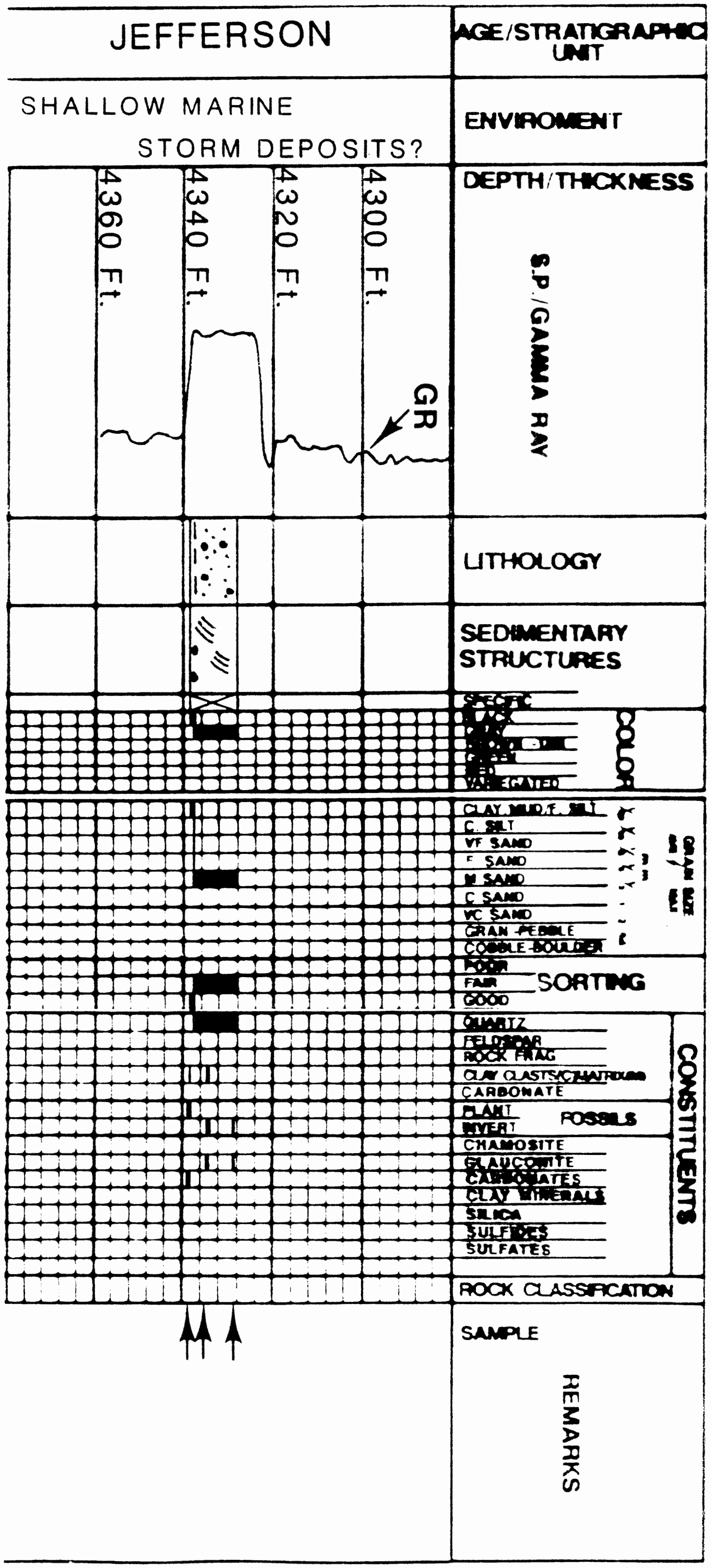
PETROLOGIC LOG

Well MIDWEST No. 1 H. PIERCE

Location C NE NW Sec. 12 T. 5 N., R. 9 E

HUGHES Co., OKLA.





JEFFERSON
AGE/STRATIGRAPHIC UNIT
SHALLOW MARINE
STORM DEPOSITS?
ENVIROMENT
DEPTH/THICKNESS
4360 Ft.
4340 Ft.
4320 Ft.
4300 Ft.
GR
S.P./GAMMA RAY
LITHOLOGY
SEDIMENTARY STRUCTURES
SPECIFIC
BLACK
GRAY
GREEN
RED
VARIEGATED
COLOR
CLAY MUD/F. SILT
C. SILT
VF SAND
F SAND
M SAND
C SAND
VC SAND
GRAN PEBBLE
COBBLE BOULDER
GRAIN SIZE
POOR
FAIR
GOOD
SORTING
QUARTZ
FELDSPAR
ROCK FRAG
CARBONATE
PLANT
INVERT
FOSSILS
CHAMOSITE
GLAUCONITE
CARBONATES
CLAY MINERALS
SILICA
SULFIDES
SULFATES
CONSTITUENTS
ROCK CLASSIFICATION
SAMPLE
REMARKS

PETROLOGIC LOG

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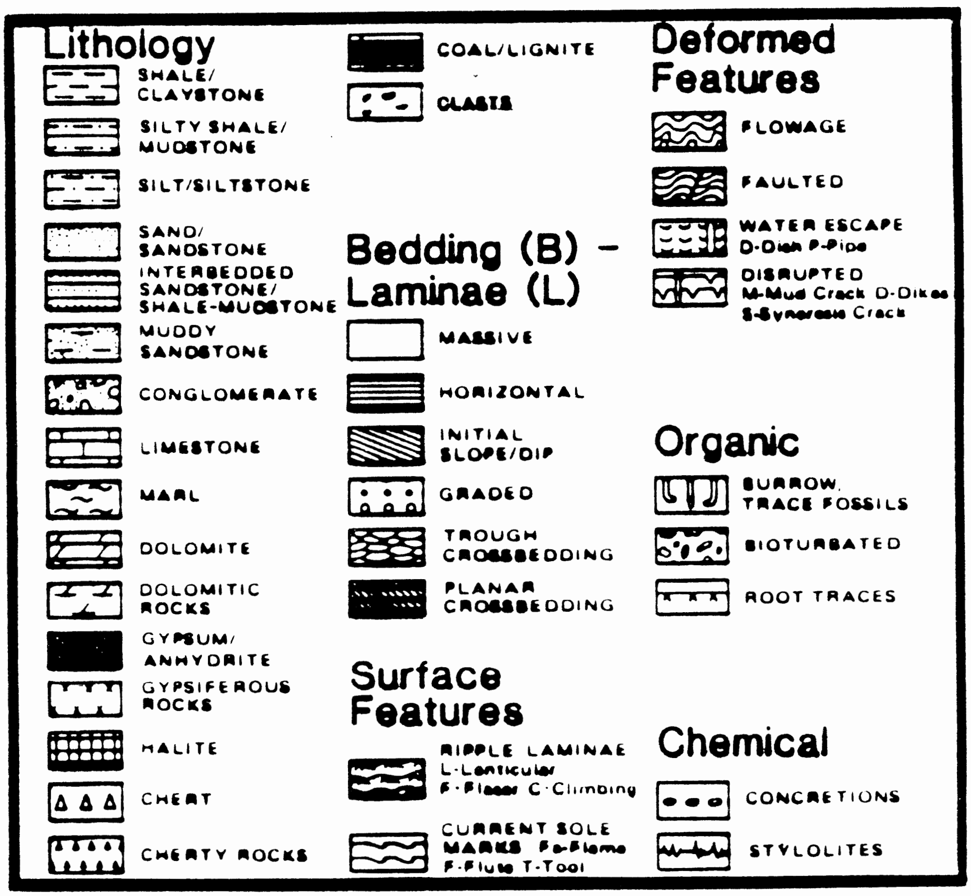
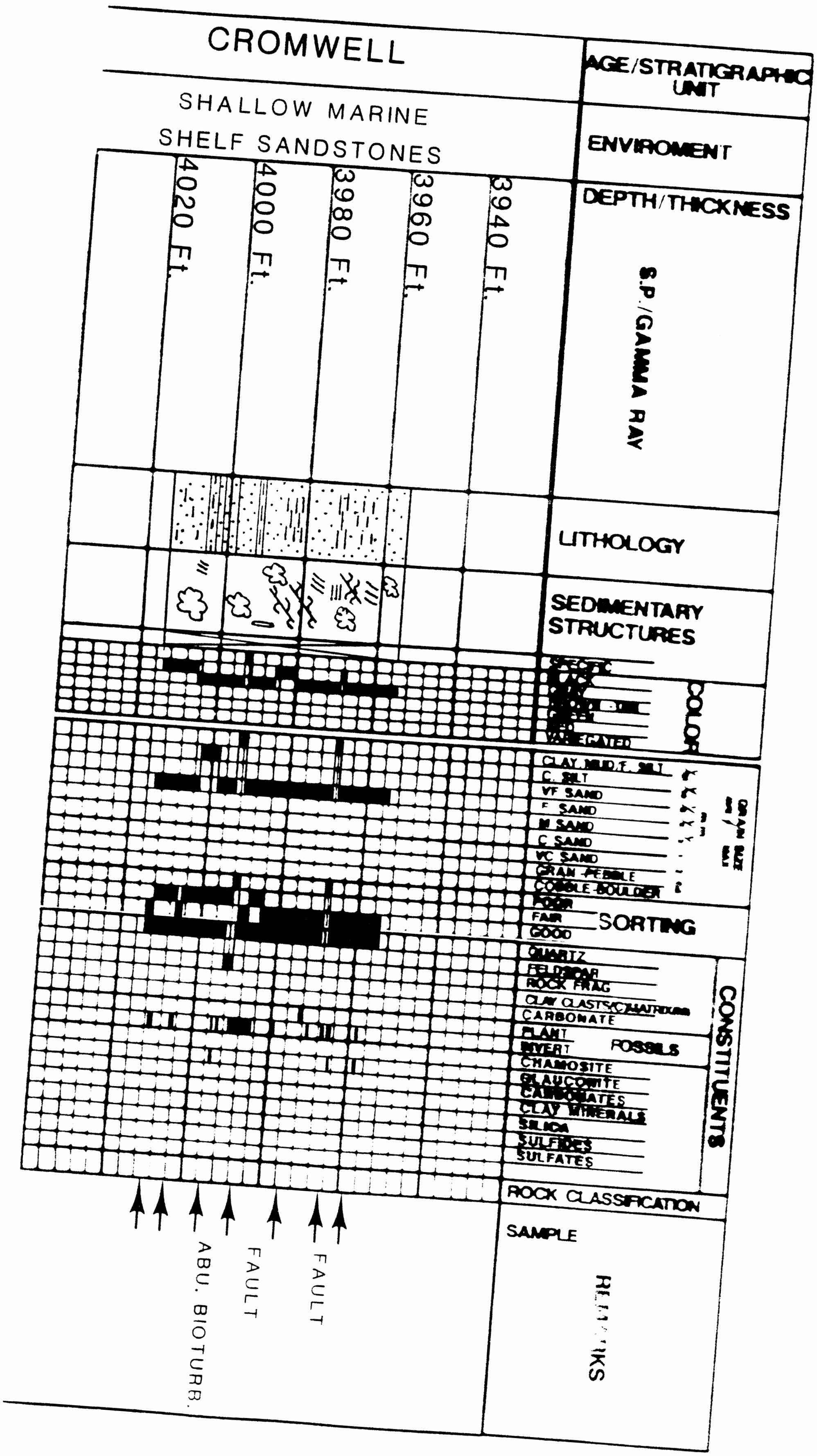
Location SW SE Sec. 31 T. 3 N., R. 9 E

COAL Co., OKLA.



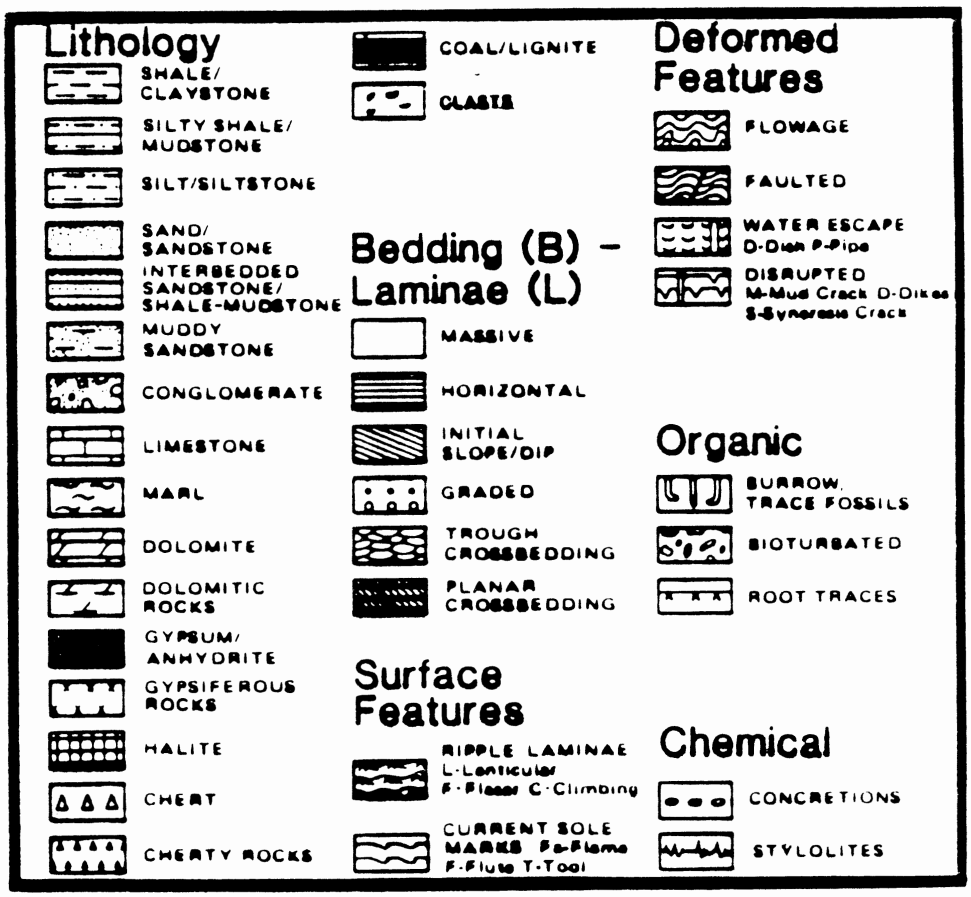

CROMWELL
SHALLOW MARINE
SHELF SANDSTONES
4020 Ft.
4000 Ft.
3980 Ft.
3960 Ft.
3940 Ft.
AGE/STRATIGRAPHIC UNIT
ENVIROMENT
DEPTH/THICKNESS
S.P./GAMMA RAY
LITHOLOGY
SEDIMENTARY STRUCTURES
VARIEGATED
COLOR
CLAY MUD,F. SILT
C. SILT
VF SAND
F SAND
M SAND
C SAND
VC SAND
GRAN PEBBLE
COBBLE BOULDER
GRAIN SIZE
POOR
FAIR
GOOD
SORTING
QUARTZ
FELDSPAR
ROCK FRAG
CLAY CLASTS/C MATRIX
CARBONATE
PLANT
INVERT
FOSSILS
CHAMOSITE
GLAUCONITE
CARBONATES
CLAY MINERALS
SILICA
SULFIDES
SULFATES
CONSTITUENTS
ROCK CLASSIFICATION
SAMPLE
REMARKS
ABU. BIOTURB.
FAULT
FAULT

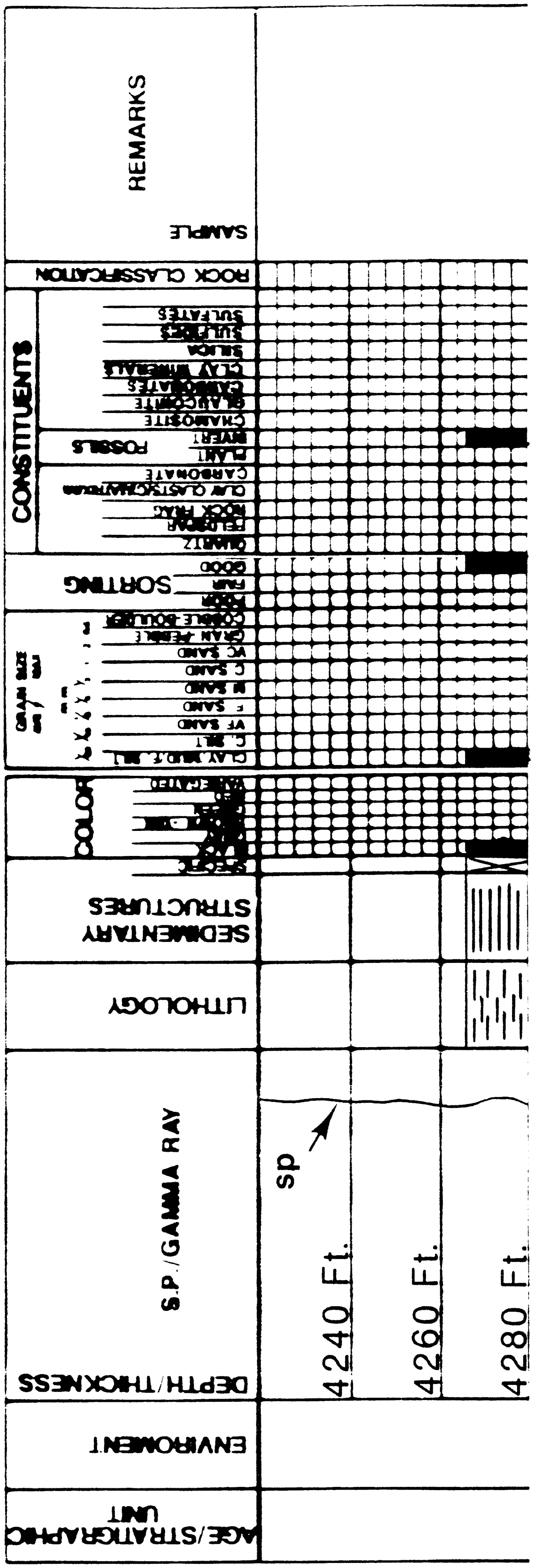
PETROLOGIC LOG

Well PAN AM No. 1 ROBERTS

Location E/2 NE SE Sec. 32 T. 2 N., R. 8 E

COAL Co., OKLA.





REMARKS
SAMPLE
ROCK CLASSIFICATION
CONSTITUENTS
SULFATES
SULFIDES
SILICA
CLAY MINERALS
CARBONATES
GLAUCONITE
CHAMOSITE
FOSSILS
INVERT
PLANT
CARBONATE
CLAY CLASTS/MATRIX
ROCK FRAG
FELDSPAR
QUARTZ
SORTING
GOOD
FAIR
POOR
GRAIN SIZE
COBBLE-BOULDER
GRAN-PEBBLE
VC SAND
C SAND
M SAND
F SAND
VF SAND
C. SILT
COLOR
VARIEGATED
SPECIFIC
SEDIMENTARY STRUCTURES
LITHOLOGY
S.P./GAMMA RAY
sp
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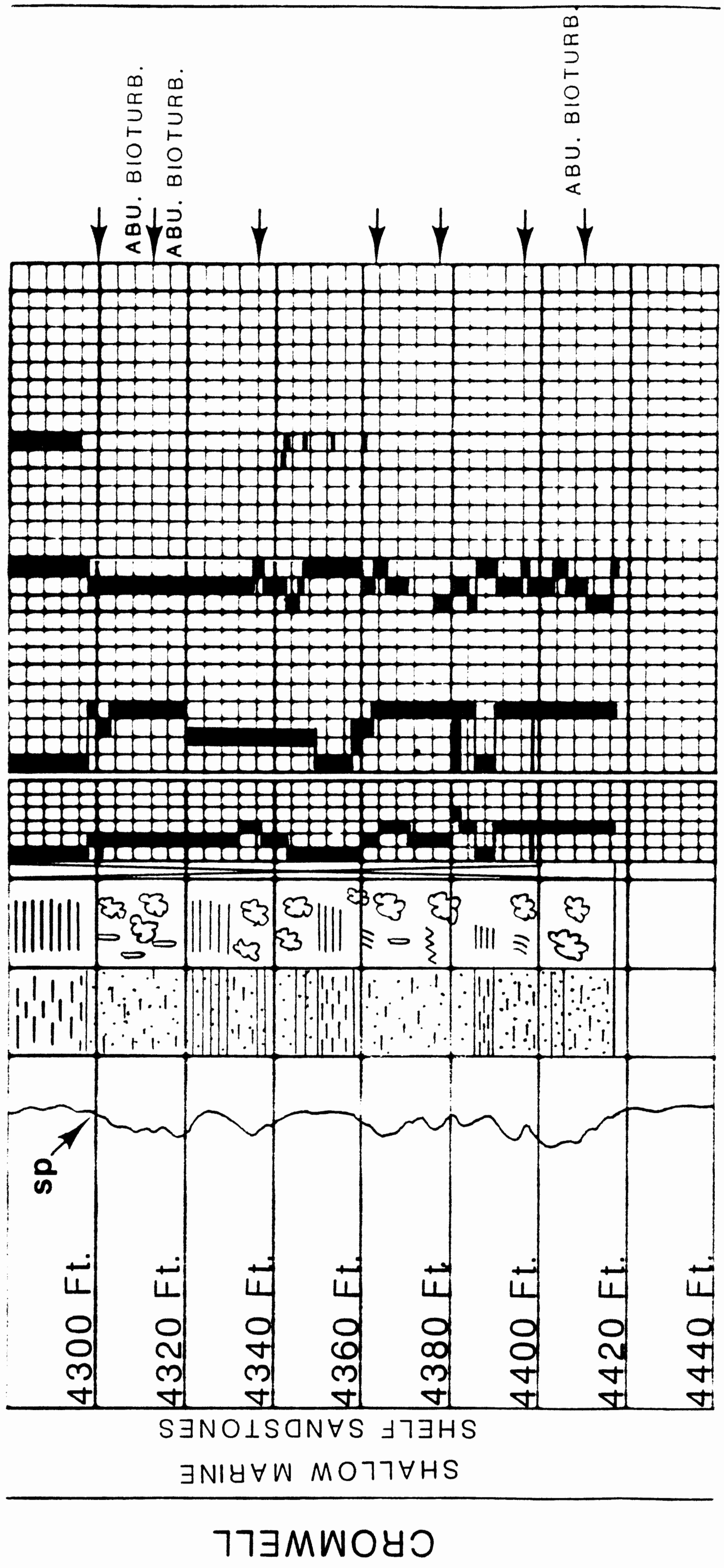
4260 Ft.
4280 Ft.
DEPTH/THICKNESS
ENVIRONMENT
AGE/STRATIGRAPHIC UNIT


ABU. BIOTURB.
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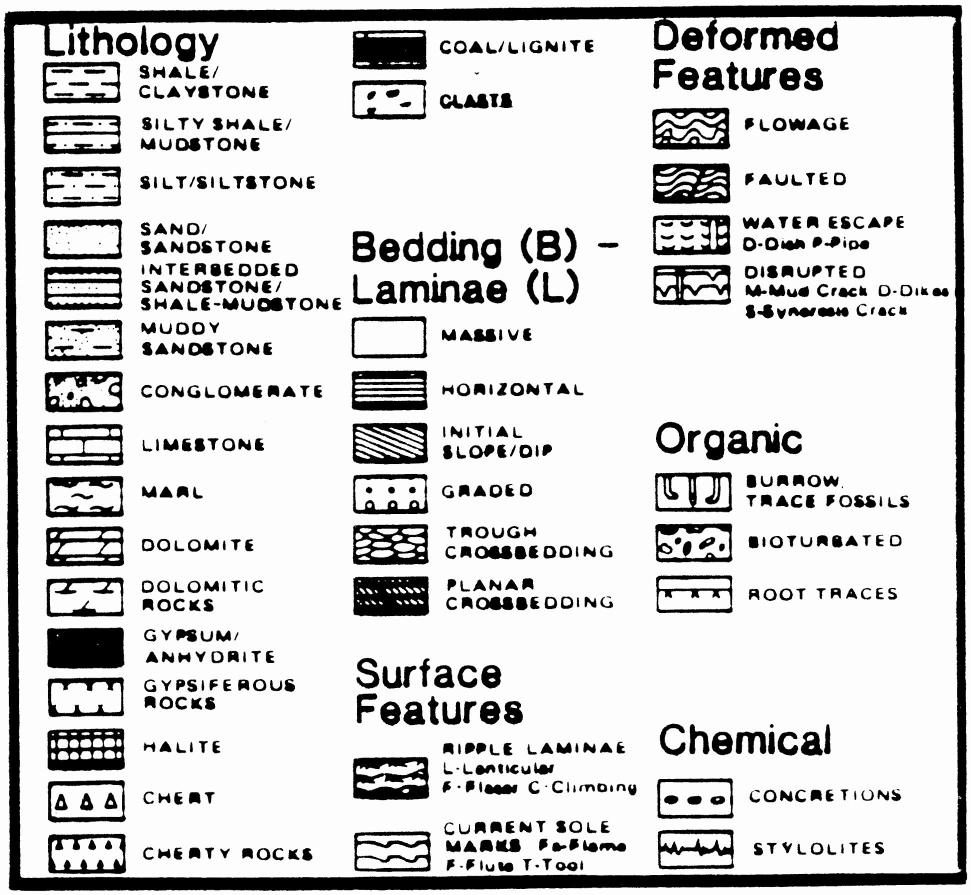
sp
4300 Ft.
4320 Ft.
4340 Ft.
4360 Ft.
4380 Ft.
4400 Ft.
4420 Ft.
4440 Ft.
SHELF SANDSTONES
SHALLOW MARINE
CROMWELL

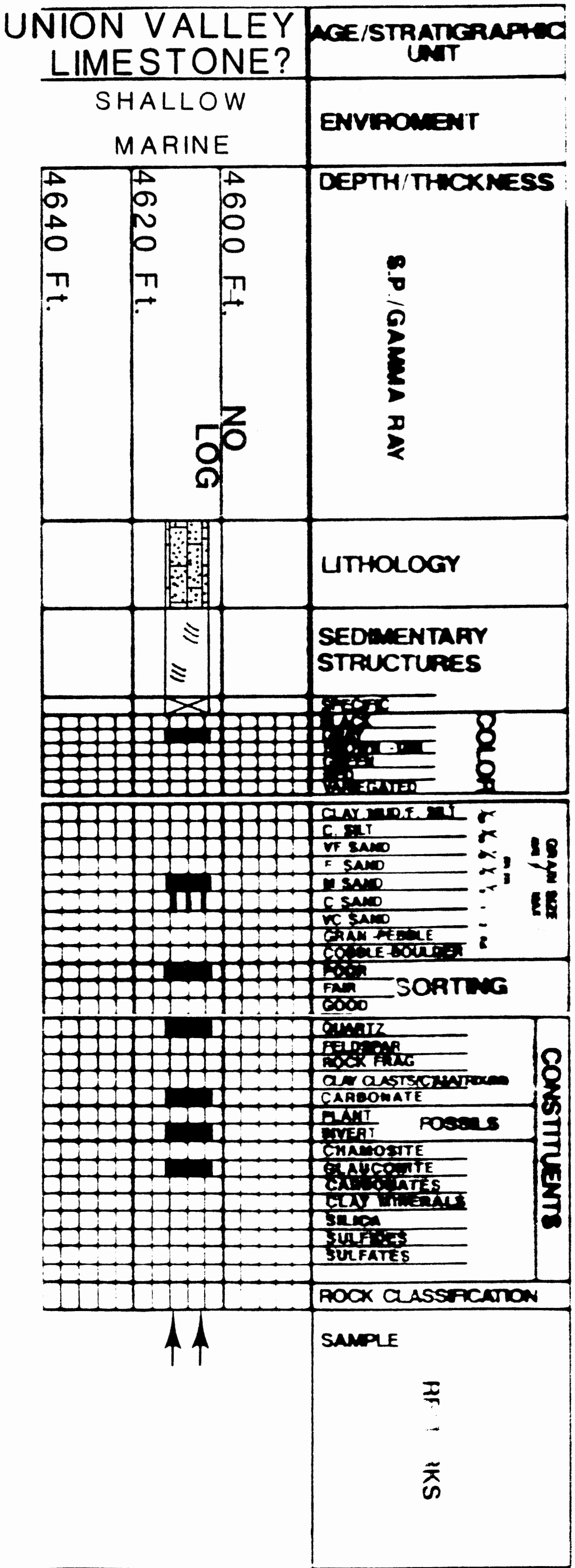
PETROLOGIC LOG

Well DELANEY No. 1 FOSTER

Location NW NE NE Sec. 17 T. 5 N., R. 10 E

HUGHES Co., OKLA.




UNION VALLEY LIMESTONE?
AGE/STRATIGRAPHIC UNIT
SHALLOW MARINE
ENVIROMENT
DEPTH/THICKNESS
4640 Ft.
4620 Ft.
4600 Ft.
NO LOG
S.P./GAMMA RAY
LITHOLOGY
SEDIMENTARY STRUCTURES
COLOR
SORTING
FAIR
GOOD
QUARTZ
ROCK FRAG
CARBONATE
FOSSILS
CHAMOSITE
CONSTITUENTS
SULFATES
ROCK CLASSIFICATION
SAMPLE

APPENDIX B

COMPOSITE CORE PHOTOGRAPHS

Austin and Emrick

No. 1 Steele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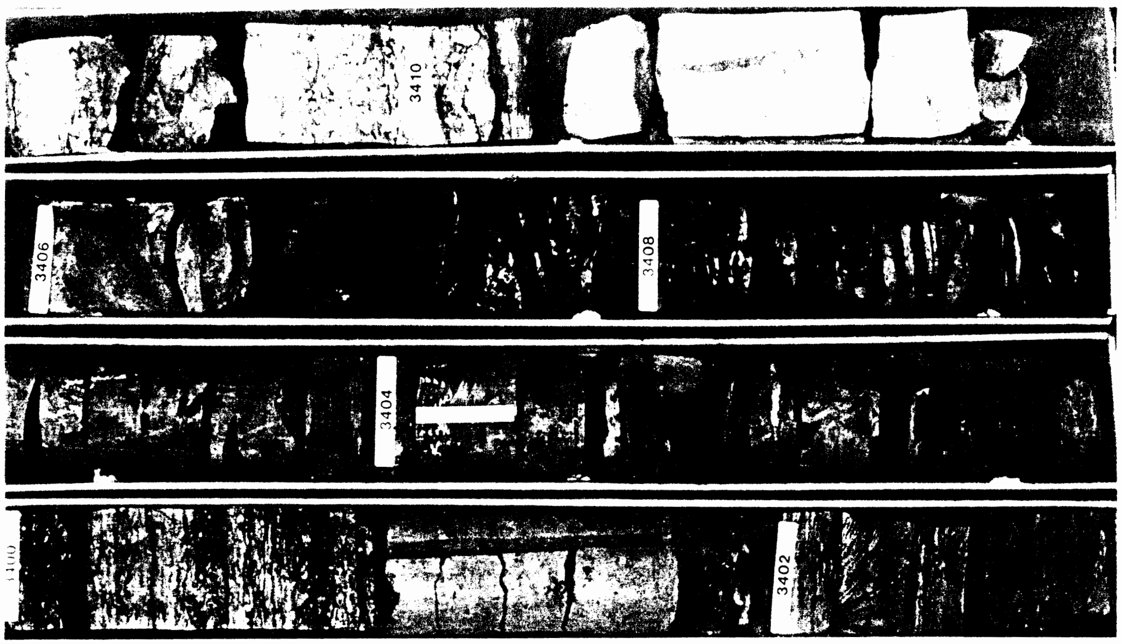
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Austin and Emrick

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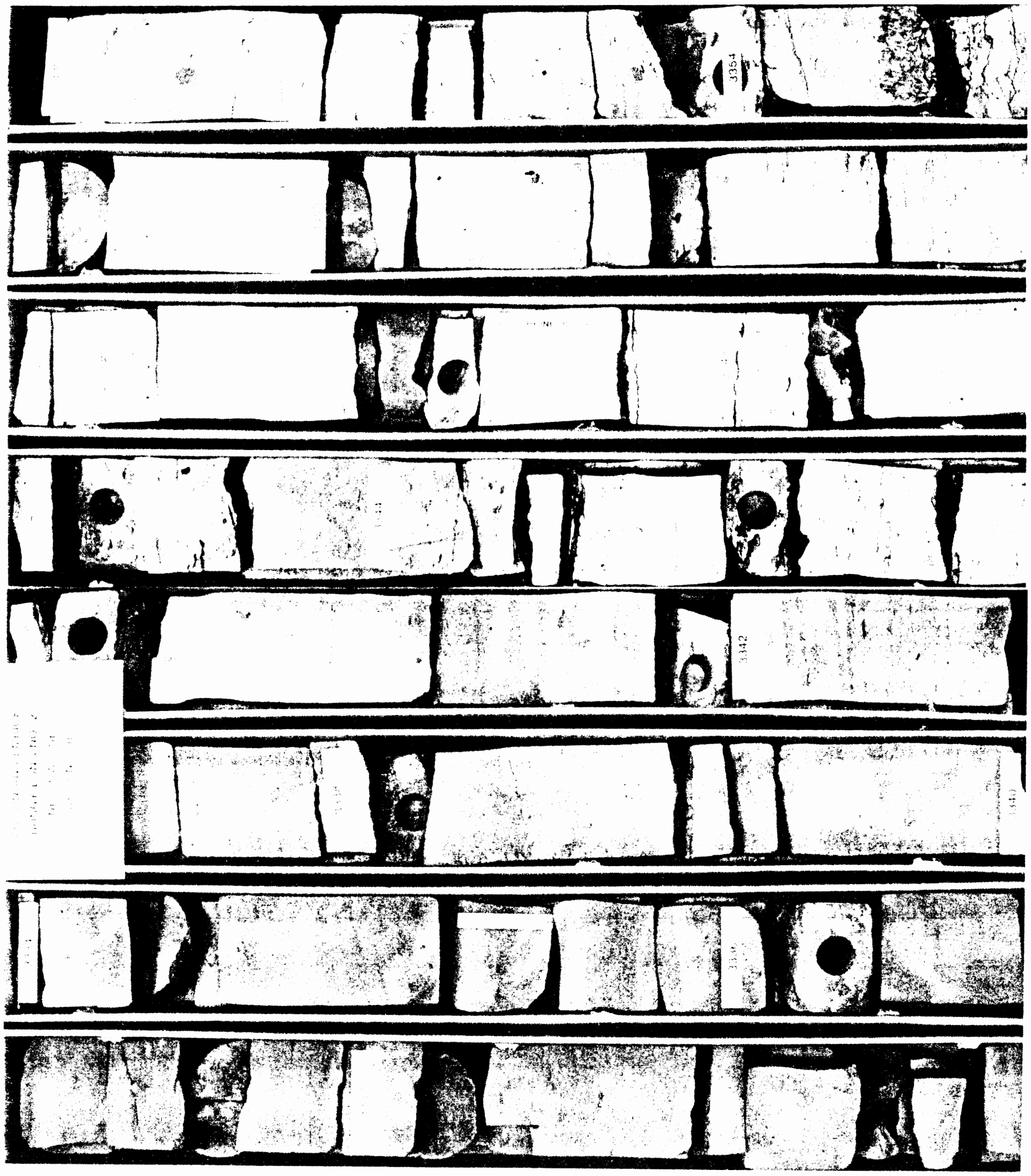

Midwest

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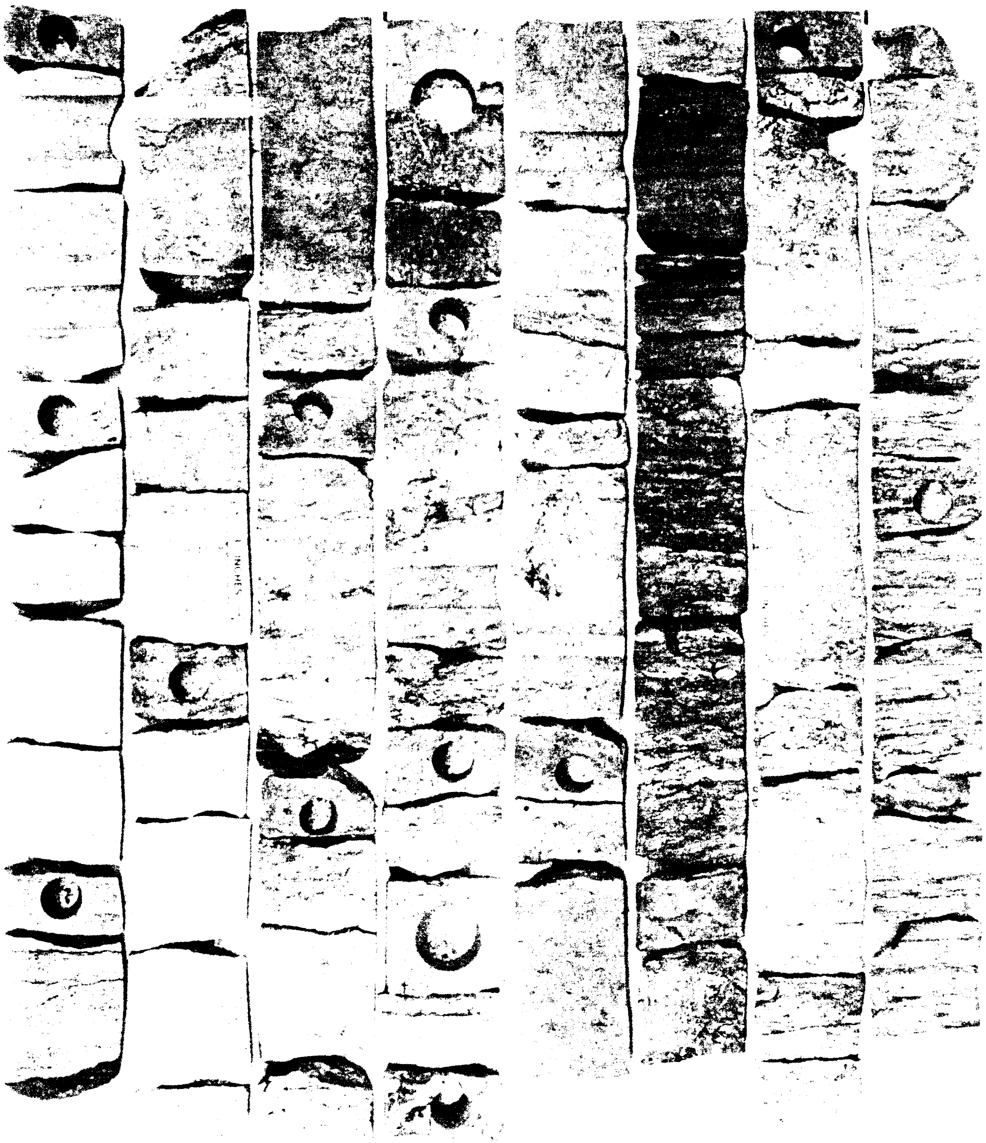
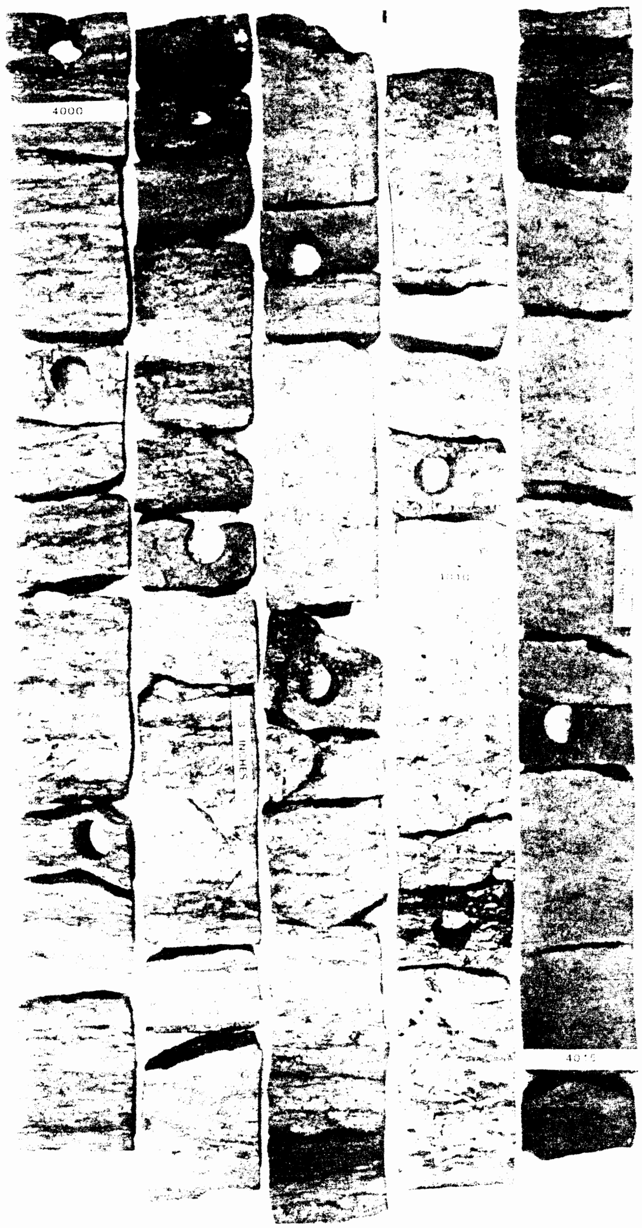
4338
4340

NCRA

No. 1 Johnson

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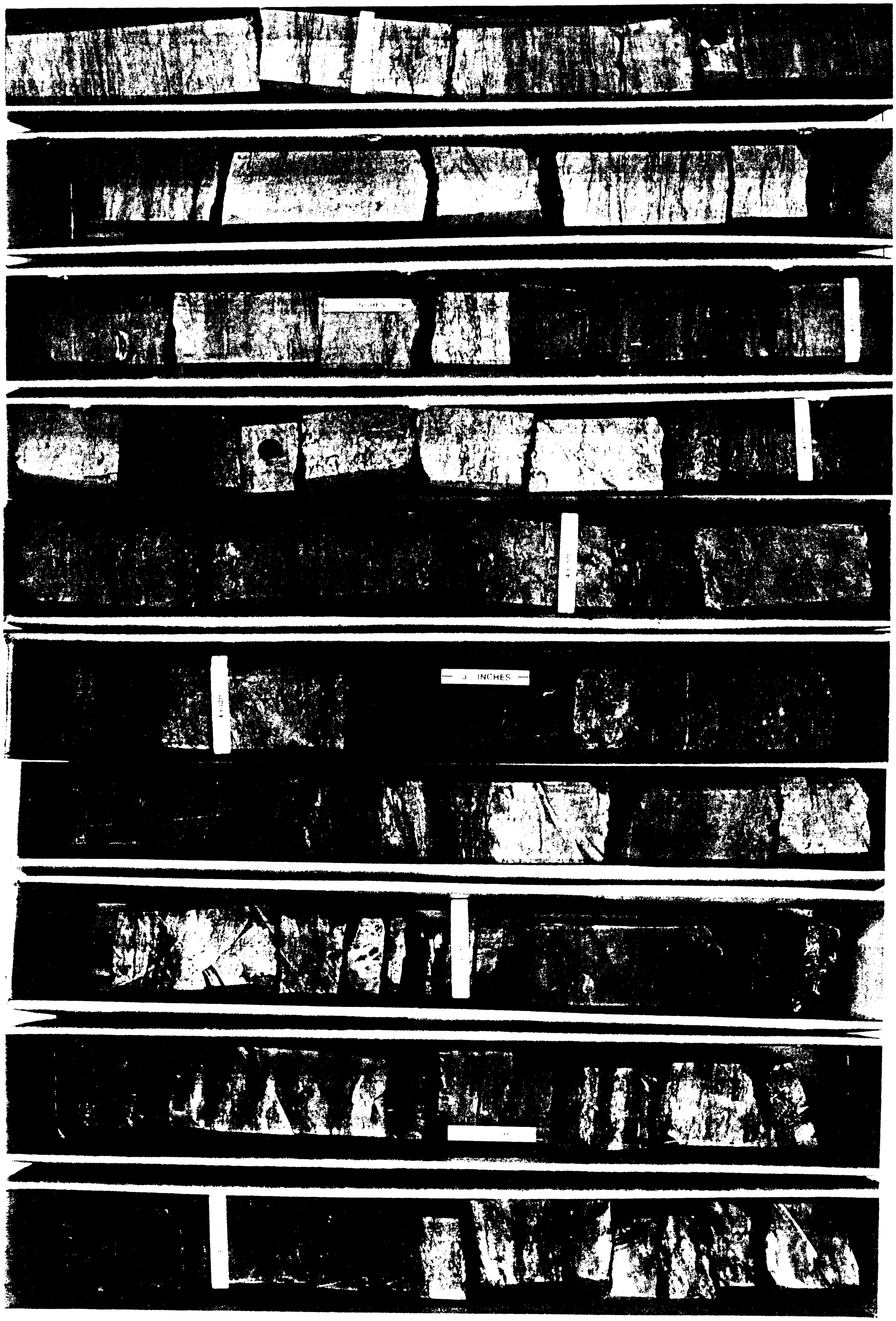
3 INCHES

Pan American

No. 1 Roberts


D ROBERTS NO 1

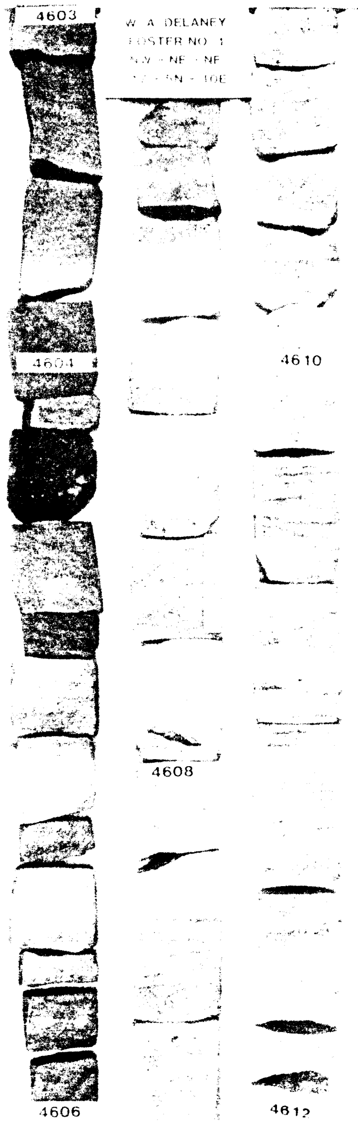

3 INCHES


INCHES


3 INCHES

Delaney

No. 1 Foster


4603
W. A. DELANEY
FOSTER NO. 1
4604
4606
4608
4610
4612

VITA

Rex David Stout

Candidate for the Degree

Master of Science

Thesis: SUBSURFACE GEOLOGY OF THE MORROWAN LOWER DORNICK HILLS (CROMWELL SANDSTONE) IN SOUTHERN HUGHES COUNTY, OKLAHOMA.

Major Field: Geology

Biographical:

Personal Data: Born in Tulsa, Oklahoma, October 19, 1963, the son of Mr. and Mrs. Ira L. Stout.

Education: Graduated from Kellyville High School, Kellyville, Oklahoma, in May, 1981; received the Bachelor of Science degree in Geology from Oklahoma State University in May, 1986; completed requirements for the Master of Science degree at Oklahoma State University in December, 1991, with a major in Geology.

Professional Experience: Associate Geologist, Samson Resources Company, Tulsa, Oklahoma, July, 1990 to Present; Research Assistant, School of Geology, Oklahoma State University, January, 1990 to May, 1990; Consulting Geologist, Louisiana Land and Exploration Company, Oklahoma City, Oklahoma, May, 1989 to September, 1989; Summer Project Geologist, Sun Exploration and

Production Company, Longview, Texas, May, 1988 to August, 1988; Graduate Teaching Assistant, School of Geology, Oklahoma State University, August, 1987 to May, 1989. Junior Member of the American Association of Petroleum Geologists; Member of the Tulsa Geological Society; Member of the Houston Geological Society.

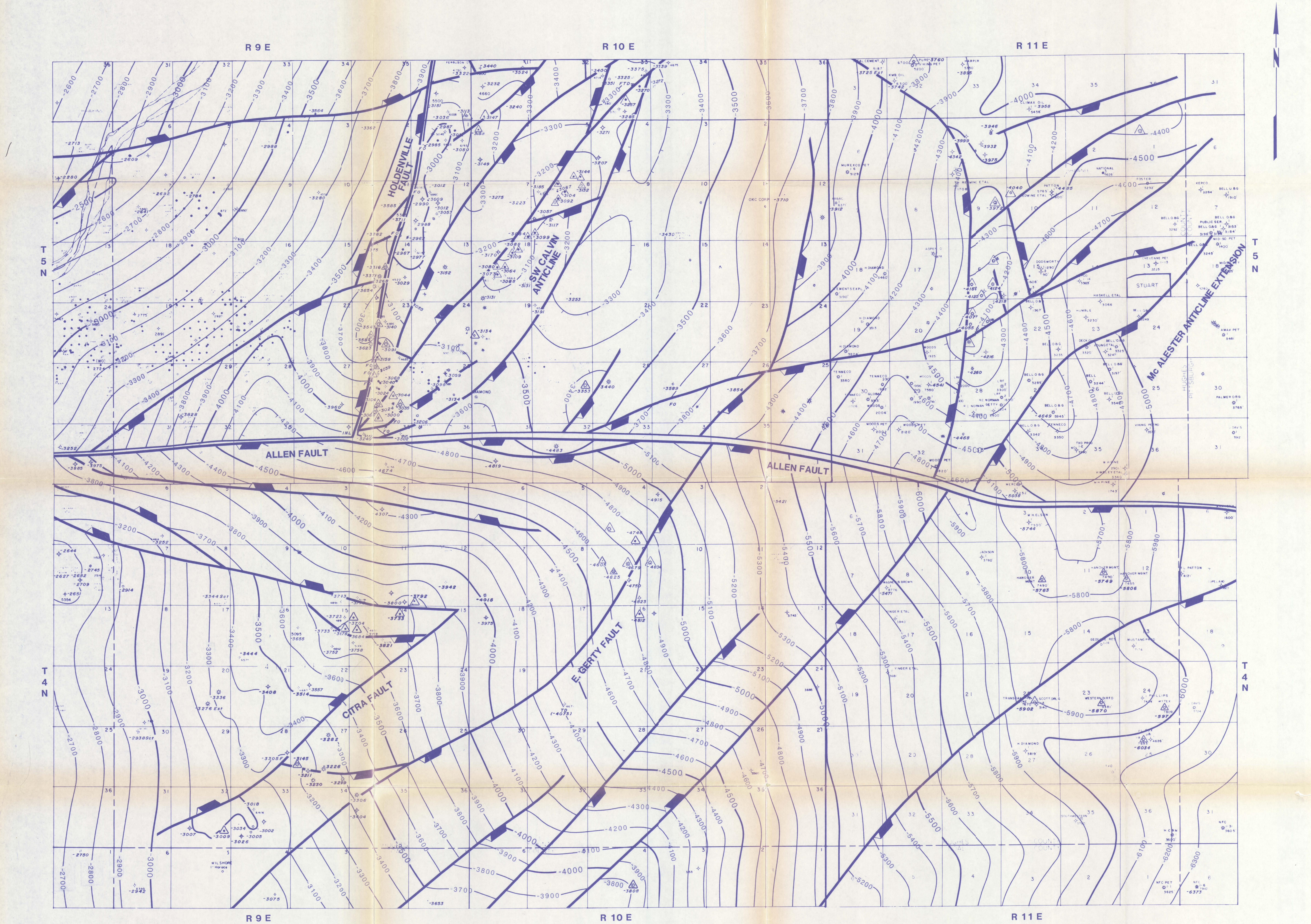


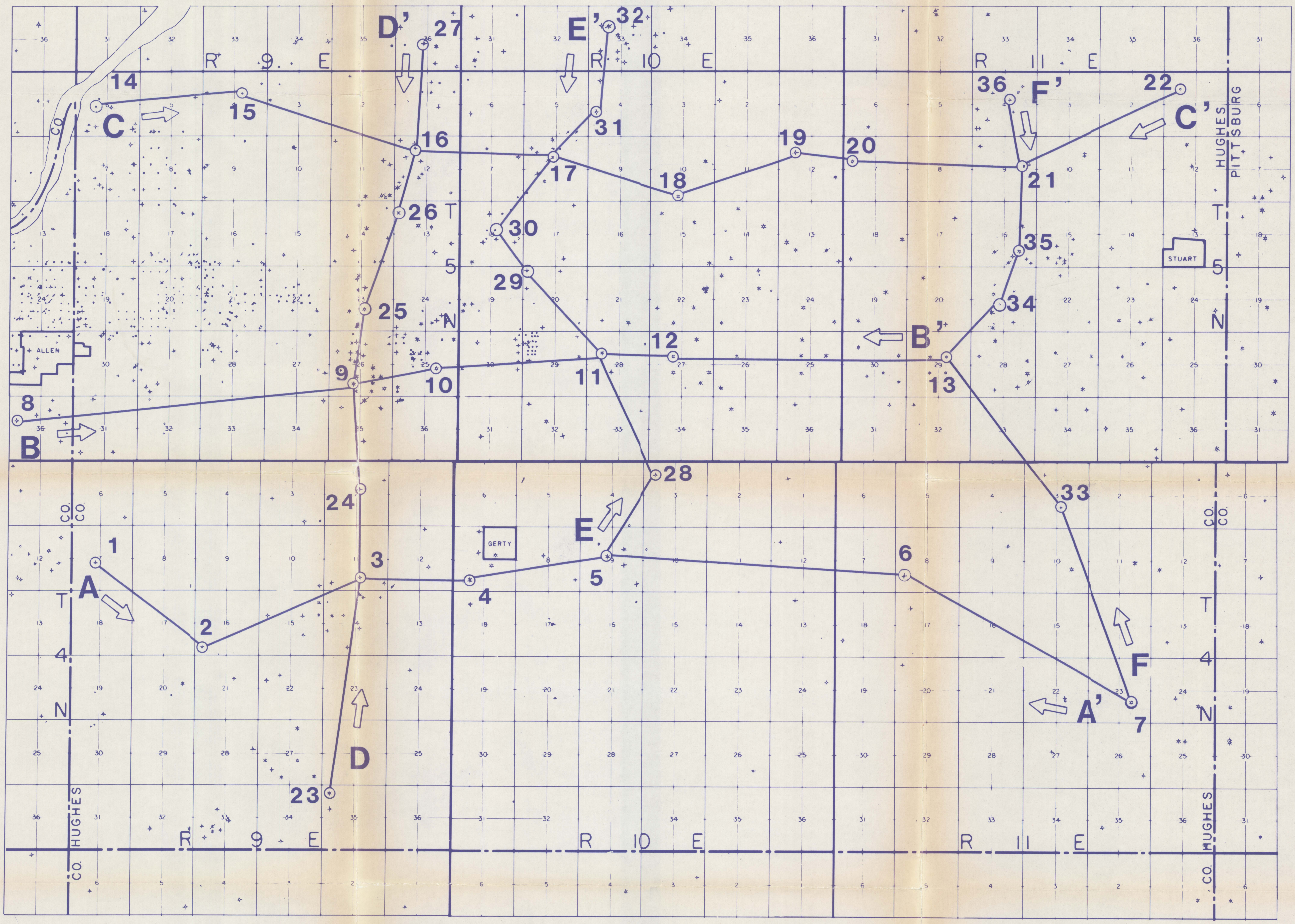
PLATE 1

STRUCTURE MAP
OF THE
WAPANUCKA LIMESTONE

MAP TYPE: STRUCTURE	C.I. 100 FT.

REX D. STOUT	OKLA. STATE UNIV.	M.S. 1991

△ UNION VALLEY PRODUCER



STRATIGRAPHIC

CROSS SECTION

INDEX MAP

PLATE 2

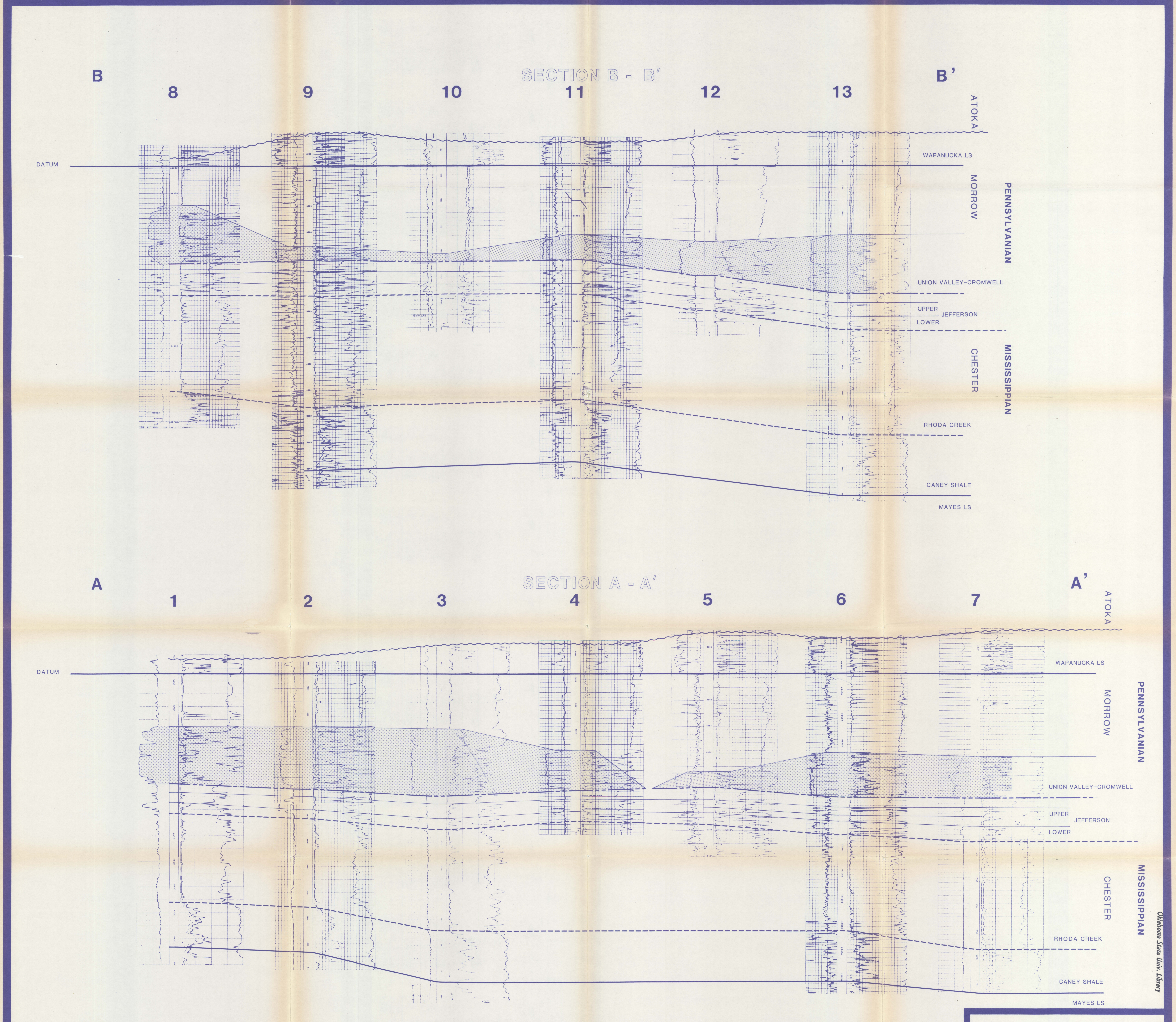
REX D. STOUT OKLA. STATE UNIV. M.S. 1991

1 0 1 2 MILES

1" = MILE

N

◯ - CROSS SECTION WELL

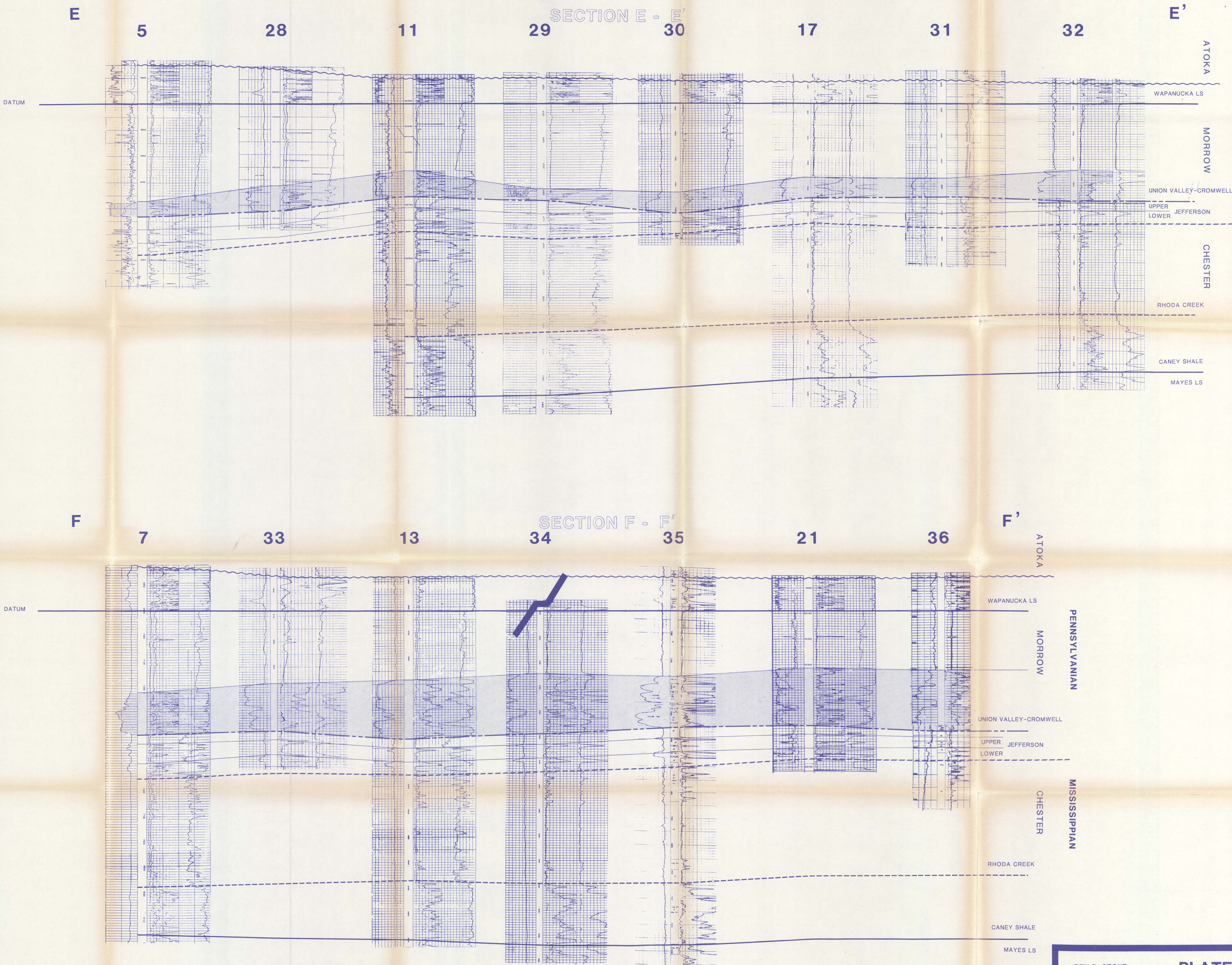


REX D. STOUT
OKLA. STATE UNIV.
M.S. 1991

PLATE 3
SECTION B - B'
SECTION A - A'

REX D. STOUT
OKLA. STATE UNIV.
M.S. 1991

PLATE 4
SECTION C - C'
SECTION D - D'



NO HORIZONTAL SCALE

REX D. STOUT
OKLA. STATE UNIV.
M.S. 1991

PLATE 5
SECTION E - E'
SECTION F - F'

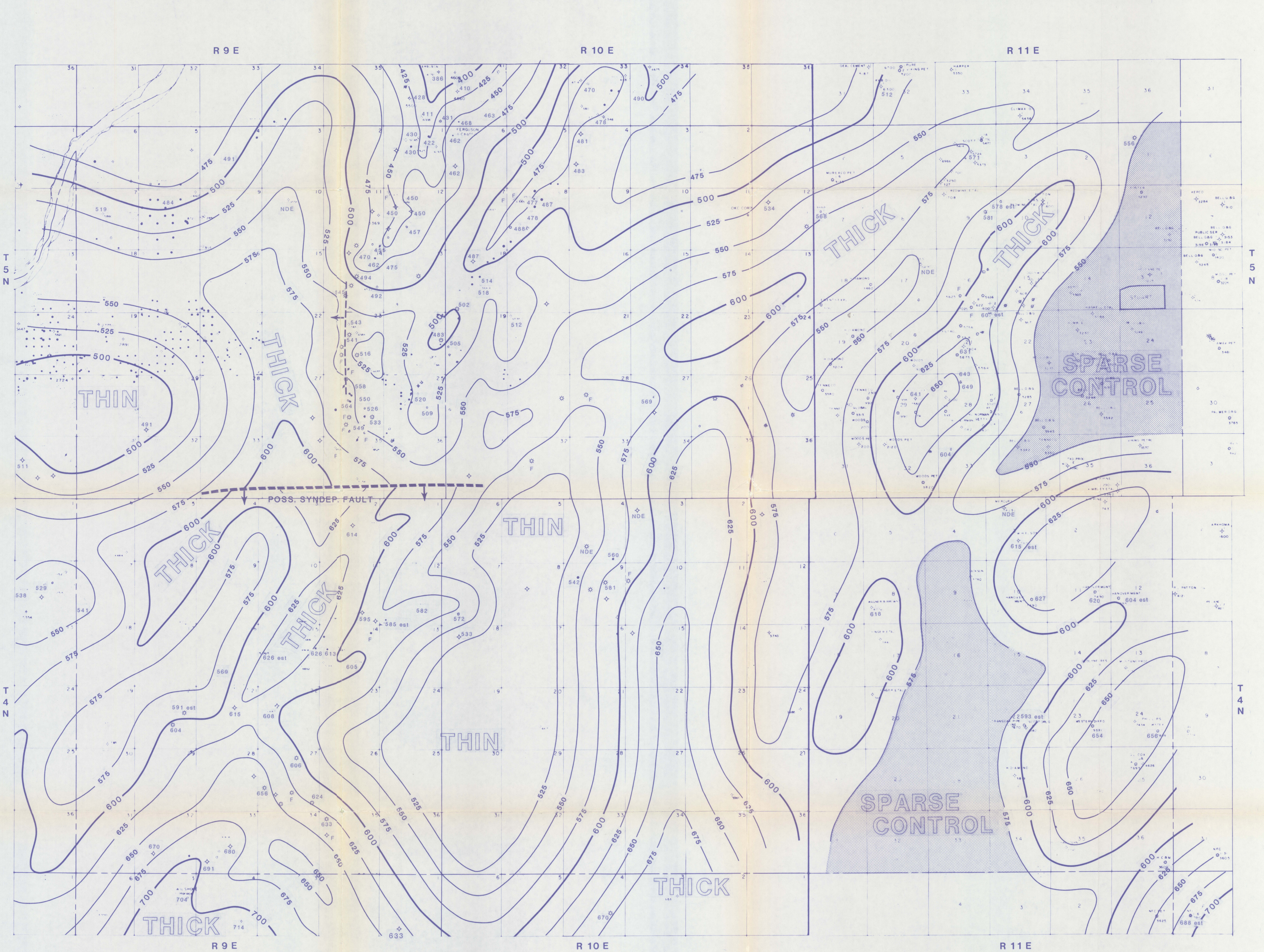


PLATE 6

UNION VALLEY GIS
ISOPACH MAP

MAP TYPE: ISOPACH		C.I. 25 FT.
REX D. STOUT	OKLA. STATE UNIV.	M.S. 1991

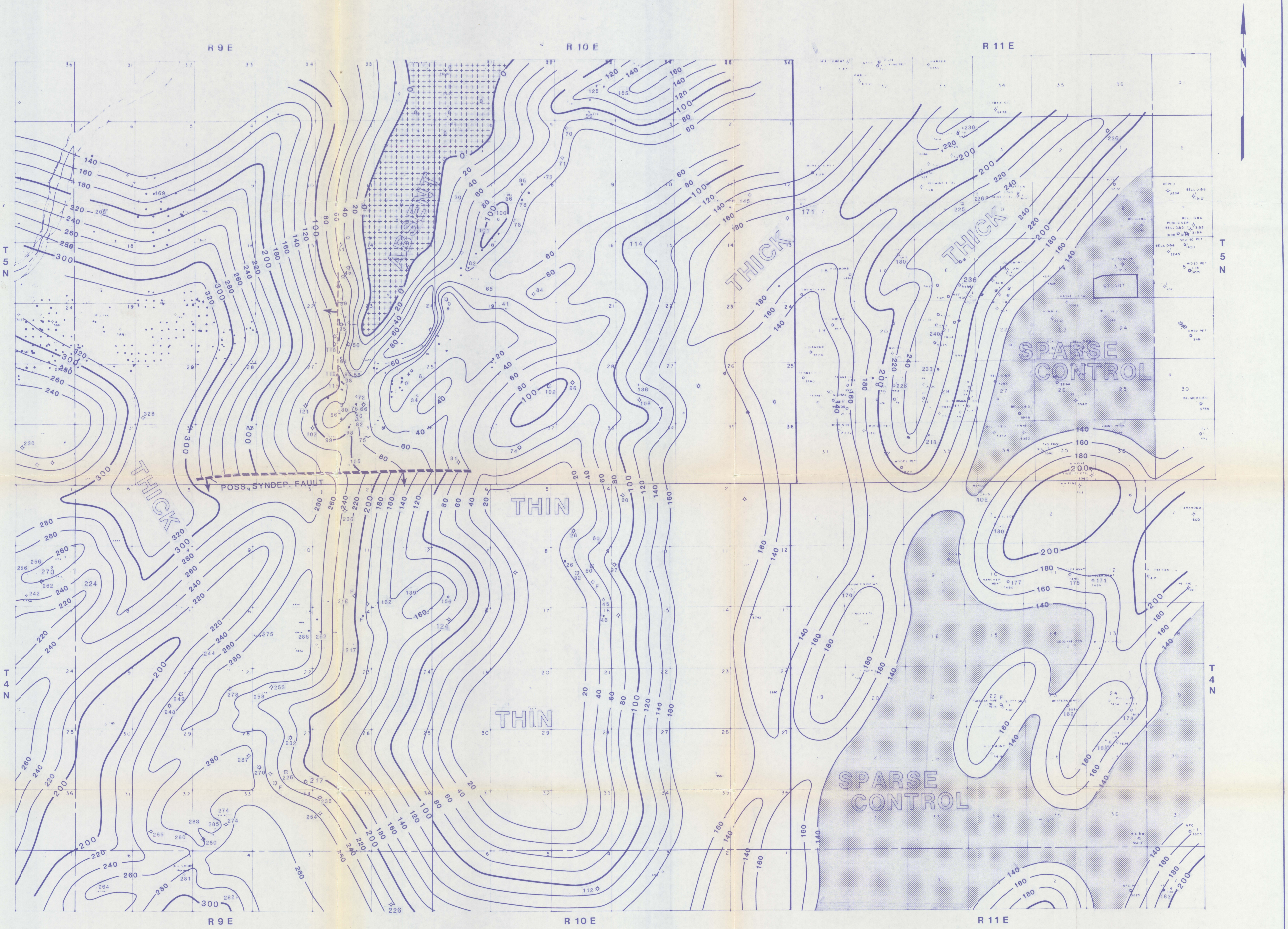
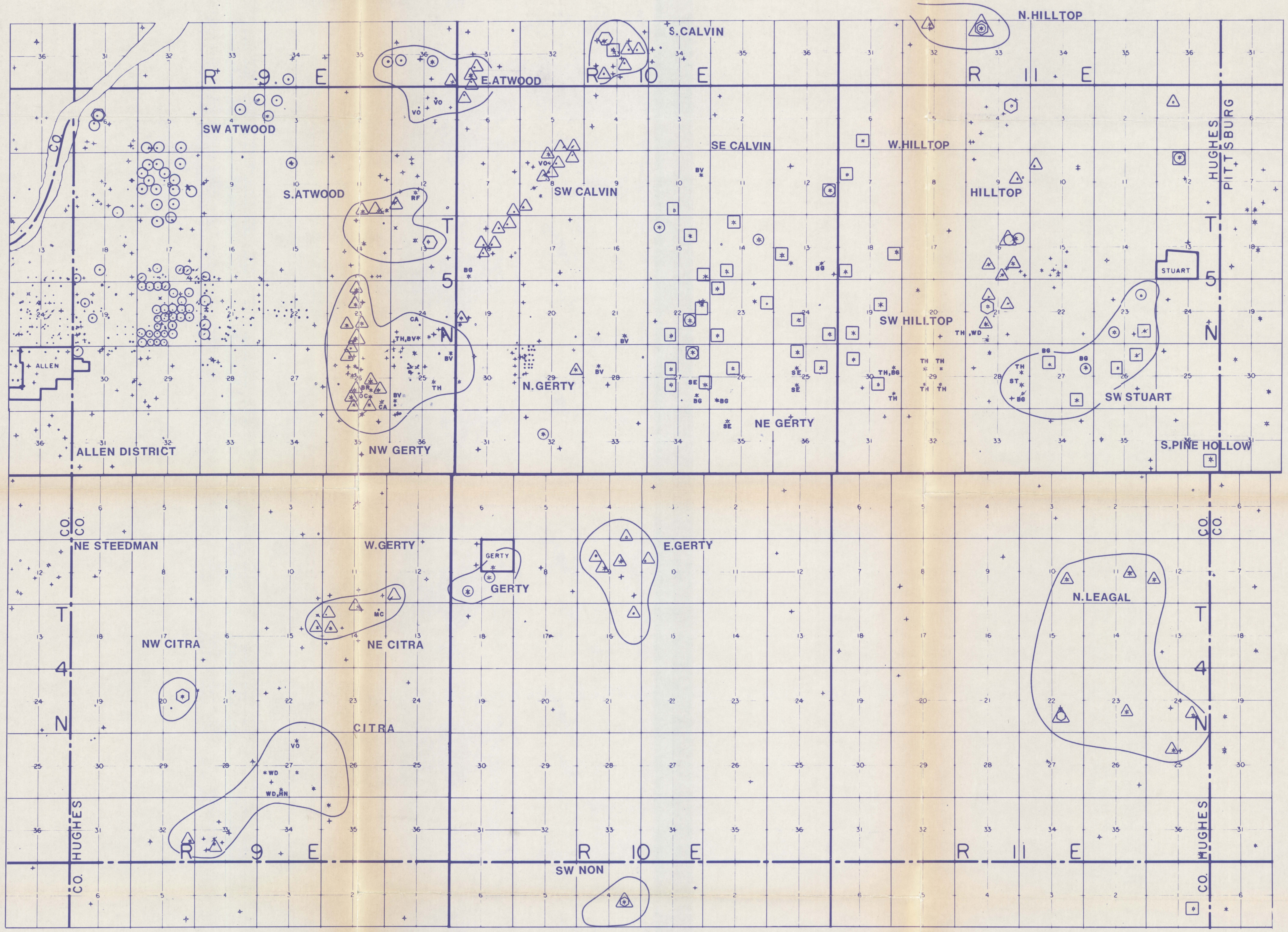


PLATE 7

UNION VALLEY LS. and CROMWELL SS.
ISOLITH MAP

MAP TYPE: INTERVAL ISOLITH		C.I. 20 FT.
REX D. STOUT	OKLA. STATE UNIV.	M.S. 1991



PRODUCTION LEGEND

CALVIN – CA	SAVANNA – SV	WOODFORD – WD
SENORA – SE	BOOCH – ○	MISENER – MS
STUART – ST	HARTSHORNE – □	HUNTON – HN
THURMAN – TH	GILCREASE – ⬡	VIOLA – VO
RED FORK – RF	WAPANUCKA – ⬡	BROMIDE – BM
BOGGY – BG	CROMWELL – △	MC LISH – MC
BARTLESVILLE – BV	RHODA CRK. – ⧖	OIL CREEK – OC

PRODUCTION MAP

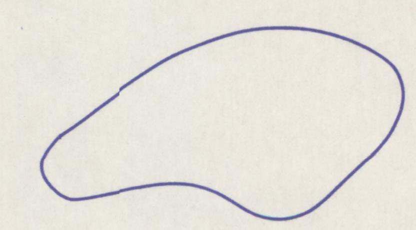
PLATE 8

REX D. STOUT OKLA. STATE UNIV. M.S. 1991

1 0 1 2 MILES

1" = MILE

N



FIELD OUTLINE