Influence of Mississippian Karst Topography on Deposition of the Cherokee Group: Ness County, Kansas

BY

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ABSTRACT

The Cherokee Group (Desmoinesian, Middle Pennsylvanian) of Ness County, Kansas was deposited on the western flank of the Central Kansas uplift. Eleven lithofacies were defined in the Cherokee Group to better understand the stratigraphy and depositional processes. Sandstone facies represent the primary oil-bearing reservoirs in the Cherokee Group.

An extensive network of groundwater-sapped paleovalleys is present on the Mississippian karst surface and two primary drainage patterns were identified. Groundwater-sapped valleys and dolines exhibit a strong structural control and develop along gravity and magnetic lineaments.

Three sequences were identified and mapped, two complete and one incomplete sequence. Potential reservoir sandstone bodies are confined to lowstand and transgressive systems tracts. Sand development is strongly influenced by Mississippian paleotopography. Thick sandstone successions were deposited in groundwater-sapped Mississippian valleys and along the paleoshoreline. Two depositional models were created to explain the lateral and vertical distribution of facies in the Cherokee Group.

ACKNOWLEDGMENTS

First off I would like to thank my committee members, Tim Carr, Tony Walton, and George Tsoflias for their comments and suggestion on this thesis. Their guidance and support throughout this process have helped shape this paper. I would sincerely like to thank my advisor Tim Carr for providing me with an opportunity to pursue my interest in geology. His wisdom and guidance have truly helped in my development as a geologist. I would also like to thank my wonderful advisors Lew Brown and Paul Kelso at Lake Superior State University for introducing me to geology and providing me with an excellent education in all aspects of the geosciences. They never tired of answering my endless questions in the classroom and the field.

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TABLE OF CONTENTS

LIST OF FIGURES AND TABLES

Chapter 1

Chapter 2

Chapter 3

Chapter 4

CHAPTER 1: INTRODUCTION

Introduction

In Ness County of west-central Kansas, the Cherokee Group (Desmoinesian Stage, Middle Pennsylvanian Series), is a mixed siliciclastic and carbonate sequence that unconformably overlies various Mississippian and pre-Mississippian carbonate units. The Cherokee Group was deposited in shallow-water marine, marginal-marine, and non-marine setting on the western flank of the Central Kansas uplift during a major marine transgression in the Pennsylvanian (Merriam, 1963; Zeller, 1968). Lithologically the Cherokee Group of western Kansas is significantly different than in southeastern Kansas, where the numerous coal seams (70% of the deep coal resources in Kansas) were deposited in deltaic environments (Brady, 1997).

Flooding associated with transgression onto the Mississippian unconformity surface deposited several marine and non marine facies, including oil-bearing reservoir sandstone facies. Facies distribution in the Cherokee Group is believed to be influenced by the paleotopography of the underlying Mississippi unconformity surface (Howard, 1990; Cuzella et al., 1991).

The goals of this project are:

1) Determine the depositional environments of lithofacies in core.
2) Understand the Mississippian karst topography and evaluate the role of basement structure in the development of the Mississippian erosional surface.

3) Generate a depositional model based on a stratigraphic framework for the Cherokee Group developed from core and log data.

4) Evaluate the, influence of the Mississippian karst surface paleotopography on the distribution of Cherokee Group facies and reservoirs.

Hydrocarbon significance

Sandstone facies in the Cherokee Group are of particular economic interest because they often form oil reservoirs. Reservoir sandstone is usually only 5-20 feet thick, highly variable, and laterally discontinuous. Early production during the 1950's from the Cherokee Group in western Kansas was often serendipitous in wells drilled for deeper formations (Geobel, 1957). Sandstone reservoirs of the Cherokee Group increased in importance as an exploration target during the 1970's because of high average production from wells (70,000 to 80,000 barrels on 40 acre spacing) and shallow drilling depths, causing a peak in production. Approximately one third of all oil fields in Ness County produce oil from the Cherokee Group (~113 out of 332). Traps in the Cherokee Group are subtle and include structural, stratigraphic, and paleogeomorphological types (Beiber, 1984). However, due to the lenticular nature of Cherokee sandstone reservoirs, correlation, distribution and architecture have always proved hard to predict (Mueller, 1967; Beiber, 1984).

Area of Investigation

The study area is confined to Ness County in western Kansas and encompasses over 1,000 square miles (2,700 square kilometers) (Figure 1.1). It is located on the northeastern shelf of the Hugoton embayment and is flanked by the Central Kansas uplift to the east. Cherokee Group rocks are only present in the subsurface at depths between 4,000 to 4,650 feet and rest unconformably on Ordovician through Mississippian strata.

Previous Investigation

Although much has been published on the Cherokee Group in eastern Kansas, few studies have been conducted on the Cherokee Group in central and western Kansas. Most of the studies in western Kansas were small-scale oil field studies and focused on sandstone facies within the Cherokee Group. Roth (1930) published a regional subsurface correlation for the Cherokee and Marmaton groups throughout the midcontinent region. Abernathy (1936) and Howe (1956) subdivide the Cherokee Group outcrops in eastern Kansas into cyclothems and formations, which became the basis of the current accepted stratigraphic classification (Zeller, 1968). Geobel and Merriam (1957) commented on the oil and gas production trends developing in the Cherokee Group on the western flank of the Central Kansas uplift. Walters (1979) interpreted Cherokee Group sandstone units east of Dickman oil field in north-central Ness County as channel deposits. Stoneburner (1982) completed detailed subsurface mapping and interpretation of the Cherokee in the extreme northeastern corner of Ness County and into Trego and Ellis counties. Bieber (1984) investigated reservoir characteristics and trap types in the Start oil field, Ness County. Nodine-Zeller (1981) examined a core in southeastern Ness County, and interpreted the Pennsylvanian Basal Conglomerate as the fill of a fault-controlled karst valley or deposition adjacent to prominent sea cliffs in a quasi-marine environment. Nodine-Zeller (1981) identified transgressive-regressive marine limestone and shale of middle to late Cherokee age. Howard (1990) applied cyclic depositional principles to the Cherokee Group of northeastern Ness County and identified two marine transgressive-regressive cycles. Cuzella (1991) performed a study in the same region as Howard and defined six distinct depositional environments. Most of these detailed studies are small scale and restricted to the eastern portion of Ness County.

Geological Setting

Ness County is located on the western flank of the Central Kansas uplift and the northeastern shelf of the Hugoton embayment of the Anadarko basin (Figure 1.2). The Central Kansas uplift is a northwest-southeast trending structural high that separates the Hugoton embayment on the west from the Salina and Sedgwick basins on the east (Merriam, 1963). It is the largest positive feature in Kansas, occupying an area of about 5700 square miles, and is outlined by the extent of the Mississippian beds. Many workers have noted the onset of deformation in the midcontinent during the early Paleozoic, with initiating movements that created uplifts, including the Central Kansas uplift and Cambridge arch, with associated basins (Kluth, 1986). These uplifts are major components of the Transcontinetal arch, and are linked to Cambro-Orodovician deformation as well as late Mississippian deformation

(Merriam, 1963). Much of the deformation is associated with the collision of North America and South America-Africa portion of Gondwanaland, which initiated the Ouachita-Marathon orogeny (Kluth and Coney, 1981). Yarger (1983) noted that Precambrian faults associated with the Central North American Rift system were likely reactivated during the late Mississippian. Gentle widespread uplift occurred contemporaneously with a major sea-level lowstand, creating a period of significant emergence and erosion (Ham and Wilson, 1967; Rascoe and Adler, 1983). Almost the entire midcontinent was affected by the epeirogeny, which was centered on the Cambridge arch-Central Kansas uplift. Since the end of the Pennsylvanian, the west-central region of Kansas has been characterized by a fairly quiet tectonic history, with a lack of large-scale structural movements (Merriam, 1963). Regional tilting and subsidence to west-southwest, along with localized uplift linked to Laramide deformation, have been the dominant tectonic influence of post-Pennsylvanian time (Merriam, 1964).

At the core of the Central Kansas uplift, Pennsylvanian beds unconformably overlie Precambrian basement rock, while toward the flanks Pennsylvanian beds on lap uplifted and truncated Precambrian through late Mississippian beds (Merriam, 1963). This creates an angular unconformity with Morrowan through Desmoinesian rocks successively onlapping truncated Precambrian through Mississippian rocks (Merriam, 1963; Rascoe and Alder, 1983). During the Early Pennsylvanian, the major sedimentation influences were marine transgression onto the erosional surface and sediment shed westward from the Central Kansas uplift. On the northeastern shelf of the Hugoton Embayment, Desmoinesian Stage sediments, composed primarily of limestone with thin interbedded shale beds, rest on Mississippian dolomite and limestone. On the tectonically stable shelf, water depths probably did not exceed 100ft (30m) (McCrone, 1964). Closer to the uplift, limestone-dominated units give way to fine-grained to coarse-grained siliciclastics that parallel the paleo-coastline along the uplift.

Stratigraphy

The main stratigraphic interval of interest throughout the study area is the Cherokee Group, which rests unconformably on the Mississippian unconformity surface in Ness County (Figure 1.3). Uplift and erosion at the end of the Mississippian removed a significant amount of strata over the Central Kansas uplift and exposed the Precambrian basement along the crest (Figure 1.4). In Ness County, the Cherokee Group overlies Meramecian, Osagean, and Kinderhookian carbonate units (Figure 1.5).

Mississippian Series: Kinderhookian, Osagean, and Meramecian

The primary Kinderhookian deposit exposed at the top of the Mississippian subcrop in the study area is the Gilmore City Limestone. The Gilmore City Limestone consists of soft, chalky, bioclastic limestone, but in western Kansas is often characterized by oolitic limestone with localized trace amounts of chert (Zeller, 1968).

Formations in the Osagean Stage consist mainly of dolomite, limestone, chert, cherty dolomite and dolomitic limestone beds. Throughout much of Kansas Osagean

Stage rocks are of characterized by chert-rich reservoirs. Basal Osagean rocks are separated from the underlying Kinderhookian Stage rocks by an angular unconformity (Zeller, 1968).

Meramecian Stage rocks lie disconformably on Osagean Stage rocks. The only Meramecian Stage formations present in Ness County are the Warsaw Limestone and Salem Limestone (Zeller, 1968). The Warsaw is characterized by limestone with interlaminated saccharoidal dolomite that contains large amounts of distinctive gray, mottled, opaque, microfossiliferous chert (Zeller, 1968). The Salem Limestone conformably overlies the Warsaw and consists mainly of coarsely crystalline oolitic limestone and saccharoidal dolomite, dolomitic limestone, and chert. The chert facies often resembles the microfossiliferous chert of the Warsaw Limestone.

Lower Pennsylvanian Series

The Pennsylvanian Basal Conglomerate (PBC) is a breccia that overlies much of the karstic Mississippian surface in central Kansas. The breccia is a mixture of highly weathered in situ Osagean, Meramecian, and Chesterian cobbles and boulders as well as fluvial deposited pebbles and cobbles. The clasts are derived from the karst terrain of the Mississippian surface. A thin paleosol is often present at the top of the PBC. Nodine-Zeller (1981) described the PBC from a core in southwestern Ness County and concluded that it is earliest Pennsylvanian or possibly early Desmoinesian in age. Morrowan and Atokan age strata are not recognized across the study area in Ness County. The PBC is readily identified in core, but is often difficult to distinguish in logs.

Middle Pennsylvanian Series

Cherokee Group

The Cherokee Group strata are the lower division of the Desmoinesian Stage. Significant stratigraphic research has been conducted in southeastern Kansas where the Cherokee Group crops out. A detailed stratigraphy has been developed for the Cherokee Group in southeastern Kansas, which includes the Krebs and Cabaniss Formations with a total of twelve formally recognized coal beds (Zeller, 1968; Figure 1.6).   Both formations contain cyclic deposits consisting primarily of gray shale, siltstone, fine-grained sandstone, paleosol and underclay, thin coal seams, black shale, and thin limestone beds.

Numerous publications have interpreted the rocks of the Pennsylvanian succession in Kansas as a series of repeating cyclothems (Wanless and Weller, 1932; Abernathy, 1936; Merriam, 1963; Heckel, 1977), and. The model for a “typical” Pennsylvanian cyclothems in Kansas consists of four recognizable and laterally extensive members: 1) outside shale, 2) lower limestone, 3) core shale, and 4) upper limestone (Figure 1.7) (Heckel, 1977).   The outside shale is relatively thick, grey to brown, sandy to shaley, with discontinuous and thin coal seams.   It may also contain continental trace fossils and evidence of pedogenesis. The lower limestone is a thin, grey to black, dense limestone with diverse marine biota. The lower limestone is referred to as the transgressive limestone, interpreted water depths and depositional environments at the base are shallower and more nearshore than those at the top of the unit (Heckel, 1977). The core shale is a thin (1.0 m or less) finely laminated dark-grey to black fissile shale. The core shale may contain phosphatic nodules that are interpreted as indicating deep, sediment-starved depositional environments and anoxic conditions (Heckel, 1977). The upper limestone, referred to as the regressive limestone, typically has a wackestone to grainstone fabric and commonly contains oolitic grainstone near the top. Usually the regressive limestone is much thicker than the transgressive limestone, and records a reduction in water depth. Typically, the upper limestone is overlain by the next cyclothem, however local and regional incision may erode parts previously deposited cyclothem (Heckel, 1977).

The Cherokee Group in central and western Kansas is significantly different, and the detailed stratigraphy developed from outcrop data is rarely used. For the purpose of this study, the Cherokee Group is defined as containing all strata between the top of the Mississippian to the base limestone units in the Fort Scott Limestone (top of the Excello Shale equivalent). In Ness County, the Cherokee Group lacks the coals found in eastern Kansas and is primarily composed of limestone and shale with sparse sandstone. The depositional environment in central and western Kansas was different and the Cherokee Group has not been divided into formal formations or members.

Marmaton Group

The upper Desmoinesian beds in Kansas are assigned to the Marmaton Group. The Marmaton is dominated by thicker limestone, thinner grey shale, and more fissile, phosphatic black shale than observed in the underlying Cherokee Group, and exhibits characteristics that are more commonly associated with the “typical” Kansas cyclothem model (Zeller, 1968). The Fort Scott Limestone is the lowest formation in the Marmaton Group and is composed of two limestone members separated by a shale member that is not readily distinguishable in the subsurface. The Labette Shale consists of gray and yellow clay-rich shale, sandy shale and sandstone, coal and limestone beds (Zeller, 1968). It conformably overlies the Fort Scott Limestone, which is not reliably identifiable or not present in the subsurface. Overlying the Labette Shale is the Pawnee Limestone. The basal Anna Shale Member, a black, platy, locally fissile shale, has a distinctive, high gamma-ray log signature, making it ideal as a stratigraphic datum. The Pawnee Limestone is a dark-grey to light-grey *Chaetetes*-bearing limestone, and typically exhibits a highly recognizable smooth cleaning-upward gamma-ray log signature (Zeller, 1968).

Methods

Two main methods of investigations were used in this study: 1) core description, 2) and correlation of well data and logs for subsurface mapping using computer applications. Well data used in this project was obtained from the Kansas Geological Survey (KGS). Cores were described at the KGS Core Laboratory. Wireline logs were obtained from the KGS and used for the subsurface mapping.

Lithologic Analysis

Since no outcrops of the Cherokee group are present in Ness County, lithologic samples were obtained from cores. Six cores were described to identify lithofacies (Figure 1.8; Appendix 1). Cores were selected based on their geographic location, length of penetration into the Cherokee Group, and the suite of logs available for each well. The cores were chosen to help show the heterogeneity of the Cherokee Group in western Kansas. Core descriptions illustrate changes in lithology, sedimentary structures, fossil assemblages, grain size and composition, and bedding types that provided the basis of the depositional environment interpretations. Selected intervals of the cores were slabbed to aide in the identification and description of sedimentary structures and key surfaces.

Geophysical Well Log Analysis

Geophysical well logs account for the bulk of the subsurface data used in this investigation. Over 550 well logs across Ness County were used for correlation purposes (Figure 1.8). Logs were selected based on interval of log, logging tools used, the spacing and location of the logs, the quality of the logs, and availability. Logs were selected to give adequate spatial distribution throughout the entire county and minimize the data needed to perform correlations. Gamma-ray–neutron or radiation guard (RAG) wireline logs were the most abundant in the study area, but when available, more modern neutron-density logs, resistivity, and bulk density logs were used to provide additional data. Neutron-density wireline logs proved particularly useful in differentiating between limestone and sandstone intervals. Resistivity logs were also helpful in identifying highly resistive limestone units. The majority of the available logs were raster images available from the Kansas Geological Survey (scanned copies of paper logs saved as .TIF files). A few digital logs (.LAS files) were available for the southeastern portion of Ness County. All selected logs were loaded into subsurface geographic information system (GIS) software.

Computer Applications and Digital Mapping

Paper logs were available for many wells throughout the study area but very in a digital format were available. A scanner built exclusively for paper well-log scanning (Neuralog) was employed to create the raster images of the logs. Raster images were calibrated in the subsurface GIS program to insure the digital logs files were matched to the correct well locations.

Subsurface mapping for this study was conducted in a subsurface GIS program (Petra^{TM}). Information from 5,840 wells including: API number, well name, well type, operator, location, Kelly-bushing or ground-level elevation, spud date, and total depth was downloaded from the Kansas Geological Survey's relational database (Figure 1.8). Logs, formation tops, and cored well locations were also obtained from the Kansas Geological Survey's Oracle database and other resources. Select formation tops were quality controlled and verified based on wireline logs. The digital mapping capabilities of Petra were used to create structure, isopach, and net sand maps. A V_{shale} ratio of 20 percent was applied to estimate net sand thickness. In addition, structural and stratigraphic cross sections were created to identify and illustrate subsurface geometries.

Gravity and Magnetic Data

Gravity data used in this project were taken from the potential-field database at the Kansa Geological Survey. Gravity data were taken by dividing the state into a number of rectangular blocks approximately 25 miles (40 km) in the east-west direction and 16 miles (26km) in the north-south direction. A base station was chosen at the center of each block at which base readings to correct for meter drift and differences in elevation at other sample stations in the block. Measurements in western Kansas were taken every mile (1.6 km) along east-west roads and every 2 miles (3.2km) in the north-south direction. Surveyors recorded elevation (with an accuracy of 1 ft. or .3 m), and gravity in mGals at each station. Tidal and drift corrections were applied to the data, and used to generate a corrected Bouguer gravity reading. The Bouguer gravity data were loaded into Petra, and gridded and contoured for further interpretation.

Magnetic data used in this project are from the potential-field database at the Kansas Geological Survey. Aeromagnetic data were taken in east-west oriented flight lines spaced 2 miles (3.2 km) apart. Data was recorded every 300-400 feet (90-125 m) providing sufficient resolution to discern Precambrian basement structure (Xia et al., 2000). Diurnal, normal-field, and topographic corrections were applied to the raw data to correct for drift, spatial variation in geomagnetic field, and elevation respectively. Corrected total field and residual magnetic data (in nanoTesla) were mapped using a 2000 X 2000 foot grid (610 X 610 meters) to generate a contour map.

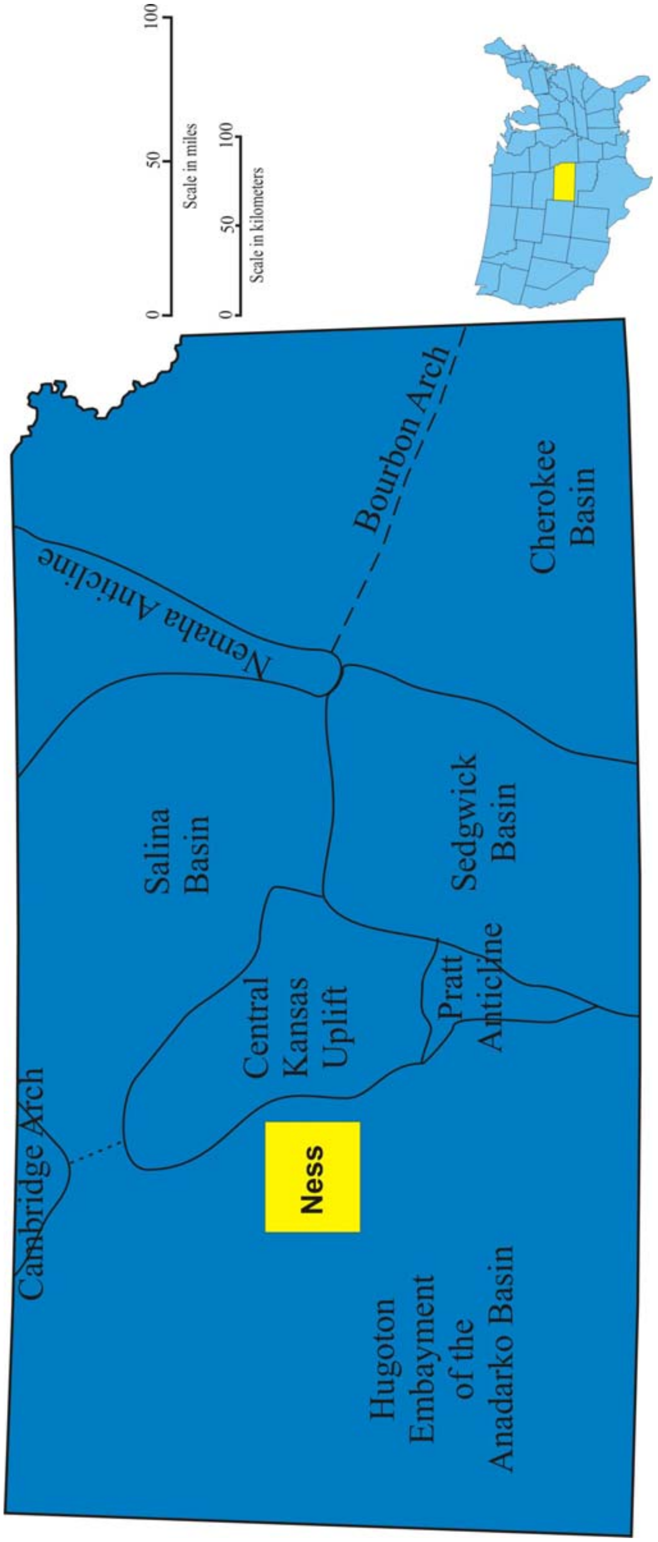

Figure 1.1. Major structural features of Kansas with the Ness County (the study area) highlighted. Modified from Merriam (1963); and Lange (2003).

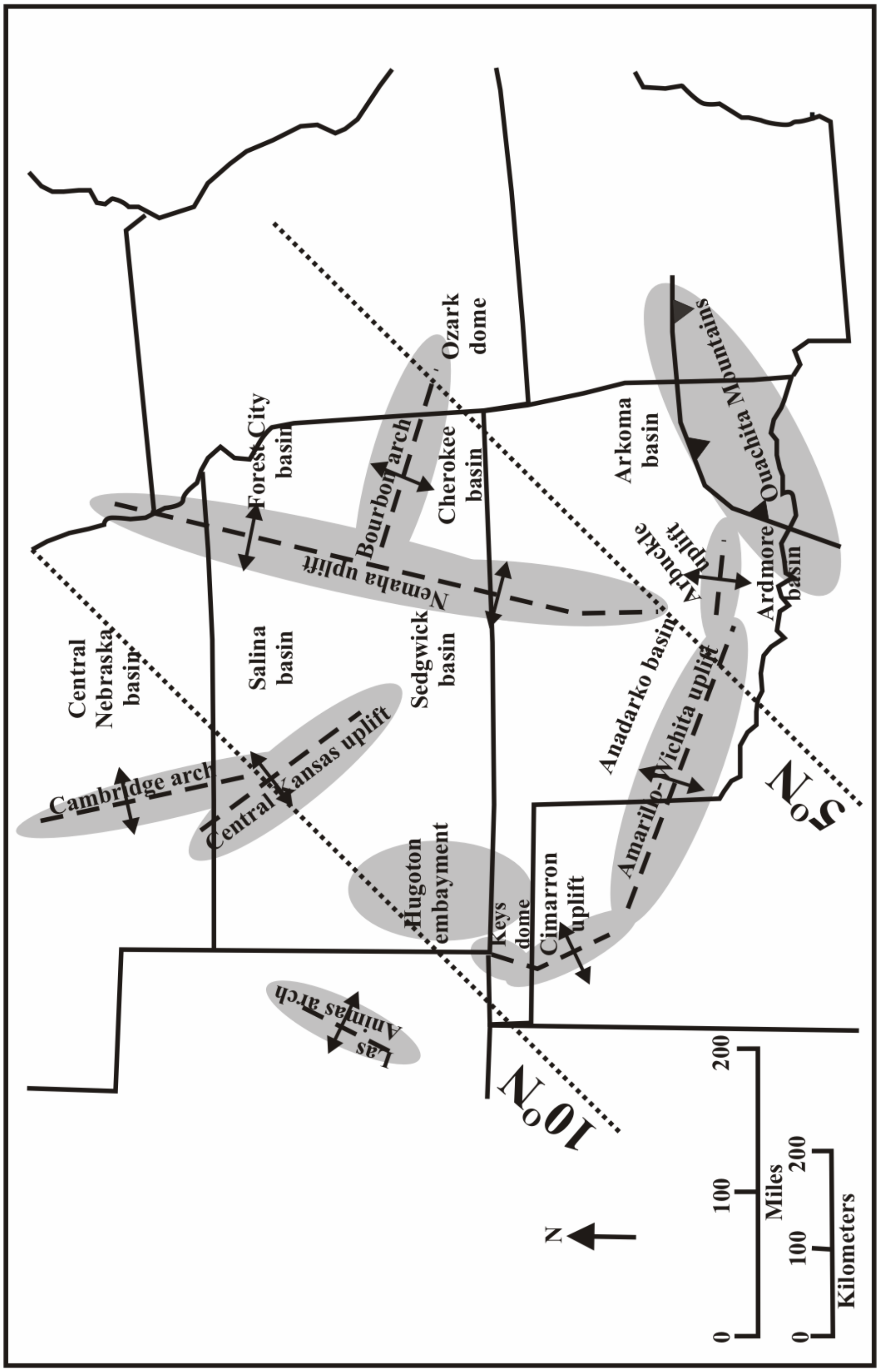

Figure 1.2. Regional Midcontinent structural features and interpreted Pennsylvanian paleolatitude. Modified from Merriam (1963); Rascoe and Alder (1983); Scotese (1999); Blakey (2005).

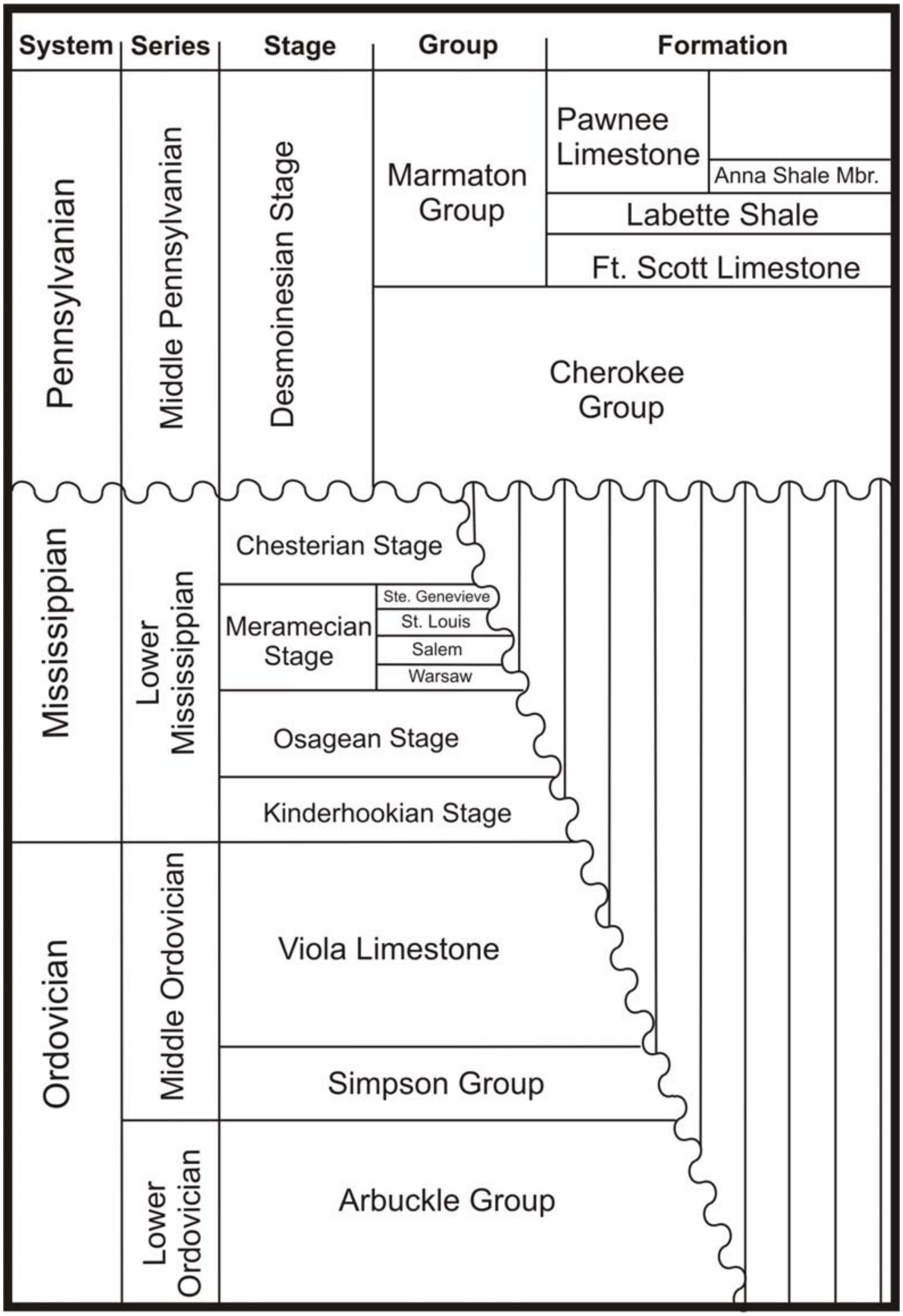

Figure 1.3. Generalized stratigraphic column for study area in western Kansas depicts the Cherokee Group resting unconformably on Mississippian through Ordovician age strata.

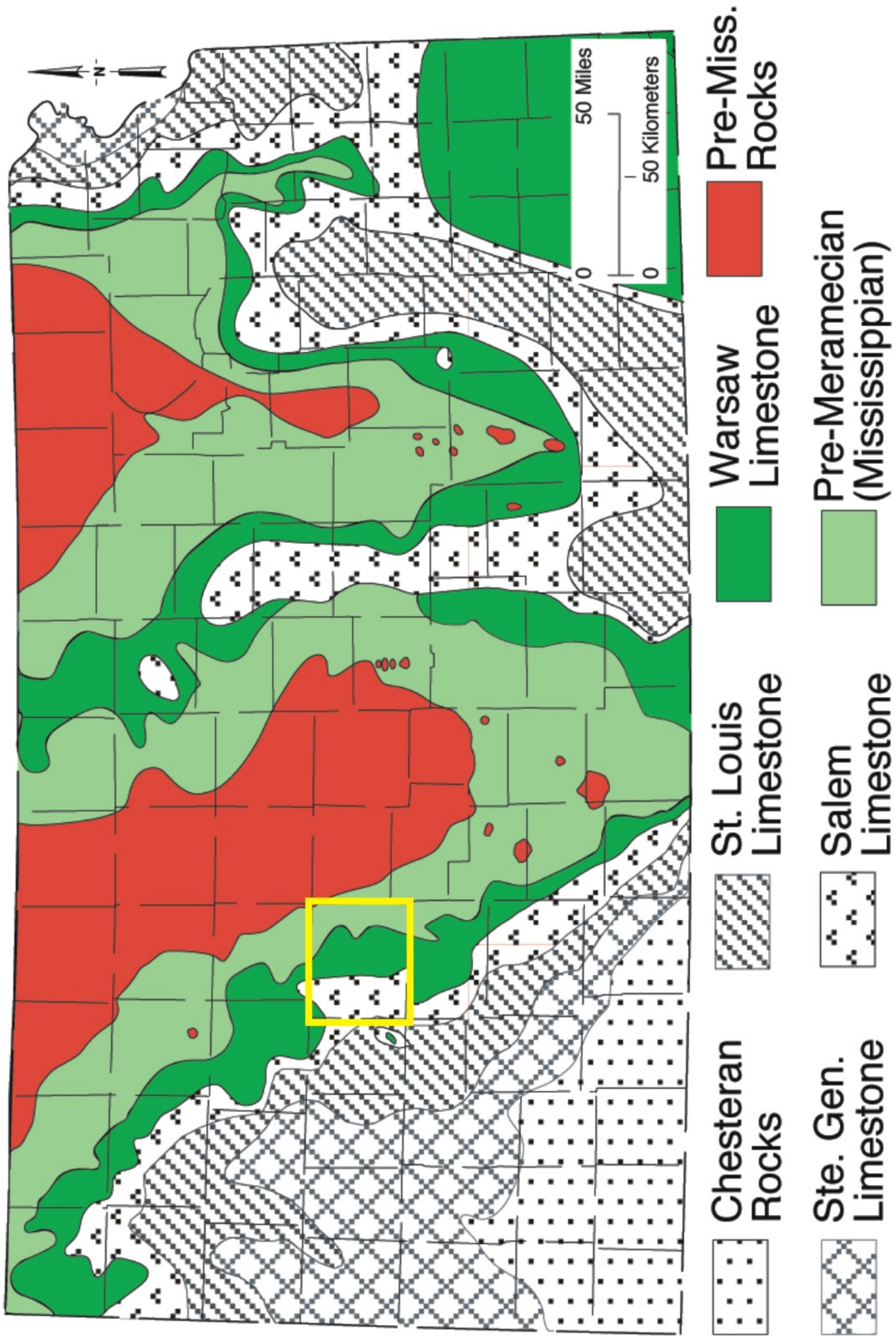

Figure 1.4. Map of the Mississippian subcrop beneath the Pennsylvanian unconformity with Ness County highlighted. Mississippian units beneath the unconformity become progressively older toward the Central Kansas uplift. Modified from Merriam (1963) and Gerlach (1998).

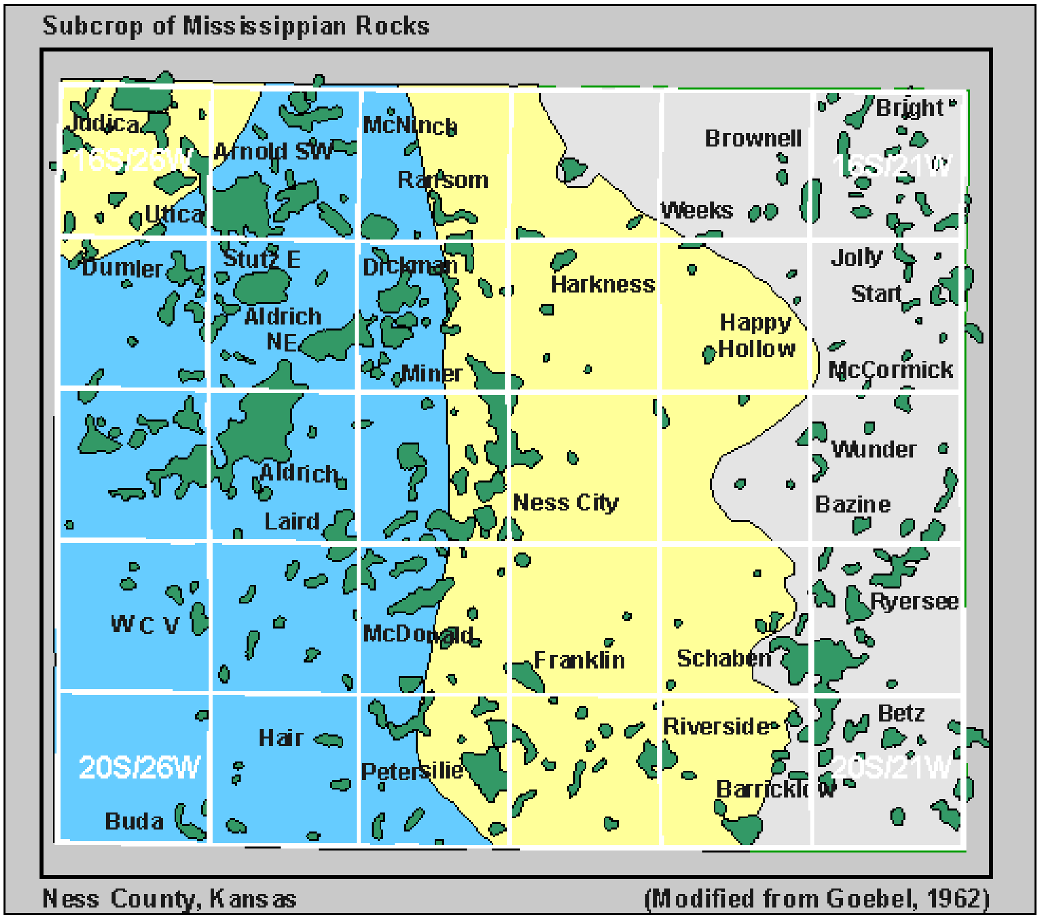

Figure 1.5. Enlarged view of the Mississippian subcrop in Ness County overlain by oil field outlines. The Cherokee group overlies the Salem Limestone (blue), Spergen-Warsaw Limestone (yellow), Osagean and Kinderhookian Limestone (grey). Taken from http://www.kgs.ku.edu/DPA/County/ness7.html (referenced 8/25/2008).

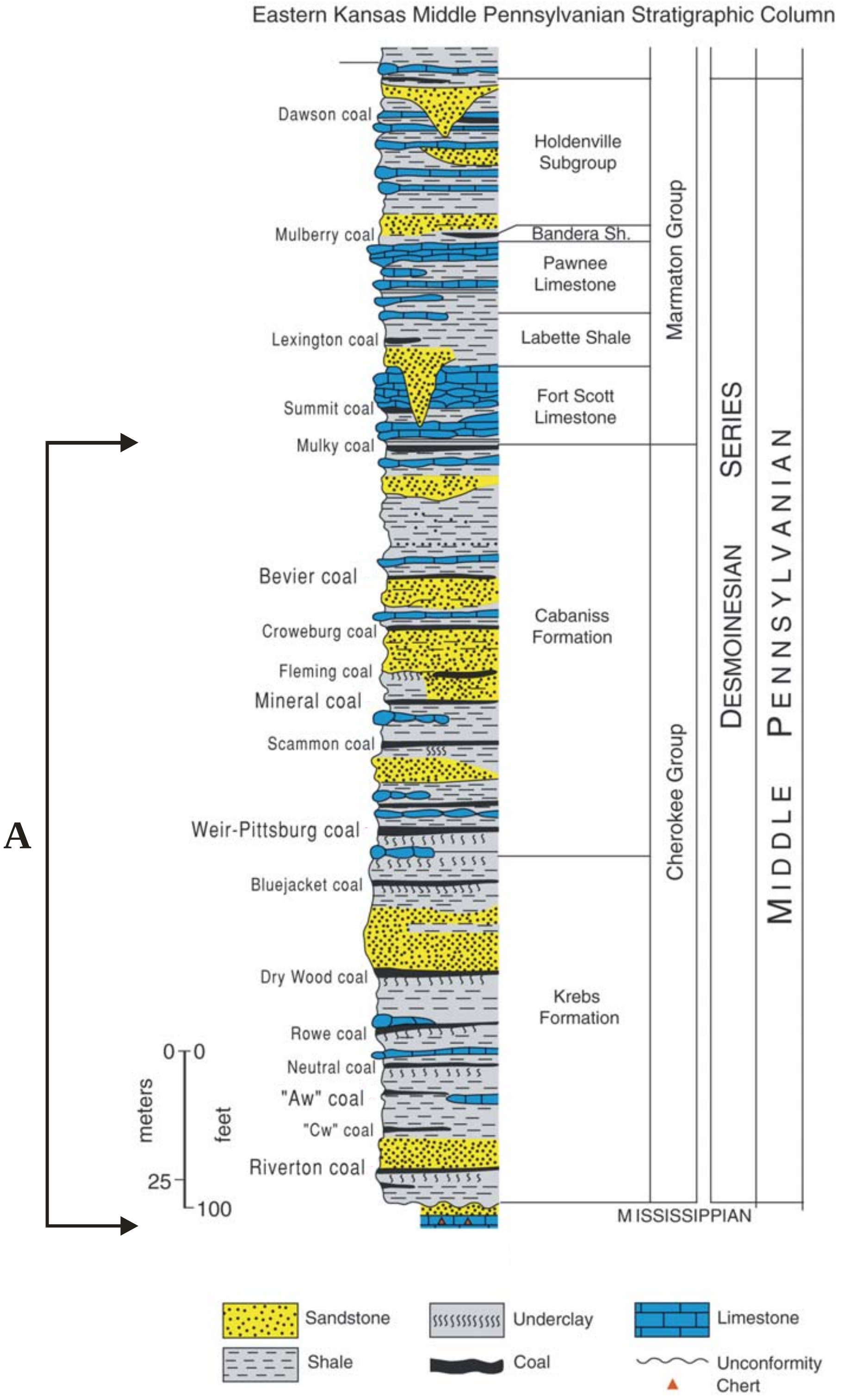

Figure 1.6. Stratigraphy of the Cherokee Group in eastern Kansas. Ness County stratigraphy examined in this study is equivalent to interval indicated with “A”. Modified from Zeller (1968) and Lange (2003).

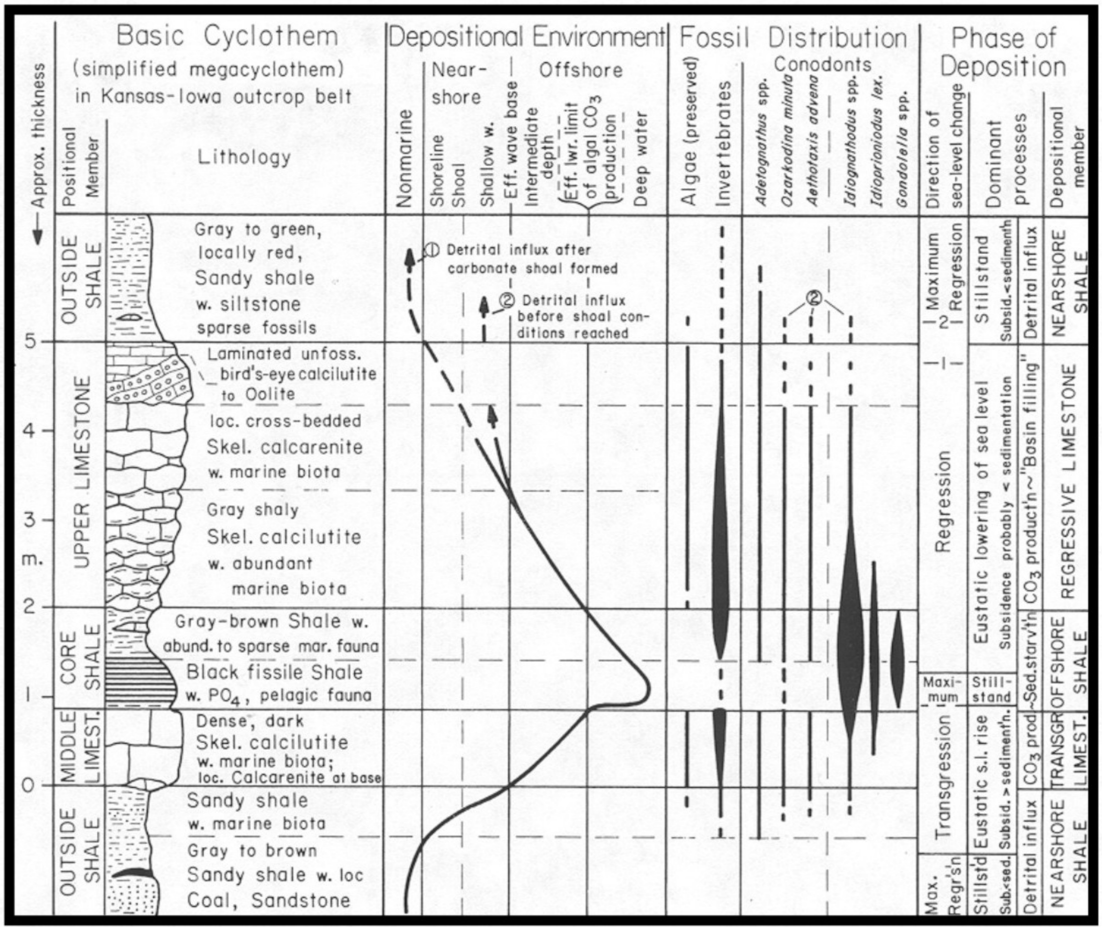

Figure 1.7. The major components of a typical "Kansas" cyclothems and their relation to geologic properties such as depositional environment, fossil distribution, and phase of deposition. Modified from Heckel (1977).

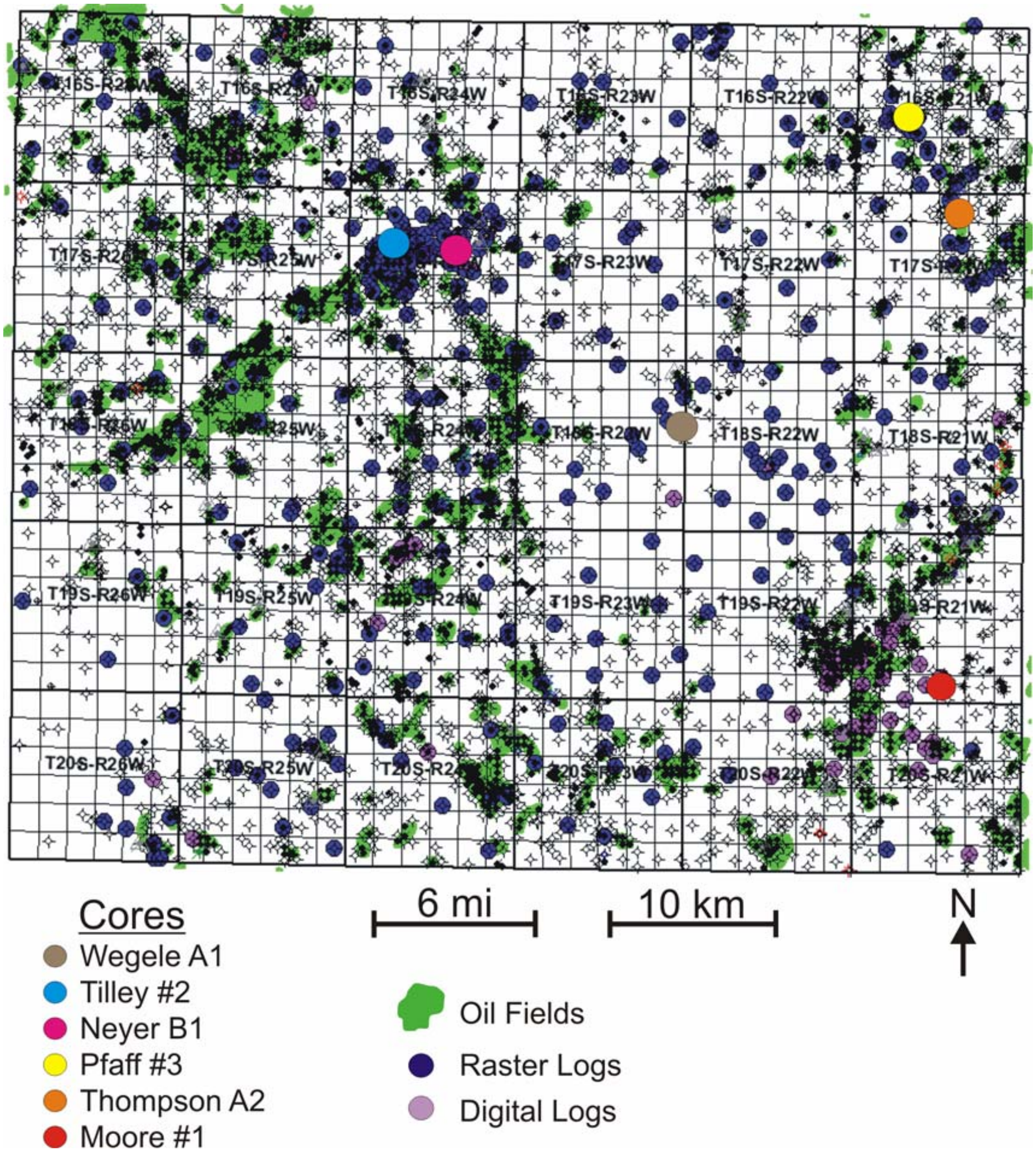

Figure 1.8. Six cores from Ness County were examined and described to identify lithofacies and determine depositional environments. Over 400 well logs were used for mapping and quality control on formation top data. Oil production dominates Ness County with only minor gas production. All oil fields in Ness County are highlighted in green.

CHAPTER 2: CHEROKEE GROUP FACIES

Introduction to Facies

In this study, core description tied to electric log response was the primary method of investigation in determining facies. From the core examination, eleven lithofacies were defined in the Cherokee Group of Ness County Kansas. The facies defined in this study are based on available cores from the Kansas Geological Survey from Ness County, Kansas, that included part or all of the Cherokee Group. Due to the high degree of lateral and vertical variability in lithology of the Cherokee Group, some of the lithofacies described in this study more closely resemble facies groups, which allow for variations in lithology. Facies groups tied to electric log response aided in understanding the deposition of the Cherokee Group over the county, and represent a different approach than used in most previous, small-scale studies of the region (Walters and James, 1979; Stoneburner, 1982; Beiber, 1984; Howard, 1990; Cuzella et al. 1991). Facies descriptions include lithology, color, grain size, grain sorting, sedimentary structures, body and trace fossils, pedogenic features, cementation, thickness, nature of contacts, relationships with other facies, and log response.

Black Shale Facies

Description

Black shale facies of the Cherokee Group is dark-grey to black and very finely laminated (<1.0 millimeter) (Figure 2.1). Light- to medium-grey phosphate nodules and laminae up to 2.0 millimeter thick were observed toward the base of the facies.

The facies is noncalcareous. Body fossils, burrowing, and trace fossils were not observed. Other features include small (< 3.0 millimeters) brassy pyrite nodules and preserved plant fragments. Facies thickness of 0.3 meters was observed in core, but facies thickness observed in logs ranged to 1.0 meter. The facies has a sharp contact with the underlying variegated silty mudstone and a gradational contact with the overlying sandy siltstone. Gamma-ray log readings of 180-250 API units are characteristic of the black shale facies. Beds of black shale are laterally continuous and can be traced over much of the study area.

Interpretation

Fine-grained sediment and thin parallel laminations indicated low energy sediment fall and a lack of burrowing organisms within a depositional environment. The dark-grey to black appearance and preserved plant material suggest a relatively high organic content. Black shale facies have traditionally been interpreted as deposited in either shallow marginal marine or deep marine environments. In the Pennsylvanian of the midcontinent, regionally extensive high-gamma ray black shale has been interpreted as condensed section and recognized as containing the maximum flooding surface, recording deposition in deep anoxic conditions (Wanless and Weller, 1932; Moore, 1936; Heckel, 1977). Interpreting any black shale as “deep” water deposits requires aerially constrained black shale to be within extreme paleotopographic lows, or at least localized areas of anoxic conditions (Brown, 2005). Regionally extensive black shale was observed in core and is present in electric logs across much of the study area.

Overall, finely-laminated localized black shale is not indicative of water depth, but of anoxic to dysoxic conditions and sediment starvation. Isolated black shale is best interpreted as a product of deposition in stratified waters or areas that are not active sites of deposition. The black shale facies is interpreted as deposited in an offshore, dysoxic to anoxic environment.

Grey Shale Facies

Description

The grey shale facies is composed of medium-grey to dark-grey shale with fine parallel laminations (1.0 to 3.0 millimeters) (Figure 2.2). The facies is slightly calcareous to calcareous. Thin silt laminations were observed (2.0 to 3.0 millimeters). Biota present includes articulated brachiopods and fish scales. Burrows were found along bedding planes. Sparse brassy-yellow pyrite occurs as very-fine, individual, cubic crystals (< 1.0 mm) and in very thin lenses between laminae. The grey shale facies is 0.6 to 1.2 meters thick in core. Sharp contacts were observed with underlying limestone and variegated silty mudstone and gradational contacts are present with overlying limestone. The grey shale facies is distinguished by gamma ray readings from 120 to 170 API units. Typical gamma-ray profiles have a sharp base, and API units gradually decrease upward into overlying limestone facies. Beds of grey shale are laterally continuous and can be traced down-dip into the laterally equivalent black shale.

Interpretation

Parallel laminated shale indicates fine grained sediment fallout in a low energy environment with a lack of abundant burrowing organisms. Grey coloration and minor bioturbation indicates conditions were still aerobic, and flooding did not reach sufficient depths to cause completely anoxic conditions or strong stratification did not occur. Dark-grey coloration in the lower portion of the facies is probably the result of slightly dysoxic conditions. Similar gray shale deposits have been noted throughout midcontinent Pennsylvanian cyclothems (Malinky and Heckel, 1998). The grey shale facies is interpreted as deposited in an offshore environment similar to the laterally equivalent black shale facies but water depth did not reach sufficient depth to establish anoxic conditions or, as evidence by the presence of bioturbation.

Grey Sandy Siltstone Facies

Description

The grey sandy siltstone facies is light-grey in appearance. The siltstone is composed of silt-size particles with minor amounts of very fine-grained quartz sand and abundant clay (up to 30%). Observed sedimentary structures include faint wavy laminations. Bioturbation is common and vertical burrows were observed (Figure 2.3). Rare, small macerated plant debris and disseminated coal fragments were noted. Facies thickness observed in core is 1.0 meters. The facies has a gradational contact with underlying black shale and a relatively sharp contact with overlying limestone beds. The facies does not have a diagnostic well signature because it is masked by log signatures of high gamma-ray signature of black shale below and clean carbonate wackestone to packstone above, but overall gamma ray response cleans upward in the facies.

Interpretation

The sedimentary structures observed in the grey sand siltstone facies typify an environment with low- to moderate-energy sedimentation. The bioturbation and burrows also suggest a marine environment. Bioturbated marine siltstone is common in upper offshore to lower shoreface environments (Bann et al., 2004). Offshore transition zones typically experience episodic deposition of fine sand, and continued sedimentation of fine clay and silt-size sediment. The presence of a gradational contact with the black shale below and limestone above above also suggests this is a transitional facies between sediments deposited in deep, anoxic waters and shallow shelf carbonate sediments. The presence of bioturbation, silt-size sediment, and, most importantly, stratigraphic location supports an offshore transitional zone depositional environment for the grey sandy siltstone facies.

Carbonate Wackestone to Packstone Facies

Description

The carbonate wackestone to packstone facies is light to medium grey. It is characterized by a fossiliferous micritic carbonate matrix and the facies alternates between matrix support and grain support (Figure 2.4). Identified fossils include whole and disarticulated brachiopods, bryozoans, sponges, gastropods, fish scales, foraminifera, and crinoids. Coated grains were occasionally observed in the upper portion of the facies along with isolated quartz grains. Slickensides occur along shale breaks and a few incipient stylolites are present in the limestone. Significant reddening was observed and decreased downward from the overlying contact. A nodular fitted texture is prevalent throughout much of the upper portion of the facies and decreases downward with reddening. Facies ranges in thickness from 0.5 to 4.0 meters in core**.** Sharp and gradational contacts were observed with underlying strata (grey shale, variegated silty mudstone, conglomeratic sandstone and cross-laminated sandstone). A gradational contact was observed with the overlying variegated silty mudstone due to pedogenic processes from above. The facies exhibits relatively clean gamma ray readings less than 40 API units, bulk density readings between 2.6 to 2.7 g/cc, and is easily recognized by its high resistivity response (200-600 ohm-meters). Limestone beds in the Cherokee Group are laterally continuous across almost the entire study area and are easily differentiated from clastic facies in electric logs.

Interpretation

Brachiopods, bryozoans, foraminifera, and crinoids form a normal marine fossil assemblage and indicate an open normal marine environment. The abundance of lime mud indicates deposition within the photic zone. The abundance of whole and disarticulated skeletal fragments and presence of matrix and grained-supported texture are evidence for varying mechanical energy during deposition. Slickensides, red coloration, and nodular fitted texture are the result of post depositional pedogenic processes that occurred during exposure before deposition of overlying beds. Lack of core data restricts the placement of the facies into a precise depositional environment interpretation, but based on the lateral continuity of the facies and fossil assemblage present the carbonate wackestone to packstone is interpreted to have been deposited across a broad shallow shelf with normal marine salinity conditions.

Skeletal Packstone to Grainstone Facies

Description

Typically, the skeletal packstone to grainstone facies is light grey to grey. The facies is grain supported and highly fossiliferous. Abundant disarticulated, broken, and abraded skeletal fragments include brachiopods, sponges, gastropopds, solitary corals, and fish scales. Micritic intraclasts were also observed. Many of the skeletal remains are aligned or imbricated (Figure 2.5 and Figure 2.6). Typically, pores between grains are filled with pale green mud or sparry calcite cement. The facies is present as a thin bed within or at the top of carbonate wackestone to packstone beds and is overlain by the variegated silty mudstone beds. Typically, a sharp contact is present at the base of the facies and a gradational contact is present at the top of the facies. Skeletal packstone to grainstone beds are thin (< 0.5 meters) and not distinguishable in electric logs from the carbonate wackestone to packstone facies, but as previously stated limestone beds are easily differentiated from clastic facies by a clean gamma ray response (<30 API units) and high resistivity readings (200-600 ohm-meters).

Interpretation

The skeletal packstone to grainstone was only observed in two cores and is a thin unit in the overall succession. In the Cherokee Group this facies is interpreted as the result of deposition in a marine shelf environment under normal conditions during times of elevated energy caused storm activity, or from higher energy currents than those responsible for deposition of the carbonate wackestone to packstone facies.

Lingulid Shale Facies

Description

The lingulid shale facies is characterized by dark-grey to dark-green, fissile, thinly laminated shale. Bioturbation was rarely observed. The facies contains abundant lingulid inarticulate brachiopods 3.0 to 5.0 millimeters in size and amorphous organic material (Figure 2.7). Facies thickness was observed in only one core, and is approximately 0.7 meters. Contacts with overlying limestone beds and underlying conglomeratic sandstone beds are sharp but not erosional. The facies exhibits a high gamma-ray reading (~225 API units) but beds are not laterally extensive and can only be traced a short distance from core control.

Interpretation

The parallel thin laminations suggest a lack of burrowing organisms and the abundance of clay-size sediment suggests deposition from sediment fallout in a low energy environment. Lingulid brachiopods are noted as euryhaline organisms common in restricted marine environments (Black, 1989; Bridges, 1976; Wehrmann et al., 2005). Ancient lingulid brachiopod fauna have been interpreted as brackish water indicators found in lagoons and restricted bays with freshwater input (Bjerstedt, 1987). Modern day lingulids are usually found in water depths less than 40 meters and inhabit intertidal mudflats, lagoons, and estuaries (Black, 1989). The dark coloration is due to a high organic content. The dominance of euryhaline lingulid brachiopods, lack of biodiversity, and minor bioturbation are strong evidence of non-normal marine salinity conditions. Often, lingulid brachiopod-dominated, low-diversity communities are interpreted as indicative of reduced salinity environments in lagoons and estuaries (Swain, 2008). Also, lack of lateral continuity supports a localized environment. The lingulid shale facies is interpreted as deposited in a lagoon or bay environment with brackish salinity.

Cross-Laminated Sandstone Facies

Description

The cross-laminated sandstone facies is dark grey-green, tan, and brown. The facies is composed of very-fine to medium-grained, subangular to subrounded quartz sand. Clay content ranges from 10% to 15%. Observed sedimentary structures include: low-angle cross-laminations, scour surfaces, and overall fining-upward successions (Figure 2.8). Subangular chert clasts up to 1.8 centimeters long and occasional shale clasts up to 0.6 centimeters long were observed on scour surfaces. Other observed features include white to tan limestone nodules up to 2.0 centimeters in size and black coal fragments less than 0.3 centimeters in size. Sedimentary structures are disrupted or completely destroyed by bioturbation and burrowing in places. Quartz cement is common, but patches of calcareous cement up to 3.5 centimeters in size create a spotty white appearance on the surface of the core. Facies thickness ranges from 2.0 to 3.3 meters. The cross-laminated sandstone facies has a sharp contact with underlying rocks (conglomeratic sandstone and variegated silty mudstone beds) and a gradational contact with overlying rocks (limestone beds). Gamma-ray readings between 30 to 65 API units with fining-upward bell-shaped profiles can be used to help identify the facies. Unfortunately, density and porosity readings are variable and typical neutron-density porosity overlay patterns are not diagnostic of the facies due to clay content.

Interpretation

The presence of shale rip-up clasts and small coal fragments suggests the cross-laminated sandstone facies was deposited in a continental or marginal-marine nearshore setting. This facies does not display the coarsening-upward succession commonly interpreted as shoreface or deltaic or deltaic (Reading, 1996). The sedimentary features observed in the cross-laminated sandstone facies are not diagnostic of any single depositional environment. Similar Cherokee Group sandstone units in eastern Kansas have been interpreted as incised-valley-fill systems (Lange, 2003). They contain similar basal pebble lags and mud rip-up clasts (Lange, 2003). Unlike the sandstone units described by Lange, in the study area the cross-laminated sandstone facies lacks the lateral extent associated with large incised-valley fills. Cuzella (1991) interpreted this facies as tidal channels, based on the presence of mud clasts derived from erosion of surrounding tidal flats. The facies cannot be reliably differentiated with electric log responses from the conglomeratic sandstone facies and exact facies geometry can not be determined. Bioturbation in the facies and the presence of carbonate nodules suggest a non-freshwater environment with saline conditions found in brackish or marine water (Zaitlin et al., 1994). The presence of a gradational contact with overlying limestone beds suggests the facies was deposited during transgression. The features listed above do not necessary indicate any particular depositional environment but based on the distribution of sand and relationship with other facies, the cross-laminated sandstone facies is interpreted as deposited by nearshore processes including tidal channels and coastal marine reworking in the shoreface.

Glauconitic Cross-Laminated Sandstone Facies

Description

The glauconitic cross-laminated sandstone facies ranges from brown to brown-green in color. It is composed of fine to coarse-grained, subangular to subrounded quartz sand. Glauconite content ranges from an estimated 10% to 15%. Facies contains an estimated clay content of 10% to 15%. Observed sedimentary structures include low to high-angle cross-laminations, normally-graded beds 3.0 to 12.0 centimeters thick, flaser bedding, isolated green mud clasts, and overall upward fining (Figure 2.9). Thin green shale laminae (<3.0 millimeters), thought to be glauconitic, occur locally (Figure 2.10). No trace or body fossils were observed. Patchy calcareous cement associated with dark-grey spherical centers and red-orange calcite concretions are common. Pyrite is present in some intervals. Thickness of the facies varies from 1.5 to 15 meters. Typically, glauconitic sandstone is underlain and overlain by the variegated silty mudstone beds. The facies has a sharp underlying contact but a gradational contact is present at the top. Gamma-ray response varies from 30 to 60 API units and the typically fining upward sequences are not distinguishable in resistivity logs. The facies is not laterally continuous, appearing to fill paleotopographic lows, and stratigraphic position was typically used to correlate the facies in wells surrounding cores.

Interpretation

Numerous studies have demonstrated that modern glauconitic mineral formation occurs in water depths of the mid-shelf to upper slope at the boundary of oxidizing seawater and reducing interstitial waters (Odin and Matter, 1981). This has caused many to use the presence of glauconite as an environmental indicator of marine shelf deposits (Suder, 2006). However, significant evidence for shallow-water, high energy glauconitic deposits have been found in the geologic record (Chaftez, 2000; Suder 2006). Due to reworking and sediment redistribution, glauconite can exist in almost all shallow-marine environments or even fluvial environments as allochthonous sediment (Suder, 2006). The presence of glauconite is an unreliable guide to environmental interpretation and must be used with caution (Suder, 2006). The close vertical relationship between glauconite sandstone beds and the variegated silty mudstone beds suggests that the facies was deposited in shallow water and not on a marine shelf. The majority of the glauconitic sandstone facies was deposited into paleographic lows during the initial transgression onto the karst surface. The presence of channelized glauconitic sandstone deposits argues against a marine shelf depositional environment. The low-to high-angle cross-stratification indicates high energy environments with normal to high rates of sedimentation. The glauconitic sandstone facies is interpreted as deposited by fluvial processes in an upper estuarine environment. The suite of sedimentary structures observed, lack of marine biota, and distribution on the karst surface suggests deposition in a non-saline environment. Similar sandstone beds deposits are recognized in the Glauconitic Member of the Mannville Formation in Alberta, Canada (Wood and Hopkins, 1989), and have been interpreted as deposited in upper estuarine, fluvially-dominated environments.

Conglomeratic Sandstone Facies

Description

The conglomeratic sandstone facies is characterized by tan to cream-colored, occasionally clay-rich, matrix-supported conglomeratic sandstone. The facies consists of medium to coarse-grained quartz sand matrix, and contains chert clasts up to 2.7 centimeters as well as limestone and shale clasts up to 0.5 centimeters (Figure 2.11 and Figure 2.12). Grains are subrounded to subangular. The facies is characterized by repetitive 4.0 to 8.0 centimeters, normally graded beds and faint low- to high-angle cross-lamination. Overall, clast content and size decrease upward in the facies. Other features include sparse disseminated pyrite, disseminated black coal material, patchy calcareous cement, and oil staining. Thickness of facies in core ranges from 1.2 to 1.9 meters. The conglomeratic sandstone facies has sharp contacts with the underlying variegated silty mudstone beds and both gradational and sharp contacts with overlying strata (typically cross-laminated sandstone, limestone, and lingulid shale facies). The facies is characterized by low gamma-ray readings of 20 to 30 API units with a blocky profile and density readings of 2.4 to 2.5 g/cc. Similar to other sandstone facies, the conglomeratic sandstone can be distinguished from carbonate facies by the lack of a high resistivity response.

Interpretation

The conglomeratic sandstone facies exhibits evidence of a high-energy depositional environment. Coarse chert clasts are probably derived from the nearby eroding Central Kansas uplift and transported westward by fluvial processes. Normally graded beds suggest fluctuating, episodic current energy. As mentioned previously, the conglomeratic sandstone facies cannot be reliably distinguished on electric logs from the other sandstone-rich facies, specifically the cross-laminated sandstone facies, thus facies geometry cannot be reliably mapped away from core control. Graded gravel beds are fairly common in fluvial systems and probably form during waning flood stage and strong unidirectional current (Kleinspehn et al., 1984). However, it is noted that wave-reworked sand conglomerates are common in shallow marine environments (Bourgeois and Leithold, 1984). Typically, wave-worked conglomerates have better segregation of gravels into discrete beds and more continuous bedding than fluvial conglomerates (Bourgeois and Leithold, 1984). The most diagnostic evidence is the presence marine fauna, which unfortunately are only occasionally present in such systems (Bourgeois and Leithold, 1984). The stratigraphic location of the conglomeratic sandstone, paleosol facies below and marine and marginal-marine facies above, suggest the facies was deposited during a rise in base level. The fining upward successions, lack of marine fauna, and stratigraphic location all provide evidence for a non marine depositional environment.

The conglomeratic sandstone facies is interpreted to have been deposited by unidirectional currents in fluvial environment, based on the evidence listed above. The linear net sand trend along the interpreted paleoshoreline suggests the conglomeratic sandstone facies may have been reworked in upper shoreface or foreshore along with the cross-laminated sandstone facies during continued transgression. The inability to differentiate these two sandstone facies in logs limits interpretation of both facies.

Variegated Silty Mudstone Facies

Description

The variegated silty mudstone facies is red to reddish brown with pale green, mauve, yellow, and tan mottling (Figure 2.13 and Figure 2.14). The facies is rich in terrigenous material primarily clay- and silt-size particles. However, in rare instances beds containing significant quantities (up to 60%) of fine to medium-grained quartz sand were observed. Water-reactive clays are common and swelling is easily observed when the core is wetted. Observed structures include slickensides, rhizohalos, and plant fragments. Blocky and poorly consolidated textures are common with many intervals reduced to rubble and bagged in core boxes. White to light grey carbonate nodules that range from 0.4 to 5.0 centimeters were noted (Figure 2.15). Sedimentary structures are rarely preserved, although occasional faint low-angle cross laminations, ripple laminations, and parallel laminations were observed (Figure 2.16). Body fossils were not identified, but bioturbation and burrows are common. Thickness of the facies in core ranges from 0.3 to 3.2 meters.

The facies has a gradational contact with underlying beds (typically the limestone, cherty conglomeratic breccia, and glauconitic sandstone) and a sharp contact with overlying beds (limestone, grey shale, black shale, and conglomeratic sandstone). The silty mudstone facies exhibits few unique log characteristics. Because of the inherent mineralogical variability within the facies, gamma-ray, neutron, density, and resistivity curves are not diagnostic. In general, gamma-ray response increases upward (60 to 130 API units) and exhibits a bell-shaped profile at contacts with underlying facies.

Interpretation

The textures and coloration observed in facies indicate subaerial exposure and continental processes. Gradational lower contacts with the parent rock, water reactive clays, rhizohalos, and slickensides indicate soil processes and the development of a soil profile. Carbonate nodules, termed calcrete in modern soils and paleosols, are the result of downward percolation and reprecipitation of carbonate minerals (Retallack, 1988). Slickensides are the result of cyclic wetting and drying of water-reactive expanding clays including smectite, illite, and kaolinite (Retallack, 2001). Block or rubble textures may represent preserved ped structures, which are vertically oriented pedogenic features that occur in a variety of configurations (Retallack, 2001). The distinctive reddish coloration is from the precipitation of iron oxyhydroxides and is commonly used as an indication of soil formation, but identical coloration can result from later oxidizing events. However coloration can be used in conjunction with other evidence for interpreting paleosols (Goldstein et al., 1991). Preserved sedimentary structures (Figure 2.6) help determine the parent material of paleosols. Paleosol development corresponds to the balance between sediment accumulation and the rate of pedogenesis (Kraus, 1999). It must be noted that compound and/or composite paleosols can develop in environments of episodic deposition of thin sediment layers alternating with subaerial exposure. This alternation is common in fluvial overbank and tidal-flat environments where pedogenic processes dominate during periods of exposure (Kraus, 1999). Lateral and vertical variations in grain size and chemical composition are expected since paleosol formation is the result of post-depositional processes that alter previously deposited sediment or substrate.

Cherty Conglomeratic Breccia Facies

Description

The conglomeratic breccia lithofacies consists of poorly-sorted, sub-rounded to angular chert, limestone, and dolomitic limestone clasts ranging in size from 0.2 to 8.0 centimeters, and a siliciclastic matrix of shale to medium-grained quartz sand (Figure 2.17 and Figure 2.18). Matrix coloration is highly variable including maroon, red-brown, pale green, and tan. Both matrix-support and clast-support were observed, and generally clast content decreases upward through an individual bed of the facies. The thickness of the conglomeratic breccia facies is highly variable (0 to 7.0 meters) over short distances due to deposition on the underlying high-relief karst Mississippian surface (Rogers, 2007). Thickest accumulations of the facies occur in paleotopographic lows and the thinnest deposits were observed on localized highs of the Mississippian surface. On logs and in core, the contact with the underlying

Mississippian strata is sharp and the facies has a gradational contact with the overlying beds. Log characteristics for the conglomeratic breccia facies can be variable, depending on the relative abundance of matrix and clast lithotypes. Gamma-ray values range from 30 to 80 API units, and a serrated log appearance related to rapid variations in facies composition is commonly observed. The variability in log response is a distinguishing feature and was used to differentiate the facies from the typically clean, low gamma-ray response of the underlying Mississippian strata.

Interpretation

The cherty conglomeratic breccia facies represents the first evidence of Pennsylvanian sediment deposition on the karst Mississippian surface and is often called the Pennsylvanian basal conglomerate (PBC) (Merriam, 1963; Nodine-Zeller, 1981). The karst surface that represents the Pennsylvanian-Mississippian unconformity is the result of a hiatus of between 30 and 40 million years (Zeller, 1968: Brown, 2005). This hiatus occurred between Kaskaskia and Absaroka cratonic sequences (Sloss, 1963). The cherty conglomeratic breccia facies is result of exposure and associated weathering during the hiatus. The angularity of chert clasts and poor sorting suggest they have undergone very little transport. James (2007) interpreted the PBC as alluvial fan deposits that were reworked during Desmoinesian transgression.   The cherty conglomeratic breccia facies is presumed to have formed from several depositional processes including insitu brecciation and pedogenesis, fluvial and colluvial deposition, and marine reworking. No specific evidence was observed to recognize deposits create by each individual process, but all of these processes were likely occurring on the Mississippian surface during exposure or during the early-middle Pennsylvanian transgression over the karst surface. Which process or processes dominated deposition is likely to have varied throughout the study area depending on topography and sea level.

The high relief karst Mississippian surface caused significant variation in the thickness and appearance of the facies.   Shale-free sand and chert rich deposits can contain significant intergranular porosity and represent significant reservoir potential (Rogers, 2007).

Figure 2.1. Black Shale Facies – Core sample from 4357.1-4358.0 feet in the Moore #1 (S34-T19S-R21W, Ness County, Kansas).

Figure 2.2. Grey Shale Facies – Core sample from 4233.3 to 4233.8 in the Wegele A1 (S21-T18S-R22W, Ness County, Kansas). All samples from core were preserved as loose rubble in core boxes.

Figure 2.3. Grey Sandy Siltstone Facies – Core sample from 4353.9-4354.5 feet in the Moore #1 (S34-T19S-R21W, Ness County, Kansas). A) Lamination disrupted by single vertical burrow. B) Bioturbation has disrupted or destroyed original lamination.

Figure 2.4. Carbonate Wackestone to Packstone Facies – Core sample from 4253.7-4254.1 in the Wegele A1 (S21-T18S-R22W, Ness County, Kansas).

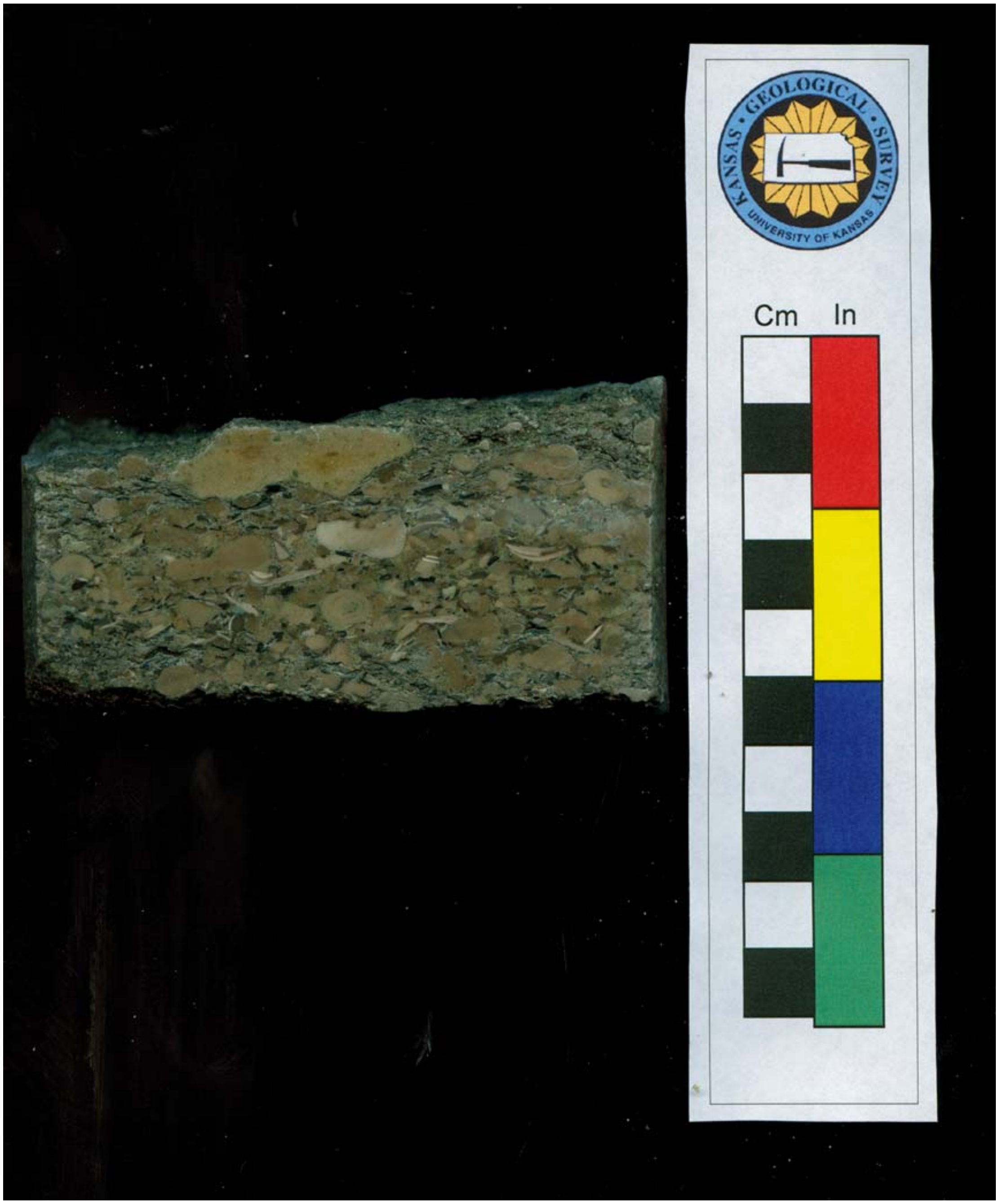

Figure 2.5. Skeletal Packstone to Grainstone Facies – Core sample from 4141.6-4141.75 feet in the Thompson A2 (S3-T17S-R21W, Ness County, Kansas). Note presence of aligned brachiopods and gastropod fragments. Large intraclasts located at top of sample.

Figure 2.6. Skeletal Packstone to Grainstone Facies **–** Core sample from 4141.75-4142.3 feet in the Thompson A2 (S3-T17S-R21W, Ness County, Kansas). Abundant intraclasts with spar pore filling cement. Reddening of grains is interpreted as the result of post-depositional weathering.

Figure 2.7. Lingulid Shale Facies – Core sample from 4230.7-4132.3 feet in the Pfaff #3 (S20-T16S-R21W, Ness County, Kansas). Photo illustrates thin laminated nature of facies. Inset photo is close-up of lingulid brachiopods that are abundant in the facies.

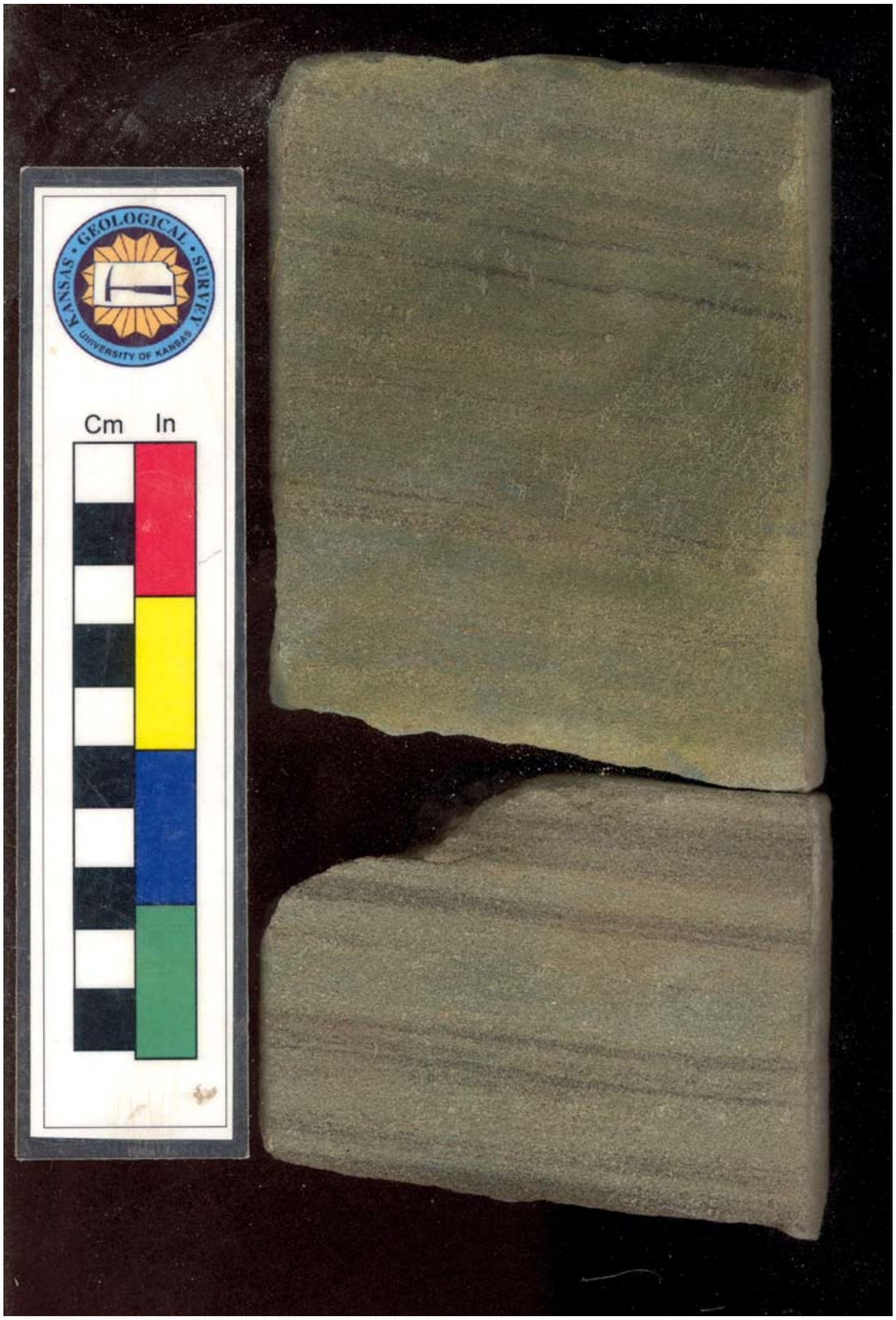

Figure 2.8. Cross-Laminated Sandstone Facies **–** Core sample from 4111.5-4112 feet in the Thompson A2 (S3-T17S-R21W, Ness County, Kansas).

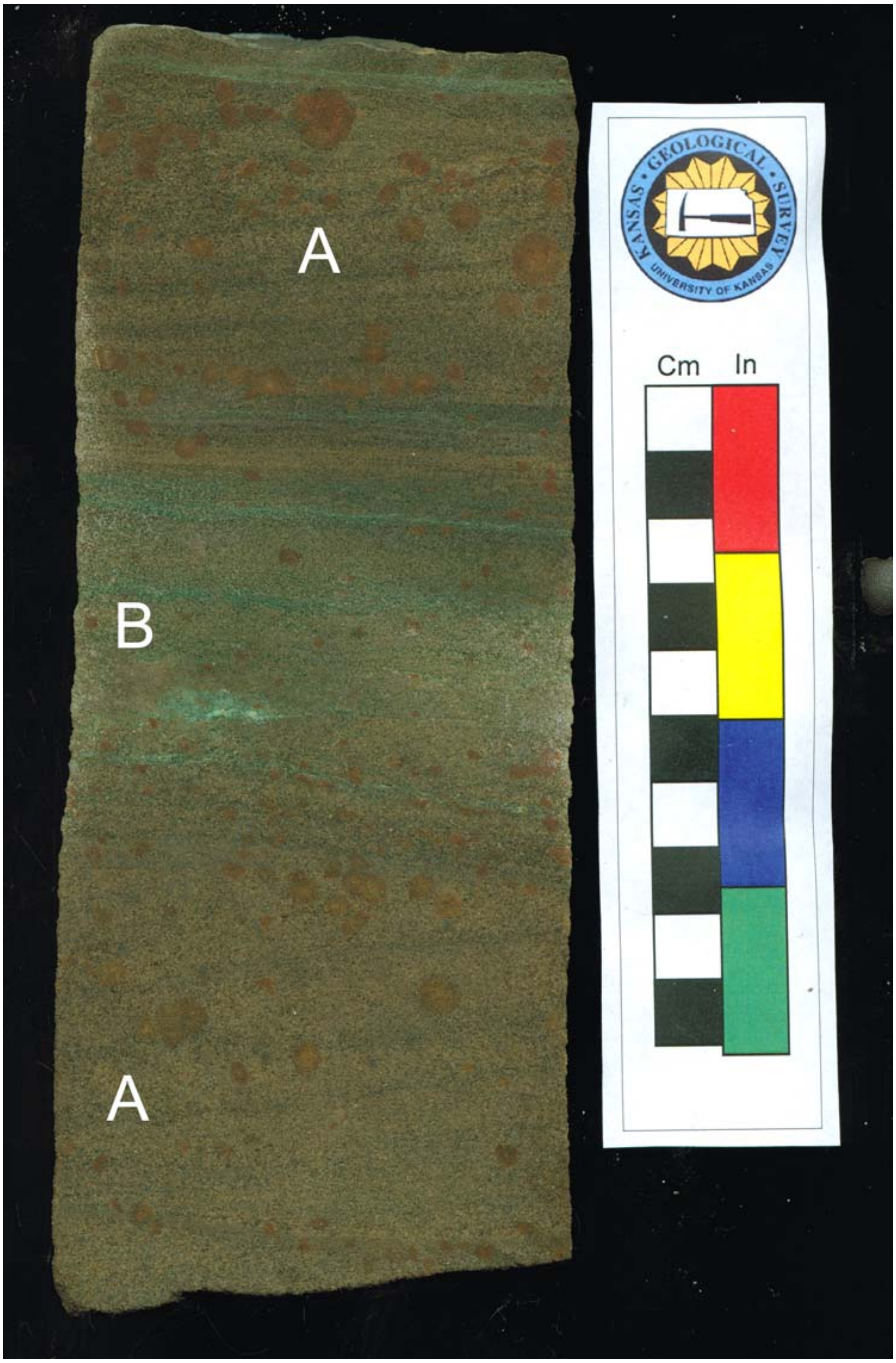

Figure 2.9. Glauconitic Cross-Laminated Sandstone Facies – Core sample from 4424.7-4428.4 feet in the Neyer B1 (S15-T17S-R24W, Ness County, Kansas). A) Rusty red-orange iron and calcite concretions. B) Thin pale green shale flaser laminae.

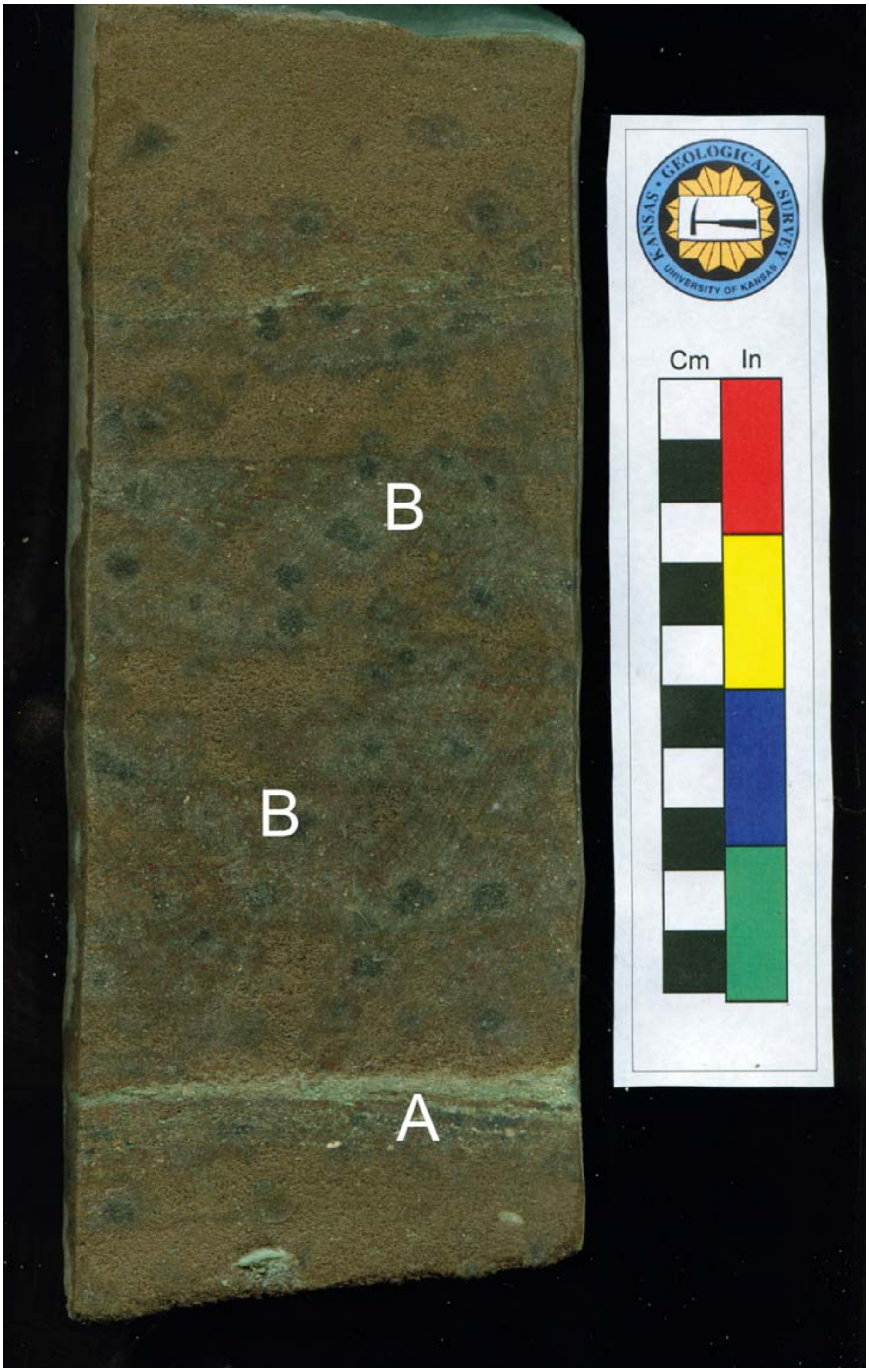

Figure 2.10. Glauconitic Cross-Laminated Sandstone Facies – Core sample from 4426.9-4427.6 feet in the Neyer B1 (S15-T17S-R24W, Ness County, Kansas). A) Pale green shale laminations and green shale rip-up clasts. B) Patchy calcareous cement concentrated around unidentified nuclei.

Figure 2.11. Conglomeratic Sandstone Facies – Core sample from 4219.5-4220 feet in the Pfaff #3 (S20-T16S-R21W, Ness County, Kansas). Clast composition includes shale, chert, limestone and quartz pebbles as observed in photo. Orientation of pebbles along bedding low-angle bedding surfaces is common in the facies.

Figure 2.12. Conglomeratic Sandstone Facies – Core sample from 4135-4135.5 feet in the Thompson A2 (S3-T17S-R21W, Ness County, Kansas). Clast lithology is highly variable, similar to sample from Pfaff 3 core.

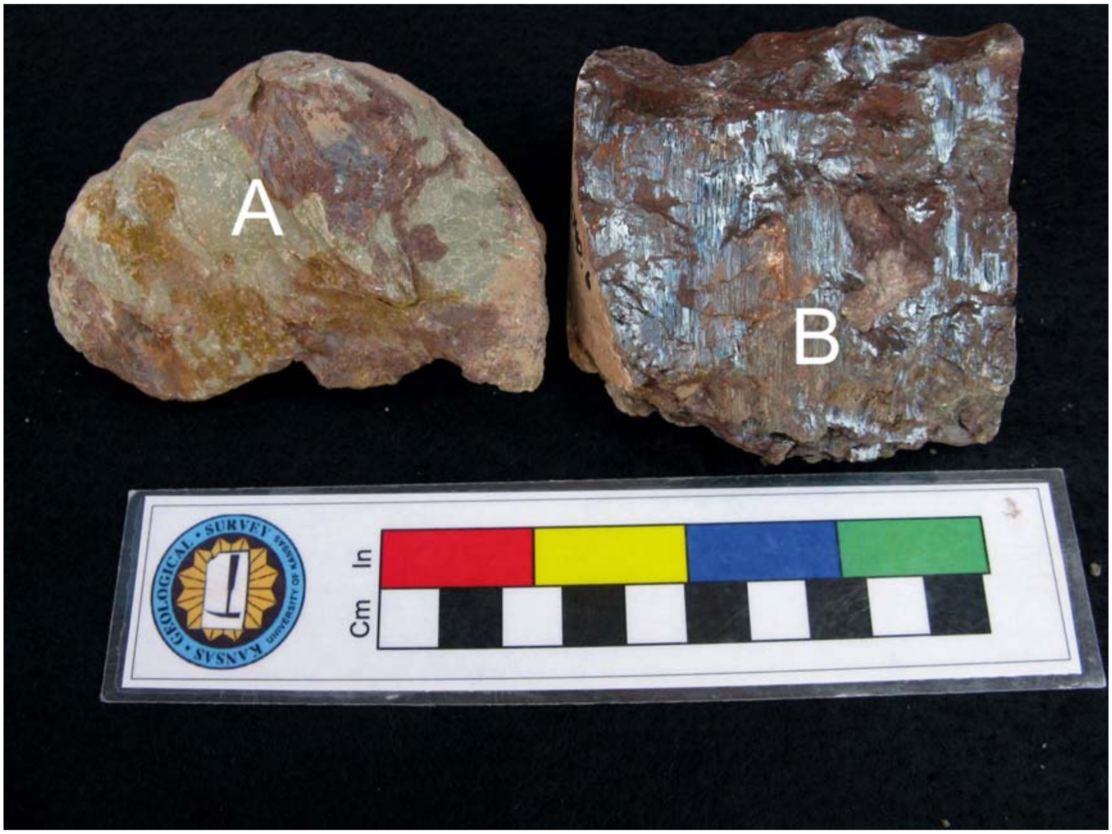

Figure 2.13. Variegated Silty Mudstone Facies – Core samples from 4150.9 feet (sample A) and 4140.6 feet (sample B) in the Thompson A2 (S3-T17S-R21W, Ness County, Kansas). A) Vibrant coloration associated with mottling and pedogenesis. B) Example of slickensides common in the paleosol facies. The metallic sheen is uncharacteristic of paleosols and is interpreted as the result of post-pedogenic compaction around calcrete.

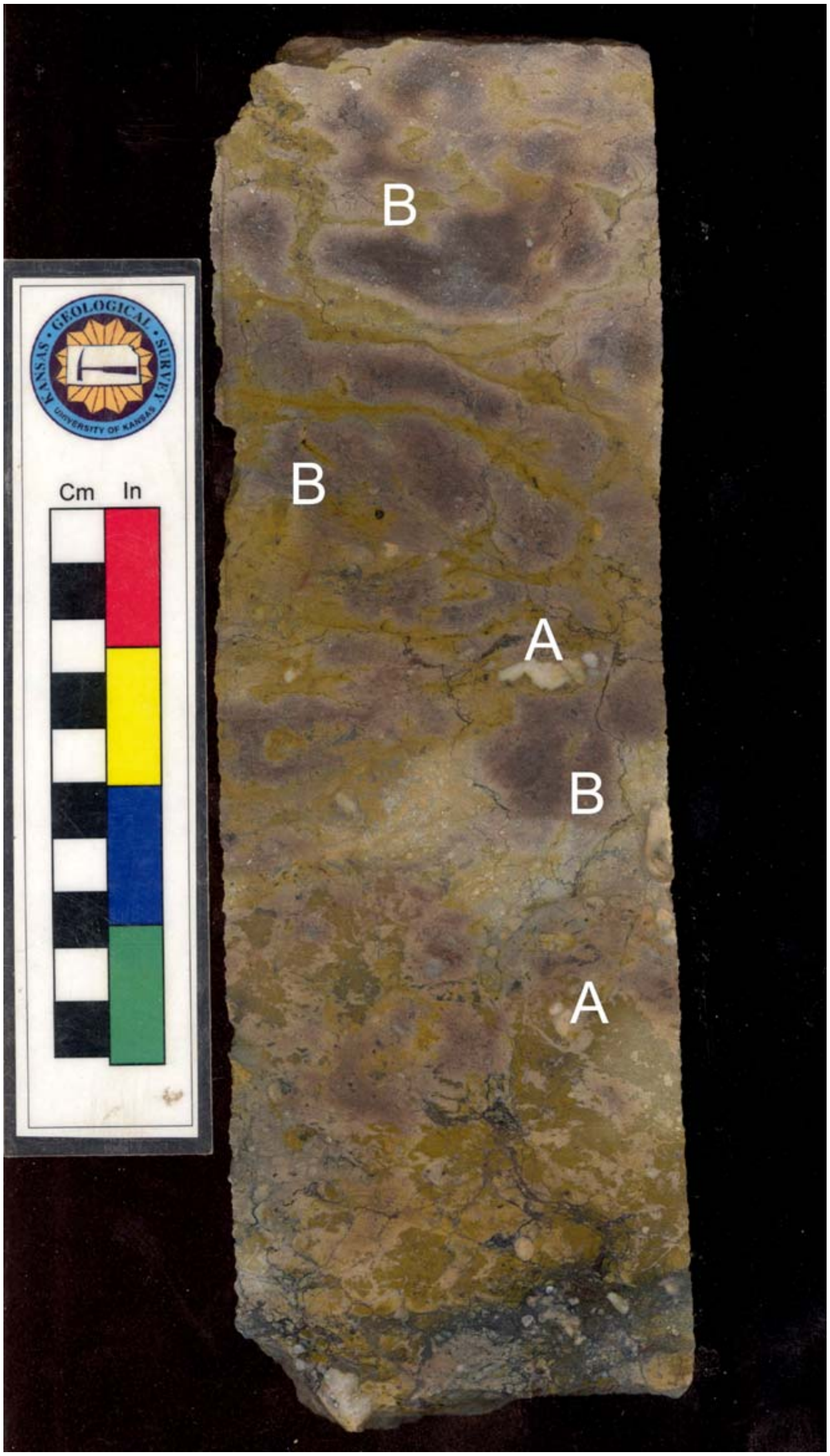

Figure 2.14. Variegated Silty Mudstone Facies – Core sample from 4245.1-4246 feet in the Pfaff #3 (S20-T16S-R21W, Ness County, Kansas). A) Isolated chert clasts are remanents of the parent material. B) Muave and yellow brown clay mottling.

Figure 2.15. Variegated Silty Mudstone Facies – Core sample from 4139.5-4140 feet in the Thompson A2 (S3-T17S-R21W, Ness County, Kansas). Example of calcrete or caliche in a soil that formed in a carbonate rich rock. The sample formed in the top of a wackestone-packstone bed.

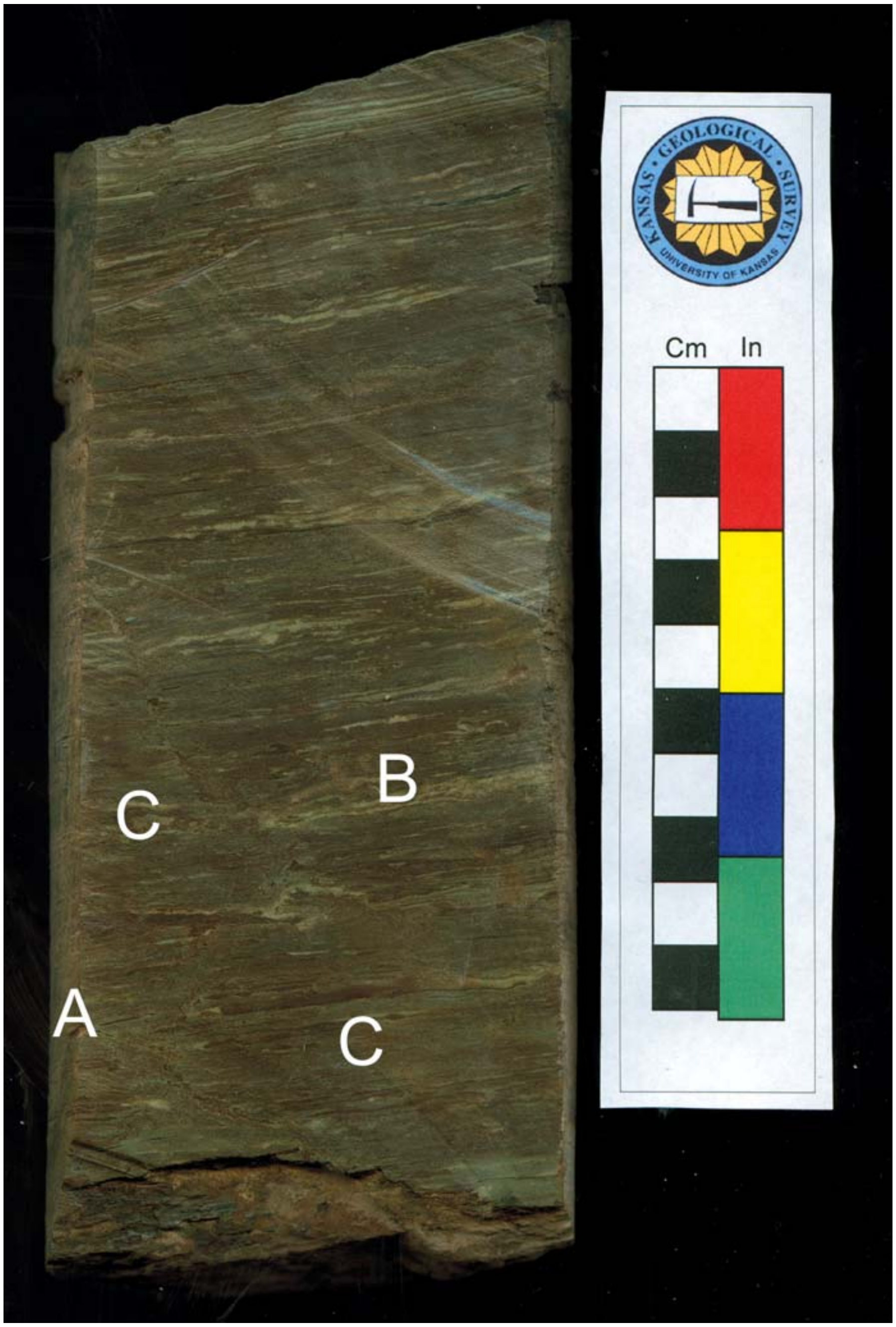

Figure 2.16. Variegated Silty Mudstone Facies – Core sample from 4430.9-4431.6 feet in the Neyer B1 (S15-T17S-R24W, Ness County, Kansas). A) Laminations disrupted by burrows. B) Red and pale green thinly-laminated water reactive shale. C) Laminated silt and shale are preserved from parent material and help indentify depositional environment. This sample experienced less pedogenesis than other samples. The parent material is interpreted as deposited in an overbank environment.

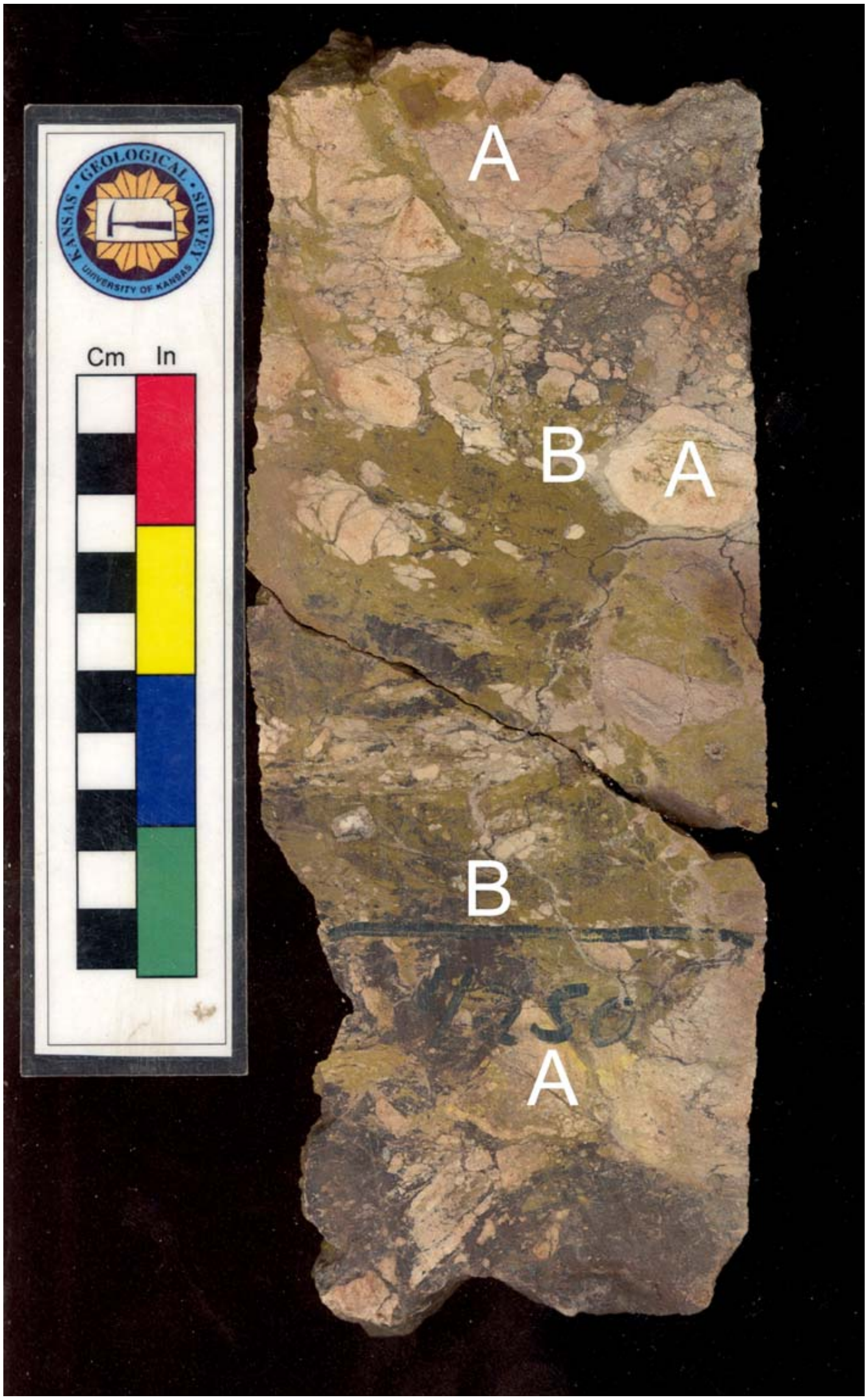

Figure 2.17. Cherty Conglomeratic Breccia Facies – Core sample taken from 4219.5-4120.2 in the Pfaff #3 (S20-T16S-R21W, Ness County, Kansas). A) Chert clasts caused by brecciation. B) Mottled brown, maroon, and tan silty clay matrix infilling fractures.

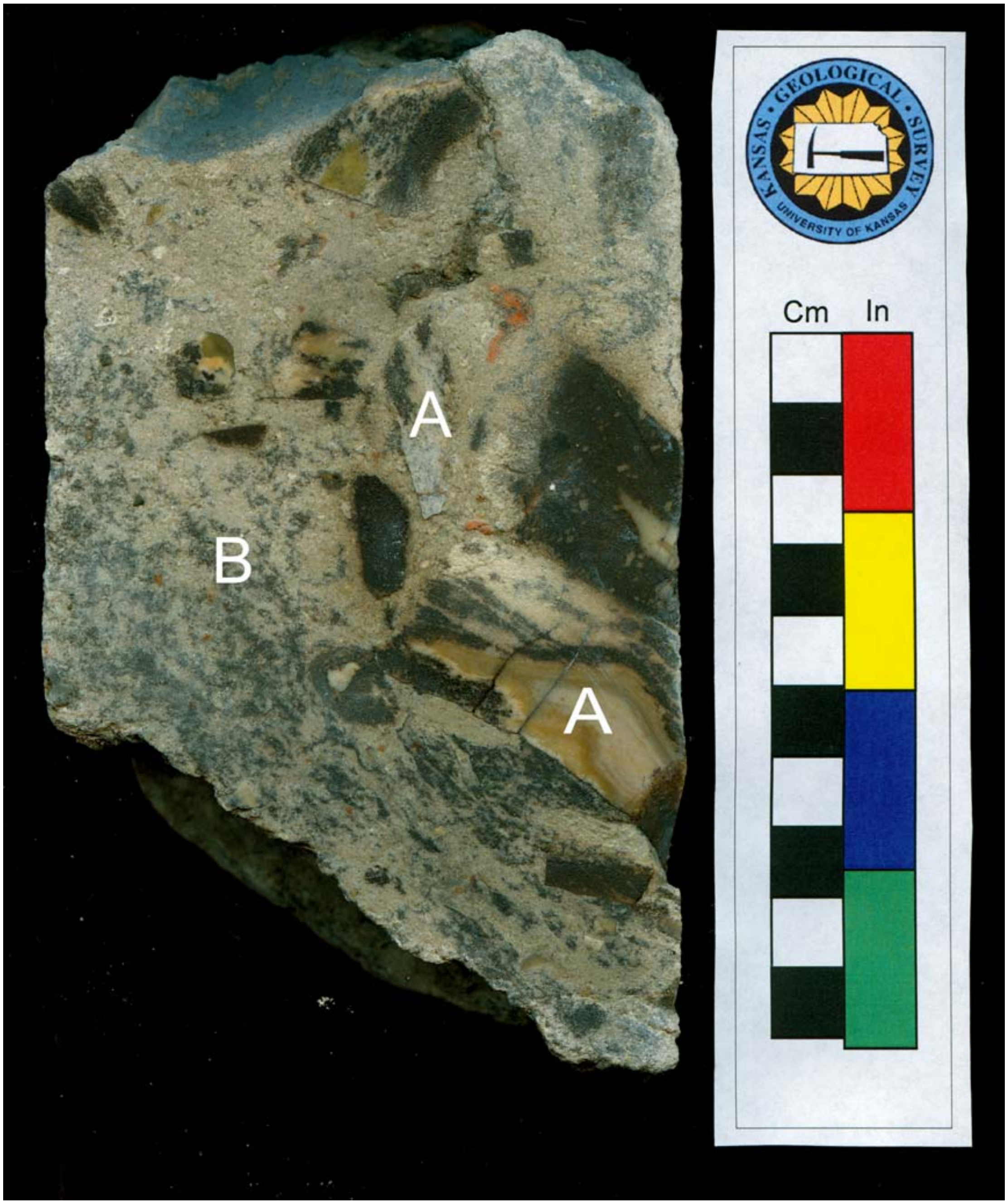

Figure 2.18. Cherty Conglomeratic Breccia Facies – Core sample taken from 4229.7-4230.1 in the Tilley #2 (20-T17S-R24W, Ness County, Kansas). A) Mississippian chert clast with blackened grains. B) Sand-rich Pennsylvanian matrix.

CHAPTER 3: STRUCTURE, PALEOTOPOGRAPHY, AND TECTONIC CONTROLS

Toward the end of the Mississippian and the beginning of the Pennsylvanian, forces to the south associated with tectonic activity of the convergent Quachita orogeny led to significant structural changes and the development of a regional unconformity across the Kansas region (Merriam, 1963). Significant downwarping of the Hugoton embayment occurred during the Mississippian, and deformation continued into the Pennsylvanian (Merriam, 1963). As active uplift and a general lowering of sea level occurred, many of the older Paleozoic rocks (Ordovician and Mississippian) were stripped from the Central Kansas uplift. Further structural movement along the Central Kansas uplift occurred until the end of the Missourian, as evidenced by the thinning of Desmoinesian and Missourian strata (Merriam, 1963). The Cherokee Group pinches out against the uplift just to the east of the Ness County study area (Merriam, 1963).

Several episodes of tectonism created a complex system of faults in the midcontinent. Deformation during the Mississippian and Pennsylvanian was concentrated along preexisting basement faults. The oldest faults in the central part of the North American craton may have initiated as early as 2.6 Ga, but the complex fault system observed today primarily formed during late Proterozoic-Cambrian rifting (Baars, 1995; Marshak et al., 2003). Faults with dominant west-northwest and north-northeast trends define rectilinear blocks in the Precambrian basement (Baars, 1995; Marshak et al., 2003). Continued Phanerozoic tectonic activity, most notably the Paleozoic Ancestral Rockies and the Laramide orogeny, lead to reactivation along many of the high-angle Precambrian basement faults (Yarger, 1983; Marshak et al., 2003). These nearly vertical faults are often difficult, if not impossible, to recognize in well logs; however gravity and magnetic data over the state of Kansas can be used to better understand the fault systems that cut across the basement.

Delineation of Basement Structure

Gravity and magnetic data from western Kansas were compiled and used to generate a series of maps in order to identify to the size and shape of anomalous masses and magnetic bodies. A relatively thin mantle of Phanerozoic sedimentary rocks, 150 to 3000 meters (500 to 10,000 ft) thick, covers virtually the entire Precambrian basement in Kansas, except for a large inclusion of Precambrian granite in the Rose dome of Woodson County (Yarger, 1983; Xia et al., 2000). The sediments were generally deposited on a near-horizontal surface resulting in sedimentary units across the state with little lateral density change and low magnetic susceptibility. There is a clear density and magnetic susceptibility difference between the overlying sediments and Precambrian basement (Xia et al., 2000). As a result, anomalies found in the magnetic and gravity data can be related to changes in basement composition and structural movement of basement blocks. Many of the anomalies occur as linear features that can be traced some distance, while others are localized features. The traceable anomalies are referred to as lineaments and help outline changes in the Precambrian basement. Most data interpretation and regional lineament placement was based on previous investigations by Yarger (1983) and Lam (1987), but additional localized lineaments were interpreted (Figure 3.1).

Magnetic Data Lineation

Several northeast- and northwest-trending magnetic lineaments are present in the study area. Both laterally extensive regional lineaments that can be traced across neighboring counties and localized lineaments are easily recognized in the total field and residual magnetic data set (Figures 3.1-3). Typically, localized lineaments terminate against regional features, but examples of localized lineaments cross-cutting regional lineaments are present in northwestern Ness County. Lineaments do not directly represent basement structure but are interpreted to represent faults and offsets in the Precambrian basement. Magnetic lineaments may correspond with edges of Precambrian basement blocks that appear to have been reactivated during the late Mississippian to early Pennsylvanian. Reactivation caused significant regional upwarping and localized rotation of basement blocks (Merriam, 1963). It is possible that significantly more of the Mississippian section was eroded from the top of uplifted blocks. The amount of erosion is difficult to determine because only a few wells within the study area penetrate below Mississippian strata, and none were drilled to Precambrian basement. Basement block movement during the late Mississippian to early Pennsylvanian would likely produce a network of lineament-paralleling fractures and faults in the subaerially exposed Mississippian surface.

Gravity Data Lineation

Examination of gravity data shows similar anomalies to the magnetic data with similar northwest- and northeast-trending lineaments (Figure 3.1 and 3.4). There are several coincidences between the regional magnetic lineaments and gravity lineaments, but lineaments are often slightly offset. This may be the result of data resolution and variations in the distance between data points. It should be noted that weaker Bouguer anomalies occur in the western Ness County and generally increase in strength to the east. This trend is probably the result of upwarping along the Central Kansas uplift where erosion has removed all pre-Pennsylvanian strata in some areas. Overall, gravity anomalies are significantly less distinct than delineated anomalous magnetic bodies.

Removing Post-Depositional Deformation

An important step in understanding the Cherokee Group is removing post-depositional deformation in order to illustrate the topography of the depositional surface at the time of deposition. The karst Mississippian paleotopography was irregular and affected the Cherokee deposition as rising sea level flooded the surface. Using the Anna Shale Member as a datum for the type cross-section does not reflect Mississippian structure at the end of the Mississippian because of compaction in the shale-rich Cherokee Group. Previous investigations in other portions of the state have successfully used the Stone Corral Anhydrite (Permian) as a datum for restoring the Mississippian-Ordovician unconformity (Cansler, 2000; Rocke, 2006). The Stone Corral is sufficiently separated stratigraphically from the Cherokee Group to avoid major issues with compaction and was deposited before Laramide deformation, making it an ideal datum. However, in the study area thinning in the Hutchinson Salt prevents the use of the Stone Corral Anhydrite as a datum. To remove post-Desmoinesian deformation and avoid the majority of the effect of compaction, the top of the Heebner Shale Member (Shawnee Group, Virgilian Stage, Pennsylvanian) was picked on logs and used as a datum. The Heebner Shale is a thin, laterally extensive, highly radioactive black shale that was deposited across most of the midcontinent. The Heebner Shale Member has an easily recognizable log signature characterized by intense gamma ray readings, making it an easily identifiable datum. Merriam (1963) reported only minor or localized post-Cherokee Pennsylvanian structural deformation in this area, with later southwest tilting of the Central Kansas uplift region due to Laramide deformation (Tikoff and Maxson, 2001). Using the Heebner Shale as a datum effectively removes post-Cherokee tectonic influence.

Heebner Shale tops from the KGS database were checked for quality and gridded in Petra. Using a grid-to-grid calculation, the current structural trend of the Heebner Shale was subtracted from the Mississippian structure map to remove the majority of post-Desmoinesian deformation (Figure 3.5). The resulting surface is a reasonable representation of the Cherokee Group depositional surface, but the resulting restored topography of the surface could be slightly attenuated due to compaction.

Timing of Aldrich Anticline Deformation

The Aldrich anticline is a prominent positive structural feature located in west-central Ness County. Aldrich field was discovered in 1929 and as of October 2008 has produced 8,942,645 barrels of oil primarily from Mississippian strata, as well as Fort Scott Limestone and the Lansing/Kansas City Group (Kansas Geological Survey, 2009). The structural closure created by the anticline and a partial water drive in the Mississippian dolomite create a highly prolific reservoir. The timing of the formation of the Aldrich anticline has been disputed for quite some time (Alfred James, pers. comm.). The most obvious difference between the restored Mississippian surface and modern day structure is the removal of positive structure along the Aldrich anticline (figure 3.5). This dates the deformation of the anticline as post-deposition of the Heebner Shale. By using a stratigraphic datum outside the Pennsylvanian, such as the Stone Corral Anhydrite, timing of deformation can be further refined. If uplift along the Aldrich Anticline occurred during the Pennsylvanian or Early Permian, strata deposited between the Mississippian and Stone Corral Anhydrite would show evidence of thinning over the crest of the anticline. This phenomenon was not observed in the data (Figure 3.6). This suggests uplift of the Aldrich anticline occurred after deposition of the Stone Corral Anhydrite.

The Aldrich anticline parallels several northeast-southwest trending magnetic and gravity data lineaments that may outline basement blocks (Figure 3.7). The northwest edge of the anticline is coincident with a lineament defined by magnetic data. As previously noted, high-angle basement faults originally associated with rifting represent zones of weakness and were subsequently reactivated as strike-slip faults or high-angle reverse faults by later tectonic compression (Van der Pluijim and Marshak, 1997). Vertical displacement of fault blocks can result in the creation of monoclinial and anticline features (Van der Pluijin and Marshak, 1997; Merriam, 2005). Deformation along the Aldrich anticline is interpreted to be the result of uplift and adjustment caused by stresses along pre-existing zones of weakness associated with the Laramide Orogeny (Late Cretaceous to Eocene).

Description of the Mississippian Depositional Surface

The exposed Mississippian surface experienced significant weathering and erosion during the late Mississippian and early Pennsylvanian at the end of the Kaskaskia Sequence. Dissolution and other karst processes sculpted the surface, creating the highly irregular configuration observed today, and were the primary agents for creating the surface on which the Cherokee Group was deposited. Evidence of karst processes have long been recognized along the Mississippian-Pennsylvanian unconformity surface. Several authors have noted and delineated karst features east of the study area on the Central Kansas uplift where Late Mississippian erosion has removed all strata down to the Arbuckle Group (Walters, 1991; Cansler, 2000; Rocke, 2006). Similar karst structures are present throughout much of the study area, developing on Mississippian rather than Ordovician strata (Figures 3.8 and 3.9). Some regions of the study area have close well spacing (40-80 acre), and provide a relatively high degree of resolution to permit identification of karst features on the Mississippian surface.

Dolines

A doline is a closed hollow or depression of small to moderate dimension, that can be cone or bowl-shaped with circular to elliptical plan (Sweeting, 1973; Jennings, 1985). Dolines have three primary components: 1) the bowl-like depression dissolved into the underlying bedrock, 2) a mantle of soil or other insoluble material draped over the bedrock, and 3) a drain connecting the depression to the conduit drainage system in the subsurface (White, 1990). Typically, dolines are considered the most common karst feature and a primary agent in forming karst surfaces (Sweeting, 1973). Several processes are involved in the formation of dolines including solution, piping, subsidence, and cave collapse. Jennings (1985) outlined a classification system of five doline types based on the dominant mechanism of formation: solution dolines, collapse dolines, subsidence dolines, subjacent-karst-collapse dolines, and alluvial stream-sink dolines (Figure 3.10).

In the study area, individual dolines are circular or elliptical in plan view. Dolines on the Mississippian surface can be as deep as 160 feet (50 meters) and encompass an area as wide as a one mile (1.6 kilometers). However, more typical dimensions of dolines are 10 to 50 feet deep (3-15 meters) and diameters ranging from 1000-2500 feet (300-750 meters). Smaller dolines may be present on the Mississippian surface, but well spacing is insufficient to delineate small-scale karst features. The center third (east-west) of the county appears to have the higher density of dolines, but this is probably the result of well distribution. Well spacing is adequate in this region to delineate dolines, while in other areas the low well density makes dolines difficult to reliably delineate, and may result in an apparent subdued paleotopography.

Dolines rarely occur as isolated features and are typically observed in clusters. Kemmerly (1982) noted that secondary dolines often form around an initial primary doline. As focused runoff from the wide radius around the primary doline flows inward, it encounters joints, fractures, and other surface anomalies, causing the formation of secondary dolines (Figure 3.11). This relationship between primary and secondary dolines is observed on the Mississippian surface (Figure 3.12).

In humid tropical and temperate zones dolines sometimes totally pock mark the land surface and occupy all available space. The resultant karst topography consists of closed depressions segmented by high-relief drainage divides forming a cellular mesh pattern termed polygonal karst (Ford and Williams, 2007). Polygonal karst was observed only in limited areas on the Mississippian surface. This may be because of insufficient resolution provided by the well data, or development of polygonal karst may be limited.

Mississippian Paleovalley Network

A valley network is recognized on the Mississippian karst surface over the entire study area. Mississippian paleovalley systems were delineated by examining the restored Mississippian surface and Cherokee isopach maps. Any valley present during the deposition of the Cherokee Group would be filled as sea level transgressed the unconformity surface. Coincidences of topographic lows on the Mississippian surface and thick Cherokee Group deposits were used to identify paleovalley configurations.

Large-scale valley networks were interpreted by examining the Cherokee isopach and restored Mississippian surface map for the entire study area (Figure 3.13). Paleovalleys of differing size and magnitude can be identified in well-log data, but overall most valleys trend north to south. Drainage on the Mississippian surface appears to be broken into two distinct drainage patterns: an eastern and western drainage pattern. The two regions each appear to drain different portions of the study area. The drainage pattern in the east, present on very edge of the county, is primarily northeast-east to southwest-west. The northeast-southwest orientated valleys join into larger north-south oriented valleys toward the west. The primary orientation of valleys in the western portion of the area is north to south toward the Hugoton embayment.

East to west drainage on the eastern edge of the study area is typified by relatively narrow valleys 0.5 to 1.5 miles wide (0.8 to 2.4 km). Typical valley depths range from 10-40 feet deep (3-12 meters). These valleys exhibit smaller overall dimensions and are significantly shallower that valleys in the rest of the county. The paleovalleys appear to drain directly to the west off the Central Kansas uplift. To the west, and in the majority of the rest of the study area, approximately north-south oriented valleys are 0.5-2.5 miles wide and up to 90 feet deep (28 meters). Smaller, tributary valleys are quite common, joining large valleys at moderate to high junction angles (Figure 3.14). Overall, valley dimensions are quite variable. While valleys can be traced over 10 miles, several valleys are relatively short (<1.5 miles) with a constant width and originate at dolines that exhibit abrupt, steep valley-head terminations.

Groundwater Sapping Processes and Paleovalley Development

Groundwater sapping is the process in which groundwater flows down-gradient through gently dipping permeable strata, dissolves constituents, and entrains soils and rock from the medium through which it flowed. Subsurface flow discharges from the ground surface where the water table intersects topography. Groundwater emerging from the seepage zone slowly removes material that provides basal support for overlying slopes. Dissolution undermines neighboring slopes and leads to eventual slope collapse (Lou, et al., 1997; Laity and Malin, 1985). Slope failure occurs in a headward direction as the zone of seepage is progressively eroded. This creates theatre-headed valleys with steep sides (Lou, et al., 1997; Laity and Malin, 1985).

Heterogeneity of the rock as well as irregularities, such as joints, fractures, or faults concentrate groundwater flow, and accelerate dissolution and erosion as progressively more and more groundwater is diverted (Dunne, 1980). Once the process is initiated it is self enhancing, because more and more groundwater flow lines converge on the spring which increases flow (Baker, et al., 1990). This concentrates erosion at the head of a valley and results in headward migration of valley development. Intersecting irregularities that intersect the valley are susceptible to sapping and may result in a network of tributaries. Theatre-headed valleys typically show the strong influence of structural controls because of the importance of joints and fractures in their development (Laity and Malin, 1985).

Groundwater sapping processes produce different channel and valley morphologies than fluvial processes (Table 3.1). Sharp, headward valley terminations are characteristic features of groundwater-sapping (Lou et al., 1997). Groundwater-sapped valleys are typically relatively short and exhibit a steep walled and flat floored U-shaped cross-section. It must be noted that surface runoff processes are present in valleys of groundwater sapped origin, especially during flooding and times of high water level. Surface processes help remove eroded valley wall material.

It appears that valleys on the Mississippian surface are primarily the product of groundwater sapping and karst processes. Interpreted paleovalleys exhibit several morphological characteristics of groundwater sapped valleys. In Figure 3.13, several of the interpreted large-scale paleovalleys originate and terminate in dolines. In Figure 3.14, several dolines are present along the axis of paleovalley floors and interpreted as alluvial stream-sink dolines that captured surface flow. Mississippian paleovalleys in Ness County have steep walls, relatively flat floors and are uniform in width; typical of groundwater sapped valleys. High tributary-junction angles provide further support for a groundwater sapping origin. Almost all paleovalleys observed on the Mississippian surface originate at steep-walled dolines resulting in theatre-headed valley configurations. The steep valley walls were caused by gradual slope erosion by sapping and eventual failure. It is likely that groundwater sapping processes in addition to surface dissolution from other karst processes result in the formation of the extensive paleovalley network on the Mississippian surface.

Influence of Basement Features on Mississippian Erosion

Dissolution is the primary agent of doline formation and is concentrated along irregularities in the surface, such as joints, faults, or fractures (Jennings, 1985). Continued dissolution along these features eventually produces dolines. Polygonal karst forms on surfaces fissured by a series of intersecting conjugate joints (Williams, 1972). As previously noted, movement of basement blocks would produce networks of fractures and faults that parallel magnetic and gravity lineaments, providing conditions advantageous to doline development. Doline and paleovalley development would be expected to parallel or align with basement block boundaries delineated by gravity and magnetic lineaments. Doline development on the Mississippian surface appears to align with the lineaments throughout much of the study area (Figures 3.15-3.17). The correlation between paleovalley and doline development parallel to magnetic and gravity lineaments suggests that Precambrian basement faulting affected the Mississippian surface and influenced erosion on the surface. Preferential dissolution along fractures and faults associated with basement block movement resulted in the irregular karst surface on which the Cherokee Group was deposited.

A correlation between Precambrian basement structure and Mississippian structure on a localized scale has been noted on 3-D seismic data across Dickman field, northwestern Ness County (Figure 3.18) (Nissen et al., 2006). By using 3-D seismic data they were able to image the Precambrian basement surface and compared it with a high resolution image of the Mississippian unconformity surface (Figure 3.19 and Figure 3.20). The Mississippian surface mimics the basement structure and Cherokee Group paleovalleys were aligned over lows in basement structure. Lows on the basement structure probably represent small, downdropped basement blocks and nearby highs are the result of upward movement on neighboring blocks. Cherokee Group thickness increases into the interpreted paleovalley supporting the conclusion that pre-Desmoinesian movement along basement faults affected the paleotopographic configuration of the Mississippian unconformity surface.

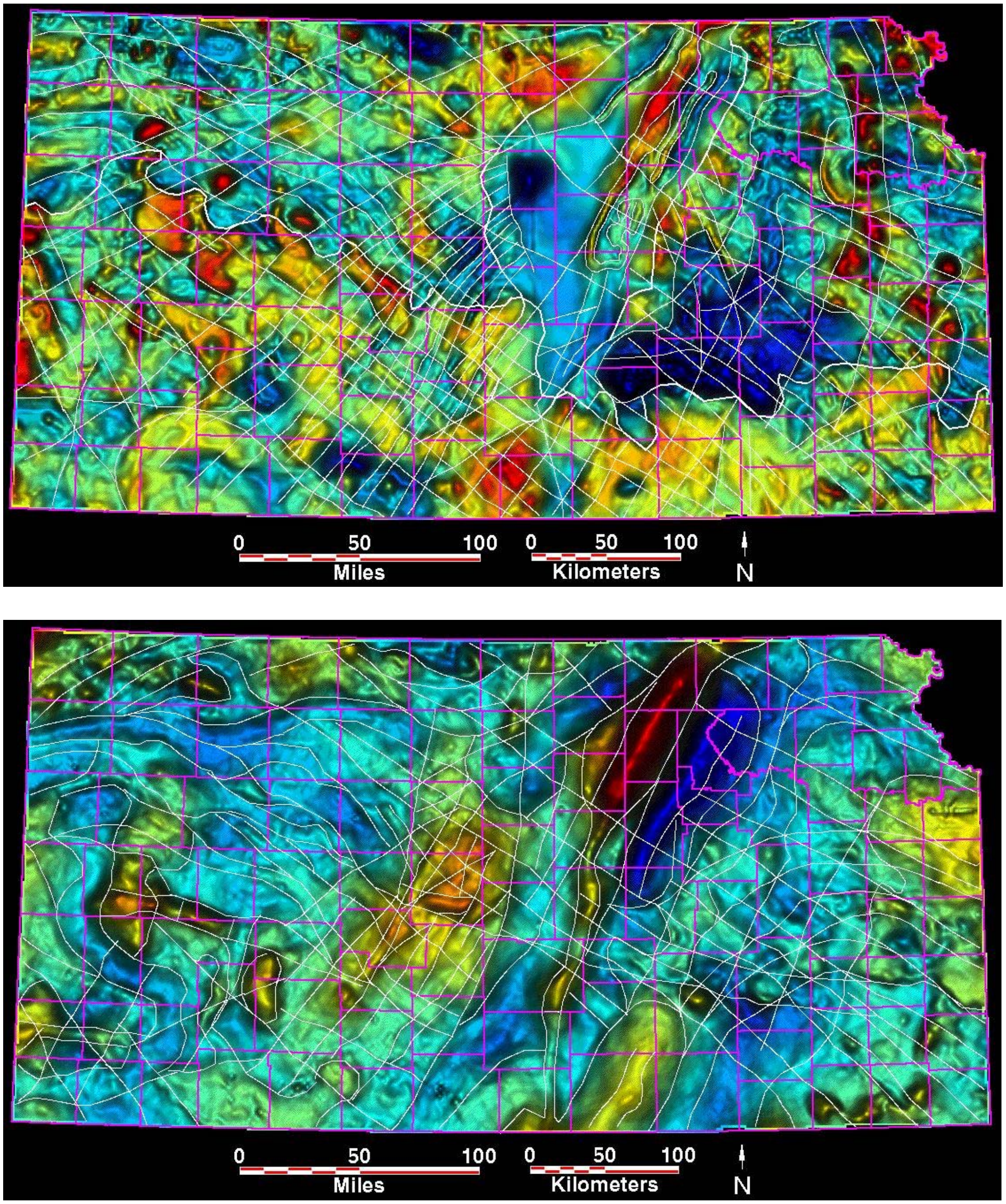

Figure 3.1. State-wide magnetic (top) and Bouguer anomaly (bottom) maps overlain by interpreted regional lineaments. Continuous northwest and northeast trending lineaments have been identified in both data sets by previous studies (Yarger, 1983; Lam, 1987). Modified from Kruger (1996), taken from http://www.kgs.ku.edu/PRS/PotenFld/potential.html (accessed 8/13/2009).

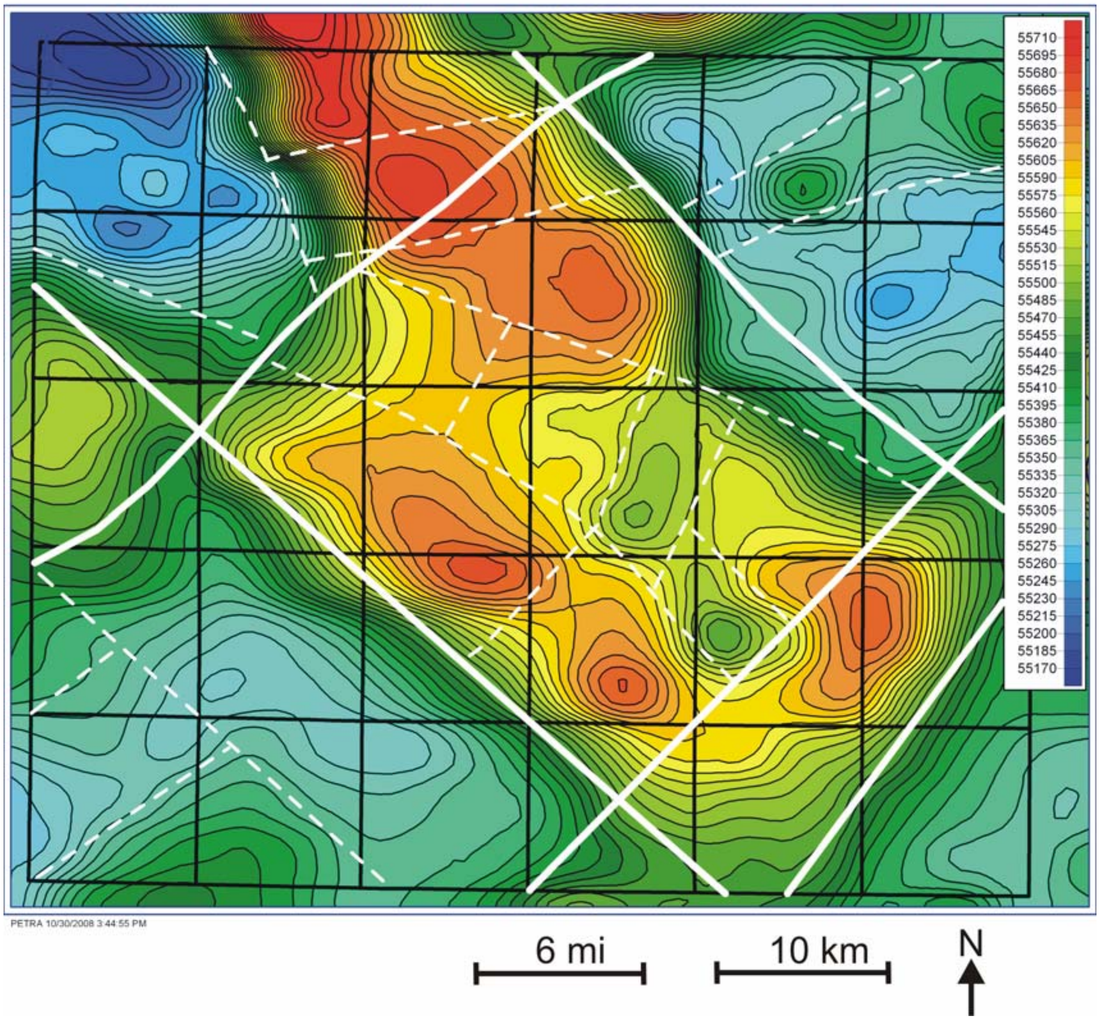

Figure 3.2. Map showing the contoured total magnetic field data in nanoteslas (nT) for Ness County, Kansas. Solid lines represent regional west-northwest and north-northeast oriented lineaments. Dashed lines represent localized lineaments. Lineament interpretation is based on previous investigation by Yarger (1983). These lineaments outline anomalies caused by significant changes in susceptibility. Magnetic anomalies could be the result of differences in basement rock composition or the displacement of basement blocks along vertical or high-angle reverse faults.

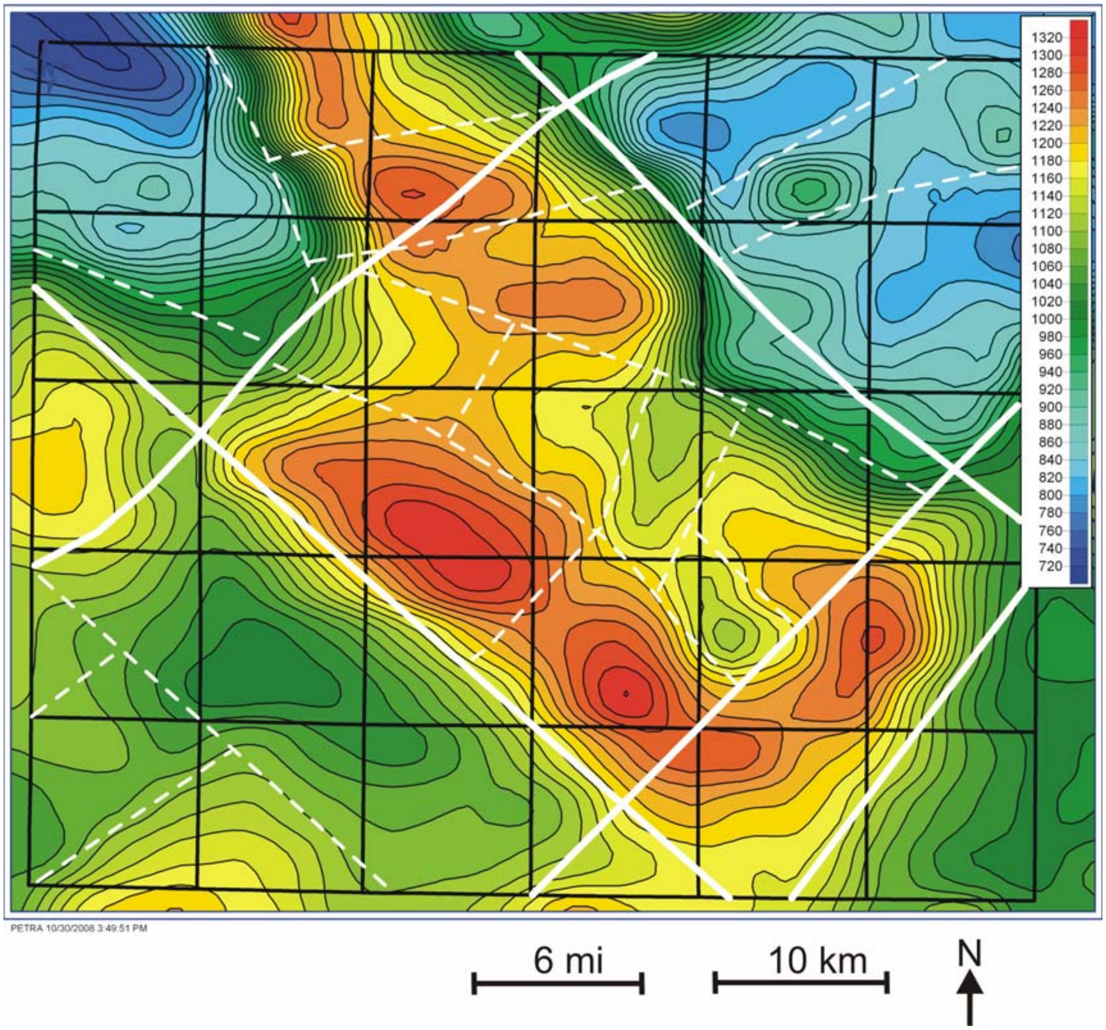

Figure 3.3. Map showing the contoured residual magnetic field data (in nT) for Ness County, Kansas. Solid lines represent regional west-northwest and north-northeast oriented lineaments. Dashed lines represent localized lineaments. Lineament interpretation is based on previous investigation by Yarger (1983). These lineaments outline anomalies caused by significant changes in susceptibility. Magnetic anomalies could be the result of differences in basement rock composition or the displacement of basement blocks along vertical or high-angle reverse faults.

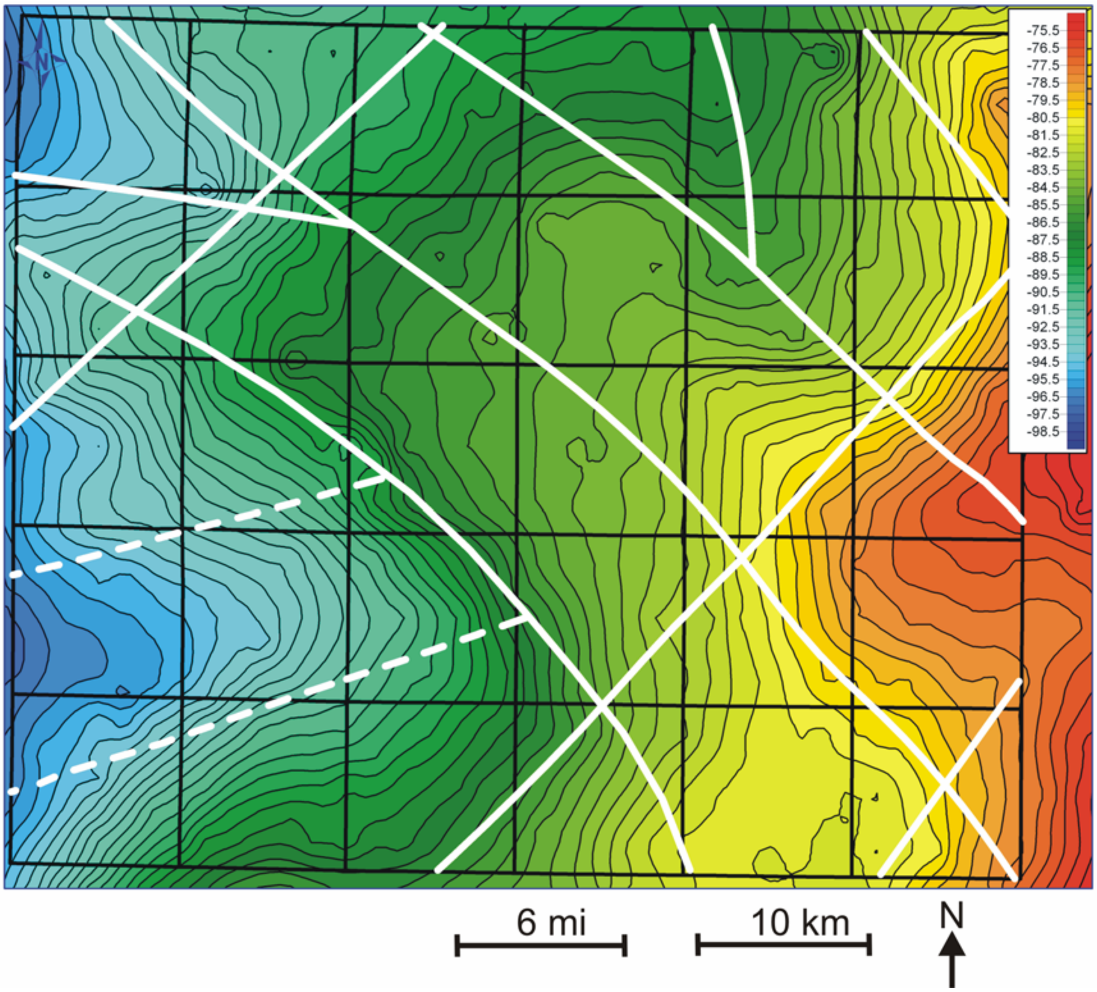

Figure 3.4. Map showing the contoured Bouguer gravity data for Ness County, Kansas. Solid lines represent regional west-northwest and north-northeast oriented lineaments. Dashed lines represent localized lineaments. Lineament interpretation is based on previous investigation by Lam (1987). Lineaments outline anomalies caused by significant changes in density. Density contrasts could be the result of differences in basement rock composition or the displacement of basement blocks along vertical or high-angle reverse faults.

Figure 3.5. Available in supplemental files

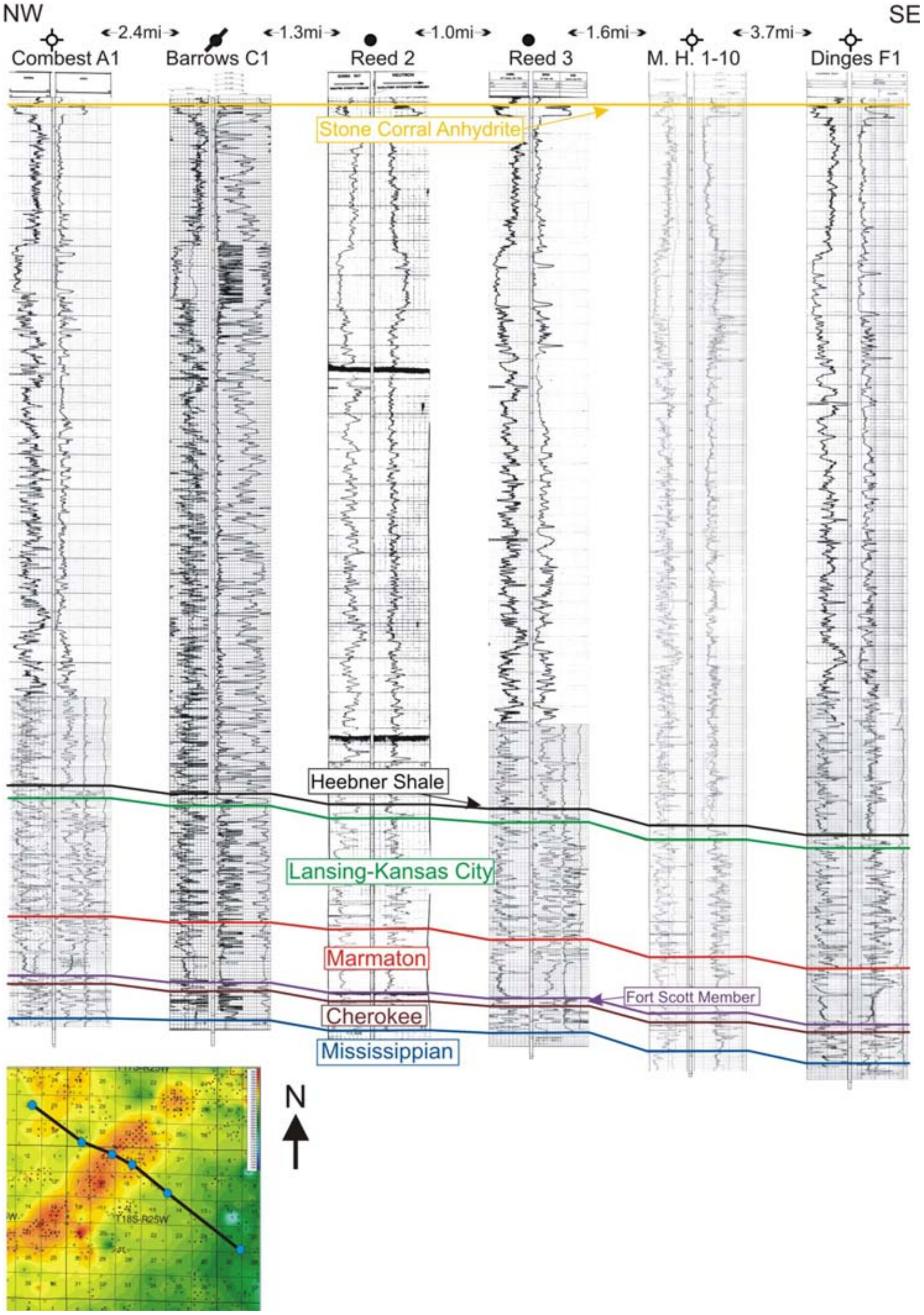

Figure 3.6. Cross-section across the crest of the Aldrich Anticline. Missourian and Desmoinesian units show no evidence of stratigraphic thinning over the crest of the anticline. Datum on top of Stone Corral

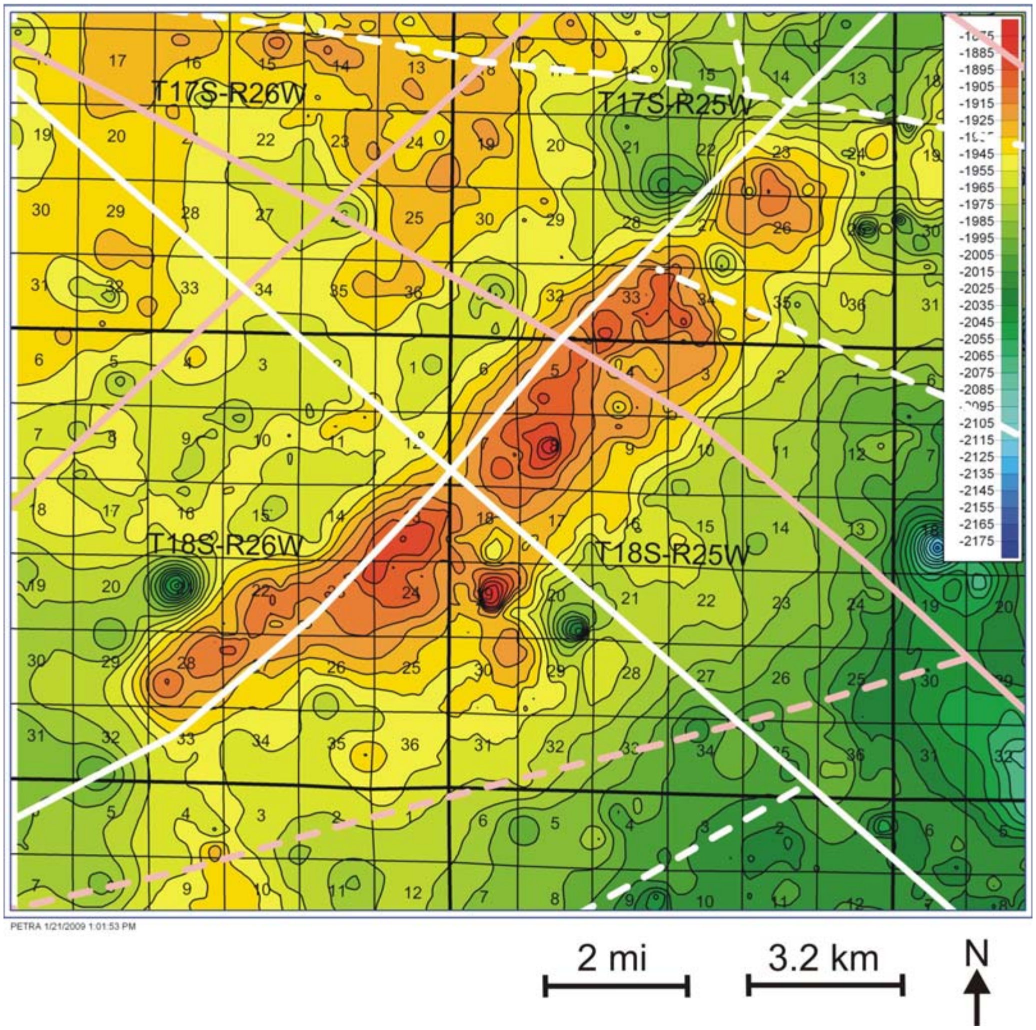

Figure 3.7. Mississippian structure on the Aldrich anticline overlain by gravity lineaments in pink and magnetic lineaments in white. Northeast-southwest orientation of the anticline crest parallels magnetic and gravity lineaments. Lineament along northwest edge of anticline may represent basement block edge where uplift occurred during the Laramide Orogeny. Depth in feet subsea.

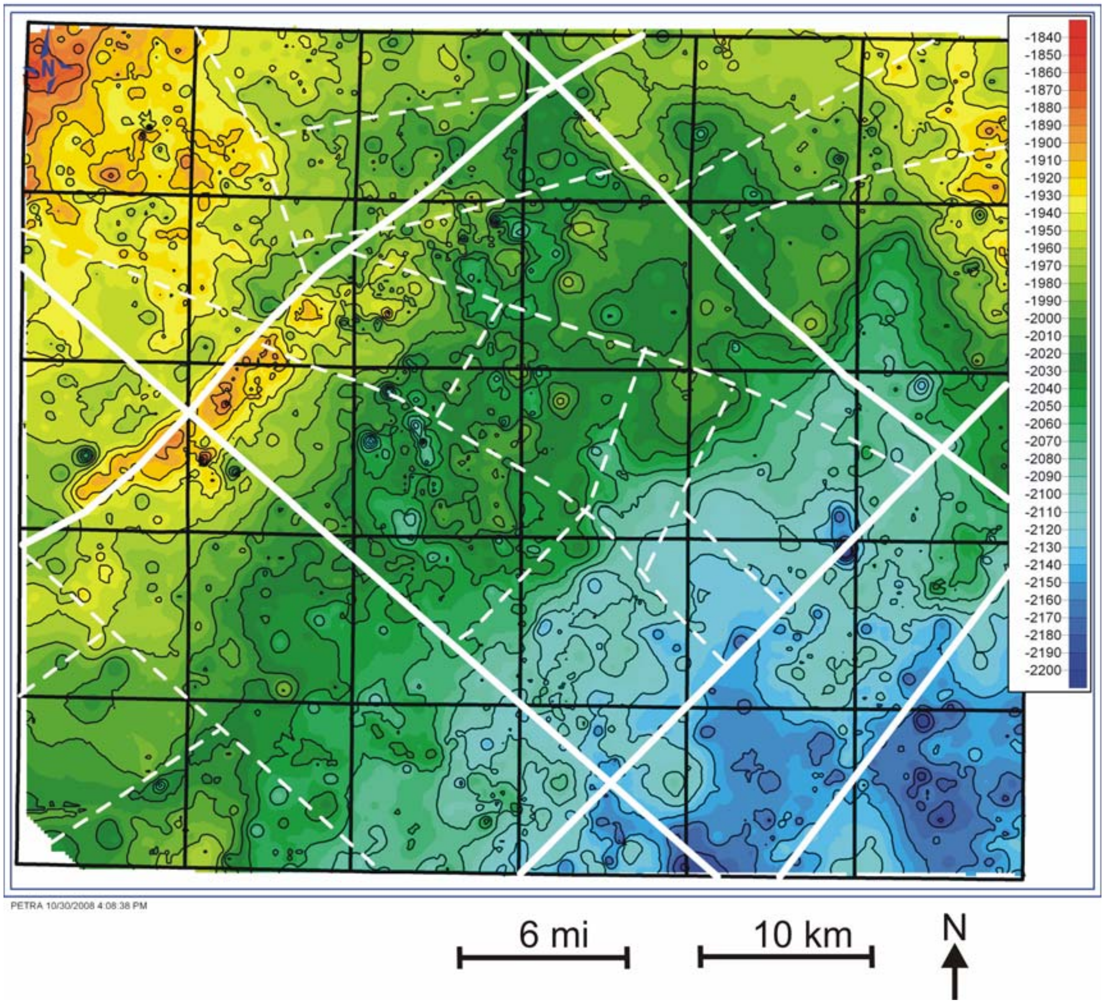

Figure 3.8. Map showing contoured Mississippian structure overlain by magnetic anomaly lineaments. Regional and local magnetic lineaments are interpreted to represent basement block boundaries and are interpreted as influencing Mississippian structure. The Mississippian surface is marked by series of high and low structural feature interpreted as dolines and other karst features. Prominent positive structural feature in west-central Ness County is Aldrich anticline. Color contour interval is 10 feet and outlined contour interval is 20 feet. Depth in feet subsea.

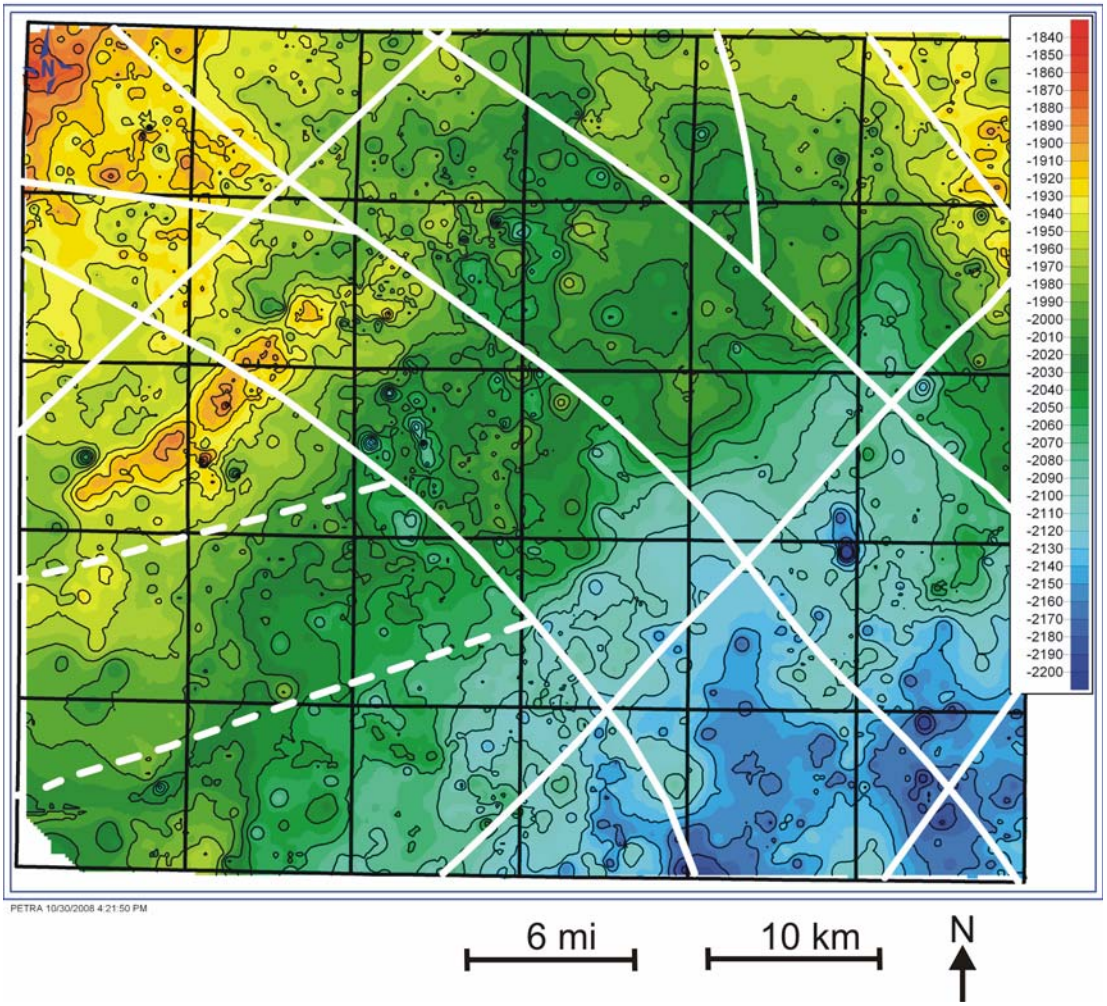

Figure 3.9. Map showing contoured Mississippian structure map overlain by Bouguer gravity anomaly lineaments. Regional lineaments are interpreted to represent basement block boundaries. The Mississippian surface is marked by series of high and low structural feature interpreted as dolines and other karst features. Color contour interval is 10 feet and outlined contour interval is 20 feet. Depth in feet subsea.

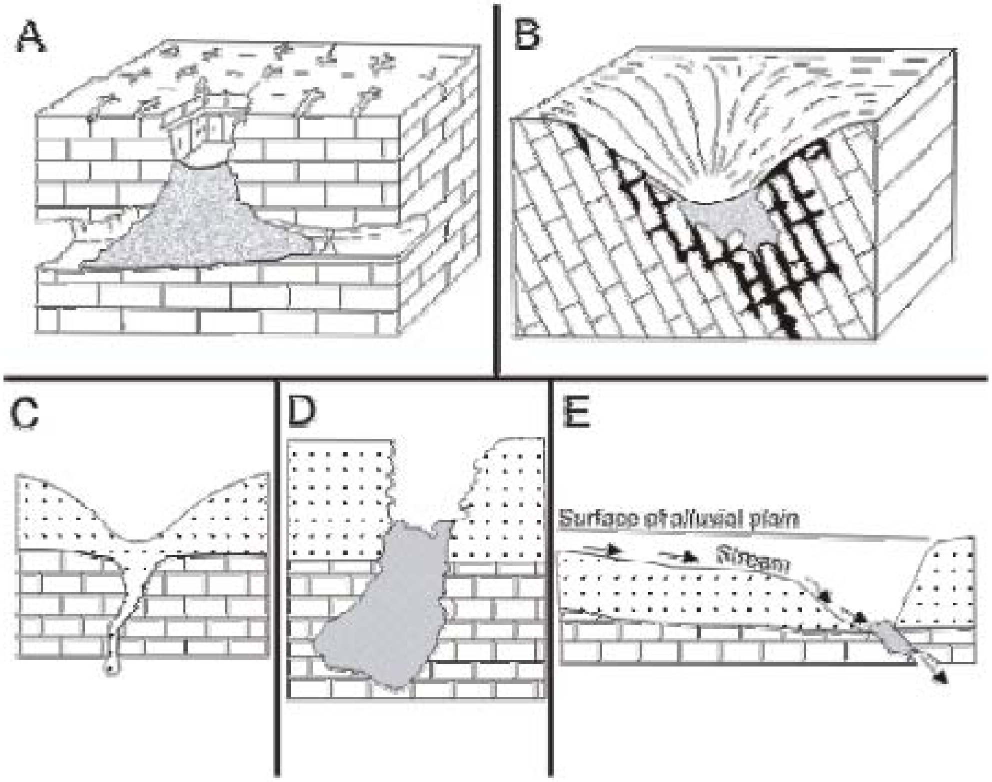

Figure 3.10. Five types of dolines: A) collapse doline, B) solution doline, C) subsidence doline, D) subjacent karst collapse doline, E) alluvial stream sink doline. Modified from Jennings, 1985.

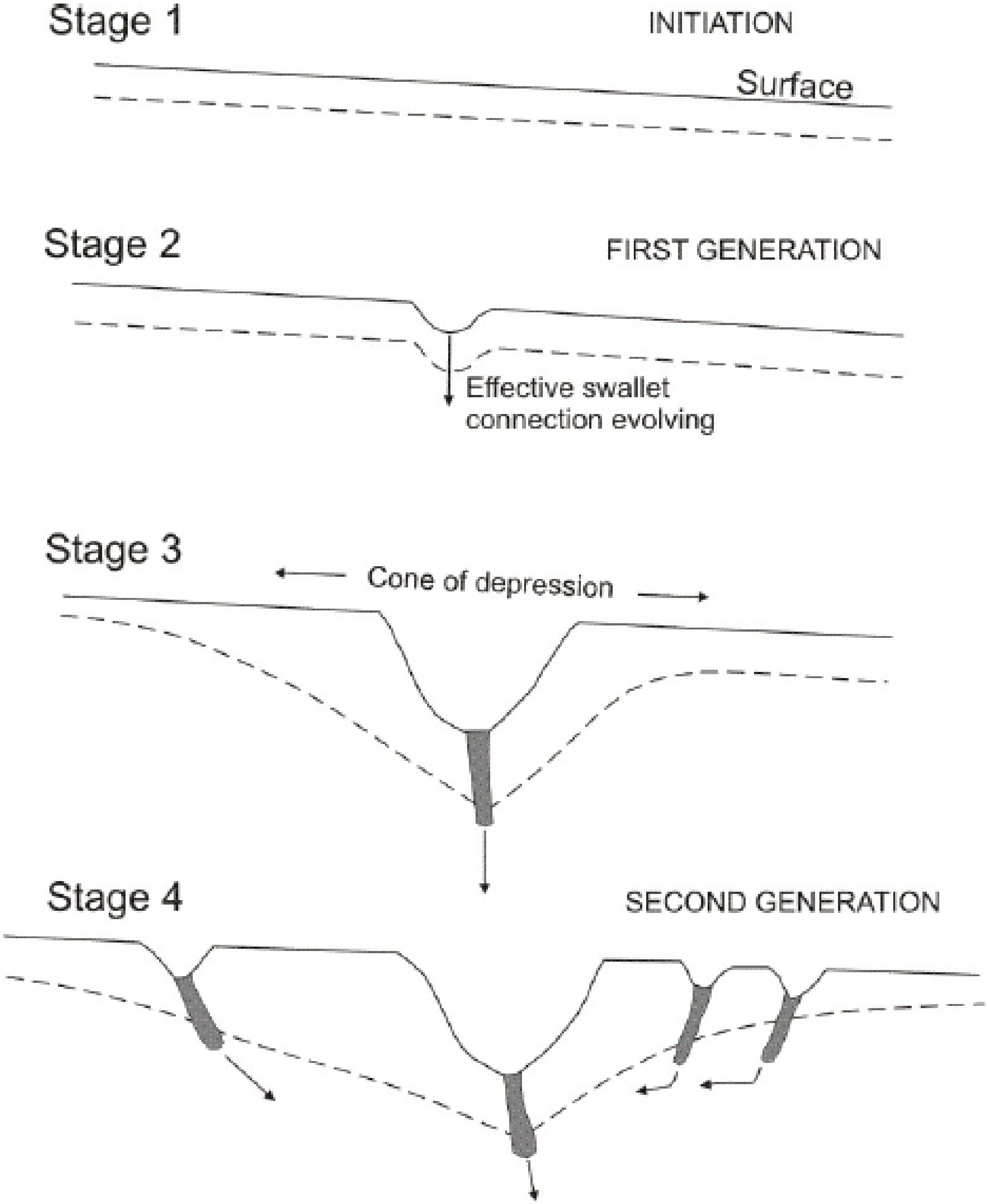

Figure 3.11. Generalized model of doline development and how runoff triggers the development of secondary dolines. Runoff entering the primary cone of depression encounters joints, fractures and other surface features that inhibit flow and form a series of secondary depressions. Modified from Kemmerly (1982) and Rocke (2006)

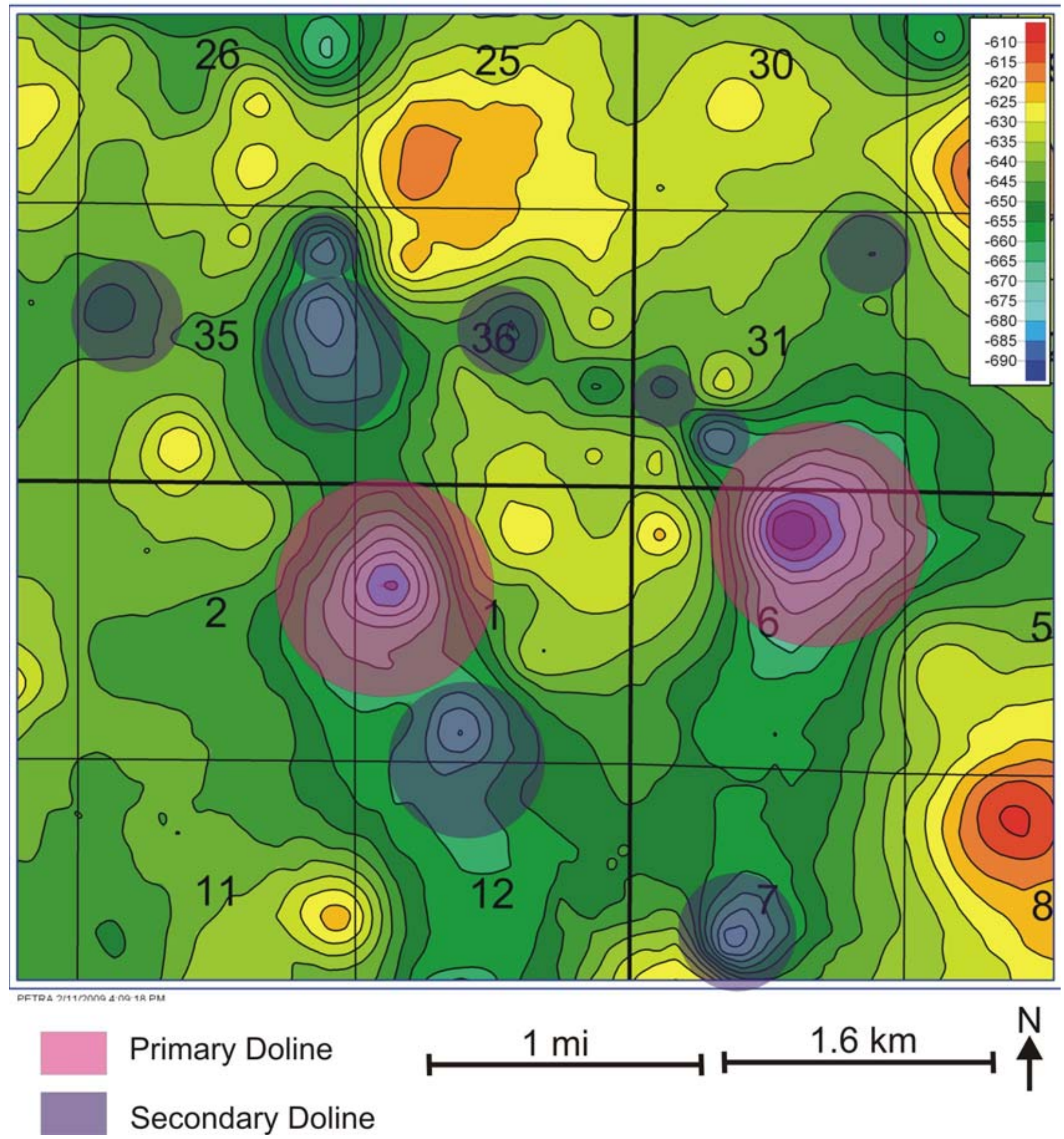

Figure 3.12. Example of primary doline with associated secondary doline development. Depth in feet subsea.

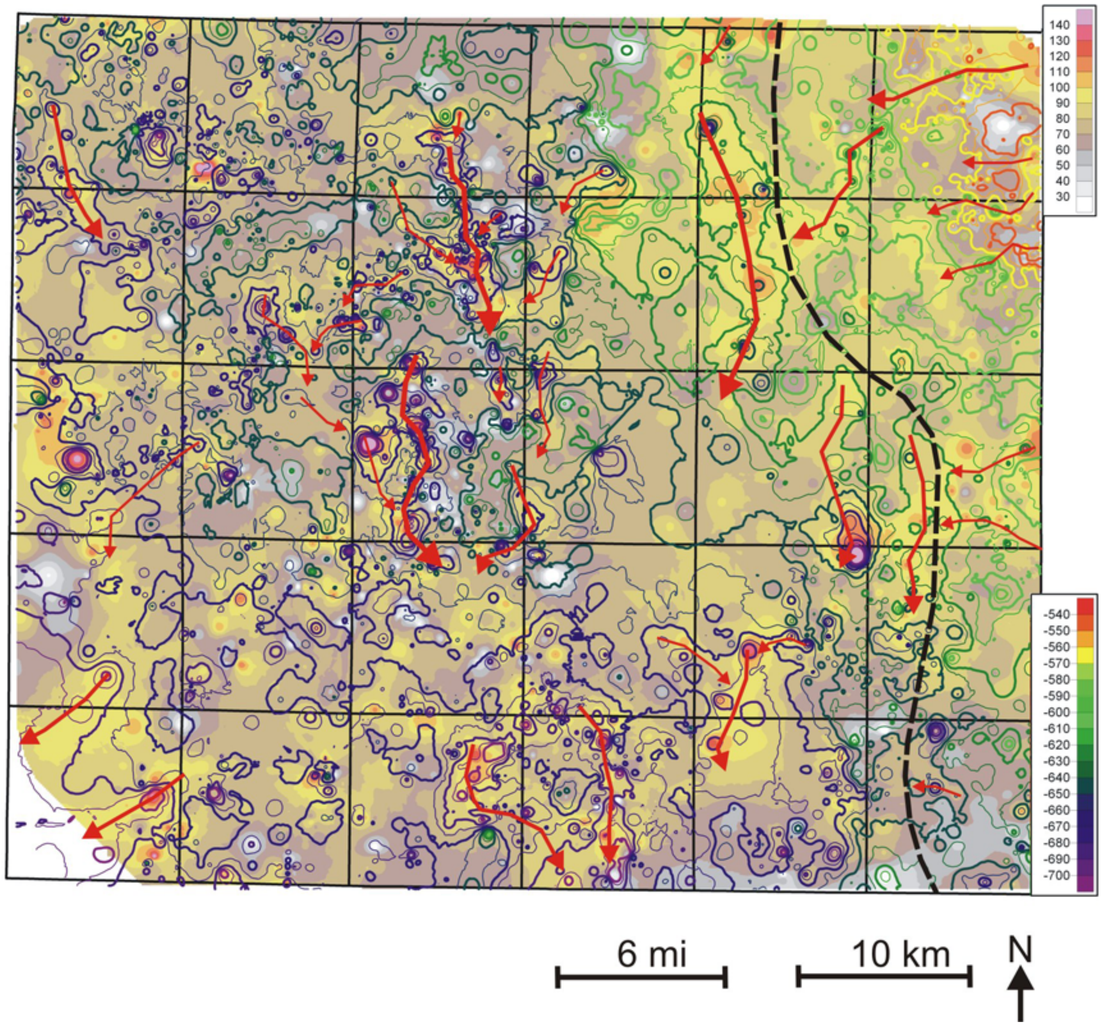

Figure 3.13. Cherokee Group isopach overlain by restored Mississippian depositional topography. Red arrows indicated paleovalley systems and arrow thickness is indicative of valley order. There appear to be two large-scale drainage systems in the study area. Large drainage system in the eastern half of the county contains thick Cherokee Group successions as does the slightly smaller drainage system in the west-southwest portion of the county. The patterns are separated by dashed black line. Depth in feet subsea and thickness in feet.

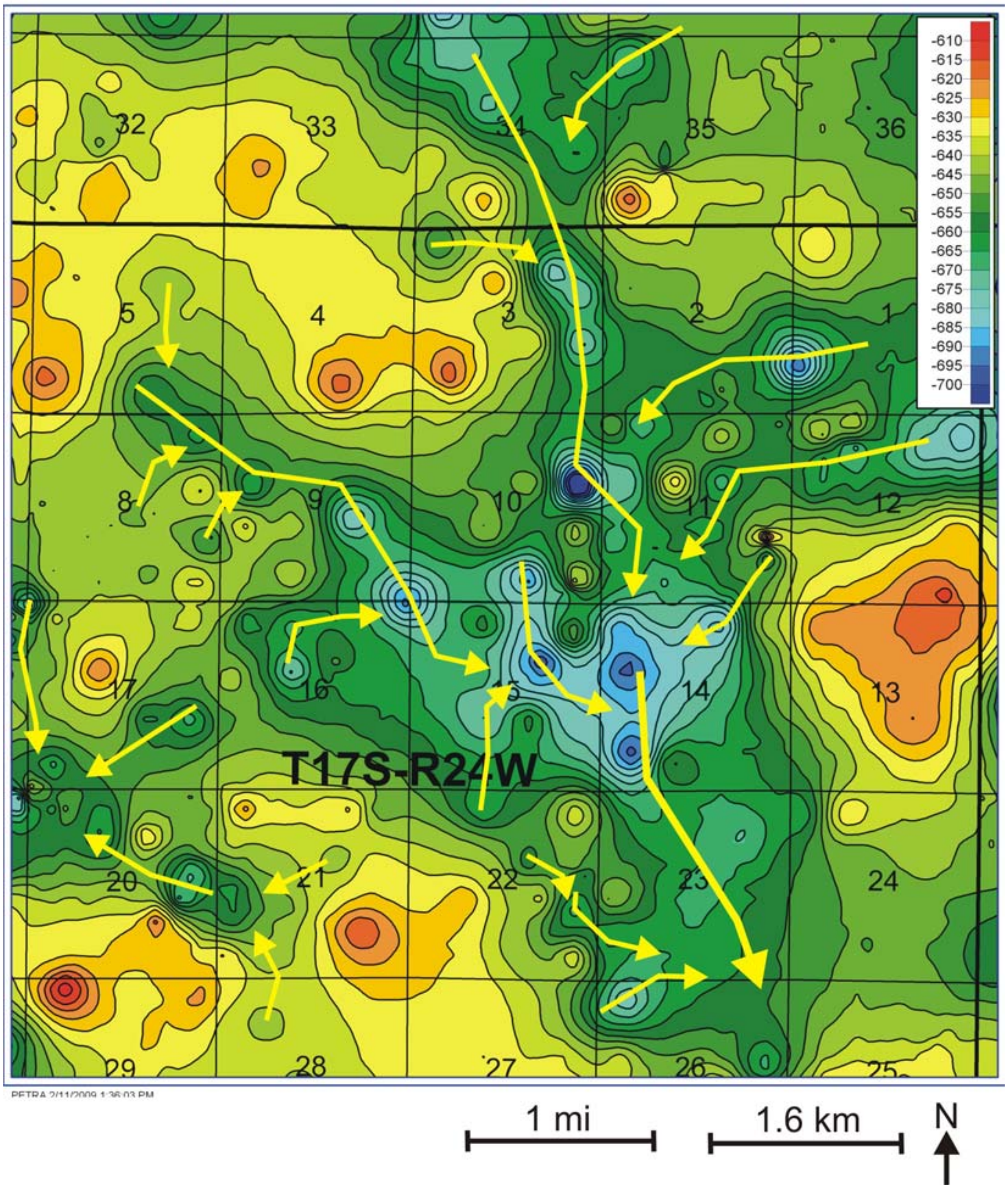

Figure 3.14. Contoured restored Mississippian surface with paleovalleys delineated. Dense well control combined with smaller contour interval help identify the complex drainage systems on the Mississippian surface. Several short paleovalley tributaries feed into a primary valley. Dolines line the axis of valley floors and are interpreted as alluvial stream-sink dolines. Contour interval is 5 feet. Depth in feet subsea.

Geomorphic Characteristics of Sapping vs. Fluvial Channels

Parameter	Runoff-dominated	Sapping-dominated
Basin Shape	Very elongate	Light bulb shaped
Head Termination	Tapered, gradual	Theatre, abrupt
Channel Trend	Uniform	Variable
Pattern	Parallel	Dendritic
Junction angle	Low (40-50 degrees)	Higher (55-65 degrees)
Downstream Tributaries	Frequent	Rare
Relief	Low	High
Drainage Density	High	Low
Drainage Summary	Symmetrical	Asymmetrical
Cross-section Shape	V-shaped	U-shaped, steep wall, flat floor
Valley Width	Widening downstream	Relatively constant
Tributary Length	Relatively long	Short stubby tributary
Structural Control	Less strong	Strong
Basin Area/Canyon Area	Very high	Low

Table 3.1. Summary of geomorphic characteristics of sapping and runoff-dominated fluvial valleys in the Colorado Plateau and Hawaii (modified from Luo et al., 1997)

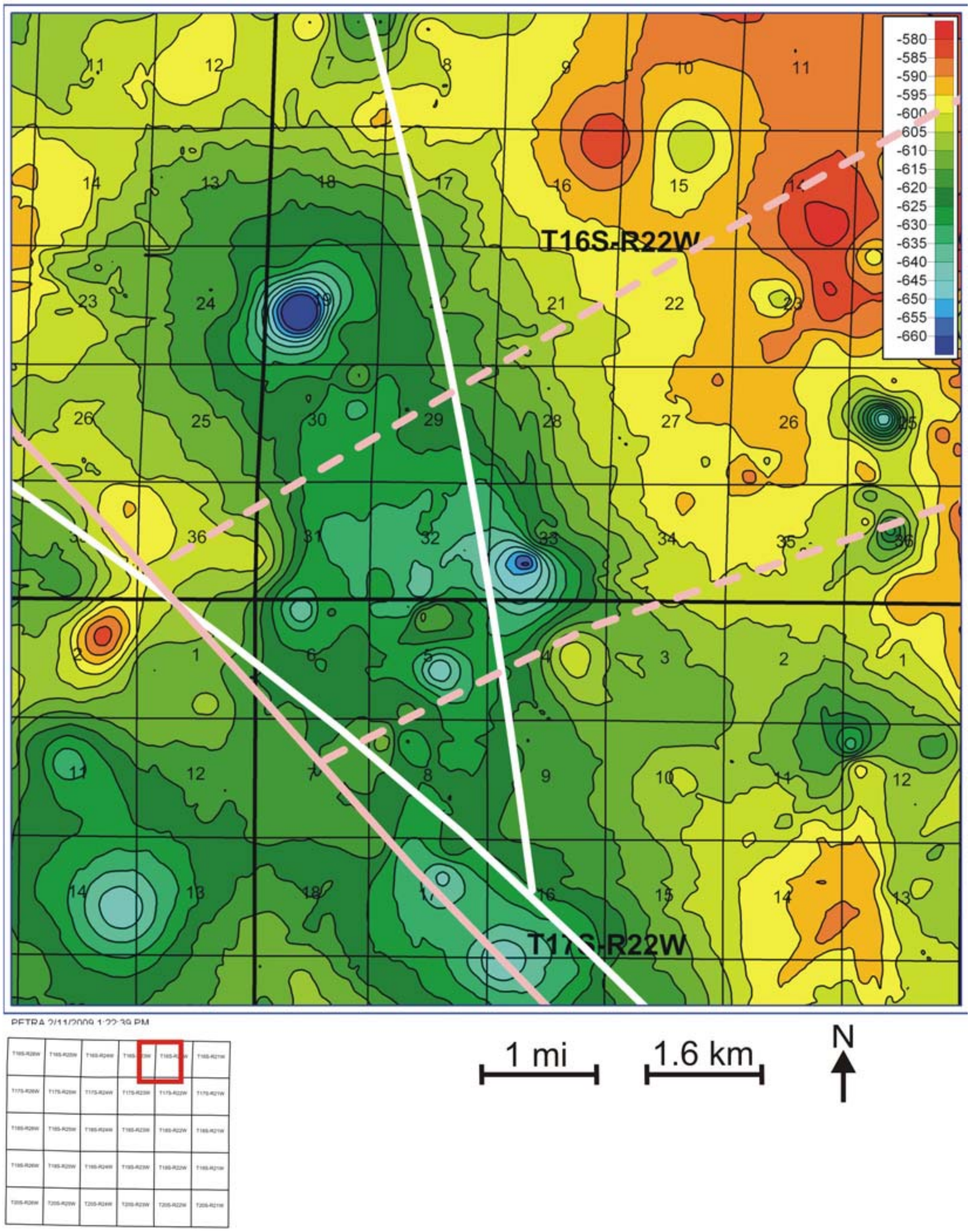

Figure 3.15. Map showing contoured Mississippian structure overlain by gravity lineaments in white and magnetic lineaments in pink. Doline and paleovalleys generally parallel gravity and magnetic lineaments suggesting that they may be developing along fracture and faults associated with reactivated basement blocks. Contour interval is 5 feet. Depth in feet subsea.

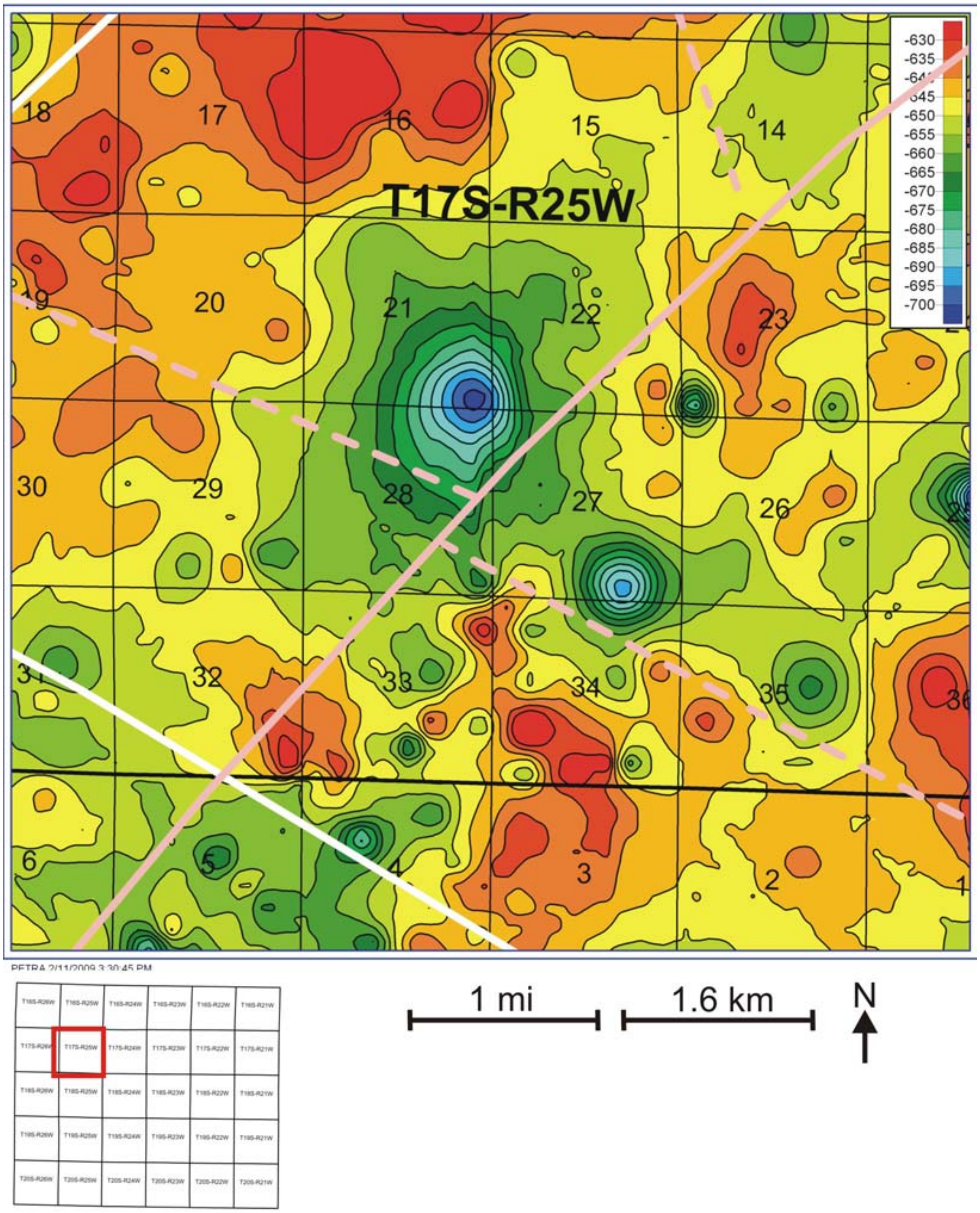

Figure 3.16. Map showing contoured Mississippian structure overlain by magnetic lineaments in pink and gravity lineaments in white. A series of closed depressions interpreted as dolines and sapped valleys are present along the junction magnetic lineaments. Contour interval is 5 feet. Depth in feet subsea.

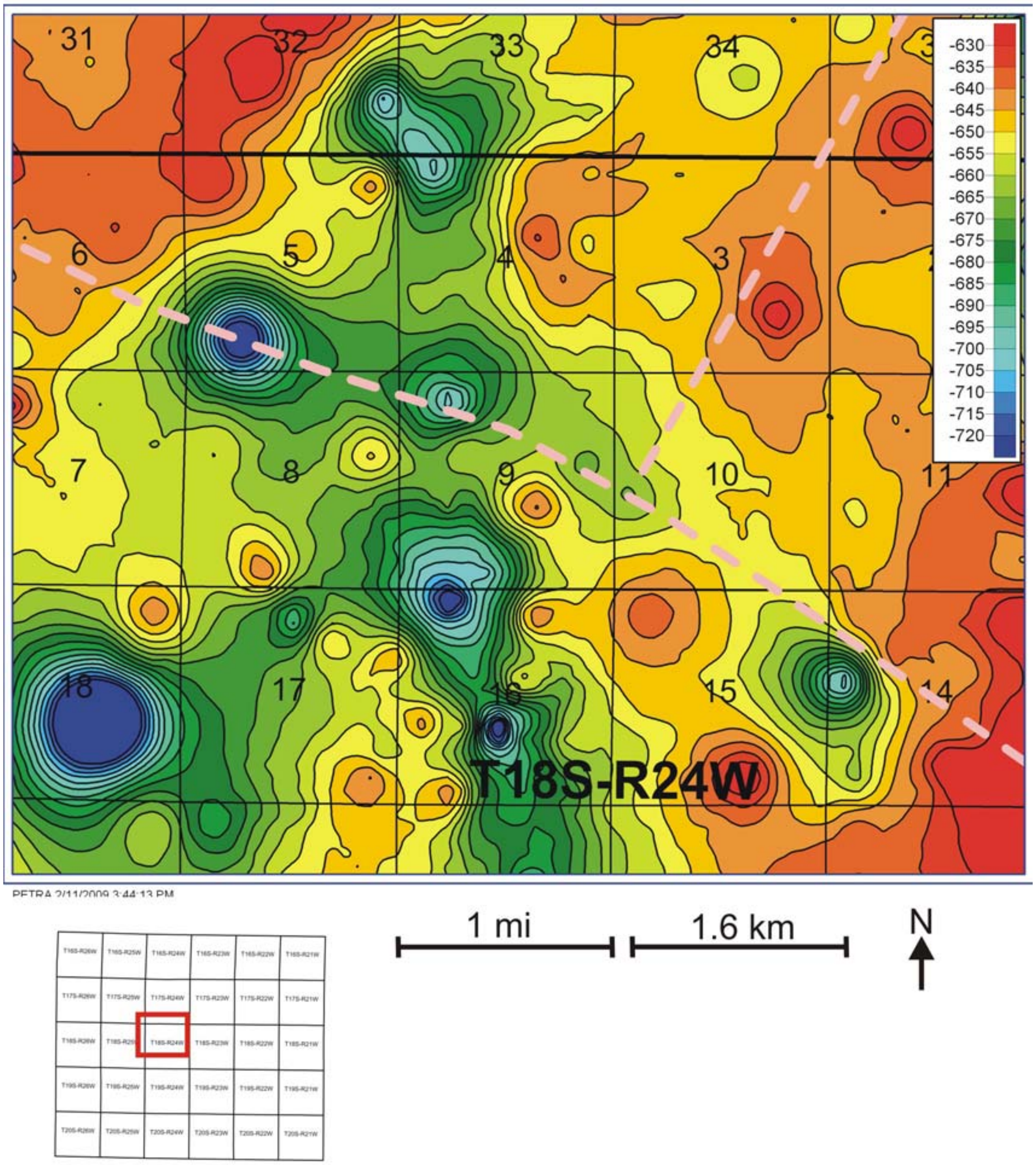

Figure 3.17. Map showing contoured Mississippian structure overlain by gravity lineaments in white and magnetic lineaments in pink. Note interpreted paleovalley paralleling a regional gravity anomaly. A series of closed depressions interpreted as dolines are present throughout the paleovalley. Contour interval is 10 feet. Depth in feet subsea.

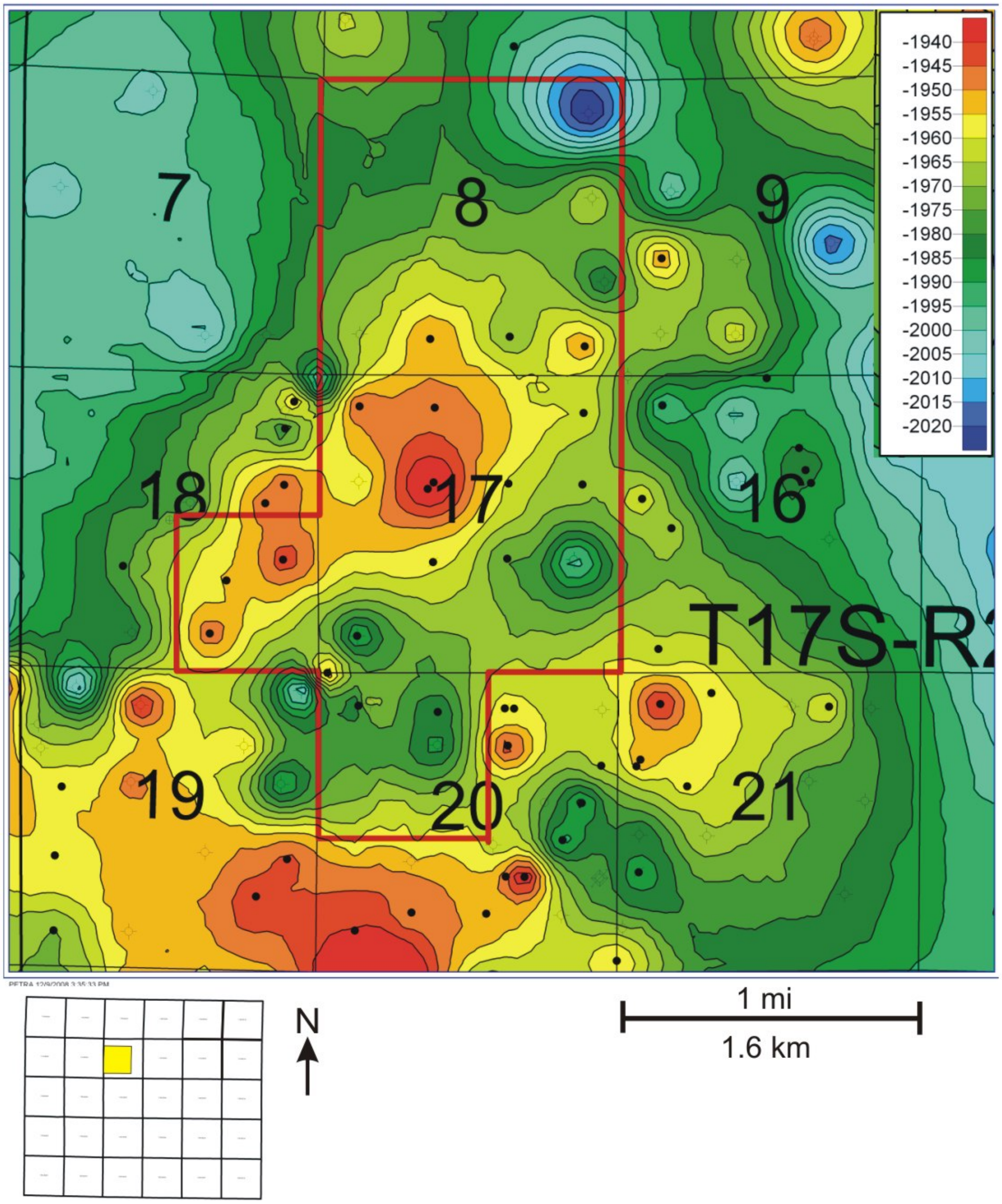

Figure 3.18. Map showing contour Mississippian surface (from well data) in the 3-D seismic area of Dickman field in northwestern Ness County, Kansas. Depth in feet subsea.

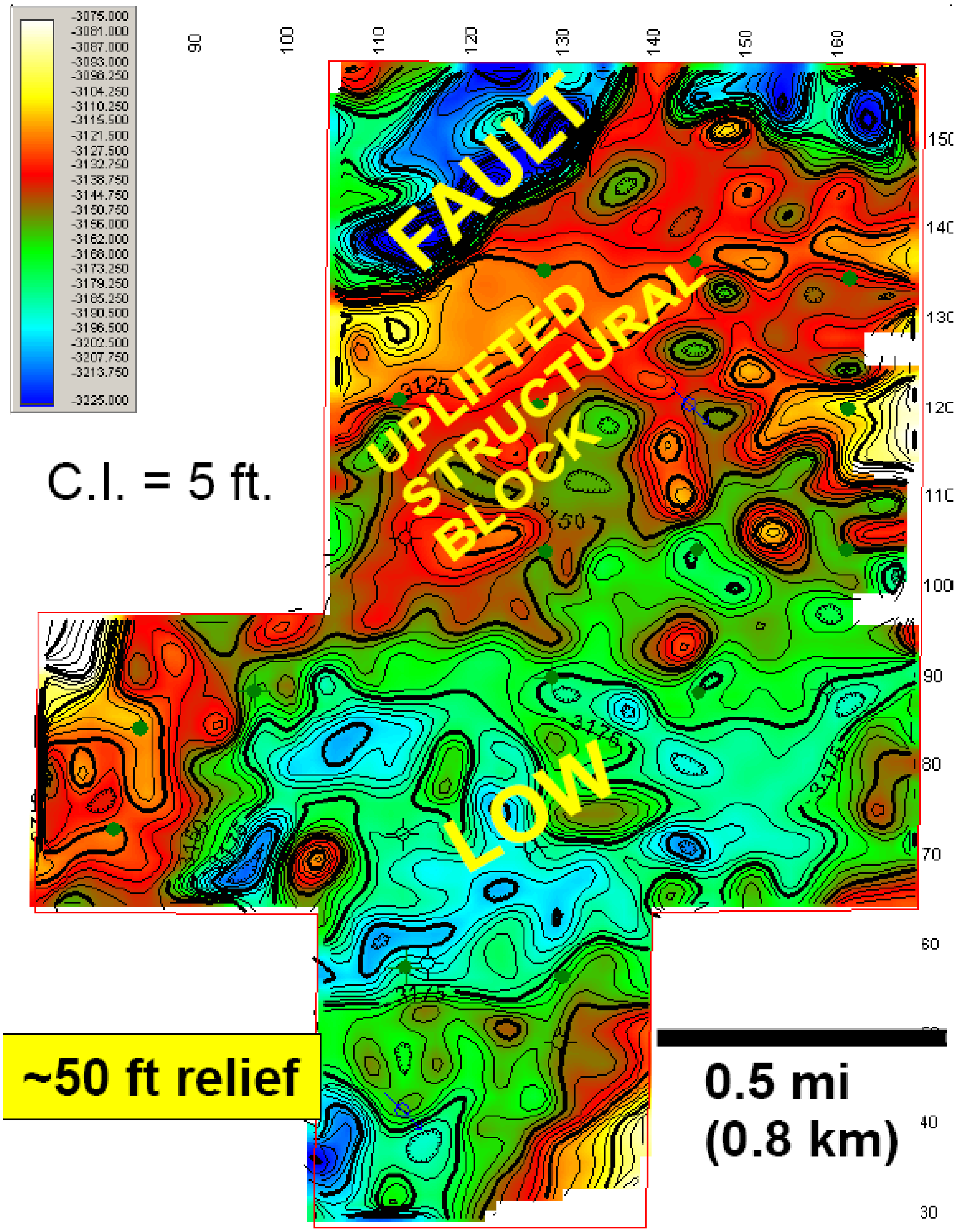

Figure 3.19. Map showing contoured basement structure from 3-D seismic data covering Dickman Field. High and low areas on the surface are interpreted to outline localized basement blocks that have experienced significant movement. 50 feet of relief is present between uplifted and downdropped basement blocks. Depth in feet subsea and contour interval is 5 feet. (Modified from Nissen et al., 2006)

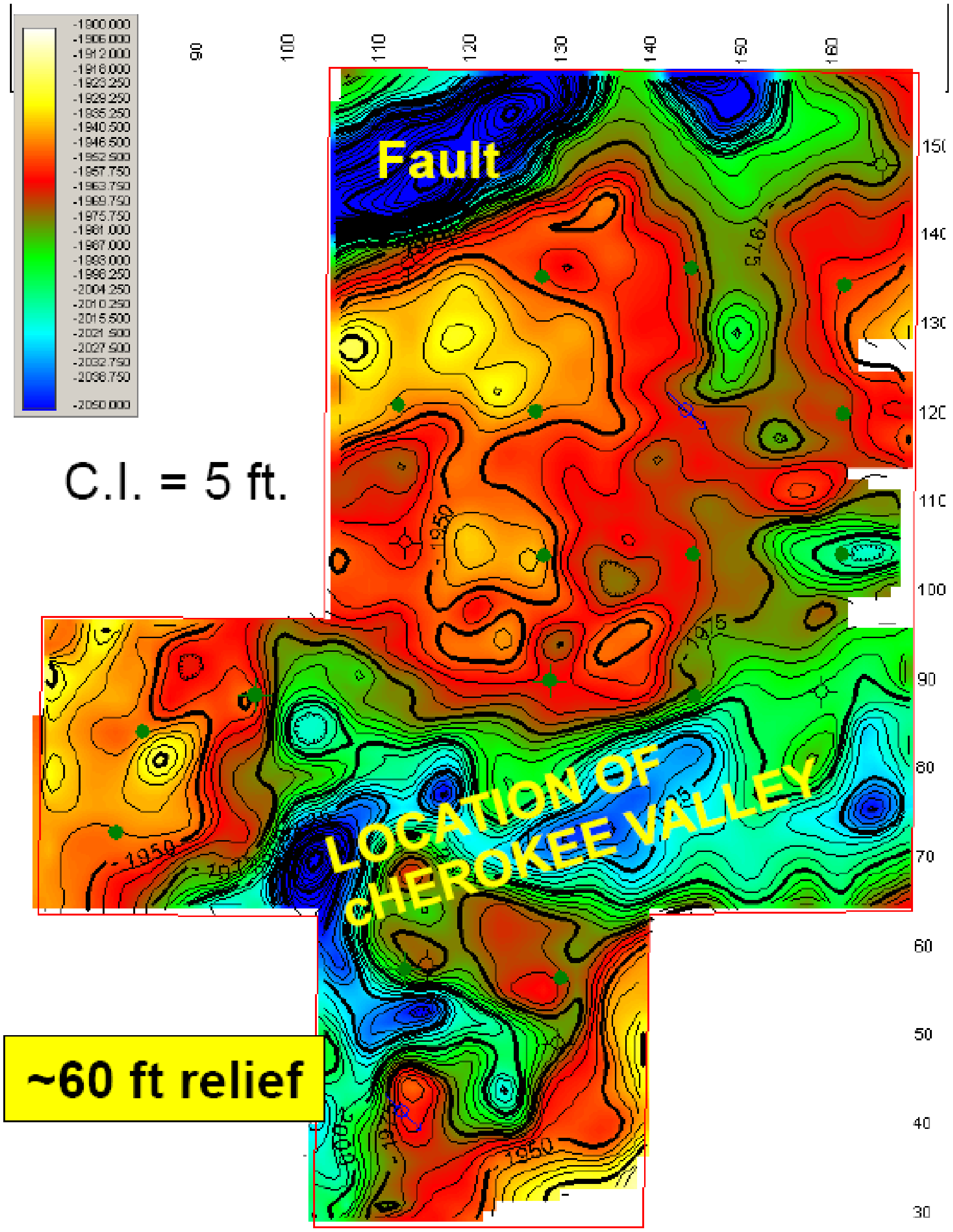

Figure 3.20. Map showing the contoured Mississippian surface from 3-D seismic data covering Dickman field. High and low areas on the surface coincide with structure of basement surface. Low area in on Mississippian surface is interpreted as a Cherokee paleovalley and overlies a low area in the basement structure. 60 feet of relief along the paleovalley is comparable to the 50 feet of relief along the basement structural low. Depth in feet subsea and contour interval is 5 feet. (Modified from Nissen et al., 2006)

CHAPTER 4: SEQUENCE STRATIGRAPHY OF THE CHEROKEE GROUP AND SANDSTONE FACIES DISTRIBUTION

Introduction to Sequence Stratigraphic Nomenclature

Sequence stratigraphic concepts provide a framework to better explain and predict the spatial distribution, relative thickness, and vertical succession of facies in the Cherokee Group in Ness County. Also, sequence stratigraphy provides a method of predicting and understanding the deposition of oil-bearing reservoir sandstones. A complete review of sequence stratigraphic concepts, methodology and terminology is beyond the scale of this study, but a brief synopsis of essential concepts and terminology is provided.

Sequence stratigraphy is the study of genetically related facies within a framework of chronostratigraphically significant surfaces, where the depositional sequence is the fundamental stratigraphic unit for sequence-stratigraphic analysis (Van Wagoner et al., 1990). The depositional sequence is defined as a genetically related succession of strata bounded by unconformities and their correlative conformities (Mitchum et al., 1977). Sequence stratigraphy incorporates several geologic variables to understand depositional patterns (e.g., subsidence, tectonic uplift, eustacy, sediment accumulation, and sediment influx). Different methodology has been applied to defining the depositional sequence (Mitchum et al., 1977; Galloway, 1989), but this study of the Cherokee Group employs the Mitchum et al. (1977) and Van Wagoner et al., (1990) technique to define a depositional sequence.

In Ness County, the Cherokee Group is a mixed system of carbonate and siliciclastic lithologies, and requires a combination of siliciclastic and carbonate sequence stratigraphic terminology and concepts. Sequence stratigraphy was first developed and applied to siliciclastic successions so the majority of the terms have been adapted to carbonate rocks. Perhaps the main difference between carbonate and siliciclastic sediment is carbonate grains are typically created in the basin in which they originate. As a result carbonate deposition is more susceptible to a variety of factors that influence the basin, such as water circulation and chemistry, climate, basin geometry, and water depth. Siliciclastic grains often originate outside the basin and are transported into the basin by physical processes. These variables combined with subsidence, eustacy, and sediment accumulation are the basic parameters for sequence stratigraphy.

Identification of Parasequences and Parasequence Boundaries

Parasequences are the stratal building blocks of sequences (Van Wagoner et al., 1990). The parasequence is defined as a relatively conformable succession of genetically related beds or bedsets bounded by marine-flooding surfaces or their correlative surfaces. As such, a parasequence boundary is a marine flooding surface or its correlative surface that shows evidence of deeper-water deposits sharply overlying shallower-water deposits (Van Wagoner et al., 1990). In this study, well logs through sections of the Cherokee Group aided in determining and tracing major flooding surfaces laterally (Figure 4.1). Well log control is abundant throughout the study area, however core control is sparse and was not sufficient to correlate individual beds and associated flooding surfaces so individual parasequences are not correlated. However, maximum flooding surfaces are recognizable, and were correlated across most of the study area. Maximum flooding surfaces in the Cherokee Group of Ness County are characterized by a sharp base and fossil lag deposits, a sharp base with in basinward facies shift (continental to marine), or a sharp base with an apparent increase in clay content. Typically, maximum flooding surfaces in the Cherokee Group are associated with significant and rapid increase in gamma-ray values, allowing one to recognize the surfaces in the subsurface.

Parasequence Sets and Systems Tracts

A parasequence set is a succession of genetically related parasequences forming a distinctive stacking pattern and commonly bounded by sequence boundaries or major marine-flooding surfaces and their correlative conformities (Van Wagoner et al., 1990). Stacking patterns of parasequences within a parasequence set are used to designate the type of parasequence set; either progradational, retrogradational or aggradational. Stacking patterns are often used to identify systems tracts, but in this study only sequence boundaries and maximum flooding surfaces were correlated due to lack of core data and lateral variability in the strata. Systems tracts are used to define three sectors within each sequence: lowstand, trangressive, and highstand systems tracts. The transgressive systems tract begins at the first major flooding surface and continues to the maximum flooding surface (Van Wagoner et al., 1988). The highstand systems tract begins at the maximum flooding surface and continues to the overlying sequence boundary (Van Wagoner et al., 1988). Lowstand systems tracts start right above the sequence boundary and continue to the first major flooding surface (Van Wagoner et al., 1988). It must be noted that maximum flooding surfaces correlated in this study were mapped at the base of the petrophysically defined facies, but it is implied that the deepest flooding event could actually be recorded within the facies.

Identification of Sequences and Sequence Boundaries

The depositional sequence is the fundamental stratal unit for sequence-stratigraphic analysis, and is defined as a succession of relatively conformable, genetically related strata bounded at the top and base by unconformable surfaces or their correlative conformities (Mitchum et al., 1977; Van Wagoner et al., 1990). Sequence boundaries are defined as an unconformity and its correlative conformity that is a continuous and correlatable surface (Van Wagoner et al., 1990). Sequence boundaries are laterally continuous basin-scale features that could be synchronous with sequence boundaries in basins worldwide (Vail et al., 1977). Sequence boundaries may be recognized by one or more of the following basin-scale criteria: (1) subaerial erosional truncation and laterally equivalent exposure surface; (2) basinward shift in marine facies; (3) coastal onlap; and (4) downward shift in coastal onlap (Van Wagoner et al., 1990). Similarly, sequence boundaries in carbonate units are characterized by exposure of the platform and concurrent submarine erosion (Sarg, 1988).

In this study of the Cherokee Group, four cross-sections were created to correlate the sequence-stratigraphic surfaces across the study area (Figure 4.1). Core analysis tied to well-log response provided criteria to recognize stratigraphic surfaces, but the lack of continuous core covering the complete Cherokee Group interval made it a challenge to reliably trace surfaces across the study area. Only three cores located in the eastern half of the study area covered the entire Cherokee Group limiting characterization of the Cherokee Group. The widespread features of erosion and subaerial exposure, recognized and mapped from core and log data in the Cherokee Group, are interpreted as sequence boundaries (Figure 4.2). All sequence boundaries in the Cherokee Group as interpreted as sequence boundaries and concurrent flooding surfaces.

Galloway (1989) applied a different methodology to sequence stratigraphy, defining genetic stratigraphic sequences bounded by stratigraphic surfaces and correlative condensed marker bed deposited during transgression and the ensuing period of maximum marine flooding. The depositional sequence and genetic stratigraphic sequence are both defined by a single, widespread surface that separates younger rocks above from older rocks below the boundary. Because sequence boundaries are based on subaerial exposure, maximum flooding surfaces in the Cherokee Group are easier to identify than sequence boundaries (at least in the subsurface with well logs). The duration of exposure, and chemical and physical processes that occur during exposure, influence the rock record. Evidence of exposure such as erosion and pedogenesis is easily identified in core, but is a challenge to consistently identify with the available limited well-log suites. As a result, sequence boundaries are inferred based on stratigraphic correlation tied to limited core data across the study area. Further study using genetic stratigraphic sequences based on maximum flooding surface could provide additional insight into understanding the deposition of the Cherokee Group.

Sequence CG1

Sequence Cherokee Group 1 (CG1) is distributed over the entire study area, and directly overlies the Mississippian erosional unconformity surface (Figures 4.3-4.6). Sequence Boundary 1 (SB1) is a regionally extensive surface of subaerial exposure on top of Mississippian strata marking the base of Sequence CG1. The Mississippian strata below Sequence CG1 exhibit extensive paleokarst features creating the varied topography for deposition of Sequence CG1. In core, the basal sequence boundary is overlain by three facies: cherty conglomeratic breccia, glauconitic sandstone, and variegated silty mudstone facies (Figures 4.3-4.6). All of these facies were deposited during regression on the Mississippian unconformity (SB1) and are grouped into the lowstand systems tract. The conglomeratic breccia facies may not be entirely the result of deposition during lowstand, as significant sediment may have been reworked during transgression. In situ brecciation, fluvial transport, and mass wasting processes were the main mechanisms of deposition during exposure. However, since in situ and fluvial conglomeratic breccias deposits cannot be differentiated from transgressive reworked deposits, the facies is grouped into the lowstand systems tract.

Glauconitic sandstone geometries (interpreted as fluvial-estuarine deposits) appear as channel-fill sand bodies capped by variegated silty mudstone (interpreted as paleosols) (Figure 4.4). Up-dip in northeastern Ness County, conglomeratic sandstone facies is overlain by lingulid shale facies (interpreted to represent shallow restricted lagoon environment) (Figure 4.5). The lowstand systems tract filled most of the Mississippian paleotopography resulting in a relatively smooth surface dipping gently south-southwest (Figure 4.4).

A regionally extensive carbonate wackestone-packstone unit overlies the sandstone, shale, and conglomerate of the lowstand systems tract, marking the maximum flooding surface (MFS 1) and transition into the highstand systems tract (Figures 4.3-4.6). The carbonate body thins up-dip to the northeast and eventually pinches out against the Central Kansas uplift at the edge of the study area (Figure 4.4). The open shallow marine shelf deposits are interpreted as the deepest water facies of Sequence CG1. Marine flooding did not reach sufficient depths to induce anoxic bottoms conditions and a regionally extensive high gamma-ray black shale is not present.

Spatial Distribution of Sandstone Facies in Sequence CG1

Sequence CG1 herokee Group sand accumulations in Ness County are present below the maximum flooding surface and regional wackestone-packstone bed. Sandstone facies are distributed in elongated, sinuous bodies (Figure 4.7). Mapped net sandstone accumulations range in size from 0.5 to 5.0 miles (0.8 to 8.0 kilometers) wide, and 1.0 to 22 miles (1.6 to 35.2 kilometers) long. The thickest and most persistent sandstone successions in Sequence CG1 are orientated north-south in central Ness County and reach a maximum thickness of 58 feet (17.5 meters). Net sandstone distribution shows extensive branching and convergence of sand bodies.

Thick north-south trending sand accumulations are also present to the east (T16S-R22W and T17S-R22W). On the northeastern edge of the study area, sand is less well developed and thin accumulations trend east-west. In Sequence CG1, thickest sandstone development is generally associated with paleotopographic lows (Figure 4.5). By overlaying Sequence CG1 net sand distribution with interpreted paleovalley lineaments, a strong correlation is observed between sand development and interpreted paleovalley orientation (Figure 4.8). Sand in Sequence CG1 is interpreted as paleovalley fill successions. Fluvial process carried sand across the unconformity surface from the nearby Central Kansas uplift. Accommodation, created during continued regression across the shelf because the steep-walled karst valleys had higher gradient than the shelf or during initial transgression, was filled with potential reservoir sand bodies. Eventually, karst valleys were completely filled with sediment and only a smoothed over residual topography remained.

Sequence CG2

Sequence Cherokee Group 2 (CG2) is present over the entire study area between Sequence CG1 and CG3. Sequence Boundary 2 (SB2), is marked by paleosol development on top of the carbonate wackestone-packstone facies of Sequence CG1. Commonly the surface exhibits brecciation, destruction of bedding, caliche development, reddening from oxidation, and clay infiltration from above. The sequence boundary is regionally extensive and can be traced downdip across most of the study area (Figures 4.3-4.6). A marine flooding surface is associated with SB2. Overlying SB2, a thin carbonate wackestone-packstone (interpreted as an open marine environment) is present throughout the western half of the county (observed in core from Wegele A1) (Figures 4.3-4.6). The thin limestone is overlain by grey shale (interpreted as an offshore environment). Westward the facies shows increasing gamma-ray response and is interpreted to transition into a black shale facies (> 200 API units), but no core data is available for verification. The maximum flooding surface (MFS2) is interpreted below the grey shale facies and marks the transition into the highstand systems tract. Up-dip to the northeast, SB2 is overlain by conglomeratic sandstone (interpreted as high-energy stream deposits) and cross-laminated sandstone (interpreted as shoreface environment) deposited as accommodation was created during flooding onto the exposure surface. A thin limestone is present above the sandstone facies (observed in core from the Pfaff #3 and Thompson A2 wells) (Figure 4.6). MFS2 is present below the limestone facies in the northeastern portion of the study and represents the deepest water deposits on the edge of the Central Kansas uplift. Water depths did not reach sufficient depths to deposit offshore shale in the northeastern region of the study area. MFS2 is correlated down-dip, and a transition from carbonate deposition to grey shale and eventually to black shale can be observed in well logs (Figure 4.3). The carbonate facies in Sequence CG2 pinch out on the eastern edge of the county, and Sequence CG1, CG2, and CG3 can no longer be differentiated with the current correlation system.

Spatial Distribution of Sandstone Facies in Sequence CG2

Sand accumulation in Sequence CG2 is limited to the northeastern four townships of the study area (Figure 4.9). Primary sand development occurs as a linear trend orientated north-northwest to south-southeast with up to 12 feet (4.0 meters) of sand accumulation. A few thin, isolated sand deposits are present up to 8.0 miles (12.8 kilometers) west of the primary sand accumulation. The conglomeratic sandstone facies (interpreted as high-energy coastal stream deposits) and cross-laminated sandstone facies (interpreted as nearshore deposits) are present in Sequence CG2. Sand accumulation is generally associated with the linear band that trends parallel to the interpreted paleoshoreline based on the restored Mississippian surface. It is common for sand facies in mixed siliciclastic and carbonate systems to trend parallel to shoreline (Miall, 2000). Most isolated sand deposits in Sequence CG2 occur on or near interpreted paleotopographic highs on the restored Mississippian surface (Figure 4.10). Deposition of Sequence CG1 probably smoothed most of the Mississippian surface topography, but a subdued residual topography is interpreted to remain during deposition of Sequence CG2. Minor elevation changes on the shelf are sufficient to increase energy and spark shoal development. Isolated sand bodies lying to the west are interpreted as sand shoal deposits that formed over subdued paleotopographic highs on the shelf. Unfortunately, no core has been taken from any of these isolated sand bodies and sedimentological evidence to prove their origin is unavailable. Overall, sand development in Sequence CG2 is concentrated along the interpreted paleoshoreline in northeastern Ness County.

Sequence CG3

Sequence Cherokee Group 3 (CG3) is correlated over the entire study area and contains the uppermost Cherokee Group rocks. Sequence Boundary 3 (SB3), developed on top of the carbonate units in Sequence CG2, is the base of Sequence CG3, and can be correlated as a regionally extensive surface. However, correlation of the surface down stratigraphic dip is difficult, because of the lack of core data and the decreasing response in well logs. In the eastern half of the county, SB3 is characterized by paleosol development in the underlying carbonate units during exposure, but westward paleosol development disappears and is interpreted to represent the possible downdip limit of exposure (Figures 4.3, 4.4). In the northeast portion of the study area, the basal deposits of sequence CG3 are cross-laminated sandstone (interpreted as nearshore environment) and variegated silty mudstone (interpreted as paleosol). These facies record deposition during transgression on the SB3 exposure surface. Grey shale and high gamma-ray black shale overlies the Sequence CG3 shoreface deposits in eastern Ness County and directly overlies SB3 in the rest of the study area, marking the maximum flooding surface (MFS 3) and transition into the highstand systems tract. The highstand systems tract of Sequence CG3 starts at the regionally continuous black shale at the top of the Cherokee Group (the Excello Shale of eastern Kansas) and includes the carbonate rocks of the Fort Scott Limestone.

This sequence is not a complete sequence, because the bounding upper sequence boundary is above the top of the Cherokee Group in the Fort Scott

Limestone (Marmaton Group). An inferred sequence boundary (SB4) has been correlated, but is based strictly on well log data and is not tied to core data. No available core included the complete stratigraphic succession of the Fort Scott Limestone and Cherokee Group.

Spatial Distribution of Sandstone Facies in Sequence CG3

Sand accumulation in Sequence CG3 is only present in the eastern third of the study area. Primary sand development occurs in a linear trend orientated north-northwest to south-southeast in the same location as sand development in Sequence CG2 (Figure 4.11). Accumulations up to 15 feet (4.5 meters) thick are present. Isolated sand accumulations 1.0 to 11 feet (0.3 to 3.3 meters) thick are present up to 10 miles (16 kilometers) west of the primary sand accumulation. Typically, isolated sand bodies are circular to ellipsoid but a few are elongated. A broad, lobate, east-west orientated sand accumulation is present in Sequence CG3 in the southeastern region of the study area (T19S-R21W). The sand accumulation is up to 5.0 miles wide, 7.0 miles long, and 12 feet thick (8.0 kilometers wide, 11.2 kilometers long, and 4.0 meters thick). Several thin (<4.0 feet or 1.2 meters) isolated sand bodies are present along the fringe of the main accumulation. Sequence CG3 net sand in northeastern Ness County exhibits a similar trend to sand development Sequence CG2. Sand accumulations parallel the interpreted paleoshoreline and are the result of nearshore deposits. Similar to in Sequence CG2, most isolated sand deposits in Sequence CG3 occur on or near interpreted paleotopographic highs on the restored Mississippian surface. Sequence CG3 isolated sand bodies are interpreted as sand shoal deposits that formed over minor paleotopographic highs on the shelf (Figures 4.12, 4.13). The east-west orientation and lobate configuration of Sequence CG3 sand deposits (T19S-R21W) may indicate fluvial or stream deposition on the coastal plain (Figure 4.11). Better well control would further refine sandstone facies distribution and allow for a thorough interpretation of this accumulation.

Spatial distribution of Sandstone Facies in Undifferentiated Cherokee Group

In northeastern Ness County sequences could not be differentiated and sand was mapped together. Combined net sand for the Cherokee Group is up to 35 feet (10.5 meters) thick in this region. Sand associated with each individual sequence is unknown but overall, significant Cherokee Group sand accumulation is present (Figures 4.14, 4.15). Marine limestone facies in Sequences CG1 and CG2 pinch out toward the Central Kansas uplift on the edge of the study area. Marine limestone facies in Sequence CG1 terminates on the eastern edge of two townships (T16S-R21W and T17S-R21W), while Sequence CG2 limestone facies are absent in only a small region of T17S-R21W. A larger amplitude transgression during Sequence CG2, than during Sequence CG1, deposited marine limestone facies further eastward onto the Central Kansas uplift. Sequence boundaries, typically defined by interpreted subaerial exposure surface above the limestone facies, could not be distinguished in this area due to the absence of a recognizable marine facies log signature (Figure 4.6).

Cherokee Sandstone Facies Discussion and Hydrocarbon Potential

In the study area, all potential reservoir sandstone facies occur in lowstand and transgressive systems tracts of the Cherokee Group. The thickest deposits of

Cherokee Group sandstone facies occur in Sequence CG1 and are located in interpreted paleovalleys. These sandstone successions were deposited before or during regression on the Mississippian surface. Paleovalley sandstone deposits represent a primary oil reservoir in Ness County. Paleovalley sandstone successions onlap interpreted Mississippian valley walls and are overlain by low permeability shale facies, providing favorable conditions for hydrocarbon entrapment. Exploration should be focused along the thick, north-south trending sand development in the center of the study area (Figure 4.7).

On the eastern edge of the Ness County, potential reservoir sandstone deposits are present in all three sequences. Sand thickness in each sequence is significantly thinner than Sequence CG1 paleovalley successions in the center of the study area, but the development of multiple reservoir sands provide an excellent exploration target. Sand development in eastern Ness County is concentrated along the interpreted north-northwest to south-southeast trending paleoshoreline. Potential reservoir sandstone facies in this region have significant porosity (6.5-22%) and permeability ranges from 10 to 520 millidarcies (Howard, 1990). Overlying low permeability shale or marine limestone facies provide stratigraphic seals for sandstone bodies in each sequence. Exploration efforts for Cherokee reservoirs in eastern Ness County should focus along the interpreted north-northwest to south-southeast trending paleoshoreline and extend outside the county along the flank of the Central Kansas Uplift.

Source of Cherokee Group Sand

The source of Cherokee Group sand may have been the Reagan Sandstone that was exposed along the axis of the Central Kansas uplift and the Cambridge arch to the north in Nebraska. The Reagan Sandstone (the Lamotte Sandstone at outcrop in Missouri) is a basal Paleozoic sandstone. Compositionally, the Reagan Sandstone is very diverse, including quartzose sandstone, dolomitic sandstone, quartz-glauconite sandstone, arkose, and quartz-feldspathic sandstone (Zeller, 1968). Arkose, often referred to as granite wash, occurs in the lower portion of the formation adjacent to the Precambrian granitic rocks (often referred to as granite wash). Successions up to 175 feet (55 meters) thick are documented in western Kansas but the average thickness in the subsurface is approximately 40 feet (12 meters) (Zeller, 1968).

Significant portions of the Reagan Sandstone were eroded during exposure at the end of the Mississippian, and Precambrian basement is directly overlain by Pennsylvanian rocks at several locations along the Central Kansas uplift (Zeller, 1968; Merriam, 1963). Sandstone from the Reagan was eroded, sediment transported westward to the flank of the Central Kansas Uplift, and distributed along the eastern shelf of the Hugoton embayment. The majority of Cherokee Group sand is found in Sequence CG1 and the glauconite of the Reagan may be the source of the glauconite in the glauconitic sandstone facies.

In addition to the Reagan Sandstone, weathered fragments from the exposed Mississippian (or possibly Arbuckle strata) are also prevalent in sandstone facies of the Cherokee Group. Subangular to angular chert and limestone clasts were transported off the uplift. Their angularity and size indicate limited transport distance and deposition close to their source. The Arbuckle is also known to contain sand rich intervals and represents another possible sand source for sandstone bodies in the Cherokee Group (Zeller, 1968).

Depositional Model

Depositional models are intended as teaching tools, mental concepts, and temporary fixed points in nature (Miall, 1999). The purpose and function of a model is to aid in the distillation of observations for ease of comparison, and serves to further our understanding of natural system in a simple and basic manner (Walker, 2006). Models are intended to create order out of apparent chaos and attempt to understand genesis (Miall, 1999). In the subsurface, models provide a vehicle for reconstructing facies orientations and patterns when data is limited.

In Ness County, the deposition of the Cherokee Group occurred on the erosional karst-topography of the Mississippian unconformity. Two depositional models were constructed to display the lateral and vertical arrangement of the facies in the Cherokee Group (Figures 4.16, 4.17). The models show the inferred arrangement of facies in the Cherokee Group during deposition. Two depositional models were needed due to the dramatic influence of the Mississippian karst surface on Sequence CG1 deposition. Deposition of Sequences CG2 and CG3 is very similar, and a single model provides an adequate visual aid to interpret facies arrangement.

On the edge of the Central Kansas uplift, Sequence CG1 was deposited on the Mississippian karst surface (Figure 4.16). Large karst valleys are present throughout the study area and dolines (sinkholes) are commonly filled with the residual cherty breccias conglomerate facies. The glauconitic sandstone facies and conglomeratic sandstone facies were deposited in paleovalleys by fluvial processes. Variegated silty mudstone facies was deposited across much of the continental realm in Ness County. Most of the topography was filled by sediment prior to a marine transgression resulting in deposition of limestone facies of Sequence CG1 highstand systems tract.

Sequence CG2 and CG3 were deposited after the majority of the karst topography had been filled by Sequence CG1 (Figure 4.17). The remaining subdued topography mimics the underlying Mississippian surface. Sequence CG2 and CG3 were deposited on sequence boundaries developed on the underlying marine limestone facies. Dark-grey shale facies and black shale facies were deposited on the distal shelf environment around the time of the maximum transgression. Carbonate wackestone-packstone facies and carbonate packstone-grainstone facies were deposited on an open marine shelf. Cross-laminated sandstone facies were deposited in a shoreface environment. Isolated sand shoal deposits occurred on residual paleotopograhic highs on the shelf. Variegated silty mudstone facies was deposited across the continental environment. Channelized conglomeratic sandstone facies were deposited by coastal high-energy streams.

Mechanism for Sequence Development

Sequence development is a product of the relative fluctuation between the level of land and the sea. The most common mechanisms invoked for creating relative sea-level changes are tectonics, glaciations, and climate change. From the Early to Middle Pennsylvanian the Hugoton embayment was structurally active with relatively moderate tectonic subsidence and upward movement on the Central Kansas uplift, as evidenced by the thinning of Pennsylvanian strata across the crest (Merriam, 1963). Previous studies have established that the Pennsylvanian was a time of large-scale continental glaciation on Gondwana, resulting in glacio-eustacy (Heckel, 1986; Heckel, 1994). Estimates of glacial eustatic sea-level changes on the North American midcontinent are typically on the order of 80 to 100 meters but estimates as high of 160 meters have been proposed (Heckel, 1977; Klein, 1994).

The Cherokee Group sequences are interpreted as result of frequent changes in relative sea level caused by glacio-eustatic changes. Mild subsidence due to continued downward movement in the Anadarko basin and Hugoton embayment probably played a role in creating accommodation.

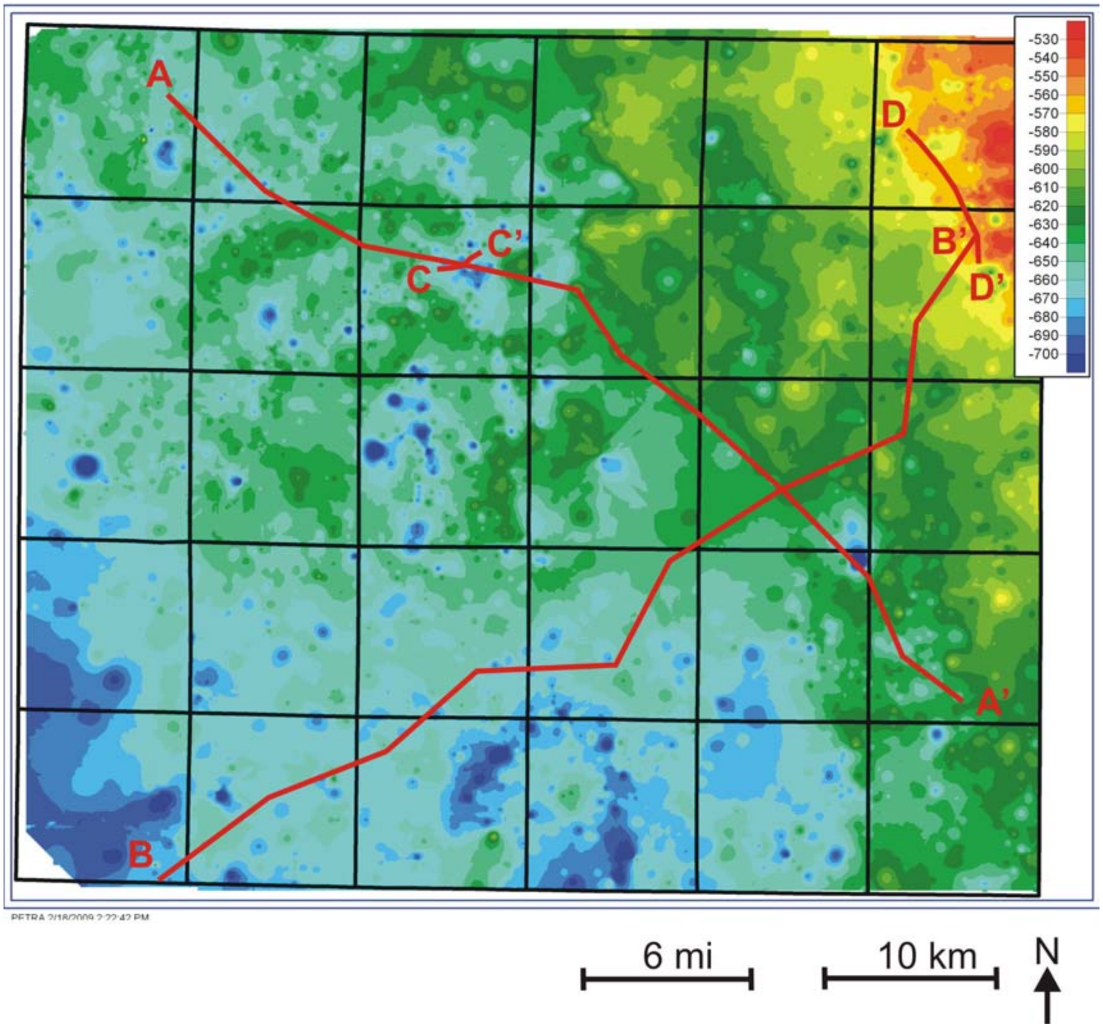

Figure 4.1. Base map of Ness County showing restored Mississippian paleotopography and highlighting location of cross-sections. Depths in feet subsea.

Figure 4.2. Core photograph of interpreted sequence boundary (SB2), indicated by the red arrow. Note caliche development in variegated silty mudstone facies (interpreted as a paleosol) sharply overlain by conglomeratic sandstone facies. Example is from 4128.6 feet to 4155.0 feet in Thompson A2 (S3-T17S-R21W, Ness County, Kansas).

Figure 4.3. Available in supplemental files

Figure 4.4. Available in supplemental files

Figure 4.5. Available in supplemental files

Figure 4.6. Available in supplemental files

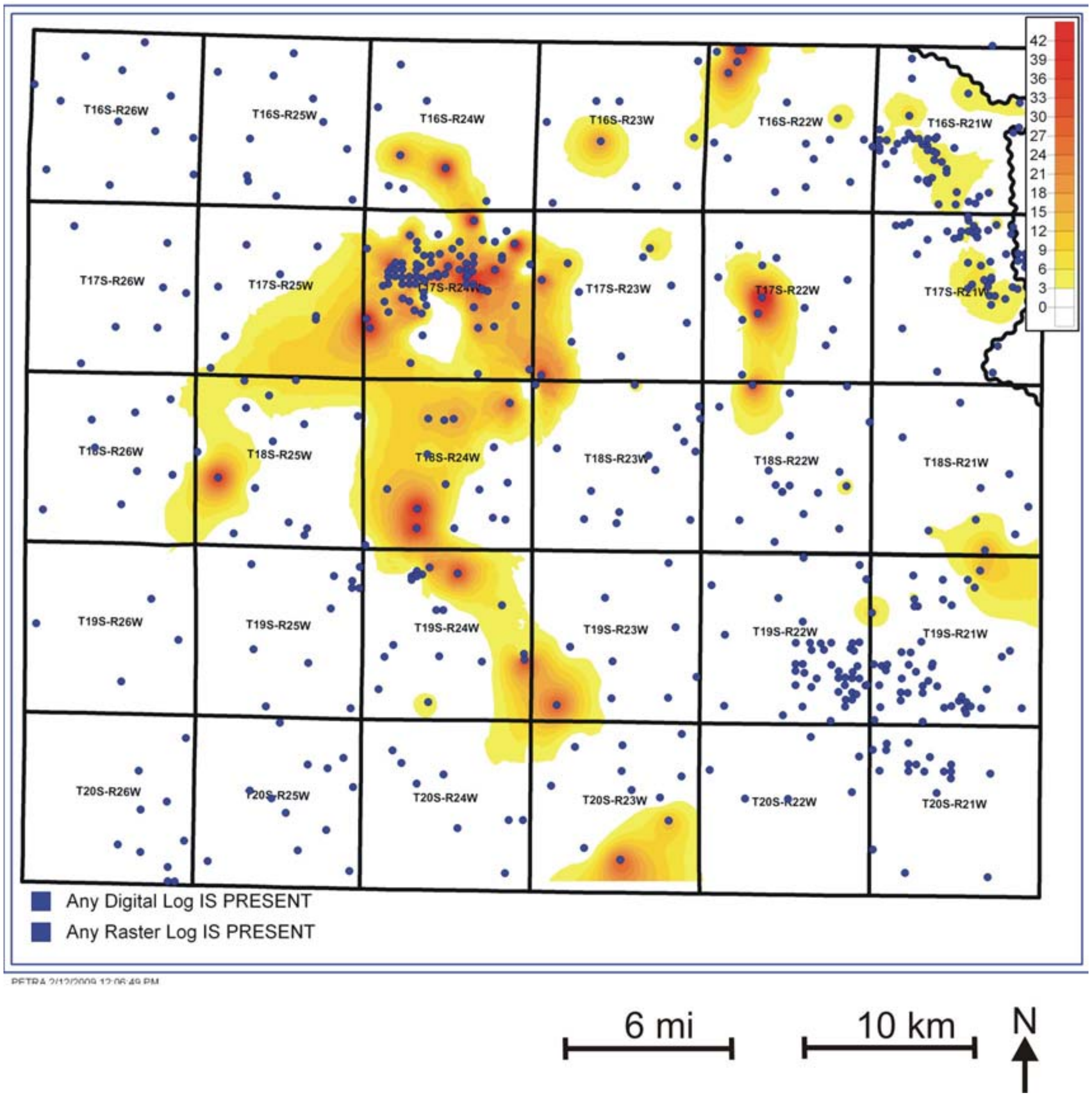

Figure 4.7. Net sand distribution in Sequence CG1 with data point locations displayed by blue circles. Sand thickness varies from 0-58 feet (0-17.6 meters) and is distributed in branching elongated bodies. Thickest sand accumulations are present in the west-central portion of the county. Sand thickness in feet.

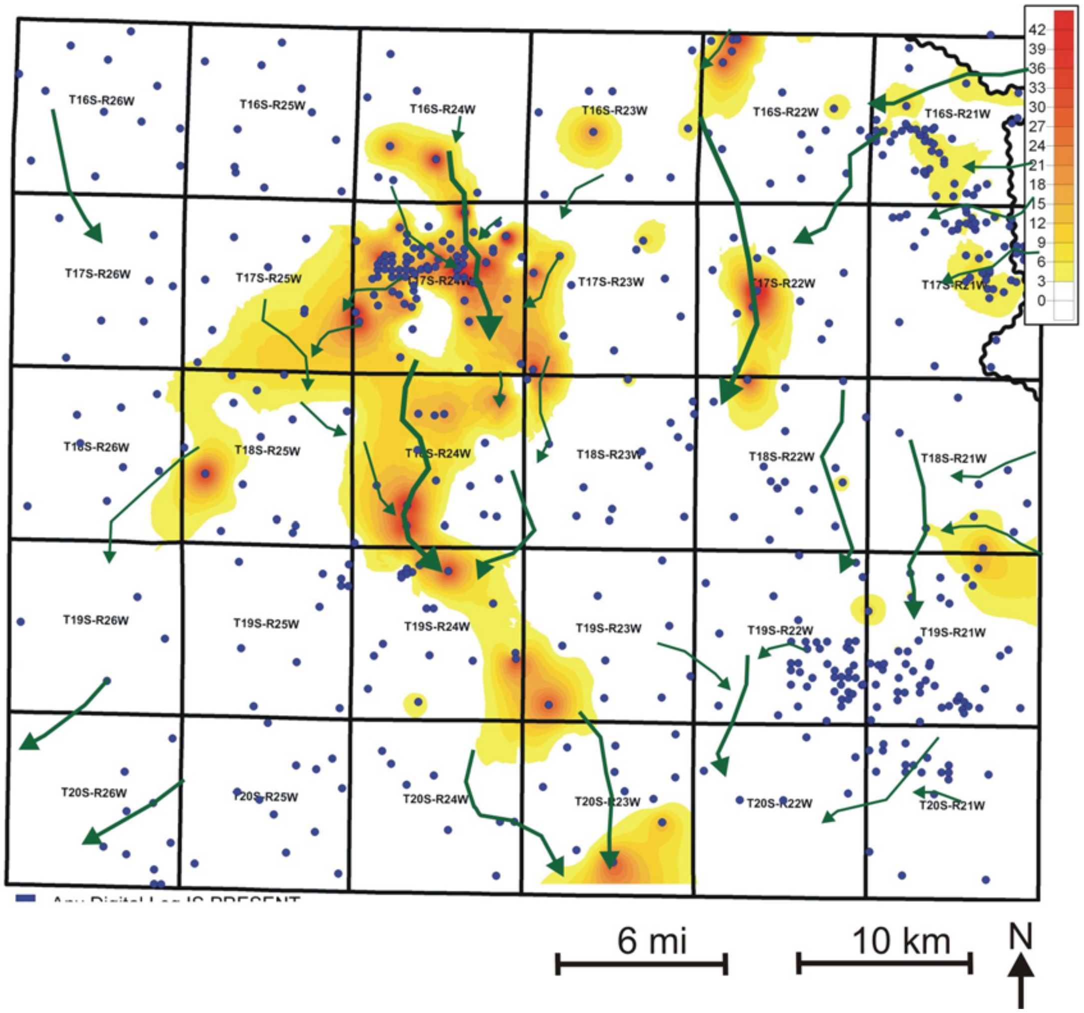

Figure 4.8. Net sand distribution in Sequence CG1 with data point locations displayed by blue circles overlain by interpreted paleovalley orientations based on Mississippian paleotopography (see Figure 3.12). Sand thickness varies from 0-58 feet (0-17.6 meters) and is distributed in branching elongated bodies. Sand thickness in feet.

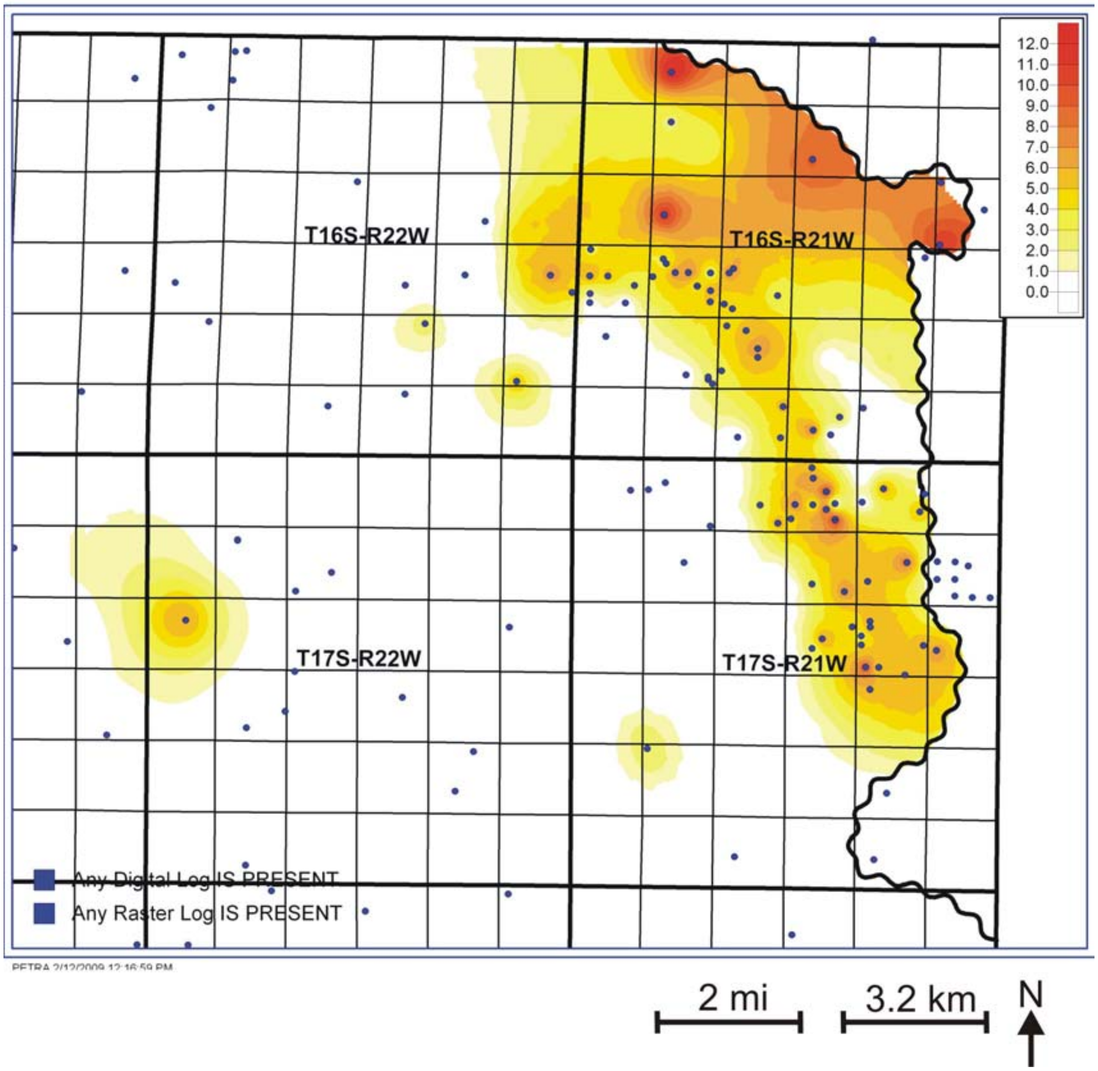

Figure 4.9. Net sand distribution in Sequence CG2 with data point locations displayed by blue circles. Sand is only present in the northeast four townships of Ness County. Sand thickness varies from 0-12 feet (0-4 meters) and the thickest sand bodies are oriented north-northwest to south-southeast. Isolated pods of sand occur further west of the main sand body. Unconformity line marks the landward edge of marine facies in CG1 and represents where Sequence CG1 and Sequence CG2 can no longer be reliably distinguished from each other. Sand thickness in feet.

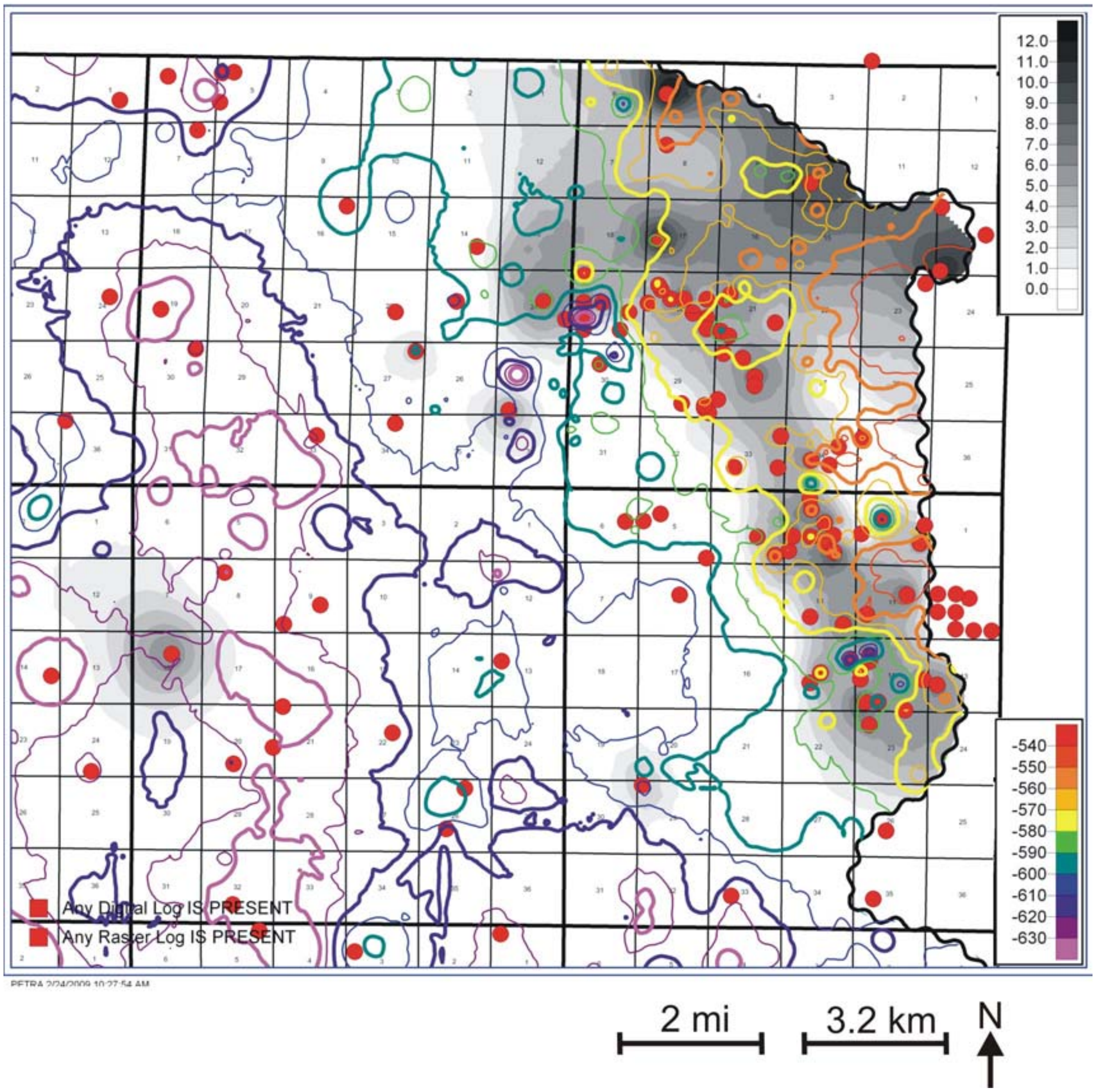

Figure 4.10. Net sand distribution in Sequence CG2 and restored Mississippian structure. Most isolated sand bodies are associated with highs in the Mississippian surface paleotopography, or are located on saddles between paleotopographic highs. Sand thickness in feet. Mississippian surface in feet subsea.

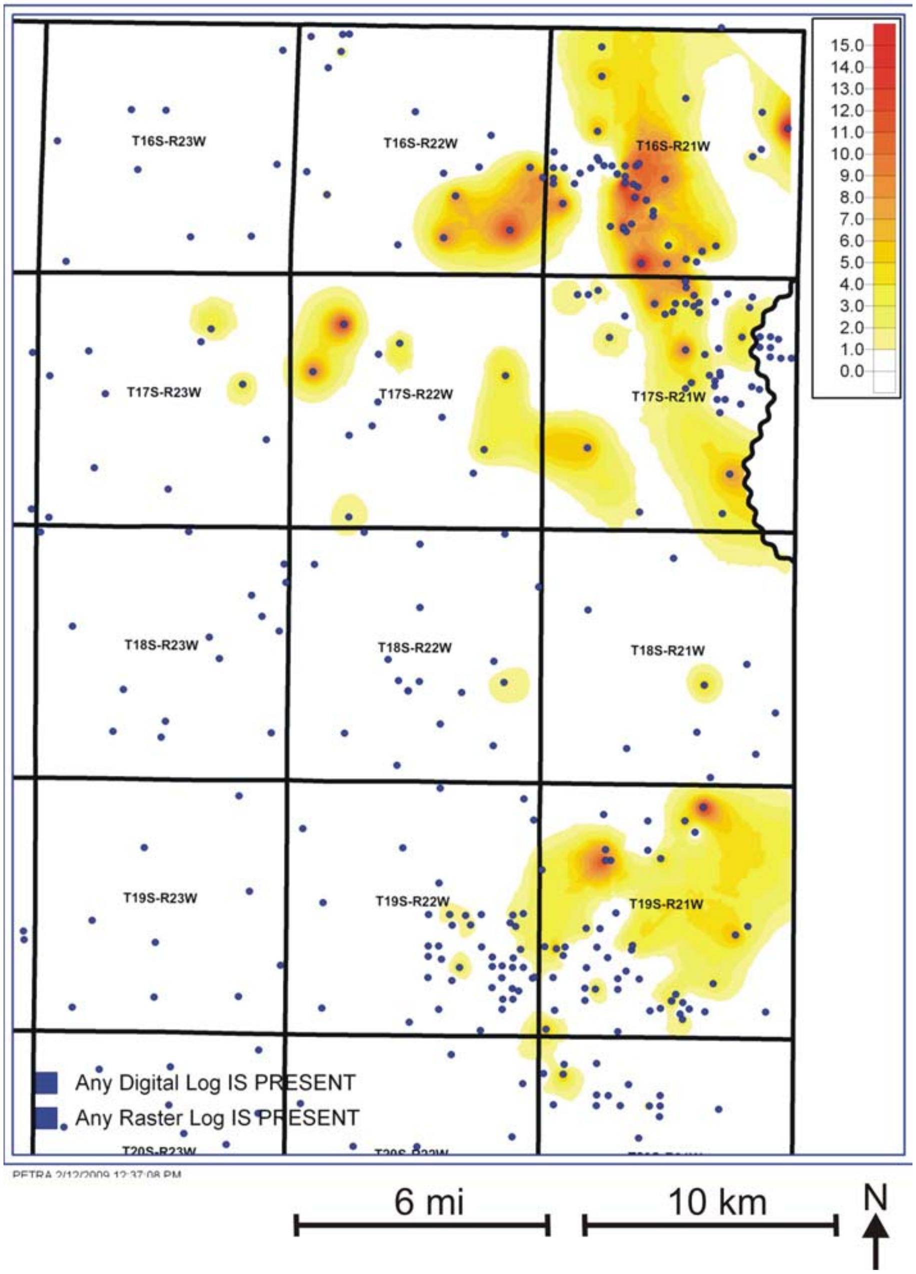

Figure 4.11. Net sand distribution in Sequence CG3 with data point locations displayed by blue circles. Sand is only present along the eastern edge of Ness County. Sand thickness varies from 0-15 feet (0-4.6 meters) and the thickest sand bodies are oriented north-northwest to south-southeast. Isolated pods of sand occur further west of the main sand body. Unconformity line marks the landward edge of marine facies in Sequence CG2 and represents where Sequences CG1, CG2, and CG3 can no longer be reliably distinguished from each other. Sand thickness in feet.

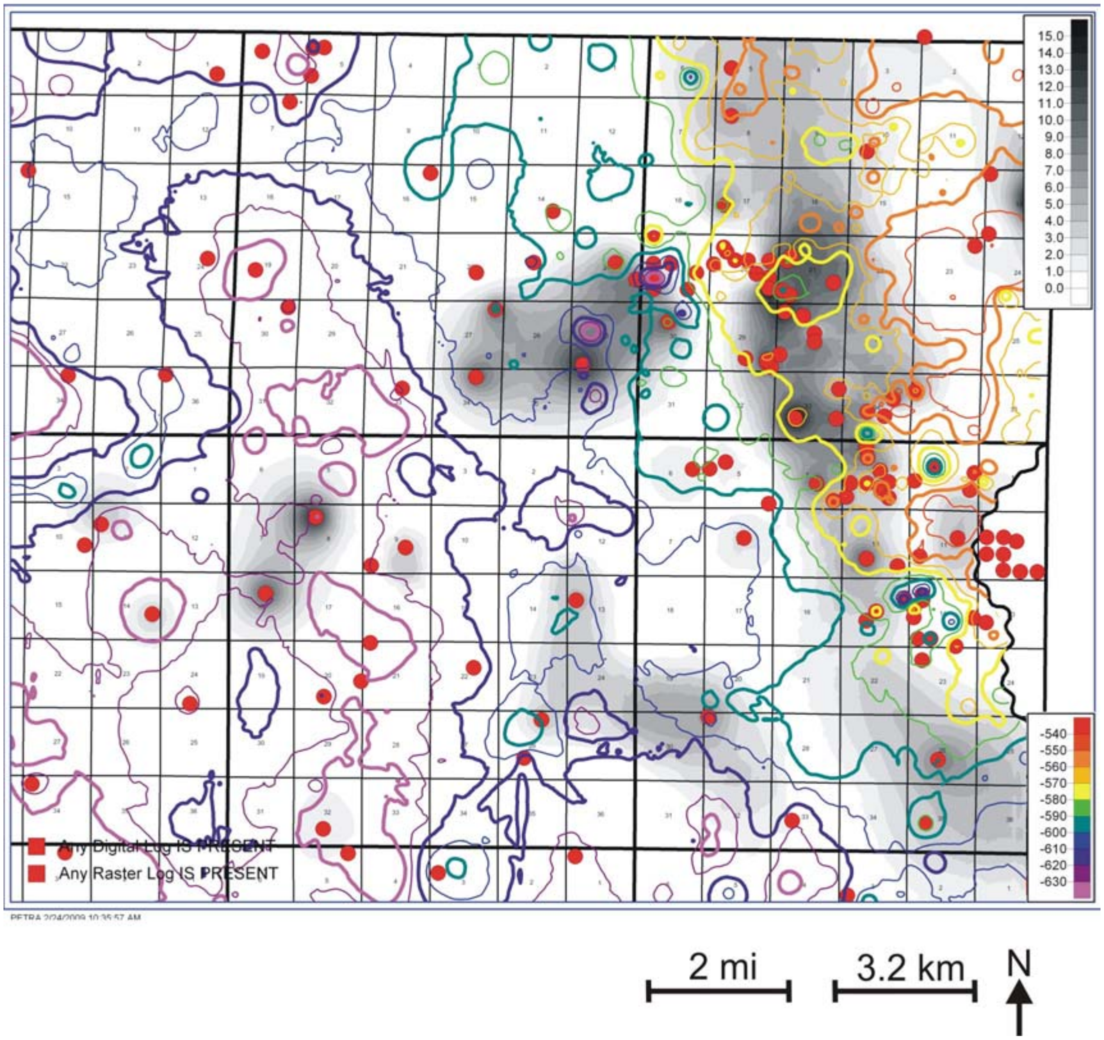

Figure 4.12. Net sand distribution in Sequence CG3 and restored Mississippian structure (northeastern portion of Ness County). Most isolated sand bodies are associated with highs in the Mississippian surface paleotopography, or are located on saddles between paleotopographic highs. Sand thickness in feet. Mississippian surface in feet subsea.

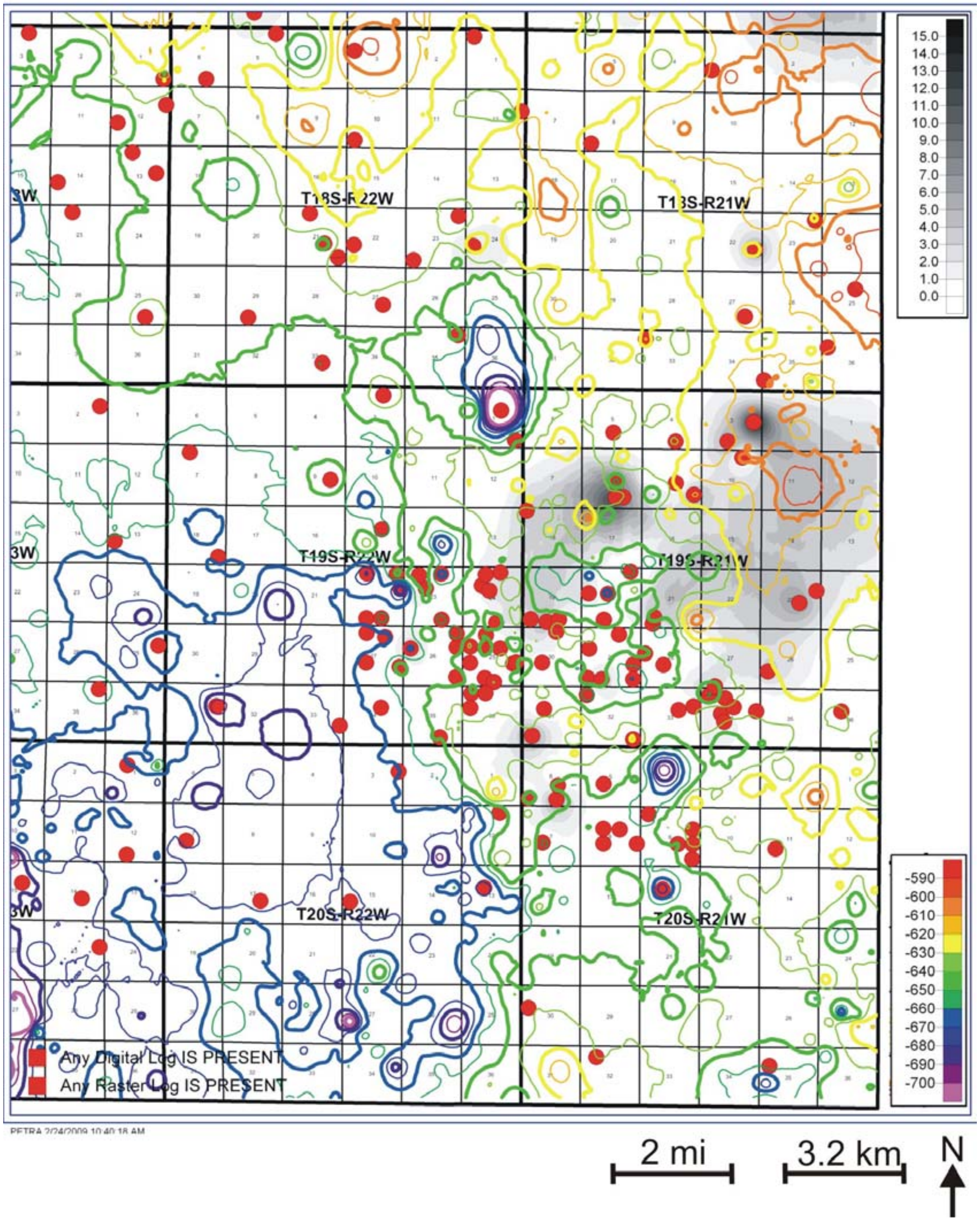

Figure 4.13. Net sand distribution in Sequence CG3 and restored Mississippian structure (southeastern portion of Ness County). Most isolated sand bodies are associated with highs in the Mississippian surface paleotopography, or are located on saddles between paleotopographic highs. Sand thickness in feet. Mississippian surface in feet subsea.

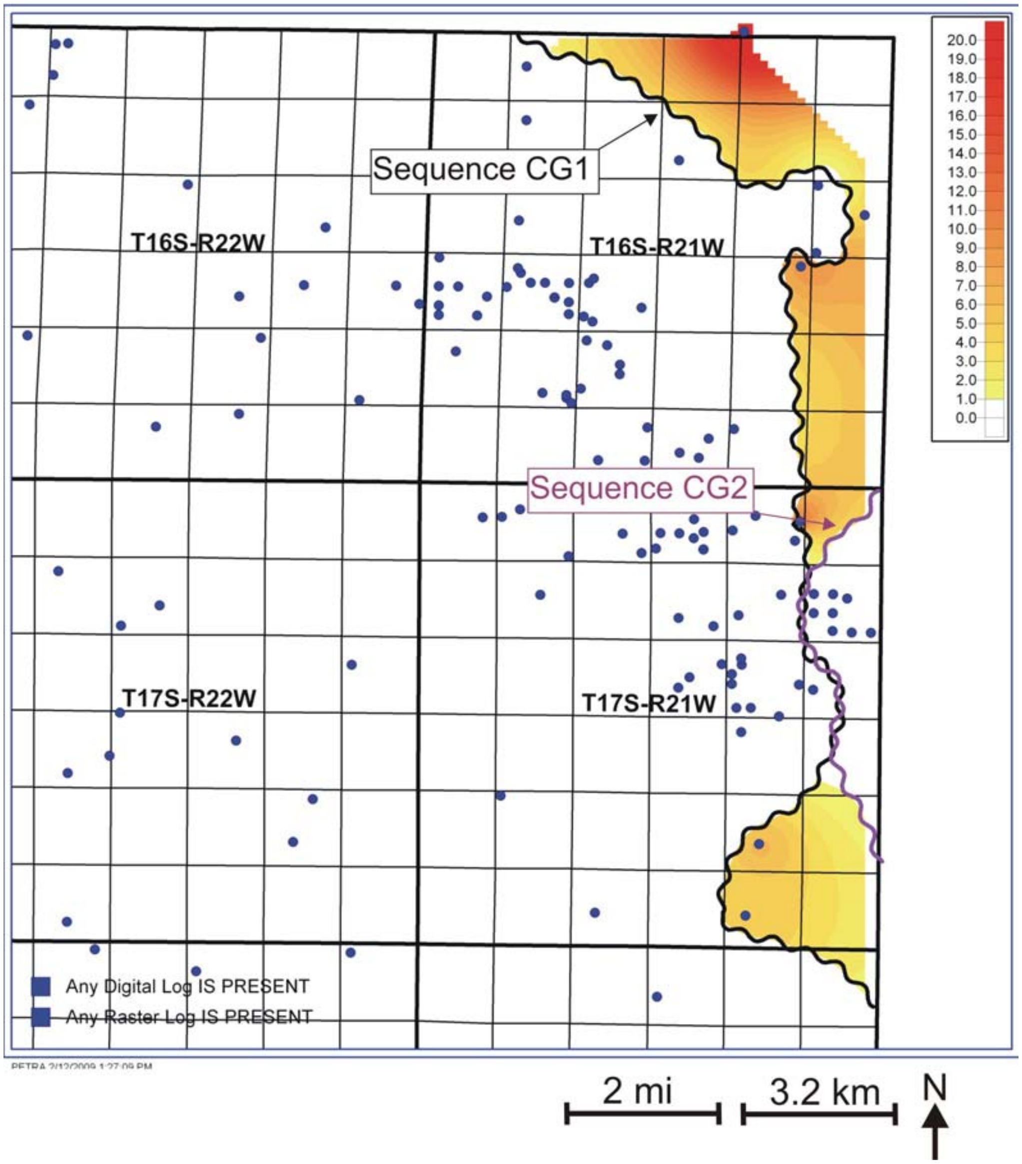

Figure 4.14. Net sand distribution as mapped in undifferentiated Sequences CG1 and CG2 with data point locations displayed by blue circles. Sand thickness varies from 0-25 feet (0-7.5 meters). Unconformity lines marks the landward edge of marine facies in CG1 and CG2. Sand thickness in feet.

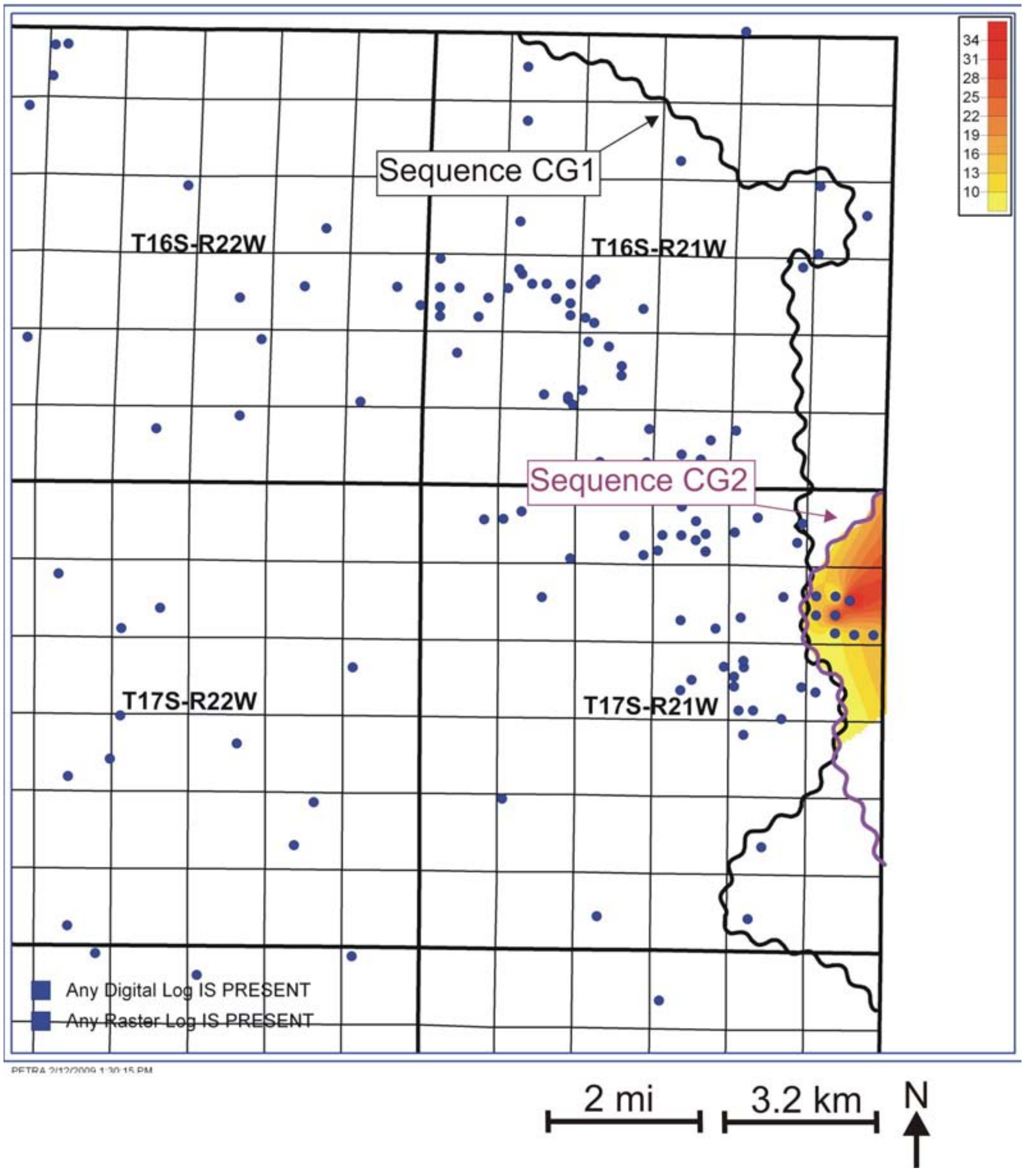

Figure 4.15. Net sand distribution as mapped in undifferentiated Sequences CG1, CG2, and CG3 with data point locations displayed by blue circles. Sand thickness varies from 10-34 feet (3.0-10.3 meters). Unconformity lines marks the landward edge of marine facies in Sequences CG1 and CG2. Sand thickness in feet.

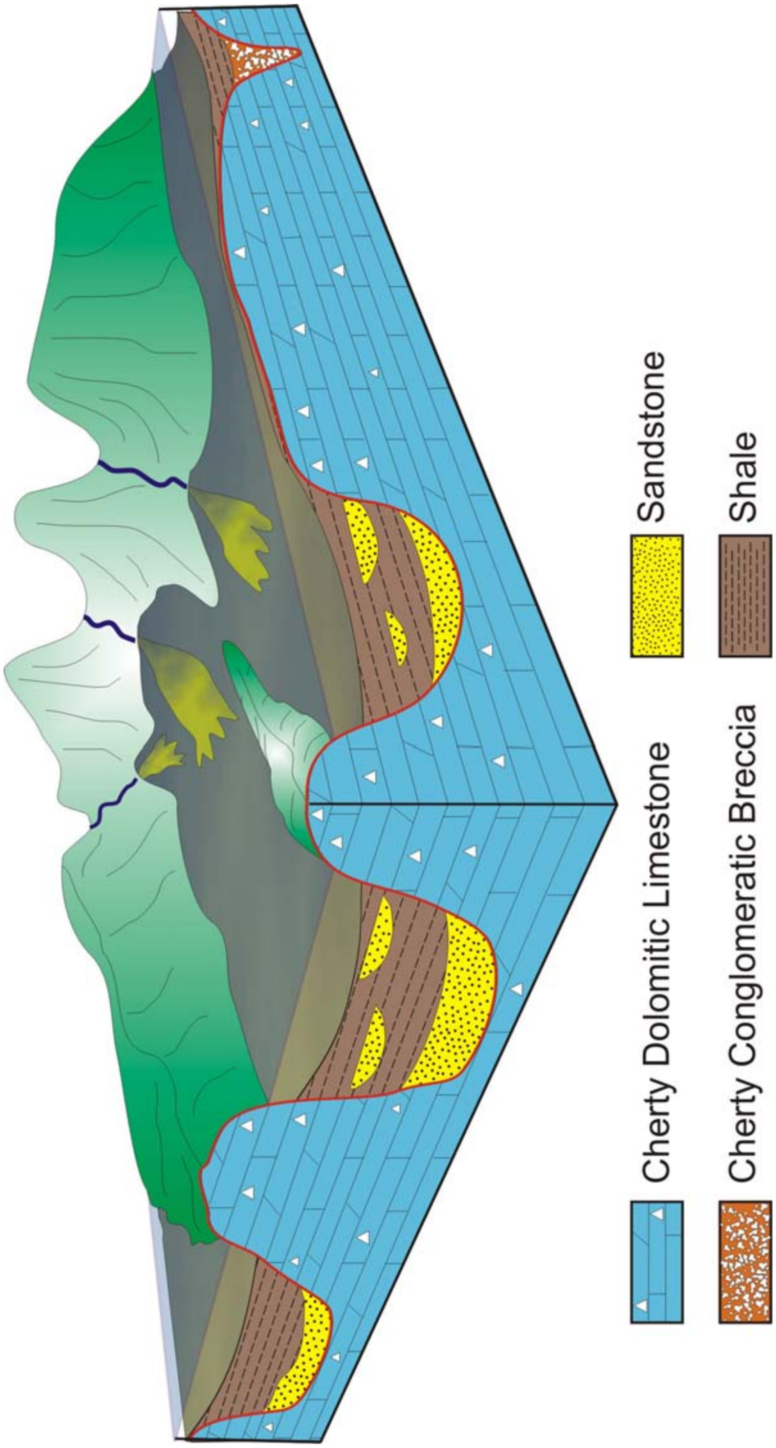

Figure 4.16. Depositional model of the Sequence CG1 on the high-relief Mississippian karst surface. Sand development in Sequence CG1 occurs in paleovalleys on the Mississippian surface. Eventually sediments deposited in Sequence CG1 filled most of the karst topography. Mississippian unconformity is shown as red line.

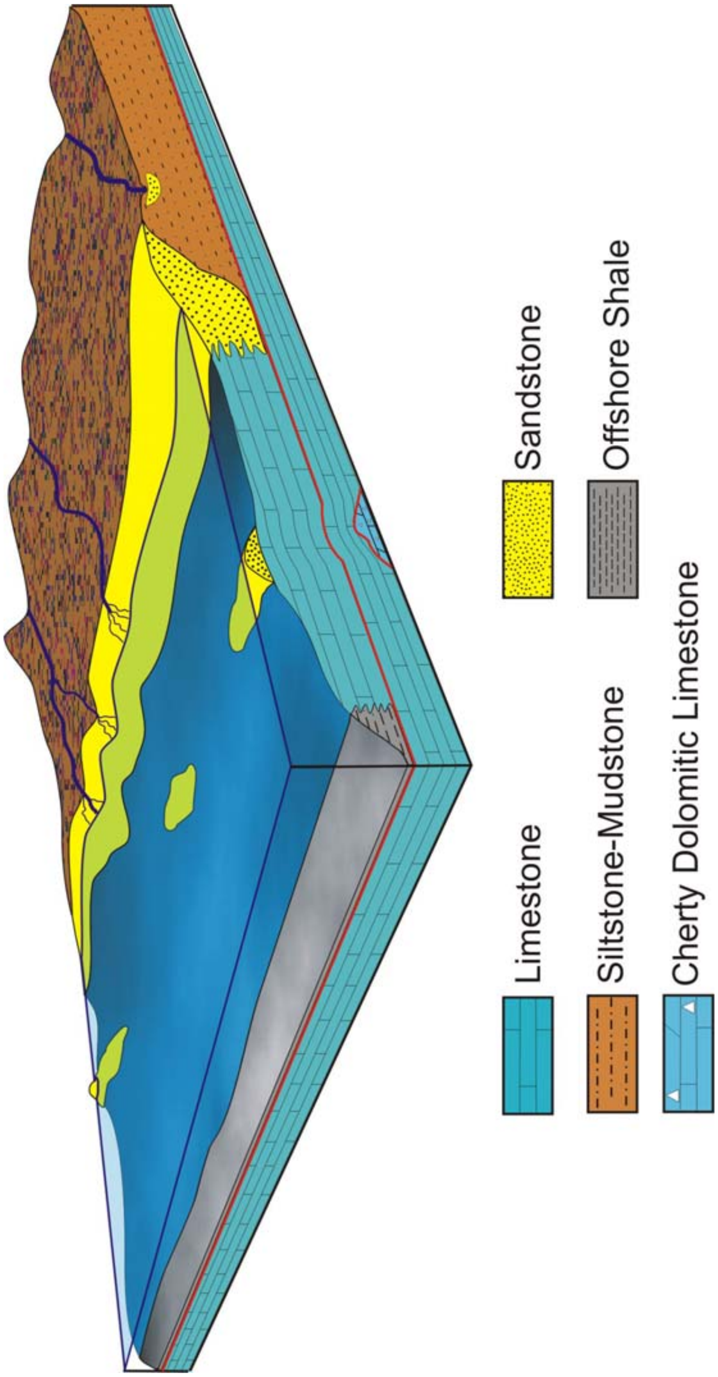

Figure 4.17. Depositional model for Sequence CG2 and CG3 showing depositional environments across a broad shallow shelf on the edge of the Hugoton embayment. Deposition occurred on sequence boundaries developed on underlying marine carbonate facies (shown by red line). Sand development occurred along the paleoshoreline and on isolated shoals that formed on residual paleotopographic highs.

CHAPTER 5: CONCLUSIONS

Oil-bearing sandstone reservoirs in the Cherokee Group of Ness County have been hydrocarbon exploration targets since the 1950's. The integration of core, well log, and potential-fields data offers insight on the deposition of the Cherokee Group on the Mississippian unconformity, and the influence of karst topography on deposition during the initial transgression. The following conclusions can be made regarding structural and stratigraphic controls on deposition, sequence stratigraphy, depositional models, and distribution of potential reservoir facies in the Cherokee Group of Ness County

1. The Desmoinesian Cherokee Group in Ness County Kansas consists of carbonate and siliciclastic sediments deposited on the Mississippian unconformity karst surface on the western flank of the Central Kansas uplift.
2. The Cherokee Group can be divided into eleven lithofacies. The black shale facies and the grey shale facies were deposited in low-energy, offshore, open marine environments. The black shale facies was deposited by sediment fallout under anoxic to dysoxic conditions, whereas the grey shale facies was deposited under non-anoxic conditions. The grey sandy siltstone facies was deposited under open marine conditions in the offshore transition zone. The carbonate wackestone to packstone facies and carbonate packstone to grainstone facies were deposited in an open marine environment of a shallow shelf. The carbonate wackestone to packstone facies formed in low energy subtidal environments, whereas the carbonate packstone to grainstone formed

in higher energy channels or as open marine storm deposits. The lingulid dark-grey shale facies was deposited in a restricted lagoon environment. The glauconitic cross-laminated sandstone facies was deposited in fluvial environment. The conglomeratic sandstone facies formed in an environment of high-energy unidirectional currents in streams along a coastal plain. The cross-laminated sandstone facies was deposited in a shoreface environment. The variegated silty mudstone facies formed from pedogenic alteration of existing deposits or from episodic deposition and pedogenesis. The cherty conglomeratic breccia facies is the product of several processes including in situ brecciation, fluvial and colluvial deposition, marine reworking, and pedogenesis.

3. Two major orientations of gravity and magnetic lineaments are present in Ness County. North-northeast and west-northwest orientated features are observed in both gravity and magnetic data sets, due to variations in potential fields caused by changes in basement rock susceptibility or density. Anomalies are interpreted to represent basement block displacement along high angle faults or variation in basement composition. The movement along basement faults is reflected in overlying strata, as faulting, fracturing, and jointing in similar orientations on the Mississippian surface.
4. Karst features resolved on the Mississippian surface include groups of closed depressions interpreted as dolines, isolated highs interpreted as karst cones,

steep-sided flat-floored valleys interpreted as groundwater-sapped karst valley networks.

5. A large paleovalley network exists on the Mississippian unconformity surface and two primary drainage patterns were identified. In eastern Ness County, drainage was from east-northeast to west-southwest, off the Central Kansas uplift. Throughout the rest of the study area Mississippian drainage orientation is north to south toward the Hugoton embayment.
6. Groundwater-sapping processes are interpreted to be the primary mechanism of valley formation on the Mississippian karst surface. Valleys exhibit classic U-shaped theatre-headed configuration documented in groundwater-sapped terrains. Favorable conditions for the development of groundwater-sapped features are present. In portions of the study area valley orientations exhibit a strong structural control and parallel magnetic and gravity lineaments. Basement faults extending through Paleozoic rocks are expressed as faults and conjugate joints on the Mississippian surface. These heterogeneities are interpreted to have concentrated groundwater flow and surface runoff causing groundwater sapping processes and surface dissolution to accelerate.
7. Deformation associated with the Aldrich anticline occurred after deposition of the Stone Corral Anhydrite (Permian). Reactivation along northeast-southwest–trending basement faults during the Laramide Orogeny (Late Cretaceous to Eocene) resulted in uplift and anticline formation.

8. Within the Cherokee Group three depositional sequences were interpreted from the six cores. Two complete sequences contain the lower and middle deposits in the Cherokee Group, and an incomplete sequence contains the upper deposits of the Cherokee Group but continues into the Fort Scott Limestone (Marmaton Group), and the upper sequence boundary was not identified in core.
9. Sequences onlap the Central Kansas uplift to the east of the study area. Individual sequence boundaries cannot be interpreted on the very eastern edge of the study area due to the lack of marine facies and amalgamation of non-marine facies. Each sequence flooded progressively further onto the uplift.
10. In Ness County, reservoir sandstone facies for the Cherokee Group occur only in lowstand and transgressive systems tracts.
11. Preexisting topography played an important role in sand development. The thickest sand accumulations in the Cherokee Group were deposited in paleotopographic lows interpreted as paleovalleys during regression across the Mississippian surface (Sequence CG1). These sand successions occur as channelized sandstone deposits. Sand development in Sequence CG2 and CG3 occurred in northeastern Ness County along the north-northwest to south-southeast trending paleoshoreline. Isolated sand bodies are present basinward of the interpreted paleoshoreline and are related to apparent paleotopographic highs on the Mississippian surface. Although most of the paleotopography was filled during deposition of Sequence CG1, a subdued

subtle topography remained, causing shoal developed on isolated topographic highs across the shallow shelf.

12. Two depositional models of the Cherokee Group were created to summarize the spatial distribution of depositional environments interpreted from core. One model illustrates the effect of the Mississippian karst surface on facies distribution in Sequence CG1. The second model shows how sand was deposited along the paleoshoreline after initial sedimentation smoothed the karst paleotopography.

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APPENDIX 1: CORE DESCRIPTIONS

Core Locations:

1) Pfaff #3
National Coop Refinery
NE NW SE, Sec. 20-T16S-R21W
15-135-23135

2) Thompson A#2
National Coop Refinery
S2 NE SW SE, Sec. 3-T17S-R21W
15-135-23062

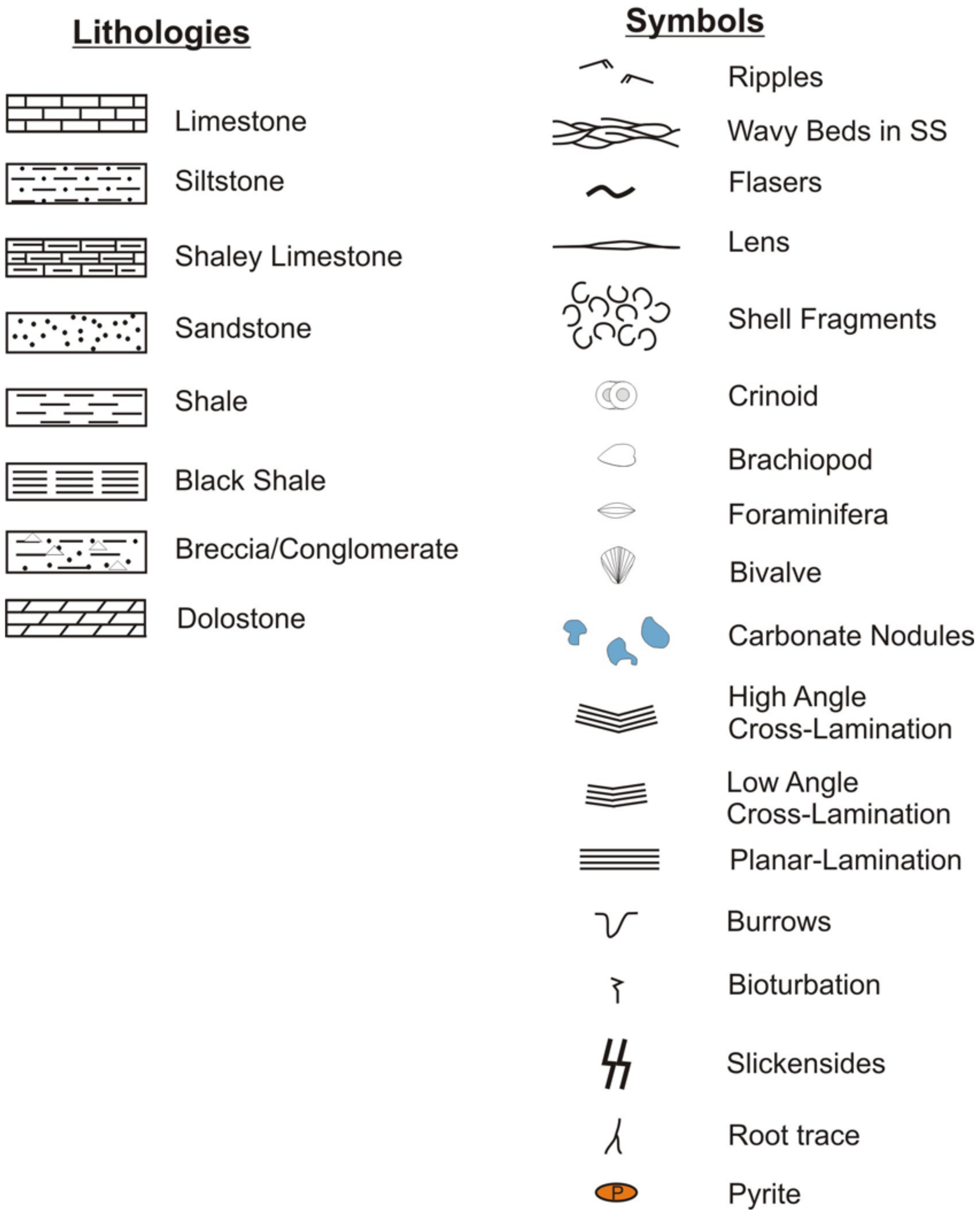
3) Neyer B#1
Beardmore Oil
C NW NE, Sec. 3-T17S R24W
15-135-20706

4) Tilley #2
Walters Drilling Company
SW SE SW, Sec. 8-T17S R24W
15-135-19026

5) Wegele A#1
Anadarko Production Company
C SE, Sec. 21-T18S-R22W
15-135-21843

6) Moore #1
Kern-Landes Exploration
C NW NW, Sec. 34-T19S-R21W
15-135-00656

Legend


Lithologies
Limestone
Siltstone
Shaley Limestone
Sandstone
Shale
Black Shale
Breccia/Conglomerate
Dolostone
Symbols
Ripples
Wavy Beds in SS
Flasers
Lens
Shell Fragments
Crinoid
Brachiopod
Foraminifera
Bivalve
Carbonate Nodules
High Angle Cross-Lamination
Low Angle Cross-Lamination
Planar-Lamination
Burrows
Bioturbation
Slickensides
Root trace
P
Pyrite

WELL NAME Pfaff 3

INTERVAL 4205-4215 ft

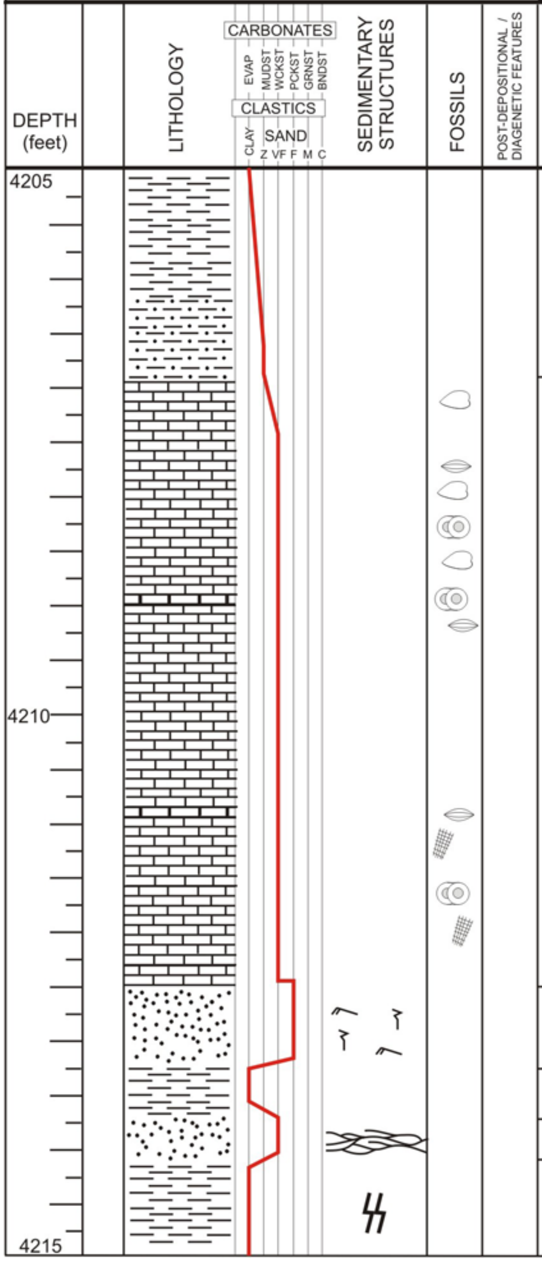
PAGE 1 OF 5

LOCATION Sec 20-T16S R 21W, NE-NW-SE, Ness Co., KS

COMPANY Kansas Geological Survey

DESCRIBED BY B.J. Ramaker

DATE June 2007



DESCRIPTION - NOTES
- Thickness
- Color
- Lithology (Grain Size, Sorting, Roundness)
- Composition
- Sedimentary Structures
- Contacts
- Body / Trace Fossils
- Post-Depositional and Diagenetic

SURFACES, FACIES, INTERVAL, and COMMENTS

Mudstone (silty) (fine silt)
- maroon to brick red/brown
- subrounded quartz grains (up to vc))
- loose rubble

Siltstone
- drk green, calcareous
- subangular-subrounded qtz grains (<10mm)
- friable, limestone nodules at base

Limestone (nodular)
- lt grey micrite nodules
  - nodules are 50-90%
- brown and green shale matrix
- large broken fossileferous blocks
  - fractured
  - filled with green clay and limestone clasts
  - laminted crust on block
- stylolites
- brachiopods, fusulinids, crinoids

Evidence of exposure and dissolution in limestone. Red/brown infilling clay and nodular texture

- very little shale matrix

- Limestone (wackestone)
- grey shale matrix
- very few micrite nodules
- fusulinids, crinoid, bryozoans

Sandstone (Qtz arenite) (fL)
- dk. green, tan, subrounded grains
- clay matrix
- ripple laminated, bioturbated

Mudstone
- green and maroon mottled, fissile

Sandstone (Qtz arenite) (vfL), green, interlaminated w/ thin maroon shale (wavy)

Mudstone
- mottled green and maroon
- thin sandy units (friable)
- slickensides
- water reactive clays present

WELL NAME Pfaff 3
INTERVAL 4215-4225 ft
PAGE 2 OF 5
LOCATION Sec 20-T16S R 21W, NE-NW-SE, Ness Co., KS
COMPANY Kansas Geological Survey
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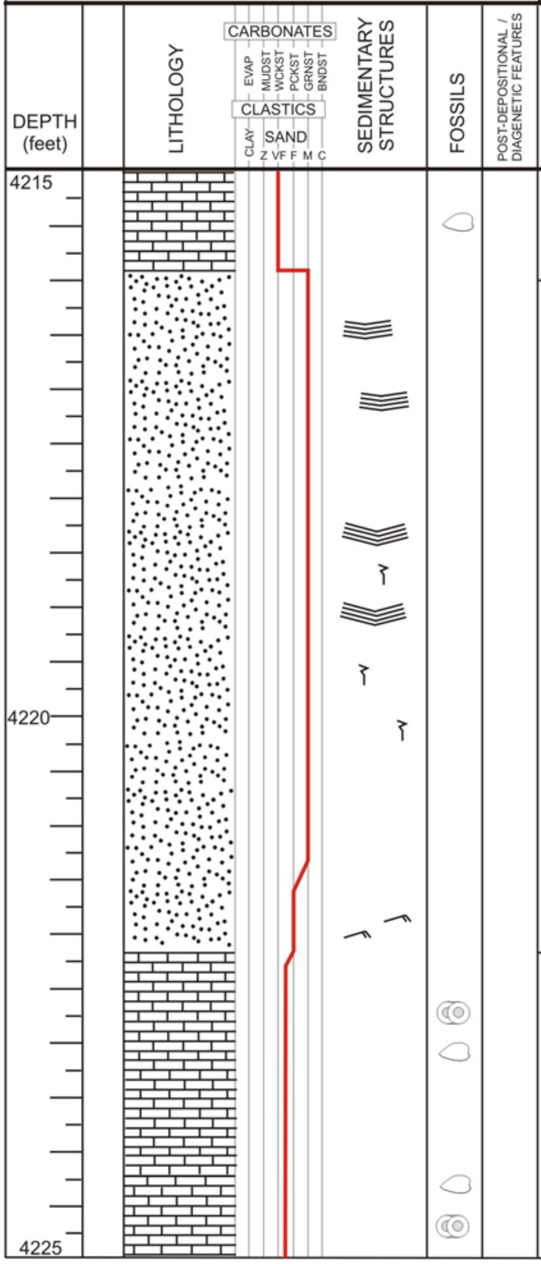
DATE June 2007



DESCRIPTION - NOTES
- Thickness
- Color
- Lithology (Grain Size, Sorting, Roundness)
- Composition
- Sedimentary Structures
- Contacts
- Body / Trace Fossils
- Post-Depositional and Diagenetic

SURFACES, FACIES, INTERVAL, and COMMENTS

Limestone (wackestone)
- wackestone at top, styolites
- brachipods
- nodular at base (micrite nodules)
- grey-green shale matrix-vfU-mL sand at base)

Irregular contact

Sandstone (qtz arenite) (mL)
- tan-cream
- subangular-subrounded
- low angle cross-laminations
- moderate sorting
- lacks abundant clast seen below

Sandstone (qtz arenite) (fU-mL) conglomeratic
- tan-cream
- subangular-subrounded clasts
  - chert, quartz, limestone and mud clasts
  - up to 8mm in size
  - clast to matrix ratio 10-95%
- faint high angle cross-laminations
- bioturbation
- very poorly sorted
- fining upward sequence defined by scour surfaces (.75-1.0 ft)

Sandstone (qtz arenite) (fL)
- tan-cream
- calcareous cement
- isolated limestone nodules
- ripple laminated, green sandstone at base

Limestone (wackestone-packstone)
- nodular texture
- micrite nodules
  - corroded edges
- maroon and green shale matrix
  - infilling matrix and thin bands
- crinoids, sponges, brachiopods, algae

Evidence of exposure: nodular texture, brecciated corroded clasts, maroon infilling clay

- sandy/silty with 2 cm chert clast

WELL NAME Pfaff 3
INTERVAL 4225-4235 ft
PAGE 3 OF 5
LOCATION Sec 20-T16S R 21W, NE-NW-SE, Ness Co., KS
COMPANY Kansas Geological Survey
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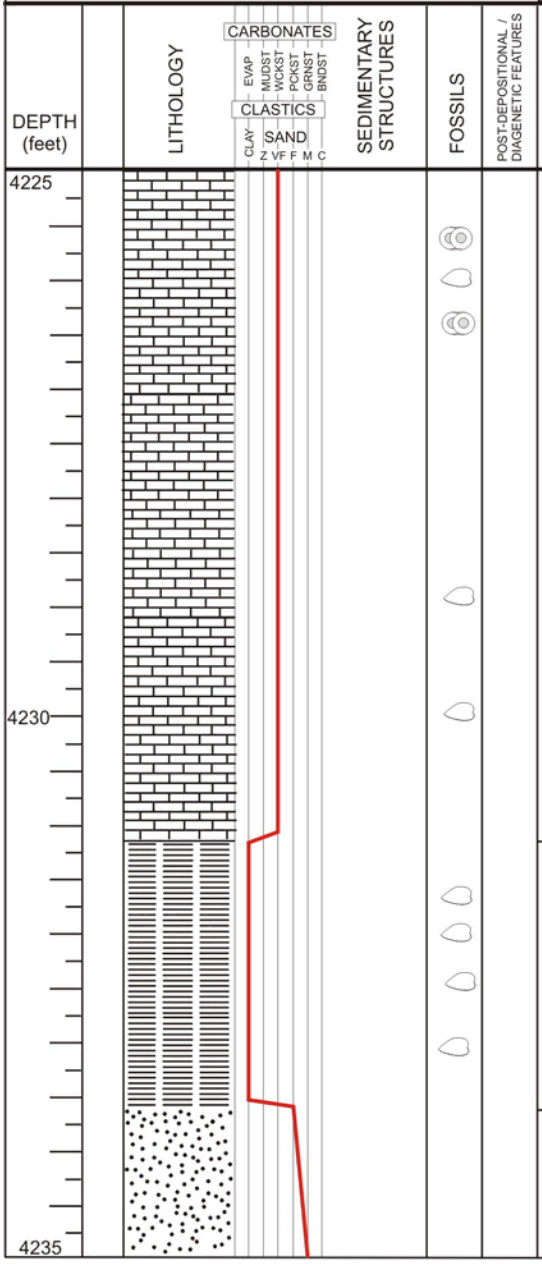


DESCRIPTION - NOTES
- Thickness
- Color
- Lithology (Grain Size, Sorting, Roundness)
- Composition
- Sedimentary Structures
- Contacts
- Body / Trace Fossils
- Post-Depositional and Diagenetic

SURFACES, FACIES, INTERVAL, and COMMENTS

Limestone (wackestone-packstone)
- nodular texture
- micrite nodules
- enclosed in thin green shale beds lt grey

- more compacted
- fossilerous: crinoids, brachs and sponges
- styolites

- nodular with green shale
  - some nodules fracture and filled with shale

- black-purple shale matrix

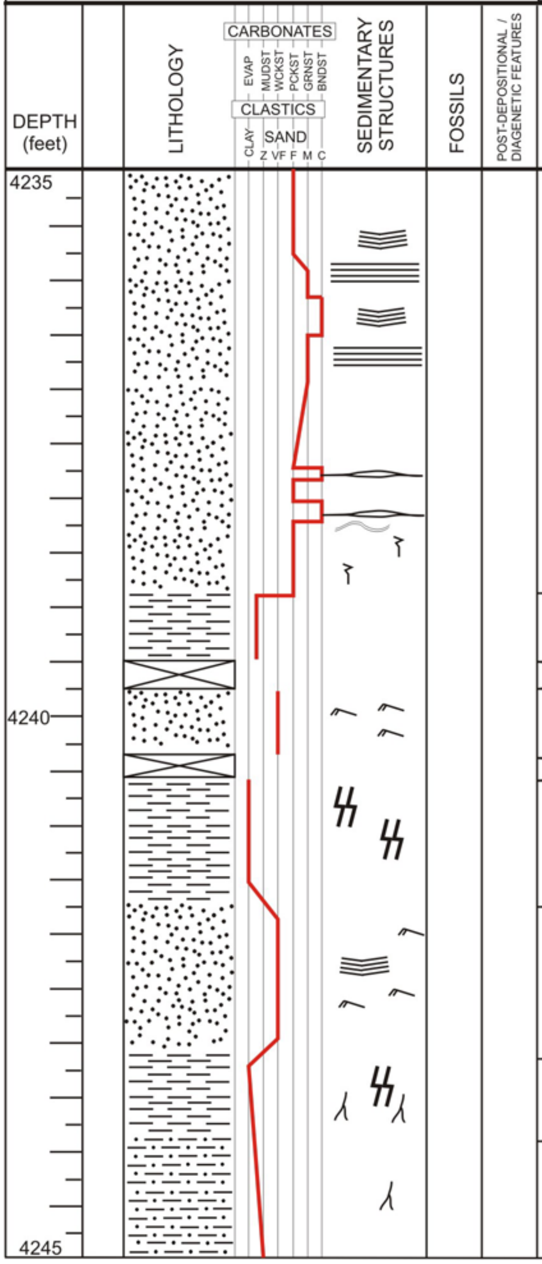
Limestone (nodular texture)
- micrite nodules
- enclosed in green shale (5-25%)
- mottling in matrix
- brachiopods present

Shale
- black, dk. grey-green
- very thin laminations
- fissile
- platy
- black shale is rich in lingula fossils' few in green-grey shale

Sandstone (Qtz arenite) (fU-mL)
- brown, cream, and white
- subangular to subrounded grains
- interbedded thin black shales toward top
- clay matrix toward top
- fines upward

- oil staining at base

WELL NAME Pfaff 3		INTERVAL 4235-4245 ft	PAGE 4 OF 5
LOCATION Sec 20-T16S R 21W, NE-NW-SE, Ness Co., KS			
COMPANY Kansas Geological Survey		DESCRIBED BY B.J. Ramaker	DATE June 2007



DESCRIPTION - NOTES
- Thickness
- Color
- Lithology (Grain Size, Sorting, Roundness)
- Composition
- Sedimentary Structures
- Contacts
- Body / Trace Fossils
- Post-Depositional and Diagenetic

SURFACES, FACIES, INTERVAL, and COMMENTS

Sandstone (Qtz arenite) (congomeratic)
- brown, tan, cream mottled
- poorly sorted (fU-vcU)
  - matrix is fL-fU
  - grain size varies in bands
  - subrounded to subangular grains
- normally graded beds (.5 to .75 ft)
- chert clast
  - sub rounded up to 20mm
- faint horizontal laminae and low angle cross-laminae
- well cemented
- some clay and bioturbation at base

- lens of cL qtz arenite
- thin green shale seams (flasers beds)

- bioturbation
- mottled tan and brown

Shale (silty)
- grey, green and maroon mottled
- friable

Sandstone (Qtz arenite) (vfU)
- alternating green and lt grey laminae
- subangular-subrounded grains
- ripple laminated, ~15% clay content

Mudstone
- maroon-green mottled
- slickensides
- friable, bagged

Sandstone (fU)
- minor calcareous material
- lt brown to grey
- limestone nodules
  - 3-20mm
- low angle cross laminations
- grades into shale above
- thin green shale at base

Shale
- maroon and green mottled
- angular chert clast up to 2cm
- slickensides, some silt present

Siltstone
- blue-grey, some yellow mottling
- friable

Siltstone
- maroon to green, pale yellow around fracs
- rhizoliths

WELL NAME Pfaff 3

INTERVAL 4245-4255 ft

PAGE 5 OF 5

LOCATION Sec 20-T16S R 21W, NE-NW-SE, Ness Co., KS

COMPANY Kansas Geological Survey

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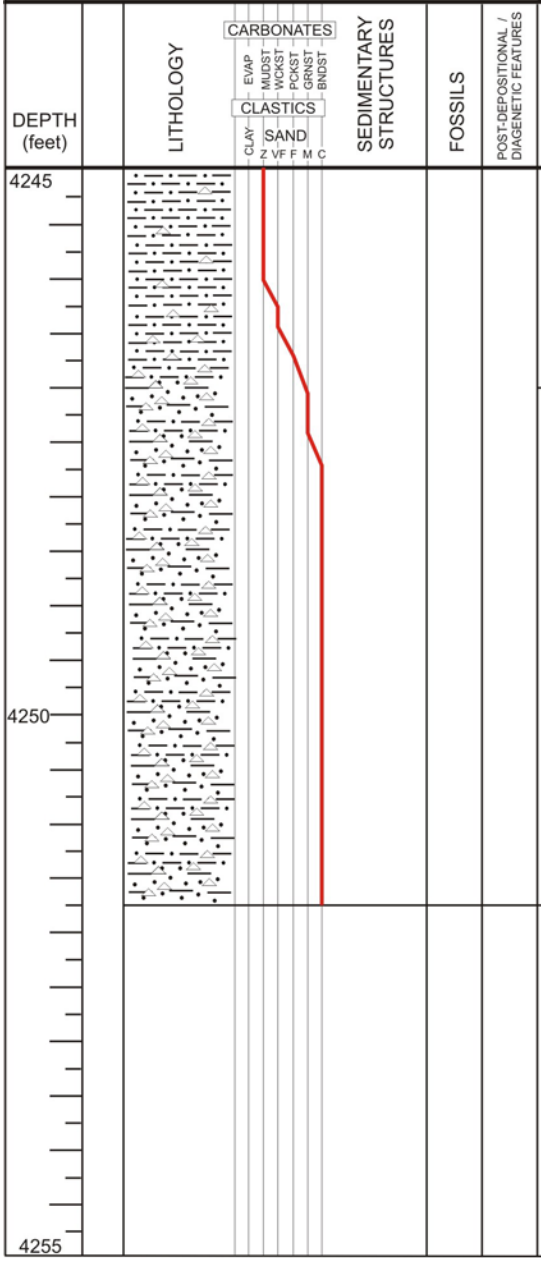


DESCRIPTION - NOTES
- Thickness
- Color
- Lithology (Grain Size, Sorting, Roundness)
- Composition
- Sedimentary Structures
- Contacts
- Body / Trace Fossils
- Post-Depositional and Diagenetic

SURFACES, FACIES, INTERVAL, and COMMENTS

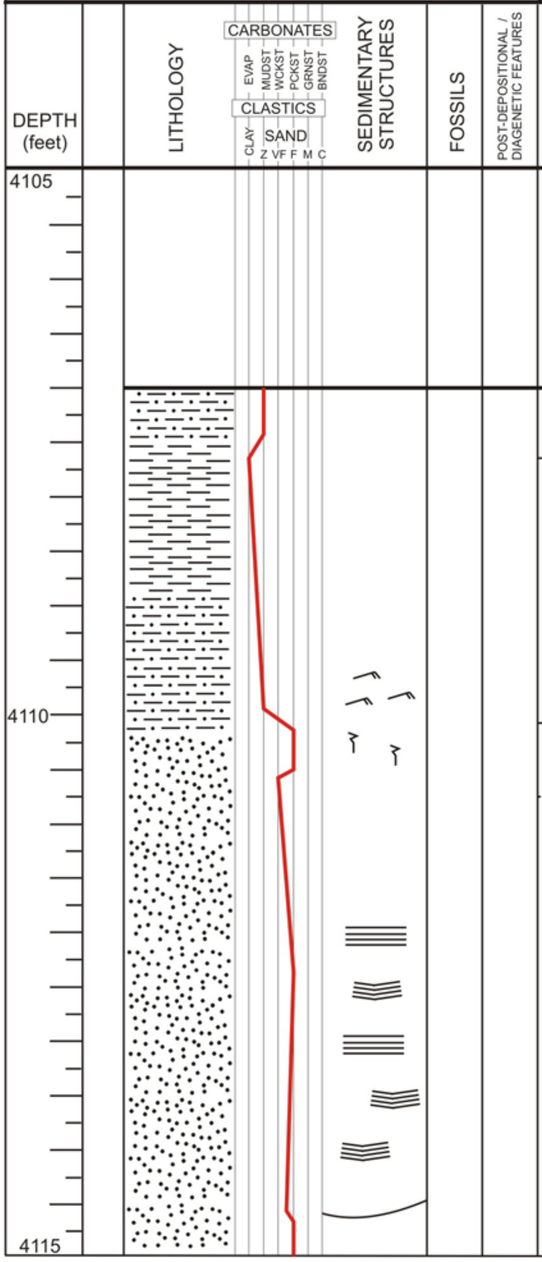
Siltstone (shaly)
- maroon-green, yellow along fractures
- very colorful
- rhizoliths
- Chert clast
  - content/size increase downward
  - 3mm-15cm
  - corroded edges

Pennsylvanian basal conglomerate

Conglomeratic Breccia
- silty, sandy shale matrix
  - maroon, tan, cream, and yellow
- chert clast
  - 5-70mm
  - cream-tan with reddish overprint
  - angular-subangular
  - fractured and corroded
    - infilled with clay
- poorly sorted

Bottom of core

WELL NAME Thompson A 2	INTERVAL 4105-4115 ft	PAGE 1 OF 5
LOCATION Sec 3-T17S R 21W, S2-NE-SW-SE, Ness Co., KS		
COMPANY Kansas Geological Survey	DESCRIBED BY B.J. Ramaker	DATE June 2007



DESCRIPTION - NOTES - Thickness - Color - Lithology (Grain Size, Sorting, Roundness) - Composition - Sedimentary Structures - Contacts - Body / Trace Fossils - Post-Depositional and Diagenetic	SURFACES, FACIES, INTERVAL, and COMMENTS
Siltstone - gray-green, limestone nodules, - ripple laminations, bivalves, green shale laminations	Top of core
Shale - interlaminated red and green - mottled - fissile	
Shaly siltstone - interlaminated red- maroon and green - ripple laminations - bioturbated - mottled	Loose rubble
Sandstone (qtz arenite) (fL) - maroon and green - mottled white and red, bioturbated	
Sandstone (Qtz arnite) (vfU- fU) - interlaminated lt grey-green and dk grey - lt grey 10mm thick - dk grey 2-3 mm thick - subrounded, moderately sorted - clay in matrix - low angle and planar cross laminations - dewatering structures - clay clasts - minor coal content -Scour surface	

WELL NAME Thompson A 2

INTERVAL 4115-4125 ft

PAGE 2 OF 5

LOCATION Sec 3-T17S R 21W, S2-NE-SW-SE, Ness Co., KS

COMPANY Kansas Geological Survey

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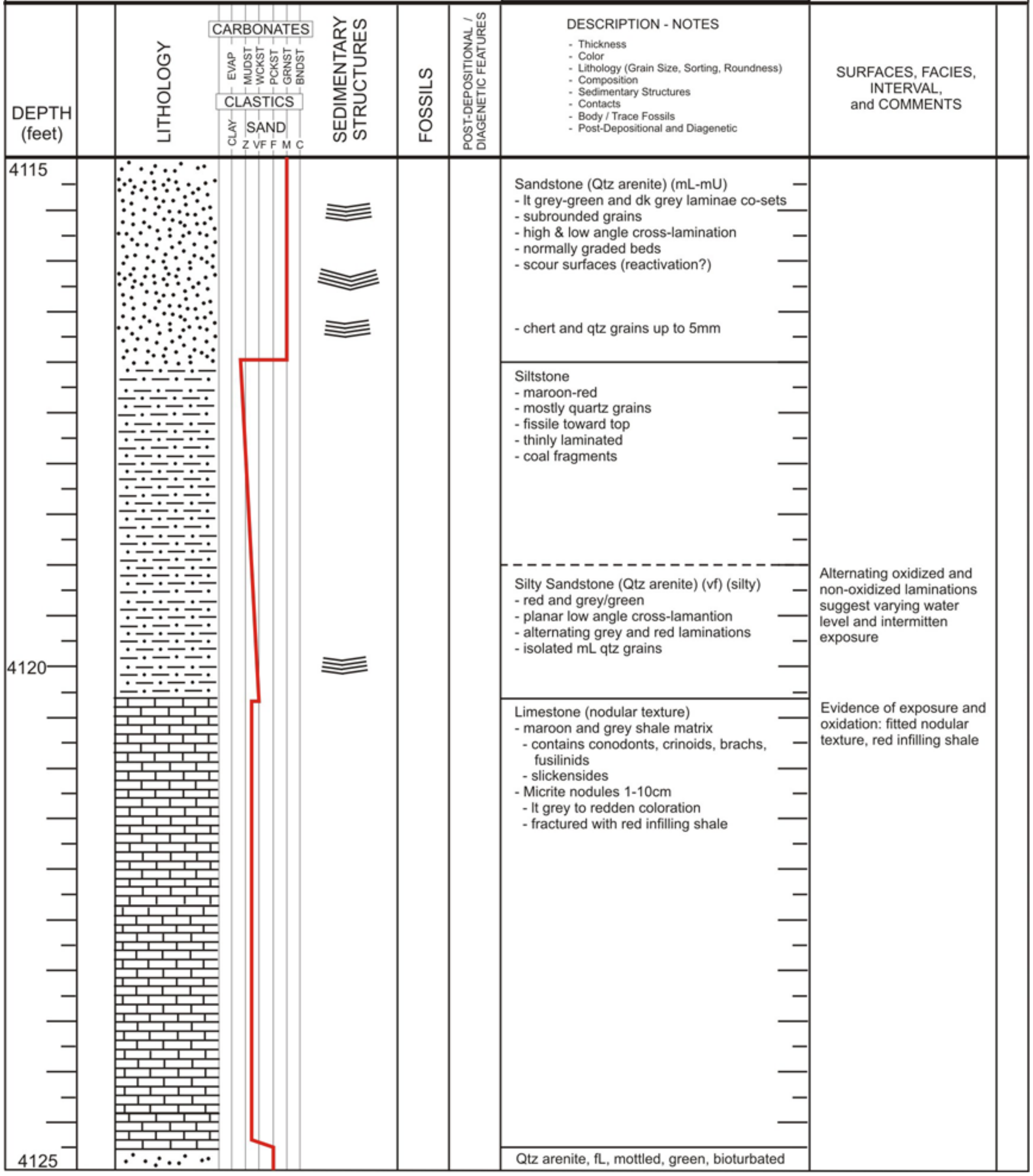
DATE June 2007



DESCRIPTION - NOTES

- Thickness
- Color
- Lithology (Grain Size, Sorting, Roundness)
- Composition
- Sedimentary Structures
- Contacts
- Body / Trace Fossils
- Post-Depositional and Diagenetic

SURFACES, FACIES, INTERVAL, and COMMENTS

Sandstone (Qtz arenite) (mL-mU)
- lt grey-green and dk grey laminae co-sets
- subrounded grains
- high & low angle cross-lamination
- normally graded beds
- scour surfaces (reactivation?)

- chert and qtz grains up to 5mm

Siltstone
- maroon-red
- mostly quartz grains
- fissile toward top
- thinly laminated
- coal fragments

Silty Sandstone (Qtz arenite) (vf) (silty)
- red and grey/green
- planar low angle cross-lamantion
- alternating grey and red laminations
- isolated mL qtz grains

Alternating oxidized and non-oxidized laminations suggest varying water level and intermitten exposure

Limestone (nodular texture)
- maroon and grey shale matrix
  - contains conodonts, crinoids, brachs, fusilinids
  - slickensides
- Micrite nodules 1-10cm
  - lt grey to redden coloration
  - fractured with red infilling shale

Evidence of exposure and oxidation: fitted nodular texture, red infilling shale

Qtz arenite, fL, mottled, green, bioturbated

WELL NAME Thompson A 2
INTERVAL 4125-4135 ft
PAGE 3 OF 5

LOCATION Sec 3-T17S R 21W, S2-NE-SW-SE, Ness Co., KS

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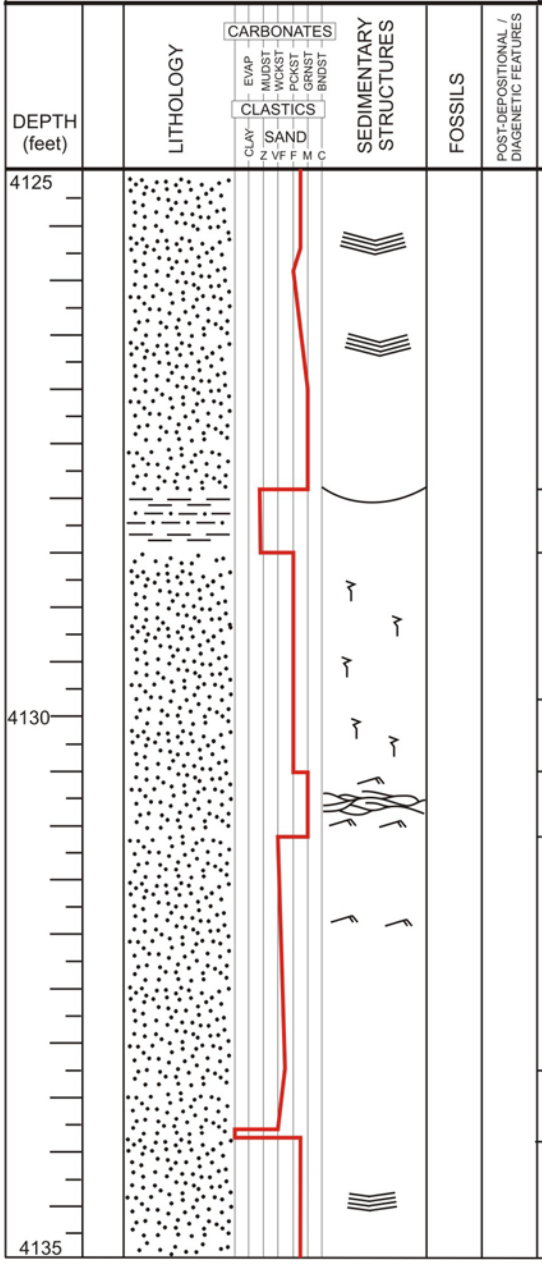

DESCRIPTION - NOTES
- Thickness
- Color
- Lithology (Grain Size, Sorting, Roundness)
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- Contacts
- Body / Trace Fossils
- Post-Depositional and Diagenetic

SURFACES, FACIES, INTERVAL, and COMMENTS

BOX

Sandstone (Qtz arenite) (fL-mL)
- tan, brown, very porous
- subangular-subrounded, well sorted
- high angle cross-lamination
- 2 normal grading cycles

Oil stains

Qtz arenite (fL)
- tan, brown
- qtz and chert clasts
- high cross-lamination
- isolated limestone and mud clasts

Oil stains

Qtz arenite (mU)
- tan
- interbedded with green shale
- poorly cemented, well sorted
- scoured contact into shale

Shale
- green, grey, fissile,
- interbedded siltstone, friable

Sandstone (qtz arenite) (fU)
- patchy green and tan
- chert and clay clasts
- bioturbated
- coal fragments

Sandstone (Qtz arenite) (mL-vfU)
- lt pale green to tan, 20-30% clay
- subangular-subrounded atz grains
- bioturbated, coal fragments, oil stains

Sandstone (Qtz arenite (mL)
- green, clay rich, calcite cement
- ripple laminated, flaser bedding
- compacted limestone nodules

Sandstone (Qtz arenite) (vfU)
- green
- weak laminations, pale green shale lenses
- wavy limestone clasts layer
- ripple laminations

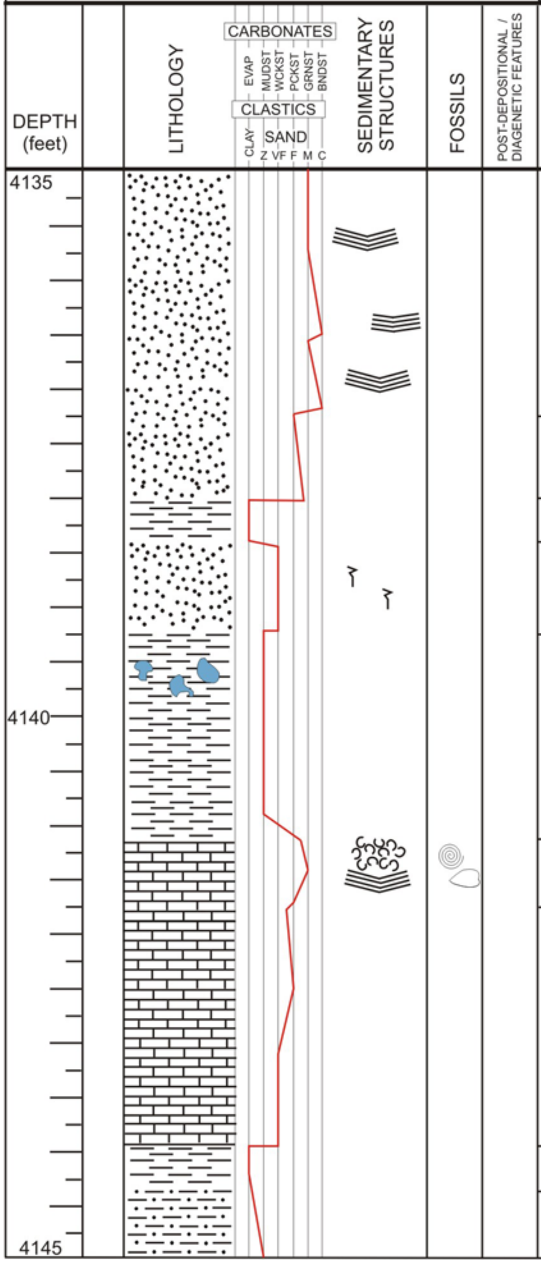
- several limestone nobules
  - elongate and in all orientations
    - parallel and perpendicular to bedding
  - 2- 34mm

- high organic content

Sandstone (vfU)
- subrounded grains,
- limestone nodules
- green shale at base

Sandstone (Qtz arenite) (fL-mL)
- tan
- limestone and chert clast
- calcareous cement bands and patches

WELL NAME	Thompson A 2	INTERVAL 4135-4145 ft	PAGE 4 OF 5
LOCATION	Sec 3-T17S R 21W, S2-NE-SW-SE, Ness Co., KS		
COMPANY	Kansas Geological Survey	DESCRIBED BY B.J. Ramaker	DATE June 2007



DESCRIPTION - NOTES - Thickness - Color - Lithology (Grain Size, Sorting, Roundness) - Composition - Sedimentary Structures - Contacts - Body / Trace Fossils - Post-Depositional and Diagenetic	SURFACES, FACIES, INTERVAL, and COMMENTS
Sandstone (Qtz arenite) (mL-cL) - tan - subrounded grains - cycles of normal grading - chert and limestone clast - 3-16mm - low angle & high angle cross-laminations - fainted or disrupted in some areas	Oil stained bands
Sandstone (Qtz arenite) fU-mL - maroon, subrounded, high sphericity - high clay content - anglular chert clast (2-4mm)	
Shale, maroon, reduction spots	
Sandstone (Qtz arenite) (fL) - motttled green, maroon and tan - clay rich - minor bioturbation - limestone clasts in green shale at base	
Shaley limestone (nodular) - red-maroon sandy shale matrix - fissile - calcareous - lt grey nodules, reddening thruughout - 3-40mm in diameter - micritic - 10-50% limestone nodules - caliche over print	Paleosol developed on the top of the limestone. Dissolution and reddening evident throughout.
Limestone (packstone to grainstone) - highly fossilierous: brachs, gastropods, sponges fish scales, and solitary corals - fossils aligned, scoured base	
Limestone (wackestone to packstone) - grey to lt grey nodules - grades upward to packstone - minor grey-green shale, decreases upward Limestone (wackestone) - lt grey - micrite nodules - green-grey shale matrix separate nodules - 5-20% matrix	
Mudstone - mottled maroon and green	
Sitlstone - brick red, fine silt, grades into mudstone	

WELL NAME Thompson A 2

INTERVAL 4145-4155 ft

PAGE 5 OF 5

LOCATION Sec 3-T17S R 21W, S2-NE-SW-SE, Ness Co., KS

COMPANY Kansas Geological Survey

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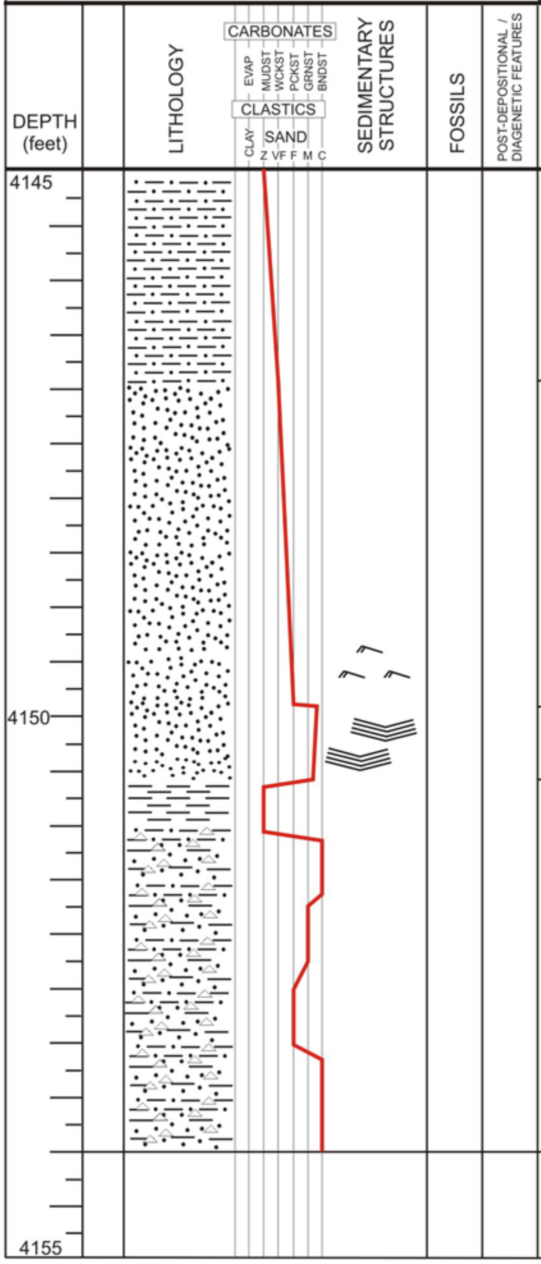

DESCRIPTION - NOTES
- Thickness
- Color
- Lithology (Grain Size, Sorting, Roundness)
- Composition
- Sedimentary Structures
- Contacts
- Body / Trace Fossils
- Post-Depositional and Diagenetic

SURFACES, FACIES, INTERVAL, and COMMENTS

BOX

Siltstone
- brick red
- massively bedded
- minor vf sandstone units
- small green reduction spots
- tan mottling toward top
- fines upward

Sandstone (Qtz arenite) (vfL-fL)
- brick red
- clay matrix
- subrounded, spherical
- faintly laminated and ripple laminated at base
- fines upward

Loose Rubble

Sandstone (Litharenite) (mL-cL)
- tan to white, green seams and red bands
- cross-laminated,
- sharp base

Mud/siltstone conlgomerate to breccia
- maroon/brown matrix
- chert clast 0-3.5cm
  - angular to subrounded
- weathering features and oxidation marks
- thin green shale seams
- poorly sorted

Bottom of core

WELL NAME Neyer B 1

INTERVAL 4420-4430 ft

PAGE 1 OF 2

LOCATION Sec 15-T17S R 24W, C NW NE, Ness Co., KS

COMPANY Kansas Geological Survey

DESCRIBED BY B.J. Ramaker

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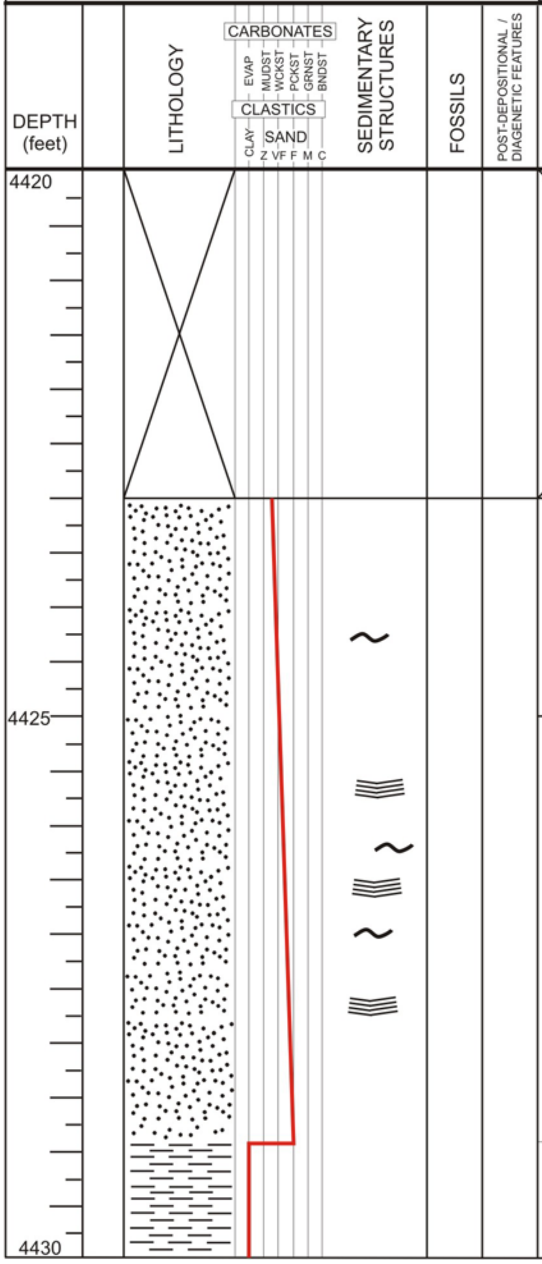


DESCRIPTION - NOTES

- Thickness
- Color
- Lithology (Grain Size, Sorting, Roundness)
- Composition
- Sedimentary Structures
- Contacts
- Body / Trace Fossils
- Post-Depositional and Diagenetic

SURFACES, FACIES, INTERVAL, and COMMENTS

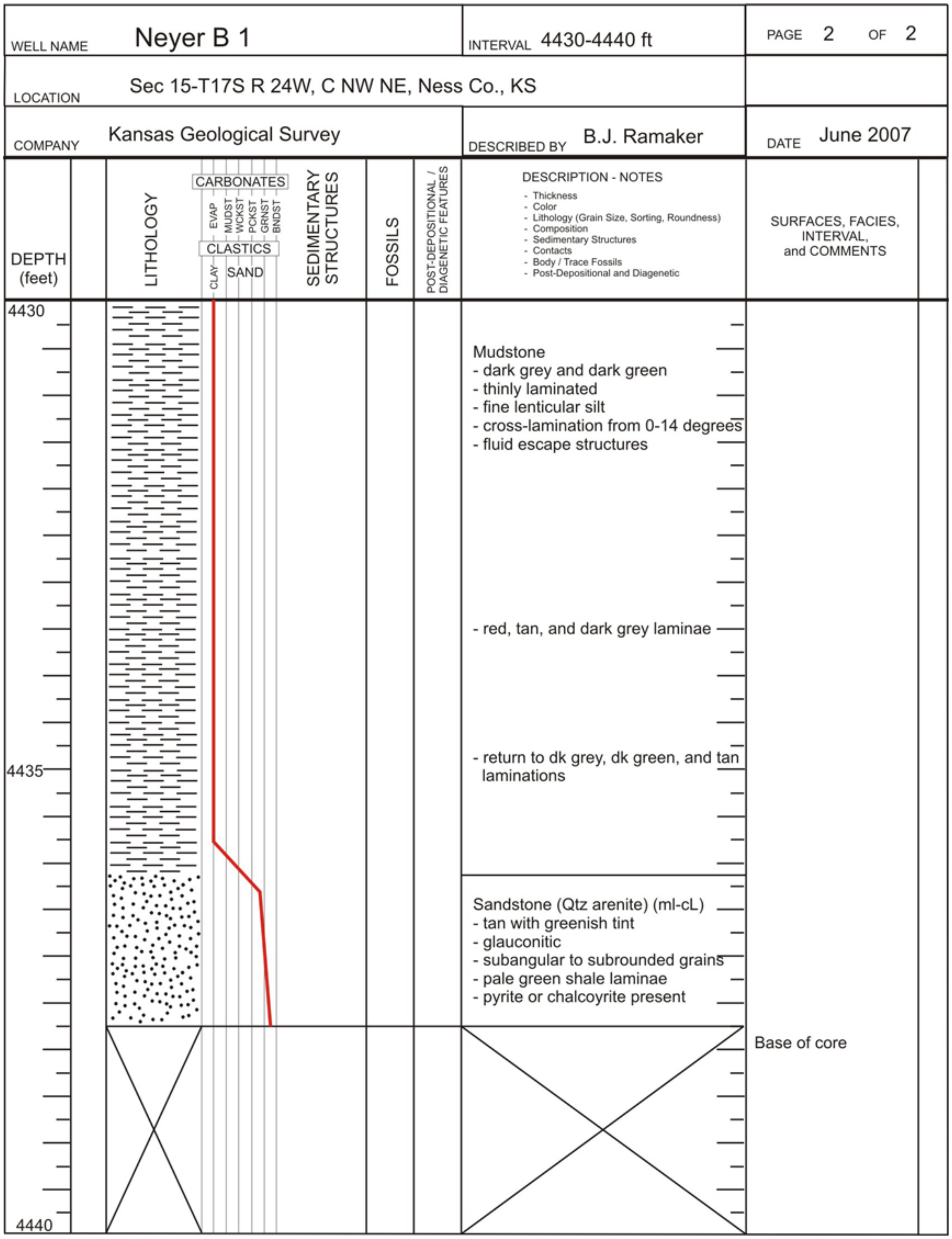
Top of core

Sandstone (Qtz arenite) (vfL)
- white at top and tan-brown below
- burrowed and bioturbated at top
- pale green flaser beds
- orange oxidation spots
- oil stains

Sandstone (Qtz arenite) (fL-fU)
- tan-green
- glauconitic
- low and high angle cross-laminae
- pale green shale flaser beds
  - thought to be gluaconitic
- spotty calcite cement
- oxidation marks
- pyrite

- chert & mud clast at base (3-28mm)
- black qtz grains and

Mudstone
- dark grey and green
- thin wavy and lenticular silt beds
- low angle cross- laminations
- fluid escape structures



WELL NAME Neyer B 1
INTERVAL 4430-4440 ft
PAGE 2 OF 2

LOCATION Sec 15-T17S R 24W, C NW NE, Ness Co., KS

COMPANY Kansas Geological Survey
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DATE June 2007

DESCRIPTION - NOTES
- Thickness
- Color
- Lithology (Grain Size, Sorting, Roundness)
- Composition
- Sedimentary Structures
- Contacts
- Body / Trace Fossils
- Post-Depositional and Diagenetic

SURFACES, FACIES, INTERVAL, and COMMENTS

Mudstone
- dark grey and dark green
- thinly laminated
- fine lenticular silt
- cross-lamination from 0-14 degrees
- fluid escape structures

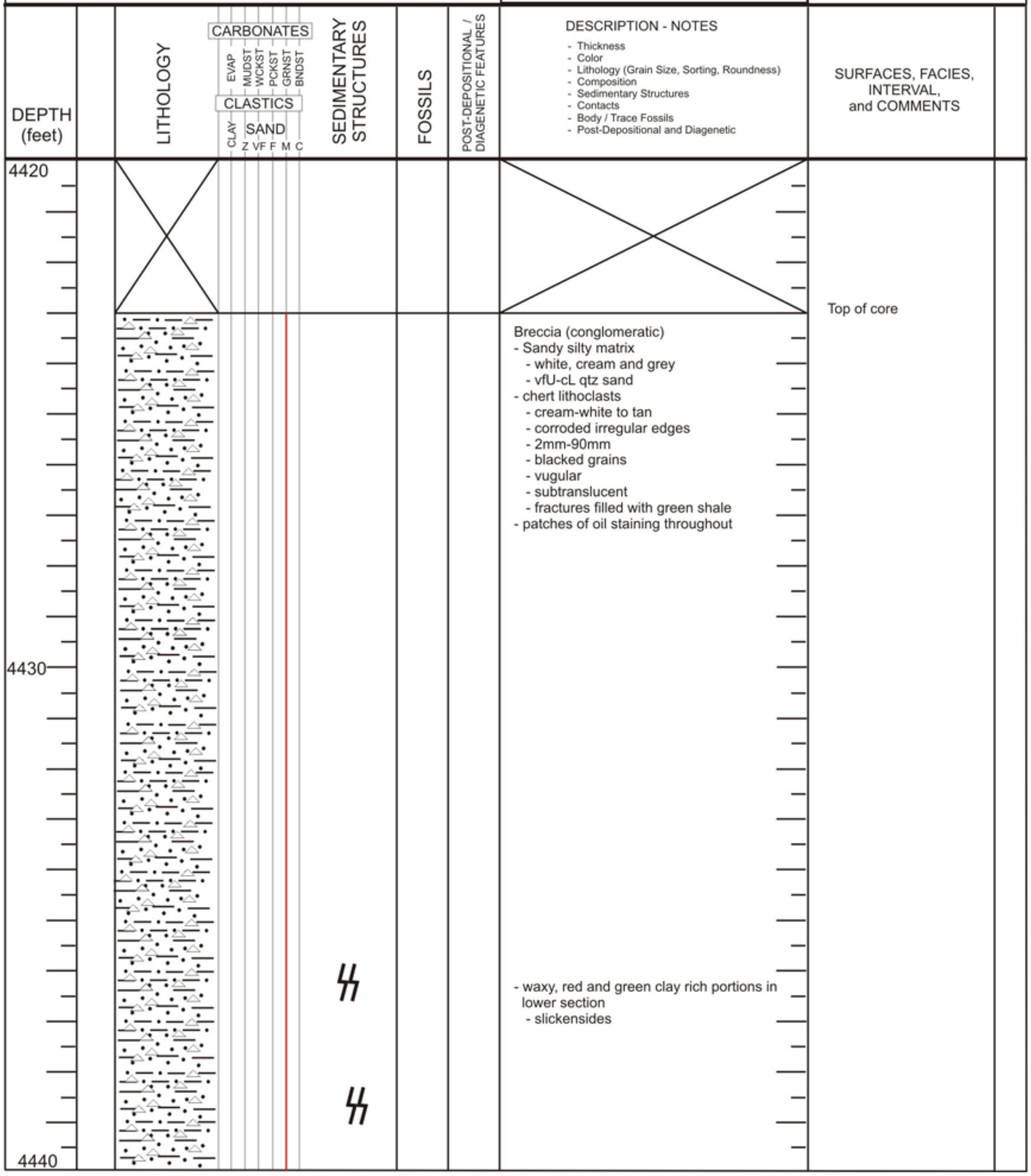
- red, tan, and dark grey laminae

- return to dk grey, dk green, and tan laminations

Sandstone (Qtz arenite) (ml-cL)
- tan with greenish tint
- glauconitic
- subangular to subrounded grains
- pale green shale laminae
- pyrite or chalcoyrite present

Base of core

WELL NAME Tilley 2	INTERVAL 4420-4460 ft	PAGE 1 OF 2
LOCATION Sec 8-T17S R 24W, Sw-Se-Sw, Ness Co., KS		
COMPANY Kansas Geological Survey	DESCRIBED BY B.J. Ramaker	DATE June 2007



DESCRIPTION - NOTES
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- Composition
- Sedimentary Structures
- Contacts
- Body / Trace Fossils
- Post-Depositional and Diagenetic

Top of core

Breccia (conglomeratic)
- Sandy silty matrix
  - white, cream and grey
  - vfU-cL qtz sand
- chert lithoclasts
  - cream-white to tan
  - corroded irregular edges
  - 2mm-90mm
  - blacked grains
  - vugular
  - subtranslucent
  - fractures filled with green shale
- patches of oil staining throughout

- waxy, red and green clay rich portions in lower section
  - slickensides

WELL NAME Tilley 2

INTERVAL 4440-4460 ft

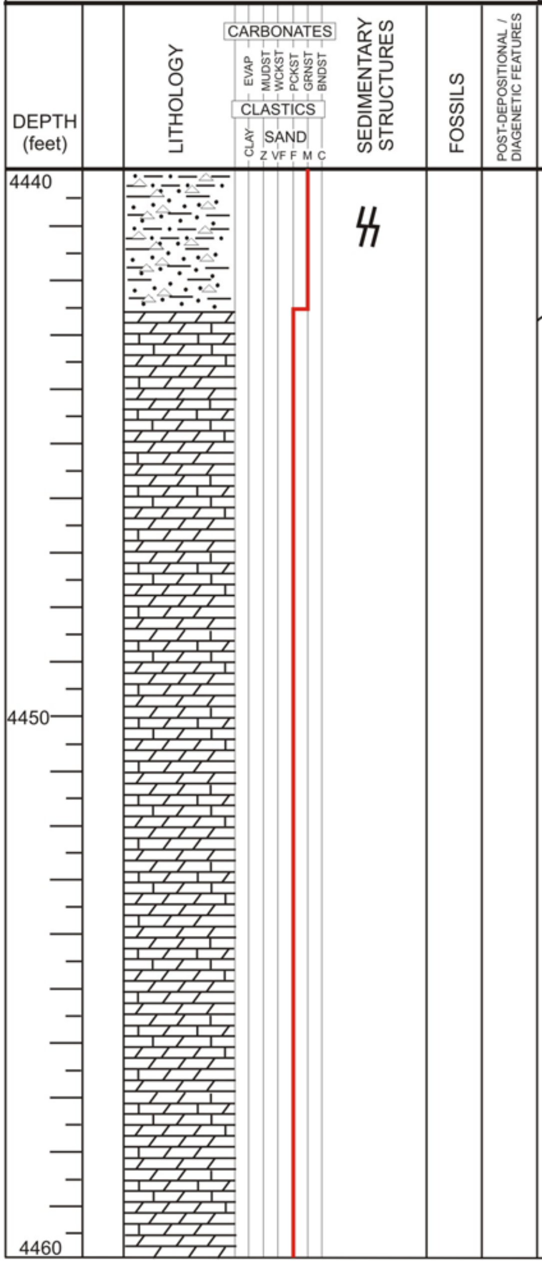
PAGE 2 OF 2

LOCATION Sec 8-T17S R 24W, Sw-Se-Sw, Ness Co., KS

COMPANY Kansas Geological Survey

DESCRIBED BY B.J. Ramaker

DATE June 2007



DESCRIPTION - NOTES
- Thickness
- Color
- Lithology (Grain Size, Sorting, Roundness)
- Composition
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- Contacts
- Body / Trace Fossils
- Post-Depositional and Diagenetic

SURFACES, FACIES, INTERVAL, and COMMENTS

Breccia (conglomeratic)
- silty shale matrix
  - dk grey, brown-red, pale green
  - waxy, slickensides
- chert lithoclasts (2-30mm)
  - cream-white to tan
  - corroded irregular edges
  - fractures filled with green shale

Mississippian Unconformity

Dolomite (minor limestone)
- tan, gray, and buff
- dense
- fossiliferous
  - abundant crinoid zone
- sucrosic
- crystalline
- vugular
- fractures (20-80 degrees across core)
  - bright green waxy shale infilling
  - cherty and dolomite lithoclast
- oil stained
- few areas of disseminated pyrite

Mississippian strata
- Spergen?

Base of core

WELL NAME Wegele A 1

INTERVAL 4230-4240 ft

PAGE 1 OF 6

LOCATION Sec 21-T18S R 22W, C SE, Ness Co., KS

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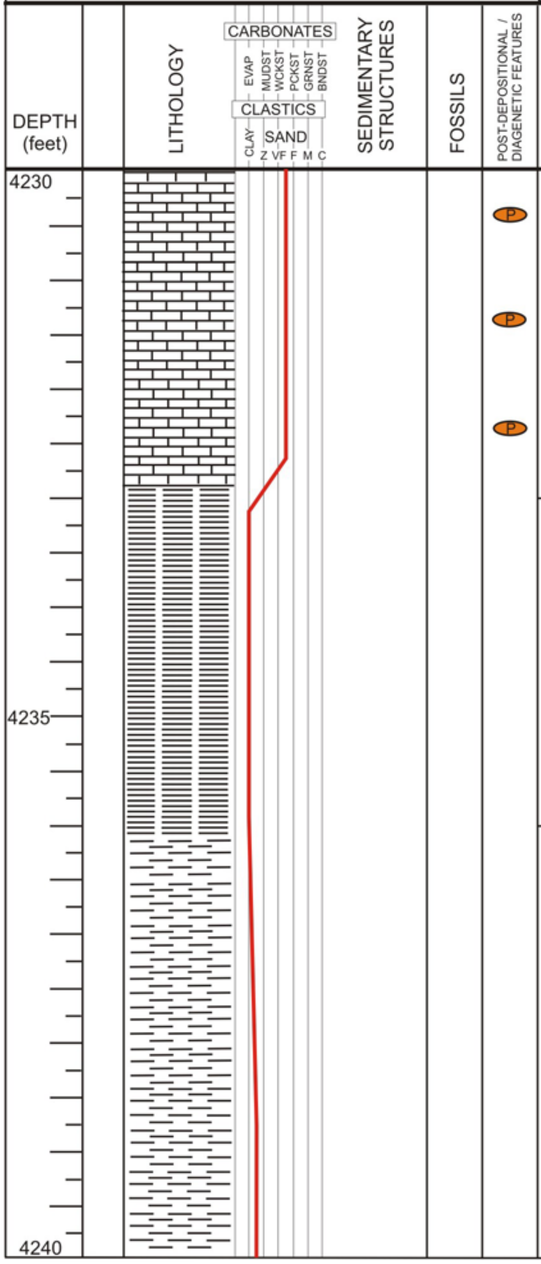


DESCRIPTION - NOTES
- Thickness
- Color
- Lithology (Grain Size, Sorting, Roundness)
- Composition
- Sedimentary Structures
- Contacts
- Body / Trace Fossils
- Post-Depositional and Diagenetic

SURFACES, FACIES, INTERVAL, and COMMENTS

BOX

Limestone
- wackstone-packstone
- light grey
- irregular bedding
- thin shale stringers
- pyrite nodules

Fort Scott Limestone

Shale
- dark grey
- thinly laminated
- laminations of dark grey and light grey mud
- thin calcareous beds toward top

Top of Cherokee Group

Contact not observed: all loose rubble

Mudstone/siltstone
- brick red
- minor grey mottling
- blocky, rubbly texture
  - possible ped structures
  - white spots toward top
    - possible oxidation/reduction spots

WELL NAME Wegele A 1

INTERVAL 4240-4250 ft

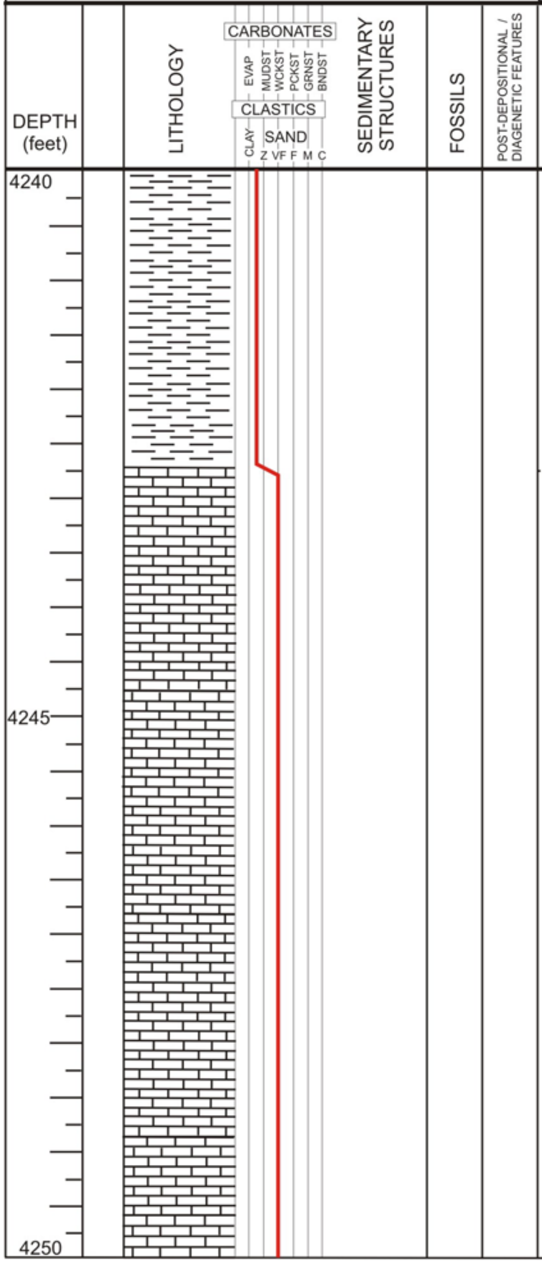
PAGE 2 OF 6

LOCATION Sec 21-T18S R 22W, C SE, Ness Co., KS

COMPANY Kansas Geological Survey

DESCRIBED BY B.J. Ramaker

DATE June 2007



DESCRIPTION - NOTES
- Thickness
- Color
- Lithology (Grain Size, Sorting, Roundness)
- Composition
- Sedimentary Structures
- Contacts
- Body / Trace Fossils
- Post-Depositional and Diagenetic

SURFACES, FACIES, INTERVAL, and COMMENTS

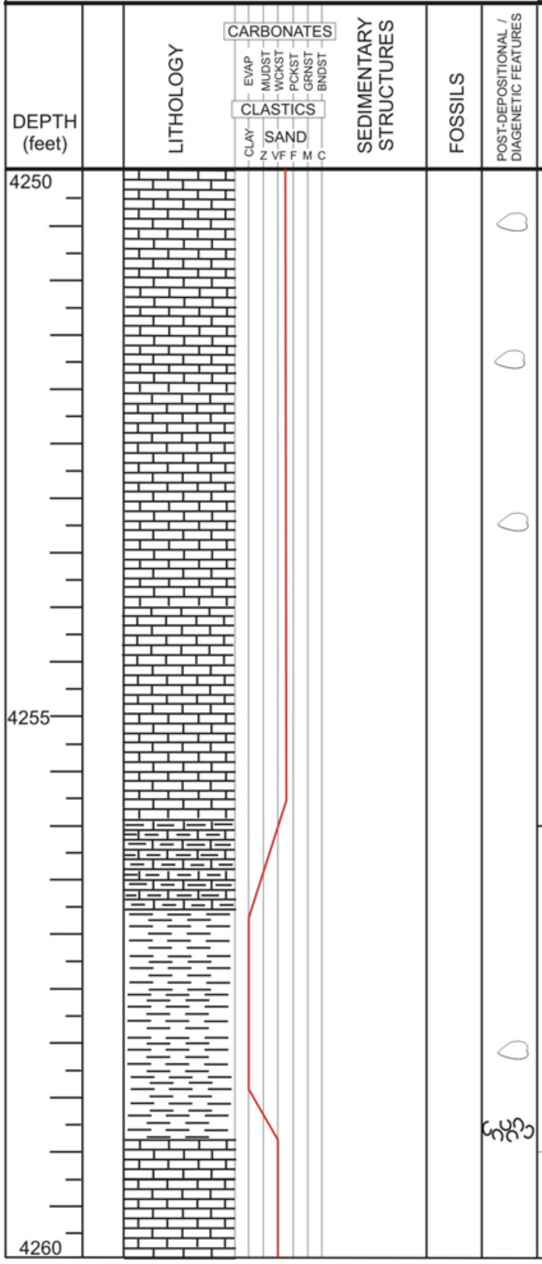
Mudstone/siltstone
- brick red
- minor grey mottling
- block, rubbly texture
  - possible ped structures

Contact not observed, loose rubble

Limestone (wackestone-packstone)
- lt grey
- nodular texture toward top
  - nodules 1-7 cm
- pale green calcareous infilling shale matrix
  - water reactive and expanding
- infilling shale decreases downward
  - 25-0% content decreasing downward

- solid limestone
- no observable bedding
- thin wispy shale laminations

WELL NAME Wegele A 1		INTERVAL 4250-4260 ft	PAGE 3 OF 8
LOCATION Sec 21-T18S R 22W, C SE, Ness Co., KS			
COMPANY Kansas Geological Survey		DESCRIBED BY B.J. Ramaker	DATE June 2007



DESCRIPTION - NOTES
- Thickness
- Color
- Lithology (Grain Size, Sorting, Roundness)
- Composition
- Sedimentary Structures
- Contacts
- Body / Trace Fossils
- Post-Depositional and Diagenetic

SURFACES, FACIES, INTERVAL, and COMMENTS

Limestone (wackestone-packstone)
- lt grey
- no bedding
- brachipods

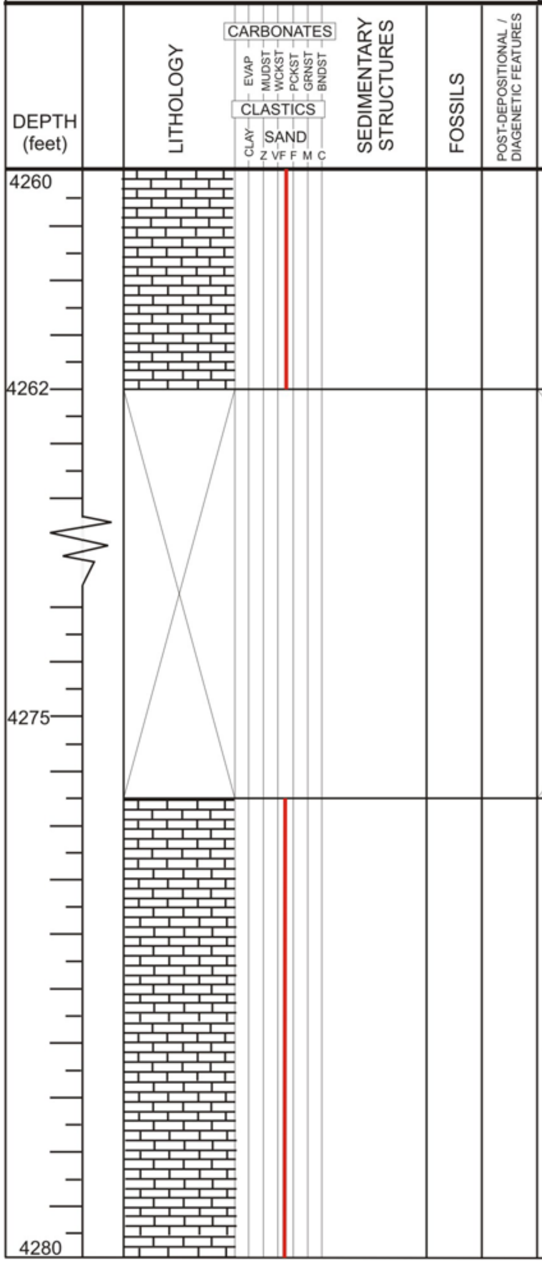
Shaly lime mudstone
- dark grey

Shale
- dark grey to grey
  - color lightens upwad
- thinnly laminated
- fissile
- platy
- brachipods

- thin lag deposit
- qtz grains, mud clasts,
disarticulated fossil fragments

Limestone
- nodular
- light grey
- green mud matrix (some vs sand

WELL NAME Wegele A 1	INTERVAL 4260-4280 ft	PAGE 4 OF 6
LOCATION Sec 21-T18S R 22W, C SE, Ness Co., KS		
COMPANY Kansas Geological Survey	DESCRIBED BY B.J. Ramaker	DATE June 2007



DESCRIPTION - NOTES
- Thickness
- Color
- Lithology (Grain Size, Sorting, Roundness)
- Composition
- Sedimentary Structures
- Contacts
- Body / Trace Fossils
- Post-Depositional and Diagenetic

SURFACES, FACIES, INTERVAL, and COMMENTS

Limestone (wackestone-packstone)
- light grey
- localized nodular texture
  - pale green infilling shale matrix

Missing Core

Limestone (wackestone-packstone)
- lt grey
- nodular texture increases toward top
  - pale green infilling shale
- brachiopods

WELL NAME Wegele A 1

INTERVAL 4280-4290 ft

PAGE 5 OF 6

LOCATION Sec 21-T18S R 22W, C SE, Ness Co., KS

COMPANY Kansas Geological Survey

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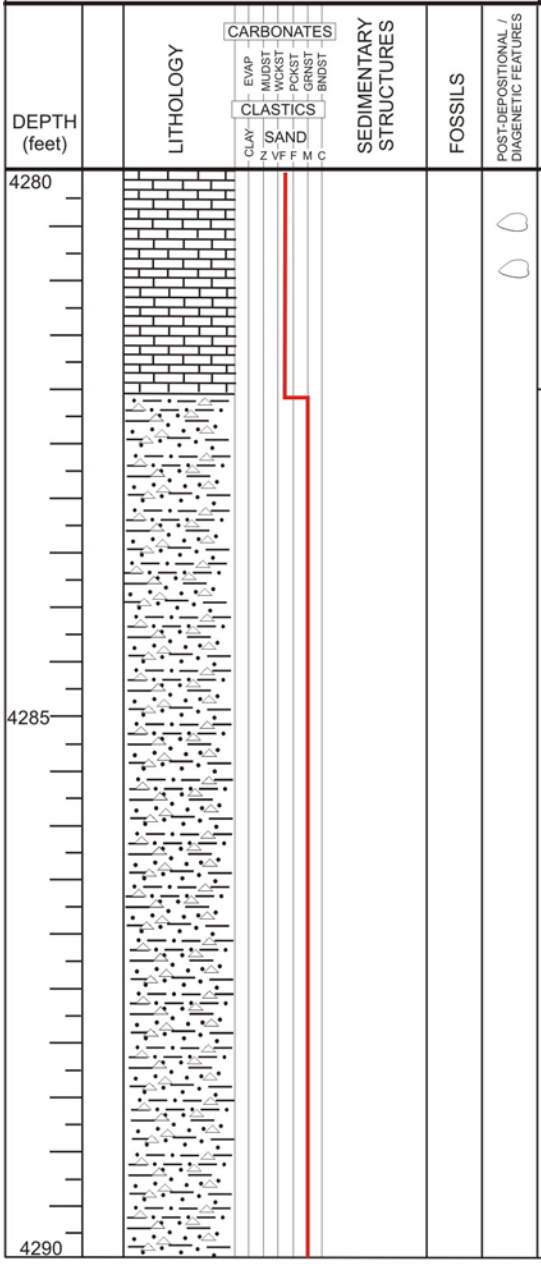


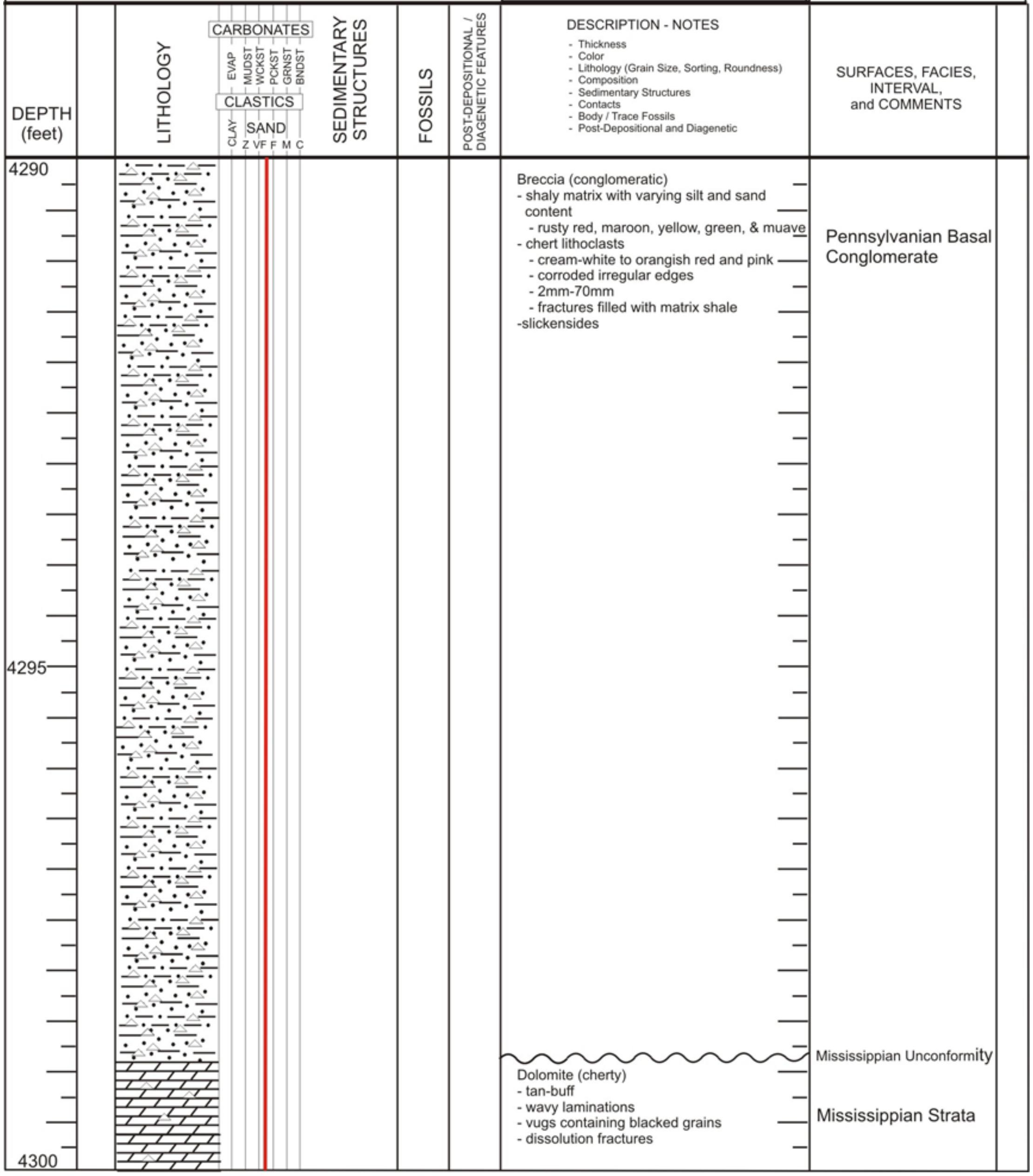
DESCRIPTION - NOTES
- Thickness
- Color
- Lithology (Grain Size, Sorting, Roundness)
- Composition
- Sedimentary Structures
- Contacts
- Body / Trace Fossils
- Post-Depositional and Diagenetic

SURFACES, FACIES, INTERVAL, and COMMENTS

Limestone (wackestone-packstone)
- lt grey
- no observable bedding
- brachiopods
- thin pale green shale stringres

Breccia (conglomeratic)
- shaly matrix with varying silt and sand content
  - rusty red, maroon, yellow, green, & muave
- chert lithoclasts
  - cream-white to orangish red and pink
  - corroded irregular edges
  - 2mm-70mm
  - fractures filled with matrix shale
- slickensides

WELL NAME Wegele A 1
INTERVAL 4290-4300 ft
PAGE 6 OF 6
LOCATION Sec 21-T18S R 22W, C SE, Ness Co., KS
COMPANY Kansas Geological Survey
DESCRIBED BY B.J. Ramaker
DATE June 2007



DESCRIPTION - NOTES
- Thickness
- Color
- Lithology (Grain Size, Sorting, Roundness)
- Composition
- Sedimentary Structures
- Contacts
- Body / Trace Fossils
- Post-Depositional and Diagenetic

SURFACES, FACIES, INTERVAL, and COMMENTS

Breccia (conglomeratic)
- shaly matrix with varying silt and sand content
  - rusty red, maroon, yellow, green, & muave
- chert lithoclasts
  - cream-white to orangish red and pink
  - corroded irregular edges
  - 2mm-70mm
  - fractures filled with matrix shale
-slickensides

Pennsylvanian Basal Conglomerate

Mississippian Unconformity

Dolomite (cherty)
- tan-buff
- wavy laminations
- vugs containing blacked grains
- dissolution fractures

Mississippian Strata

WELL NAME Moore 1

INTERVAL 4350-4360 ft

PAGE 1 OF 5

LOCATION Sec 34-T19S R 21W, C-NW-NW, Ness Co., KS

COMPANY Kansas Geological Survey

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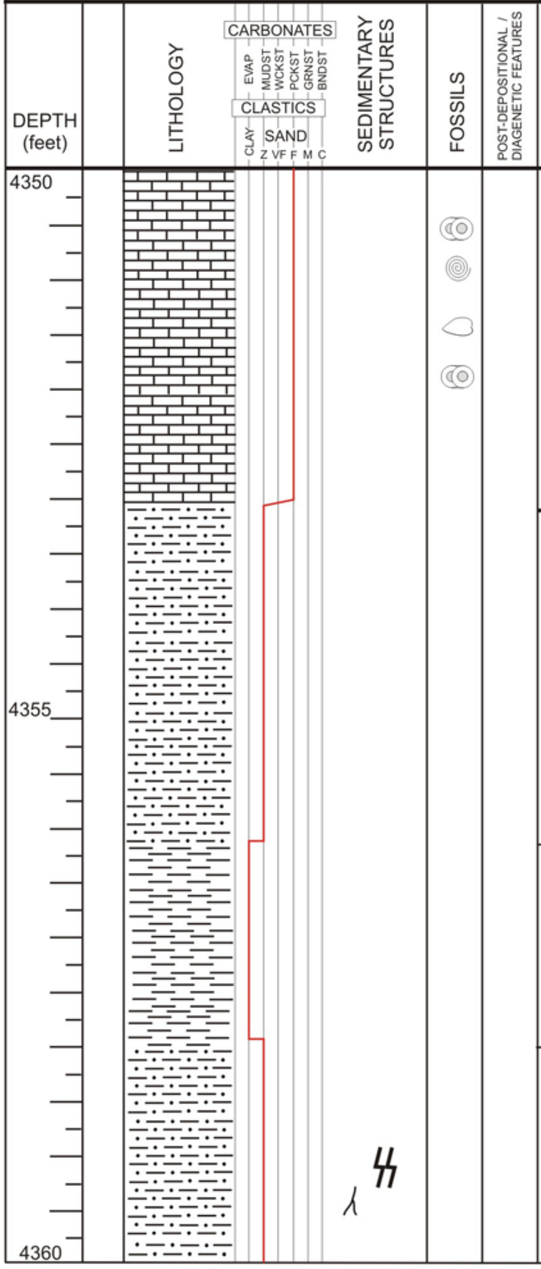

DESCRIPTION - NOTES - Thickness - Color - Lithology (Grain Size, Sorting, Roundness) - Composition - Sedimentary Structures - Contacts - Body / Trace Fossils - Post-Depositional and Diagenetic	SURFACES, FACIES, INTERVAL, and COMMENTS
Limestone (mudstone-wackestone) - light grey - fossiliferous - gastropods - crinoids - fusilinids - brachiopods - green algae	Fort Scott Limestone
Siltstone (muddy vf sandstone) - grey-tan, minor green coloration - high clay content	Cherokee Group
Shale (dk grey-black) - thinly laminated - lt grey laminae between dk grey laminae - brachiopods - wood imprints	

Siltstone (vfL-fL qtz also present)
- dk red and grey, mottled
- minor slickensides present
- dark red oxidation marks
- bioturbation
- rhizoliths?
  - dk grey to black
  - found locally at the base of siltstone.	

WELL NAME Moore 1

INTERVAL 4360-4370 ft

PAGE 2 OF 5

LOCATION Sec 34-T19S R 21W, C-NW-NW, Ness Co., KS

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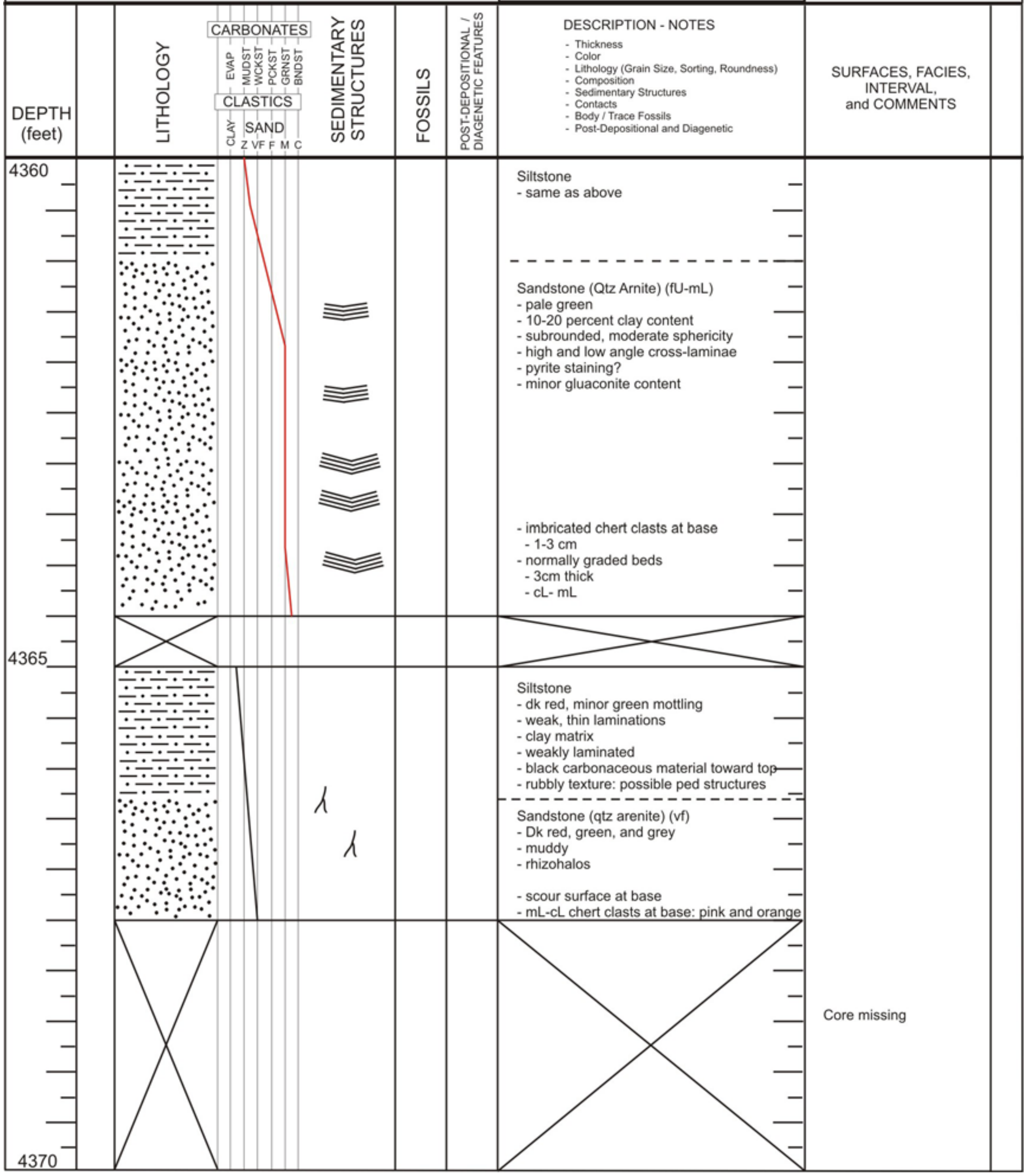


Siltstone
- same as above

Sandstone (Qtz Arnite) (fU-mL)
- pale green
- 10-20 percent clay content
- subrounded, moderate sphericity
- high and low angle cross-laminae
- pyrite staining?
- minor gluaconite content

- imbricated chert clasts at base
  - 1-3 cm
- normally graded beds
  - 3cm thick
  - cL- mL

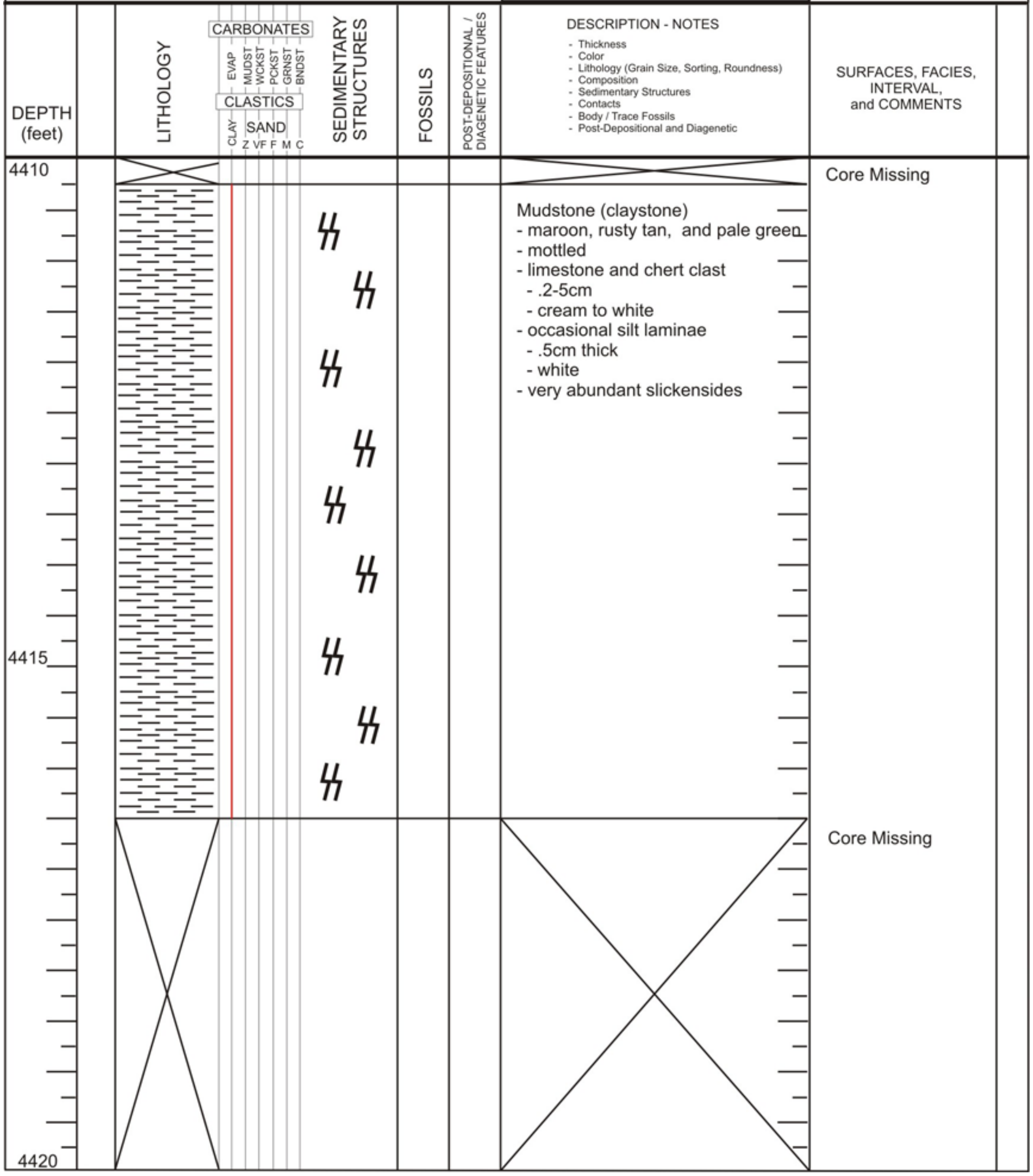
Siltstone
- dk red, minor green mottling
- weak, thin laminations
- clay matrix
- weakly laminated
- black carbonaceous material toward top
- rubbly texture: possible ped structures

Sandstone (qtz arenite) (vf)
- Dk red, green, and grey
- muddy
- rhizohalos

- scour surface at base
- mL-cL chert clasts at base: pink and orange

Core missing

WELL NAME Moore 1	INTERVAL 4410-4420 ft	PAGE 3 OF 5
LOCATION Sec 34-T19S R 21W, C-NW-NW, Ness Co., KS		
COMPANY Kansas Geological Survey	DESCRIBED BY B.J. Ramaker	DATE Sept 2007



DESCRIPTION - NOTES
- Thickness
- Color
- Lithology (Grain Size, Sorting, Roundness)
- Composition
- Sedimentary Structures
- Contacts
- Body / Trace Fossils
- Post-Depositional and Diagenetic

SURFACES, FACIES, INTERVAL, and COMMENTS

Core Missing

Mudstone (claystone)
- maroon, rusty tan, and pale green
- mottled
- limestone and chert clast
  - .2-5cm
  - cream to white
- occasional silt laminae
  - .5cm thick
  - white
- very abundant slickensides

Core Missing

WELL NAME Moore 1
INTERVAL 4420-4430 ft
PAGE 4 OF 5
LOCATION Sec 34-T19S R 21W, C-NW-NW, Ness Co., KS
COMPANY Kansas Geological Survey
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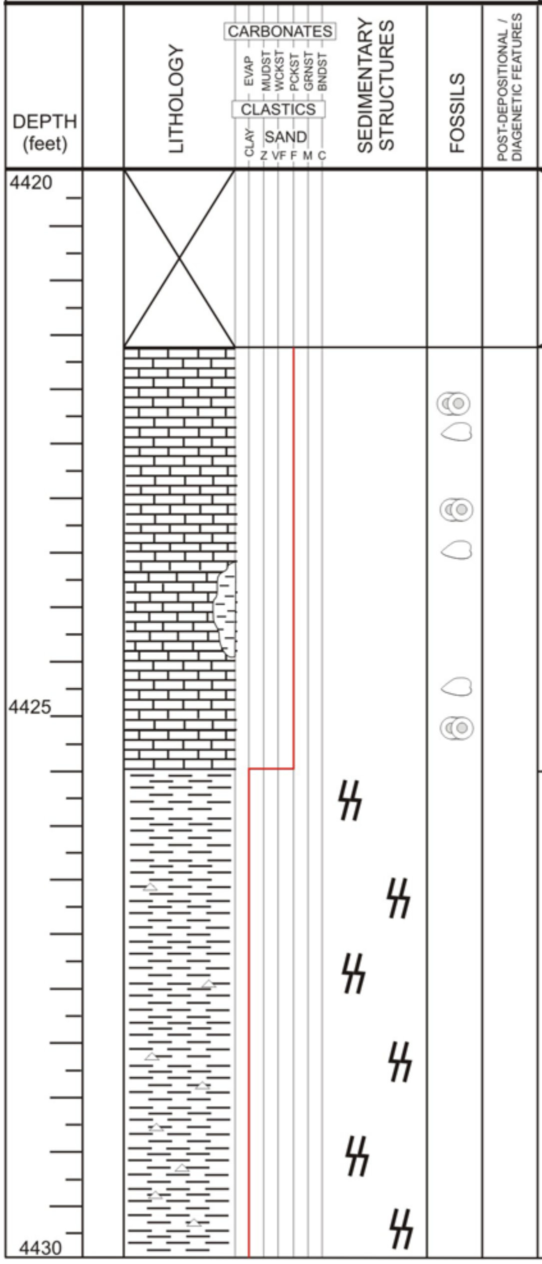
DATE Sept 2007



DESCRIPTION - NOTES
- Thickness
- Color
- Lithology (Grain Size, Sorting, Roundness)
- Composition
- Sedimentary Structures
- Contacts
- Body / Trace Fossils
- Post-Depositional and Diagenetic

SURFACES, FACIES, INTERVAL, and COMMENTS

Core missing

Limestone (wackestone-packstone)
- tan, buff, and lt grey: minor reddening
- high angle planar laminae
- brachipods, crinoids
- styolites
- brecciated in isolated regions
- dark red to grey infilling shale
- sharp, irregular, corroded contacts on edges throughout core
  - red shaley mudstone along corroded edges

mississippian boulder in mudstone matrix

Mudstone (claystone)
- maroon, rusty tan, yellow, white, and pale green
- mottled
- limestone and chert clast
  - .2-5cm
  - cream to white
- occasional silt laminae
  - .5cm thick
  - white
- very abundant slickensides

WELL NAME Moore 1

INTERVAL 4410-4420 ft

PAGE 3 OF 5

LOCATION Sec 34-T19S R 21W, C-NW-NW, Ness Co., KS

COMPANY Kansas Geological Survey

DESCRIBED BY B.J. Ramaker

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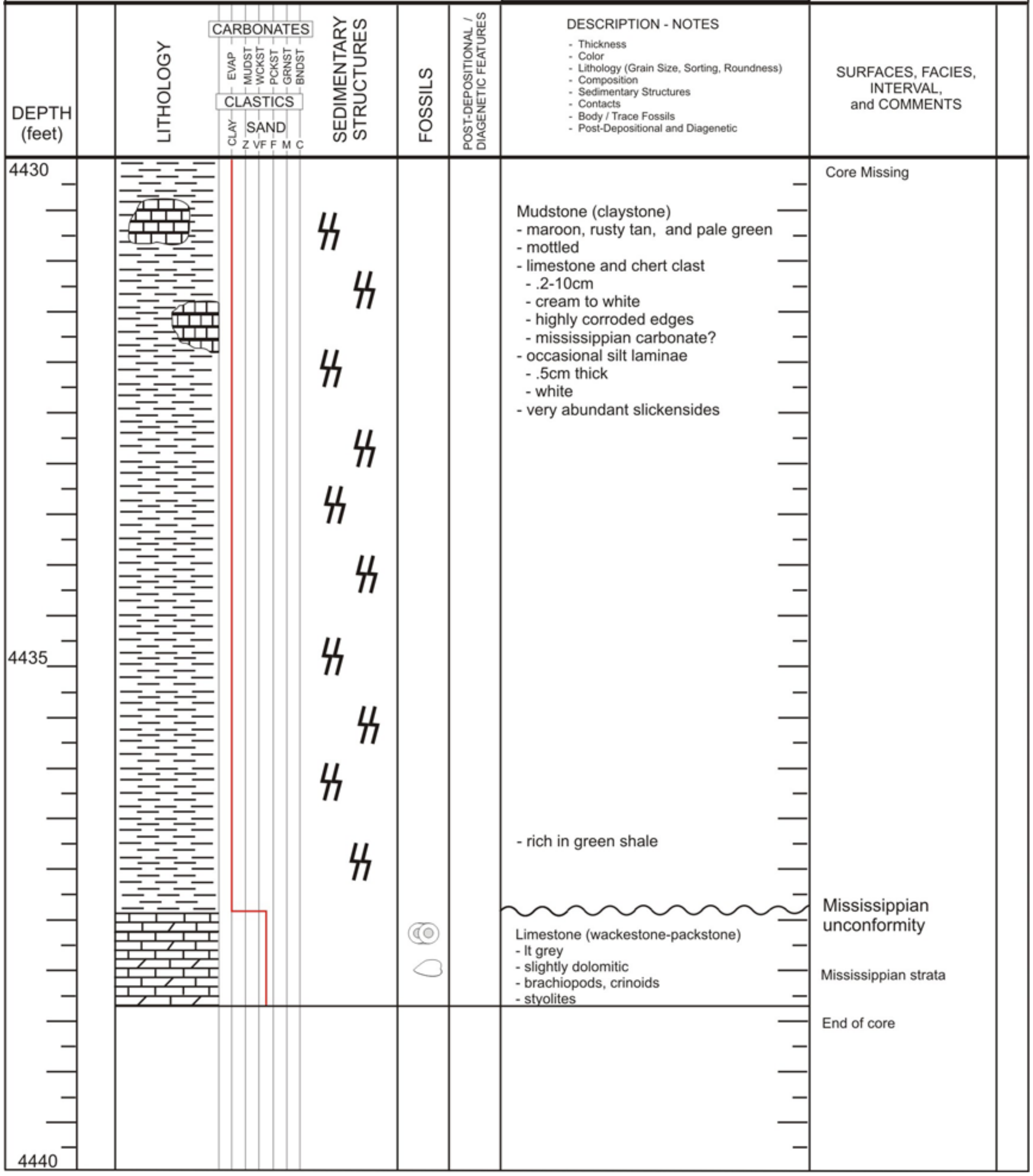


Core Missing

Mudstone (claystone)
- maroon, rusty tan, and pale green
- mottled
- limestone and chert clast
  - .2-10cm
  - cream to white
  - highly corroded edges
  - mississippian carbonate?
- occasional silt laminae
  - .5cm thick
  - white
- very abundant slickensides

- rich in green shale

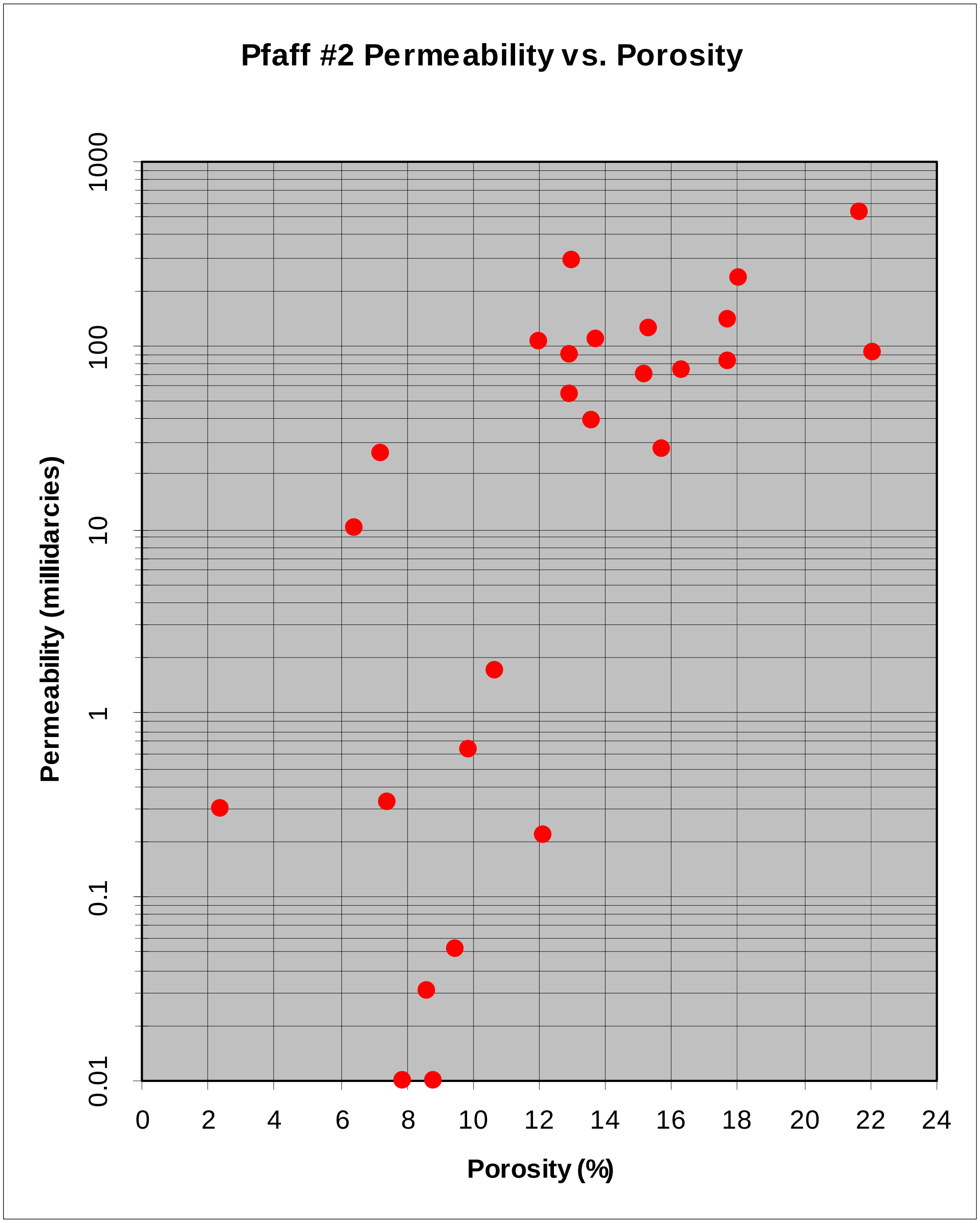
Mississippian unconformity

Limestone (wackestone-packstone)
- lt grey
- slightly dolomitic
- brachiopods, crinoids
- stylolites

Mississippian strata

End of core

APPENDIX II: POROSITY AND PERMEABILITY DATA



Porosity and Permeability data from sandstone intervals in core Pfaff #2 (T16S-R21W-Sec. 21, SW-NW-SW). Modified from Howard, 1990.