REGIONAL SETTING, DEPOSITIONAL ENVIRONMENT, AND DIAGENESIS OF THE COTTON VALLEY SANDSTONE IN VERNON FIELD, NORTH LOUISIANA

By

DAVID M. MILBURN

Bachelor of Science in Geology

Oklahoma State University

Stillwater, Oklahoma

2009

Submitted to the Faculty of the
Graduate College of the
Oklahoma State University
in partial fulfillment of
the requirements for
the Degree of
MASTER OF SCIENCE
December, 2012

REGIONAL SETTING, DEPOSITIONAL SYSTEM, AND DIAGENESIS OF THE COTTON VALLEY SANDSTONE IN VERNON FIELD, NORTH LOUISIANA

Thesis Approved:

Dr. James Puckette

Thesis Adviser

Dr. Anna Cruse

Dr. Darwin Boardman

ACKNOWLEDGEMENTS

I would first like to thank my family. My parents have been very supportive financially and in preparing me for the rigors of higher education. They, and Kristen, have always pushed me to be the best student and person I can be. I love you.

I would like to thank my graduate committee - Dr. James Puckette, Dr. Anna Cruse, and Dr. Darwin Boardman - for their patience and professionalism throughout the process of completing the research, the thesis defense, and the thesis document. Dr. Puckette was my thesis committee chair, and his time and efforts are particularly deserving of thanks. His commitment to students' needs is un-paralleled, and I'm happy to call him my mentor.

A big thank you to Samson Resources for allowing me to work on my thesis research in conjunction with their TUG department. I learned a great deal about the energy industry working with Samson at two summer internships as well as during time spent working on my thesis there in Tulsa, OK. I wish everyone I met there the best of luck and happiness in their future endeavors. Also thank you EXCO Resources for providing access to the core in the study, as well as other resources.

Sandy Earls and the office staff of Boone Pickens School of Geology were wonderful in the administration of the college in general, and in dealing with my business as well. She works hard organizing company interviews through the college, administrating all the teaching assistants and research assistants, not to mention all the grad students. Their work is greatly appreciated

Thank you, Devon Energy, for providing a great fellowship endowment to me in my first year of graduate school. This type of support is truly a great investment in higher education, allowing me to focus on my studies during some of the most technical and involved courses of my school career. It was a great blessing in my successful completion of graduate school.

My friends should also be thanked. Those from The Boone Pickens School of Geology, too many to mention individuals, were wonderful classmates and in many cases have become some of my closest friends. In class, and often in the field, we have bonded in ways that cannot be understood by non-geos. Thanks also go to my fraternity brothers for their great friendships, and unlimited support of my wellbeing. Many other friends from my College years were very important individuals in my life, and I thank them for their friendships and wonderful experiences and conversations. I love each one of you.

Name: DAVID M. MILBURN

Date of Degree: DECEMBER, 2012

Title of Study: REGIONAL SETTING, DEPOSITIONAL SYSTEM, AND
DIAGENESIS OF THE COTTON VALLEY SANDSTONE IN
VERNON FIELD, NORTH LOUISIANA

Major Field: GEOLOGY

Abstract:

Eleven cores were examined from wells drilled in the CVG in Vernon Field, LA. These core data were integrated with regional studies and wireline log data to interpret the regional context of the field, depositional facies, prosity types, and diagenetic history.

The Cotton Valley Group at Vernon field falls into a lagoonal region known as the "Hico Lagoon" during the Late Jurassic and Early Cretaceous which had low current and wave energy due to limited access to large oceans, surrounding topographic highs, and intermittent barrier islands. The Hico shale is the unit which the sands of the CVG pinch-out into up-dip.

The depositional setting of the CVG sandstones is interpreted as a dynamic tidal flat ranging from mud flats, to mixed flats, to sand flats. The primary lines of evidence are oyster shells and hash accumulations, oyster and polychaete burrows, heterolithic laminae, and bidirectional flow features.

Depositional facies include three main groups: (1) intertidal mudstones to siltstones, (2) subtidal sandstones, and (3) diagenetically modified heavily calcite cemented sandstones. Group one includes core Facies 1 (mudrocks), Facies 2 (matrix supported siltstones), and Facies 3 (grain supported siltstones) which form a continuum. Group 2 include Facies 4 which is generally darker colored and contains more biostrutures, and Facies 5 which is generally lighter colored, appears cleaner, and contains most of the flow features. Group 3 includes core Facies 6 which are calcite cemented sandstones with no porosity typically associated with zones of shells or fossil hash.

Porosity is mostly secondary intragranular and moldic, and formed by partial to complete dissolution of grains by organic acids associated with the maturation of kerogen in the system. Observed primary porosity is minimal and appear to have been reduced by early calcite and quartz cement.

Facies 4 is considered the best reservoir in the CVG sandstones of Vernon Field because it has the highest average porosity and permeability. Facies five is also important but has slightly lower porosity and permeability. Conventional wireline logs do not have the capability of resolving individual facies.

TABLE OF CONTENTS

Chapter Page

I. INTRODUCTION

LIST OF TABLES

LIST OF FIGURES

Figure Page

Figure Page

.

CHAPTER I

INTRODUCTION

Problem Statement

The Late Jurassic to Early Cretaceous age Cotton Valley Group (CVG) is an entirely subsurface, thick (up to 2000ft/600m) sedimentary section in the Gulf Coast region of the United States. The CVG is present in several basins including the East Texas Salt Basin, the Northern Louisiana Salt Basin, and the Mississippi Salt Basin (Figure 1). The northern margin of its deposition extends from East Texas and Southern Arkansas, to Mississippi and Alabama, and into the panhandle of Florida. Research is generally limited to well control, and the CVG's southern extent is not well constrained due to a lack of deep wells as the depth to the CVG increases to the south (Figure 2). As of 2001, Upper Jurassic strata in the northern Gulf of Mexico basin had produced over 20 TCFG and 900 MMBO (Ewing, 2001) since their discovery in the 1930's.

The stratigraphy of the CVG varies widely across the Gulf Coast region, and the internal stratigraphy is poorly defined. Literature on the Cotton Valley sandstones is limited and inconsistent in the interpretations of the depositional systems and stratigraphic relationships within the CVG. This is partially due to the fact that there are no outcrops of the CVG, so all research is based on well data consisting of well logs, production data, and limited core data. Compounding the problem is the issue that most of the research on the CVG is completed by the petroleum industry, confidential in nature, and in most cases unavailable.

Purpose and Objectives

The purpose of this study is to use core (photos and descriptions) along with other available data (XRD, electric logs, etc.) to constrain the depositional systems present in the CVG in Vernon Field in northern Louisiana within a regional context. Another purpose is to reconstruct a diagenetic history and evaluate the evolution of porosity in the field. This requires close observation and analysis of cores, correlation of the core facies to wireline logs, and analysis of thin sections to determine detrital and authigenic components. Ultimately, studies of this nature could be applied to expansion of this field or exploration for similar types of plays.

The specific objectives of this study are to: (1) establish the CVG in Vernon field in a regional setting; (2) constrain the depositional settings present in the CVG in Vernon Field within the regional tectonic framework, (3) describe depositional features in core of the CVG; (4) correlate cored intervals to wireline logs; (5) determine depositional environments for facies; (6) describe thin sections including detrital and authigenic components; (7) interpret the depositional systems present in Vernon Field; and (8) interpret the diagenetic history and the evolution of porosity within these facies.

This work stands to add to the understanding of the drivers of porosity and permeability within each facies, as well as providing some insight into their depositional environments. This small scale understanding of the diagenetic and porosity histories should facilitate a better understanding of local geologic history as well as serving as a guide to future geologists exploring and developing the CVG in northern Louisiana.

Study Area

Vernon field is located in Jackson Parrish, north-central Louisiana. Structurally it lies between the Monroe Uplift and the Sabine Arch (Figure 1). This study area was chosen because it is a significant CVG field, and because the company owning most of the leases (EXCO

Resources) was willing to share core and other data to make the study possible. Vernon Field was also appropriate because it is located within a region with wells producing natural gas from Cotton Valley sandstones.

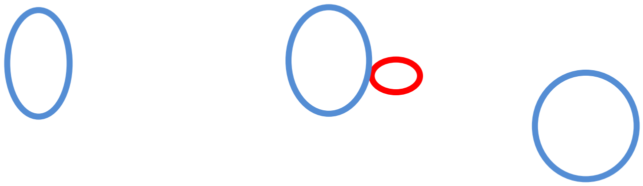


Figure 1. Major tectonic features of East Texas, southern Arkansas, western Mississippi, and Louisiana during the late Jurassic (Bartberger et. al. 2002). The blue ellipses highlight the three main regional depocenters Study area defined by red oval.

CHAPTER II

TECTONIC FRAMEWORK

Basin History

The Mesozoic rocks found in the Gulf of Mexico Basin and its associated sub-basins record and episode of passive continental margin development (Atwell et. al. 2008). The initial rifting and segmentation of Pangea started in the late Triassic and continued until the Late Jurassic. Counterclockwise rotation and southerly drift of the Yucatan block resulted in the opening of the Proto-gulf area and subsequent flooding from Pacific waters of the topographic low occurring during the Middle to late Jurassic (Callovian and Early Oxfordian) (Atwell et. al. 2008). After the rifting was completed, the crust around the basin cooled and subsided allowing early seaways, and later the deposition and preservation of a thick sedimentary section. Evaporation of the early seas in the Gulf region resulted in the deposition of the Louann Salt which is a major factor in later tectonics.

Local Structural Style

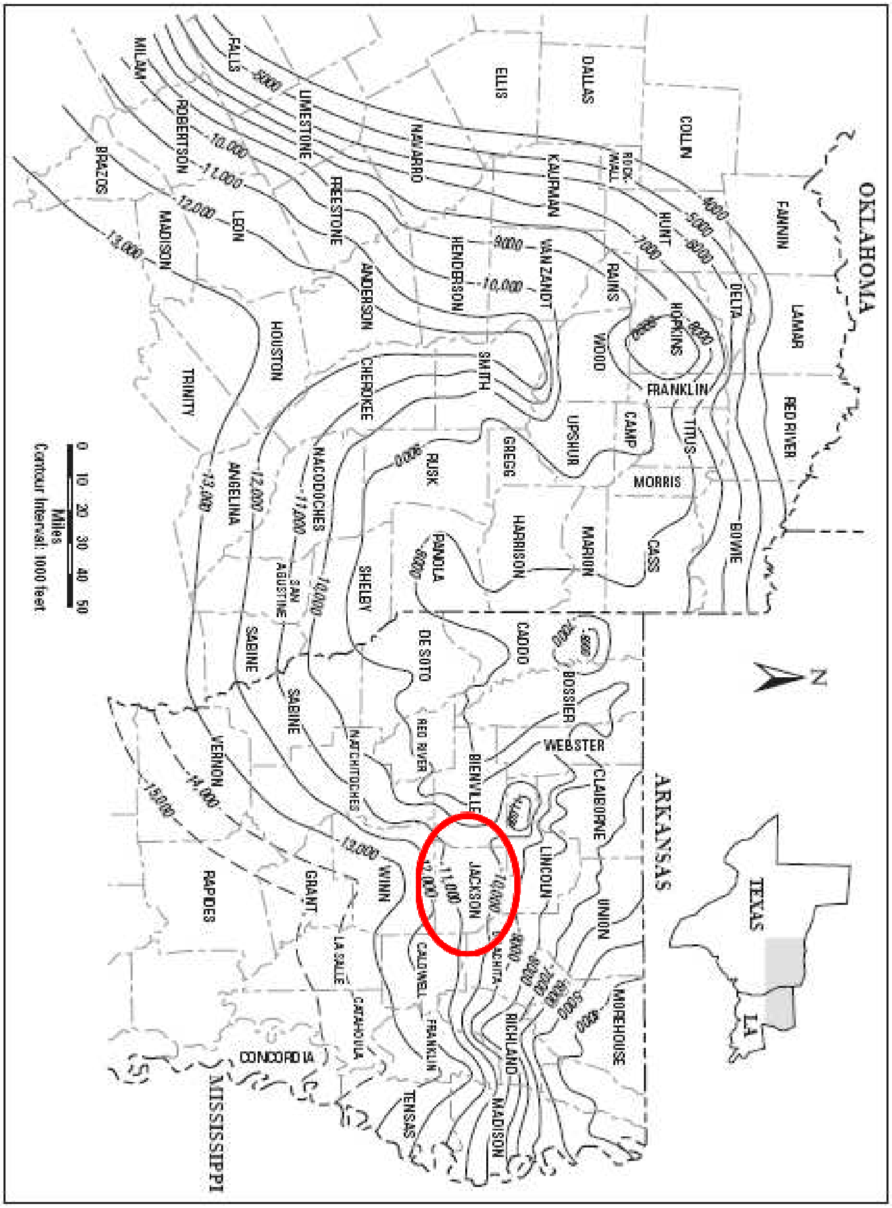
Salt movements in the Gulf region are linked to regional extension (Jackson and Vendeville, 1994). Differential loading of the Louann Salt, coupled with regional tectonically controlled extension, resulted in the mobilization of the underlying salt. This extension also thinned the overburden of the non-evaporite Jurassic sediments above and created weakened fault regions between grabens and half grabens which facilitated salt diapirism (Atwell et. al. 2008).Begin typing or pasting the rest of your chapter 2 text here. As a result of regional extension tectonics, distinct depocenters developed that influenced Cotton Valley Group sedimentation. These depocenters (Figure 1) are located in eastern Texas, northern Louisiana and Southern Mississippi. A regional structure map of the top of the CVG by Bretberger et. al. (2002) is shown in Figure 2.

The depocenters of the Gulf Coast region lie within the “Interior Zone” of the North Gulf of Mexico Basin. Within this zone are three major basins containing salt diapirs; the East Texas Salt Basin, North Louisiana Salt Basin, and the Mississippi Salt Basin. These areas are thought to represent the zones of greatest salt accumulation.

The presence of the thick (up to hundreds of feet thick) Louann Salt deposit at the base of the sedimentary section facilitated complex salt tectonic features in the basins of the region. Between and flanking the main basins, salt features are less distinct or absent, causing the salt to be interpreted as thin or absent. These areas include the Freestone Platform in central Texas, the Sabine Arch along the Texas-Louisiana state line, the LaSalle Arch and parts of the Monroe Uplift in eastern Louisiana, and the Wiggins Arch in southern Mississippi (see Figure 1 for reference). Drilling has revealed that the basement blocks below some of these features are high-standing crustal blocks. This, and their relative paleogeographic expressions causes them to be referred to as “islands” in industry and academic lexicon; the most notable are Sabine Island and Wiggins Island (Ewing, 2001).

The regional extent of the salt is closely paralleled by a “distinctive peripheral graben system” including the Mexia-Talco systems in Texas, the Quitman-Gilbertown systems in Mississippi and Alabama, and the linking systems in southern Arkansas (see the fault zones in Figure 1). These systems represent the cessation of evidence of salt tectonics in the basins, and therefore are thought to represent the boundaries of the salt deposition (Ewing, 2001).

Figure 2. Regional structure map for the Cotton Valley Group (CVG) in East Texas and northern Louisiana from Bretberger et. al., 2002. Approximate location of study area is shown by red oval.



CHAPTER III

STRATIGRAPHIC FRAMEWORK

Regional Stratigraphy

The oldest recognized sedimentary unit in the region is the Middle Jurassic Louann Salt that extends across northern Louisiana, East Texas, and into southern Texas. The aeolian and fluvial siliciclastics of the Norphlet Formation overlie the Louann Salt in most of the Gulf region, although the Norphlet is much thicker in Alabama and Mississippi than in Louisiana and Texas (Ewing 2001). After the Norphlet, the carbonate rich section of late Jurassic (Oxfordian to Kimmeridgian) age (Louark Group) was deposited. This group, which is commonly referred to as the "Haynesville" includes the Smackover, Buckner, Haynesville, and Gilmer Formations. Only limited clastic input was delivered from the north and northwest, allowing extensive evaporite pans (Buckner) to form behind carbonate shoal belts. The end of the Haynesville Formation is marked by a second order flooding surface which caused carbonate deposition to abruptly cease in most of the Gulf Region (Ewing, 2001).

The clastic-dominated Cotton Valley Group was then deposited. As discussed below, the CVG is stratigraphically complex, and varies regionally in its nomenclature. It is loosely interpreted in the literature as two main delta systems; one in east Texas and one in Mississippi with strike fed shoreline sands filling in northern Louisiana. Some conventional references for associated formation names include "Bossier" for the slope and basin shales of the shoreline

Trends, “Schuler” for up-dip alluvial sediments with red-beds, and “Terryville” for strike-fed shoreline sediments in north Louisiana (Ewing, 2001), which includes the study area.

At the end of CVG time, a major transgression led to deposition of sediments that became limestone and limy shale, commonly referred to as the Knowles Limestone. An unconformity in most areas represents an early Cretaceous second order sequence boundary that encompasses the late Berriasian and much of the Valanginian (Ewing, 2001) (Figure 3). After the hiatus, significant amounts of sand (Calvin Sandstones) were deposited on the shelf in Louisiana followed by a transgressive carbonate zone regionally known as the Winn Limestone (Ewing, 2001).

The next unit in the sand-rich sequence is the Hosston Formation. It is characterized as alluvial in origin, and is also sometimes referred to as the Travis Peak in east Texas (Ewing, 2001). After the Hosston Formation, the depositional sequence became carbonate-rich across the region, creating extensive carbonate shoals and shelf-edge limestones known as the Sligo Formation. Above the Sligo are two black shales, the Pine Island Shale, and the Pearsall Shale, followed by more mixed carbonates and clastics in the Trinity Group and younger Cretaceous rocks. The area was overrun by alluvial sedimentation during the Tertiary (Ewing, 2001). Regional relationship between stratigraphic units in each of the three main regions of the study area can be seen in Figure 4.

East Texas

The CVG in east Texas consists of the Bossier Shale at the base, the Cotton Valley Sandstone, and the Knowles Limestone at the top. The Bossier Shale is marine black shale, which extends into southern Arkansas and northern Louisiana. The Cotton Valley Sandstone is also known as the Schuler Formation in the area, and consists of a mixture of sandstones and shales. The Knowles Limestone is described as a mixture of shale, dolomitic limestone, grainstone, and algal boundstone (Heydari and Townsend, 2001). It is noteworthy that the unit known as the Cotton Valley Limestone in East Texas is not considered a member of the CVG. Instead, this limestone consists of shoals and reefs associated with the Haynesville Formation or the Gilmer Limestone (Heydari and Townsend, 2001), which are beneath the CVG (Figure 3).

The actual CVG in the East Texas basin consists of a deltaic sandstone and shale wedge deposited in the Upper Jurassic – Lower Cretaceous (Berriasian). The CVG facies identified here include pro-delta, delta-front, braided streams, and wave dominated shoreline deposits. The majority of natural gas production comes from the shoreline sands and delta-front sands (Turner 1997).

Northern Louisiana

In northern Louisiana, the Cotton Valley Group is characterized by terrigenous clastic sediments thought to be deposited in a generally regressive sequence (Eversull 1985). There are three major stratigraphic units in this sequence: the Bossier Shale, the Terryville Sandstone, and the Hico Shale. These formations grade up-dip (to the north) into the Schuler Formation, which is known for its terrestrial red beds (Eversull 1985). Above these three, the Cotton Valley is represented by the Knowles Limestone which represents a highstand of sea-level.

Gray Sandstone

Oil and gas are produced from upper Jurassic strata in northern Louisiana from a set of closely related sandstone packages known collectively as the “Gray Sandstone”. This name is simply a reference in literature to the Sandstones of the CVG in North Louisiana. Seven fields have been discovered in the play: South Sarepta, Ivan, Cotton Valley, Rocky Mount, Ruston, Sugar Creek, and Terryville. The reservoirs are 10,600-12,000 feet in depth in Cotton Valley Field. These units are among the deepest producing clastic reservoirs in Louisiana, and their discovery came in 1944 with the drilling of the A.H. Gray #1 well (Atwell et. al. 2008). These sandstones have been interpreted as shallow water, tidal flat deposits slumped off growing salt anticlines (Miciotto, 1980), as deep water submarine fans (Judice and Mazzullo, 1982), and most recently as a submarine fan deposit fed by storm events and residing below normal wave base but above storm wave base (Atwell et. al., 2008)

Atwell et. al.(2008) describe the reservoirs of the Cotton Valley Field as lenticular channels filled mostly with sandstone, but thinning laterally into thin sandstone units with intercalated mudrocks. Judice and Mazzullo (1982) notice similar characteristics of the Gray sandstones in Terryville Field. The mixed mud- and sand-rich submarine fan systems have high to moderate reservoir heterogeneity, moderate vertical communication between sandstones, and poor lateral communication (Reading and Richards, 1994). The main traps in Cotton Valley field are set up by the draping and bending of sandstone lobes over a younger, deep seated salt anticline in which the faulting and salt mobilization did not affect the depositional morphology of the sands (Atwell et. al. 2008).

Atwell et. al. (2008) concluded that the Gray sandstones are a complex of individual sandstone lobes clustered at the mouth of a down-dip bifurcating feeder channel system. Atwell (2008) admits that these are somewhat of a stratigraphic enigma because they resemble single point source mud/sand rich submarine fans of Reading and Richards (1994), but they do not appear to have been deposited below storm wave base, so they could not have been deposited in deep basinal waters. Atwell et. al. (2008) suggest perhaps a medial to distal ramp environment as an alternative.

Blanket Sandstones

The Terryville Sandstone units in northern Louisiana separate up-dip (to the north) into several distinct tongues of sandstone which eventually pinch out into the Hico Shale (Eversull 1985). These “blanket sandstones” are described by Eversull (1985) as fine to medium grained, hard, calcareous quartz sandstones which are light grey to white, or tan. They are often associated with oyster beds, and also with organic material such as lignite seams (coal spars). These blanket sandstones are also noted to be better sorted than the sandstone in the main body of the Terryville Formation, and therefore generally have higher permeability and porosity than their down-dip counterparts.

Eversull (1985) studied the blanket sandstones and found that the beds display no relationship to current structural features, implying that the structure is post CVG time. Eversull (1985) also suggests that negligible local topography was likely during the deposition of the blanket sandsstones because the widespread distribution of the blanket sandstones implies that the currents were sufficient to spread the sands evenly across their depositional area. There are anomalies in total CVG thickness that correspond to structural features including: Cotton Valley field in Webster Parish, Louisiana; Lucky field and Bear field in Bienville Parrish; and Hico-Knowles field and Ruston field in Lincoln Parish. These features are interpreted to represent local topographic highs, which locally influenced the deposition of the CVG throughout its deposition.

Eversull's (1985) model (Figure 5) for this system characterizes the massive Terryville sandstones as four stacked elongate, shore-parallel, deltaic/shelf sand complexes produced by progradational, wave-dominated deltas. The blanket sandstones thicken down-dip until they intercept the Terryville suggesting that it is their source. The blanket sands are also cleaner and better sorted than the Terryville and contain shale breaks indicating that they were reworked after their deposition in the Terryville during their intermittent transport up-dip (Eversull, 1985).

This Eversull (1985) model separates the blanket sandstones into two groups, Group I are persistent across most if not all of Eversull's study area. They are between about 70 to 140 ft. thick and pinch out far up-dip into sandy or shaley facies. Group II are varyingly less extensive and are less than 30 ft. thick pinching out into shale. Eversull suggests that Group I were deposited by minor marine transgressions bringing sand from the Terryville up-dip across an inter-deltaic lagoon, while Group II were deposited as smaller washover fans caused by variations in wave activity, current strength, or current direction.

Ewing (2001) reviewed the Cotton Valley Group and concluded that these blanket sandstone systems are still not well understood, pointing out that most are too large to be washover fans and also that they display some shore-face sequences. He suggests that they may represent episodes of barrier bar destruction where sands were transported landward and reworked into shoals.

Mississippi

The CVG is generally characterized in Mississippi as the dominantly clastic beds between the carbonates, clastics, and anhydrites of the Haynesville Formation and the clastics of the Hosston Formation (Moore, 1983). Moore (1983) divided the Cotton Valley Group in Mississippi into three informal sections of equal thickness: a Lower, Middle, and an Upper Cotton Valley. These formations were then evaluated based on well logs along with sand percentage maps produced from over 200 electric logs. The lower unit of the Cotton Valley Group is interpreted as deltaic, and barrier associated sands. The middle unit is similarly interpreted, but the depocenters are shifted to accommodate sea level, and the upper unit contains the Cotton Valley limestones which represents the deepest stand of sea level during CVG times followed by a return to the clastics of the lower and middle units (Moore, 1983).

This split of the CVG in Mississippi into lower, middle, and upper units was still the most common model for its stratigraphy in 2001, according to Heydari and Townsend’s paper from that year. However, they noted that detailed studies of lithofacies in each of the three members of the CVG in Mississippi were needed in order to determine the depositional systems. A regional paleogeographic model can be seen in Figure 6.

Figure 3. Generalized Middle Jurassic to early Cretaceous stratigraphic nomenclature for the Gulf of Mexico (Ewing, 2001).

Figure 4. Regional relationship between stratigraphic units in each of the three main regions of the study area. From Heydari and Townsend, 2001.

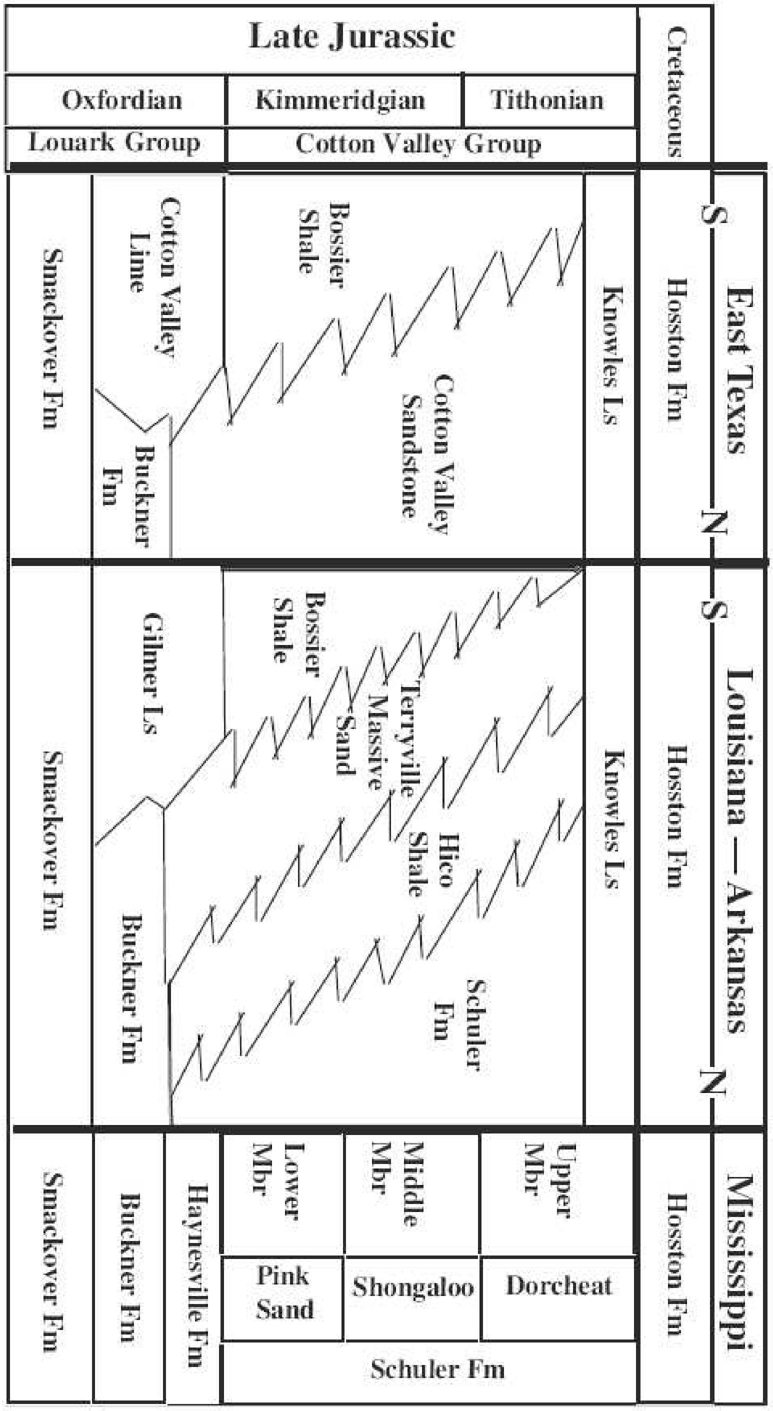
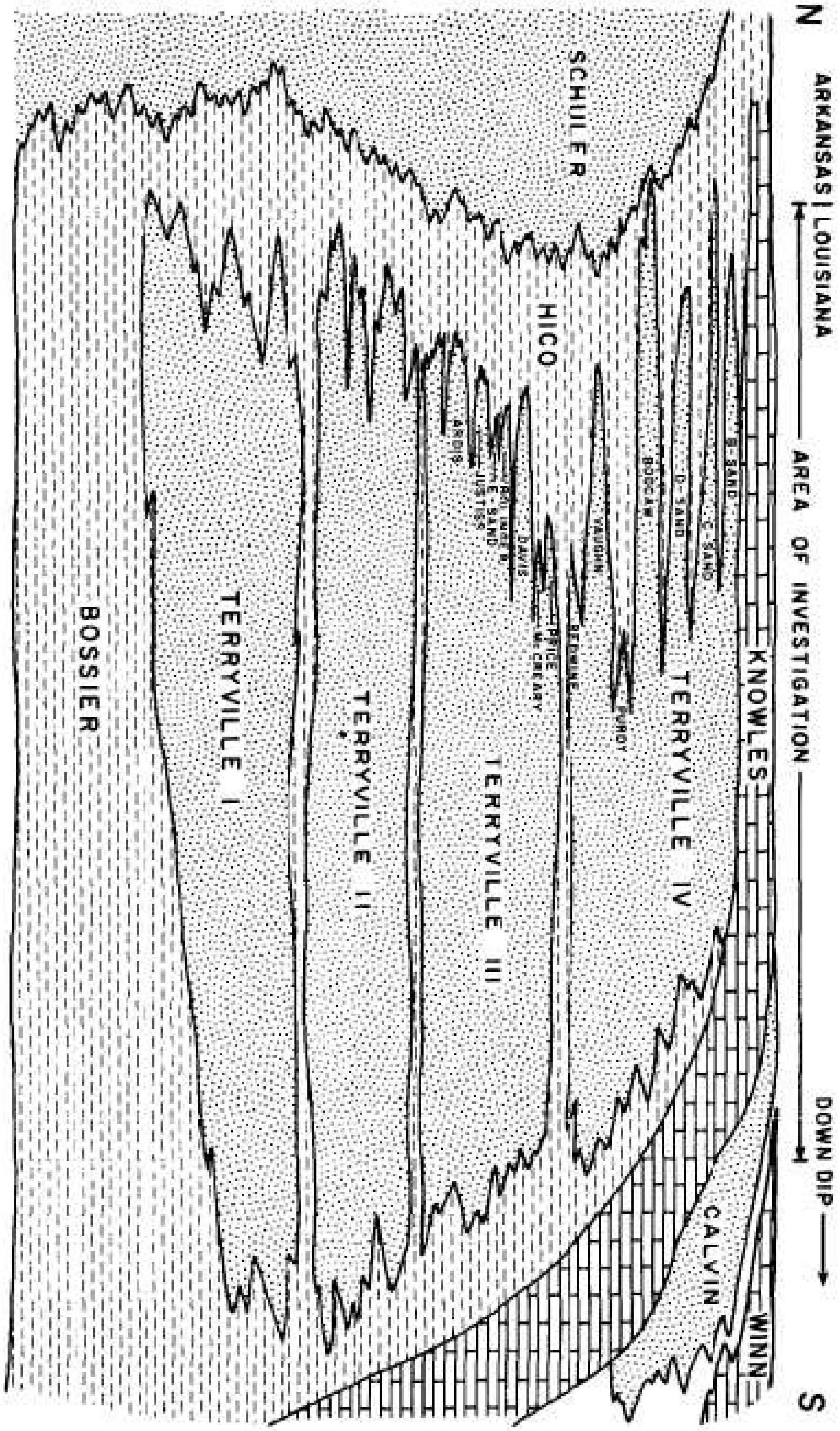


Figure 5. Stratigraphic model for the blanket sandstones and their relationship to the Terryville Sandstone (Eversull, 1985).



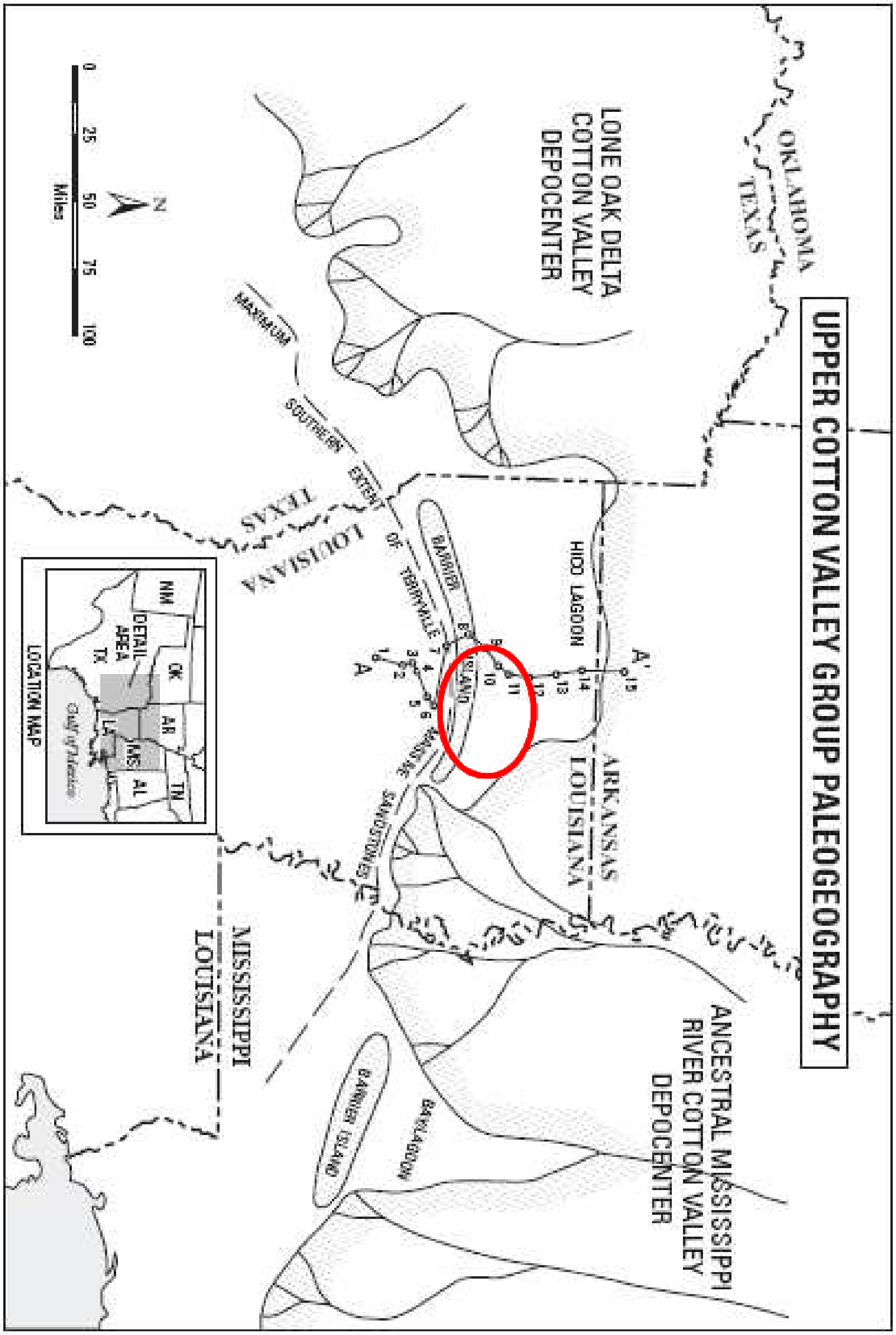


Figure 6. Regional paleogeographic model for the upper CVG from Bretberger et. al., 2002

CHAPTER IV

SEDIMENTOLOGY AND DEPOSITIONAL ENVIRONMENT

Core Descriptions

The eleven cores used in this study were recovered from four wells in the Vernon area (Figure 7). The Davis Bros 29-2 is the southernmost of the cored wells, and three core intervals were studied from it. Core 1 ranges from 13,174ft - 13,246ft; Core 2 from 14,009ft – 14,092ft; and Core 3 from 15,050ft – 15,144ft. Moving north to the center of the field, the second and third wells of the core study are Fisher 16-1 and Fisher 16-2. Core 4 (13,114ft – 13,176ft) and Core 5 (13,714ft – 13,767ft) are from Fisher 16-1. Core 6 (12,420ft – 12,511ft), Core 7 (13,083ft – 13,142ft), and Core 8 (13,657ft – 13,715ft) were cored from Fisher 16-2. The northernmost well in the study is from Kelly Land Management 13-1, from which Core 9 (12,152ft - 12,161ft), Core 10 (12,285ft – 12,426ft), and Core 11 (12,795ft - 12,903ft) were recovered.

The core resides at the Fugro core storage facility in Schulenburg, Texas. One week was spent at the facility describing, logging, sampling, and photographing the core.

Core Facies

The general lithological facies of the cores from Vernon Field include three main groups: mudstones, siltstones, and fine-grained sandstones. These groups can be subdivided into six main facies (see Table 1): (1) grey to brownish mudrock, (2) intermediate mudstone/siltstone, (3) grain supported siltstone, (4) mottled fine-grained sandstone, (5) clean very fine- to fine-grained sandstones, and (6) carbonate cemented siltstones (Figures 8-13).

The six main core facies are described below.

Facies 1 (Figure 8) consists of grey to brownish mudrock which can have significant carbonate in the form of concretions, recrystallized fossil remains, fracture filling cementation, and perhaps soft sediment deformation/injection. Samples C6-01 and C6-02 are from Facies 1 and each contained greater than 50% clay, and show quartz percentages ranging from less than 20% to just over 40% (XRD Analysis – Table 2). Unfortunately, the number of samples analyzed for facies 1, 2, and 3 were limited by funding as well as the difficulty of mounting the fine grained rocks to microscope slides.

Facies 2 (Figure 9) is an intermediate mud/silt facies with grey to brown to tan coloration. It is often heavily burrowed to bioturbated in the form of small (1-2mm wide) burrows which can be pervasive or localized. These small burrows are referred to as “tiny burrows” on field documents and notes, and are interpreted to be polychaete worm burrows. They can also be found in Facies 1, 3, and 4. Facies 2 is matrix supported. Sample C6-07 is from Facies 2 and contained 40% clay and nearly 50% quartz.

Facies 3 (Figure 10) is grain supported siltstone that contains high percentages of authigenic quartz. Facies 3 rock simply falls on the side of the clay/quartz ratio continuum with lower clay content than Facies 2. Soft sediment deformation, bioturbation, and polychaete burrowing are other features found in Facies 3. Samples C2-01 and C2-03 are from Facies 3 and range from 13% to 25% clay and 35% to 50% quartz.

Facies 4 (Figure 11) is very fine- to fine-grained sandstone with mottled texture, and a relatively high percentage of clays. It is vertically burrowed and contains the small polychaete burrows described with Facies 2. Physical sedimentary structures include soft sediment deformation features, cross bedding, horizontal laminations, and tilted laminations. In twelve samples quartz ranges from 60% - 75% and clay matrix from 5% - 18%.

The very fine- to fine-grained sandstones of Facies 5 (Figure 12) have a clean appearance, light tan color, and contain the majority of the sedimentary structures. The main dichotomy between Facies 4 and Facies 5 is F4 has a mottled base texture, while F5 appears more massive even though the bulk mineralogy is similar. This is a continuum similar to that between Facies 2 and Facies 3; i.e. the relative changes are important, but there is not a clear cutoff. Sedimentary structures such as horizontal laminations, tilted laminations, and cross-bedding can be present in either F4 or F5, although they are more common in F5. Based on a set of five samples, quartz ranges from 65% - 75% and clay from 5% - 15%.

Facies 6 (Figure 13) contains light grey highly carbonate-cemented siltstone. Core pieces of this facies react strongly to dilute, cool HCl, are more resistant to breaking than other facies, and break in random patterns rather than along bedding or structural planes. Samples ring like a bell when struck with a rock hammer. This facies is typically thin (less than one foot) and associated with facies 4 and 5. Based on two samples, F6 is around 50% quartz and 35% - 40% calcite; thin section analysis proved these rocks to be heavily calcite cemented siltstones to very fine-grained sandstones.

Wireline Log Characteristics

A type log for Vernon Field can be seen in Figure 14. At the broadest scale, the Cotton Valley section is characterized by alternating zones up to hundreds of feet thick of: 1. higher average gamma ray (Table 3), presumably more clay rich rocks with tight resistivity and porosity readings and 2. lower average gamma ray which tend to represent the ‘cleanest’ appearing sandstones (on logs), with higher porosity. The sandier units take on an overall blocky to coarsening upward trend, but are highly variable from well to well across the field. These larger-scale zones are likely due to changes in morphology of the shoreline systems (wave and current energy, sediment supply, channel meander, etc), or higher-order changes in sea level and the resulting shift of the depositional facies and shoreline seaward or landward.

Both of these types of zones contain lower than shale baseline gamma ray readings, and based on core these are sandy zones, which range in thickness from a few feet to tens of feet. Some of these cleaner zones also have increased porosity, and deep resistivity values up to 8ohmms. Typically the resistivity baseline averages slightly less than 1 ohmm. It is also evident from the gamma-ray logs that the shift from sandstone to shale occurs at a high frequency resulting in the thick sections of interbedded sandstone and shale.

Table 3 shows a statistical evaluation of gamma ray and deep-resistivity values across cored facies classifications. Gamma ray decreases in response to increasing sand content, but delineating between the facies just based on basic wireline logs is next to impossible due to the resolution of data relative to the rate at which facies changes are seen in core. Intuitively the lower gamma ray zones correspond to higher sand ratios, but the facies change at higher frequency than the traditional logs can resolve. Often the best markers for matching core with wireline were the Facies 6 zones where resistivity increased up to 3 ohms, but even these were inconsistent and therefore somewhat unreliable.

Depositional Features

The main features evident in the cores are biogenic structures, sedimentary structures, fractures, inclusions, and concretions.

The biogenic features (Figure 15) include: (1) beds of fossil hash, (2) oyster beds, (3) isolated oyster shells, (4) small worm burrows which are interpreted as polychaete, (5) large vertical burrows interpreted as oyster burrows, and (6) bioturbation.

The sedimentary structures (Figure 16) found in the Vernon cores include flow features such as horizontal and inclined bedding surfaces, and cross-bedding. Sometimes opposing inclined beds are located adjacent to one another. These preserved bedding features display flaser to lenticular bedding or horizontal laminations alternating between differential grain sizes. Rip-up clasts are also seen in these zones.

Soft sediment deformation (Figure 17) is common in the cores, especially along facies changes. Some features even appear to have been injected into the surrounding sediments creating pillows and flame structures.

Vertical and oblique calcite filled fractures (Figure 18) were found in the Vernon cores, but were not pervasive.

Other features found in the Vernon cores (Figure 18) include coal spars inclusions in sandstone; they appear to have been deposited along with the sediments. There were also common calcite concretions and one zone of oxidized colored concretions, which upon XRD (Table 2, C6-02) and thin section analysis are interpreted as exotic chlorite rich concretions.

Tidal Flats

Tidal flat environments occur in open coasts of low relief and relatively low energy as well as protected areas on high energy coastlines associated with estuaries, lagoons, bays, and other areas lying behind barrier islands (Weimer et. al., 1982). These situations allow for the necessary conditions to facilitate a tidal flat: (1) a measurable tidal range, and (2) the absence of strong wave action. Modern analogues (Figure 19) of tidal flats range in size from localized areas of several hundred square meters to regional features spreading over hundreds of square kilometers. Variations depend on: (1) sediment type and supply, (2) presence or absence of vegetation, (3) tidal range, (4) coastal energy and morphology. Most preserved deposition occurs from the lateral accretion and progradation of meandering tidal channels so that much of the sedimentary records for tidal flats are features associated with channel fill and tidal point bars (Figure 20) (Weimer et. al., 1982).

There are two general facies associated with tidal flat environments (Figure 21). The first is the intertidal facies which is deposited between high and low tide. These deposits dominate the areal extent of the tidal flats although they are seldom preserved because they are constantly reworked into tidal channels during alternating tides. Intertidal deposits typically display alternating layers of mud and sand, which vary in ratio due to tidal action and system dynamics. These various ratios are modeled conventionally in Weimer et. al. (1982) as mud flats, sand flats, and mixed flats (Figures 22 and 23) depending on the grain size of the dominant sediments. The second general facies is the subtidal facies which is deposited below low tide. The subtidal facies are more commonly preserved during deposition, and typically consists of channel fill and progradational point bars which are discontinuous and therefore difficult to map individually without extreme well control. Comparison of modern tidal flats to ancient tidal flats can be misleading because the facies which are most prevalent during deposition are the least likely to be preserved; when they are preserved however, intertidal deposits are typically only thin veneers overlying channel fill sequences (Weimer et. al., 1982).

Flora and fauna can play important roles on a tidal flat environment because they: (1) trap sediments, (2) create sediments like peloids and shells, (3) form biogenic sedimentary structures and bioturbation from feeding, dwelling, or moving, (4) leave trace fossils often well preserved and visible due to the alternating mud/sands of the tidal flat, and (5) leave zones of shells which can be preserved whole or in a disarticulated state (Figure 24) (Weimer et. al., 1982). Generally ecological diversity is low in these environments, but the number of individuals can be large. Extreme and varied currents, water depths, salinity, temperatures, desiccation, erosion, and deposition make for a “biologically rigorous” environment, so the critters who live in tidal flats must be well adapted and flexible to these varying conditions. Typically, areas of slower sedimentation like intertidal flats can be highly bioturbated while areas of progradation or point bar construction tend to have no to only very slight bioturbation or reworked/disarticulated biogenic material (Weimer et. al., 1982).

Both intertidal and subtidal sediments can be affected by tidal and wave currents. These currents are highly variable based on regional and local geomorphology, height and stage of the tide, and strength and direction of local and prevailing winds. Energy of these currents and waves may vary widely within the period of one tidal cycle as well as over other orders of magnitude based on climate conditions, tectonic cycles, and other forcing mechanisms. This, coupled with variations in sediment supply, leads to a continuum of sedimentary structures and facies changes. Particularly important for the identification of a tidal flat environment are bidirectional structures resulting from the ebb and flow of the tides (Weimer et. al., 1982).

Tidal flats that develop under regressive or prograding conditions have an overall fining upward sequence. This reflects the slowing energy as the deposition moved from high energy subtidal zones to lower energy intertidal zones. This also applies laterally as a researcher would expect grain size to grow larger distal from shore. This change in energy typically results in one of three depositional facies: (1) A dominantly sandy subtidal zone of channel-fill, point bar, and shoal (barrier bar) sediments, (2) a mixed sand/ mud intertidal flat deposit, or (3) a muddy upper intertidal flat or salt marsh deposit (Weimer et. al., 1982).

Despite many sedimentary structures being observed in tidal flats, no structures appear to be explicitly tied to them, so recognition of tidal flats requires examination of individual features as well as the relationships between lateral and vertical facies. Tidal flats typically have an inverse relationship of biologic structures and physical sedimentary structure. Distal facies are more channel dominated and therefore contain physical sedimentary structures whereas proximal facies show more biogenic activity and less physical structures (Weimer et. al., 1982). Channel fill (Figure 25) from the subtidal facies can contain mega ripples and large-scale-trough crossbedding as well as small scale current ripples and flaser bedding. Intertidal deposits typically contain intertidal sand/mud layering (including flaser, wavy, and lenticular bedding), while upper intertidal surfaces are often heavily bioturbated or contain slightly laminated muds with thin sand lamina. Where large quantities of biologic entities are present, all structures can be destroyed by intense burrowing, bioturbation, or profuse tracks and trails (Weimer et. al., 1982).

Depositional Interpretation

The rocks of the CVG in Vernon field contain many features that are consistent with the features of modern tidal flat systems. First, there is an increase in grain size in the cores moving distally from shore, and this trend holds when extrapolated to the entire section judging from wirleline logs as well. Sedimentary structures, although not pervasive, are common and represent a wide range of energies and flow directions – including bidirectional wave forms very near one another. In subtidal facies where sedimentary structures are not present, the rocks often display a mottled texture which may be due to sediment reworking from the muds of the intertidal facies with the sands and silts which are transported in subtidal channels, or heavy bioturbation from oysters and other burrowing biota which are observed in many cores. The cores of the CVG also display an inverse relationship between biological structures and sedimentary structures wherein the distal facies (down-dip) contain more structures while the proximal (up-dip) facies display more biological activity. Moving up-dip toward the continent, the cores generally become more and more mud dominated even though the few sandy areas are similar to the sands seen in the more distal cores. These sandstones appear to be genetically related based on their overall mineralogy and texture, but they are on the opposite ends of the mud/sand ratio. This lends itself to a tidal flat interpretation because tidal flats typically display a coarsening of grain size moving distally from shore due to the nature of tidal energy.

Due to the narrow context of core, it is impossible to see whether mega-ripples and large scale trough cross bedding are present, however there were many instances of tilted bedding in sandy intervals that could be interpreted as an expression of these subtidal features. Other subtidal features of tidal flats include small scale current ripples and flaser bedding, which are observed in the sandstone facies of these cores. Intertidal sediments contain flaser, wavy, and lenticular bedding which are diagnostic of a tidal flat environment (Weimer et. al., 1982), as well as heavy bioturbation and laminated mud-sand intervals.

Another line of evidence for the tidal flat interpretation is that the oil and gas being produced from the CVG is hypothesized to have matured in place, and that the kerogen is of type III (Goddard et. al. 2008). Together these indicate that there was a woody marsh just upstream producing sufficient organic matter, and that it was then trapped within the sediments, and subsequently underwent hydrocarbon-genesis during burial diagenesis. Core 1 displays a coal spar in sandstone (Figure 18), which also supports the hypothesis that there was a salt marsh environment or other accumulation of organic matter upstream from the main tidal flat area, which is typical of tidal flat environments (Weimer et. al., 1982).

Tidal flats are often associated with shallow lagoons and estuaries where tidal forces are more powerful than currents and wave action. The traditional interpretation of the CVG time in northern Louisiana fits this type of environment due to flanking deltaic systems in east Texas and Mississippi and barrier bar systems in central Louisiana (Figure 6) largely blocking current and wave actions; these deltas and barrier bars would also provide proximal and distal sources for the tidal transport of sands and silts of the CVG into Vernon Field.

Little of a tidal flat is typically preserved, and in such low circulation waters and the closed-off regional setting from main oceans the sediments are reworked constantly by the tides

(Weimer et. al., 1982). The facies found in the core are representative of certain preserved sediments within the TF system, and they will be discussed below.

While more evidence is needed, the Cotton Valley Group sandstones are interpreted as a dynamic long-lived tidal flat deposit. Little else fits with the array of structures and other features of these cores, and a tidal flat could have been set up in the lagoonal setting of the present north Louisiana region during the deposition of CVG.

Depositional Facies Analysis

Tidal flat deposits consist of two main facies, intertidal and subtidal. Intertidal facies are deposited between high and low tide, which means they commonly display alternating layers of mud and sand. Intertidal facies of tidal flats make up the areal extent of the deposit while they are active, but are not commonly preserved because they are constantly reworked into the subtidal deposits. Subtidal deposits are deposited below low tide, and make up the vast majority of preserved rock in ancient tidal flat deposits. Channel-fill material including prograding point bars and shoaling barrier bars are the most common types of deposits seen in subtidal tidal flat deposits.

According to Weimer et. al. (1982), there are three main depositional facies associated with tidal flats; (1) A dominantly sandy subtidal zone of channel-fill, point bar, and shoal (barrier bar) sediments, (2) a mixed sand/ mud intertidal flat deposit, or (3) a muddy upper intertidal flat or salt marsh deposit. These are highly generalized and represent somewhat of a continuum of depositional facies.

The facies observed in the cores were considered in the context of a TF environment.

Facies 1 – Mudrocks in these cores could represent one of two depositional settings. One would be pro-delta marine muds deposited when sea level rose and flooded the tidal flat system.

These prodelta sediments would be associated with the flanking delta complexes of eastern Texas and Mississippi. The other setting for these mudrocks would be upper tidal flat intertidal deposits such as muddy upper intertidal flat or salt marsh deposits, which are commonly reworked by bioturbation causing them to lose their classic layered structure. In terms of sea level fluctuations, the mudrocks represent the endpoints with the prodelta marine mud reflecting the highest sea levels and the upper intertidal muds representing the lowest sea levels. Although they are not a part of this study, the author has observed redbeds in other unreleased cores from the Vernon area. These represent the very lowest sea levels when the area was subjected to alluvial sedimentation and oxidation as a result of subaerial exposure.

The delineation of the types of mudrock in the CVG at Vernon field, deserves further study. It is possible the deeper prodelta mudrocks would have less calcite and bioturbation, and be more fissile than the intertidal muds where carbonate is derived from allochems such as the oysters and bivalves that live in the tidal flat environment.

Facies 2 and 3 – These muddy to silty facies are interpreted as a lower intertidal mixed sand/mud deposit. Facies 2 and 3 form a continuum in which the only distinction between them is that one is matrix supported while the other is grain supported. While some of the rocks labeled Facies 1 are upper intertidal, with very little detrital quartz, Facies 2 and 3 would be rocks of similar genetic properties, but with a significant amount of silt to fine sand sized quartz (>25% based on XRD) and rock fragments. Similar to the intertidal Facies 1, Facies 2 and 3 sediments were moderately to heavily bioturbated and contained allochems of oysters and bivalves which can be whole, but are typically disarticulated.

Facies 4 and 5 - These siltstone to fine-grained sandstone facies of the CVG at Vernon Field represent the dominantly sandy subtidal zone of channel-fill, point bar, and shoal-barrier bar sediments. Facies 4 and 5 contain the vast majority of the sedimentary structures, although they are not exclusively structured. Some of these subtidal coarser-grained rocks display a mottled texture wherein any sedimentary structures which may have been present are destroyed. This destructive homogenization could be from bioturbation or soft sediment deformation. The structures observed in the subtidal facies of the CVG Vernon cores include horizontal bedding, inclined bedding, and crossed bedding. In some cases inclined bedforms are oriented in opposite directions within the same bed, and even adjacent to one another. These bidirectional features (Figure 16a) are attributed to the ebb and flow within tidal channels.

Within this subtidal interpretation, the Facies 4 rocks with more mottled textures and less sedimentary structures represent the shoaling barrier bar sediments and channel fill, whereas the cleaner and more structured sands of Facies 5 would represent the point bars that are better sorted. Cored Facies 5 is less common and likely the result of the constant reworking in subtidal channels and destruction by bioturbation and soft sediment deformation.

Facies 6 – These heavily carbonate cemented zones are found in association with any facies with significant quartz, and are often found near oyster accumulations. This facies is interpreted as being more of a diagenetic feature than a depositional one. During burial, calcite derived from bioclast dissolution could have mobilized and re-precipitated as cement in nearby porous beds. This may explain why the calcite cementation is associated with rocks from a variety of facies.

Figure 26 shows the depositional model of the sediments at Vernon. It is adapted from the Eversull (1985) paper on the “blanket sandstones” seen in Figure 5. It is not to scale, but it places the main body of Vernon field in the central area of heavily mixed and inter-tounged sands and muds with the KLM-13 well showing more up-dip in the more mud-dominated proximal setting.

Figure 27 displays the depositional model with the general depositional facies overlain onto its dominant area of deposition. It is likely that all facies may be able to be found in any of these areas; the overlay is simply pointing out the one that would be most common or dominant.

The sandstones of the CVG in the region occupy a pocket within the mud/shale facies that dominate the subsurface. The furthest down-dip sandstones are the strandplains of the Terryville Sandstone which were theoretically transported by longshore currents and deposited at the mouth of the “Hico Lagoon” (Figure 6). Updip from the Terryville Sandstones is a zone dominated by mostly subtidal sandstones of the distal parts of the tidal flat systems. Moving further updip brings us across the zones dominated by intertidal siltstones, and then intertidal mudstones, until the sandstone pinches out into the Hico Shale, which encapsulates the sandy zones.

The Terryville strandplain sediments may have been intermittently worked into barrier bars. Behind these bars, in the calm “Hico Lagoon”, tidal flat systems could have evolved under the proper conditions, and the evidence supports such an interpretation. These systems would have transported sand from the Terryville sand deposits updip and potentially mixed it with other sediments from the flanking deltaic systems creating large areas of blanketed sand over their lifetimes. Each cycle of sedimentation set up a new tidal flat system and in such a manner these were stacked over the late Jurassic and very early Cretaceous into the thousands of feet of section evident today

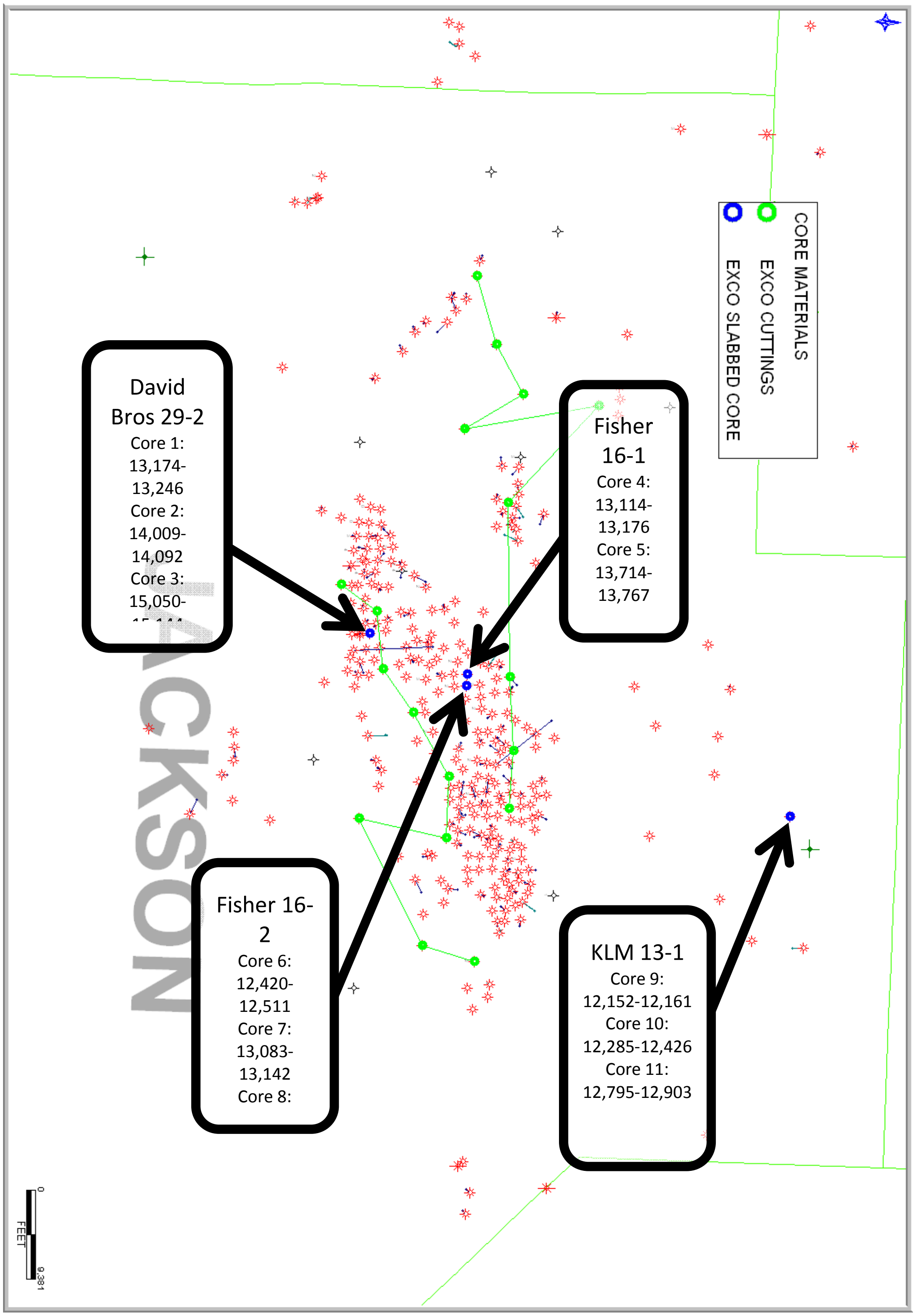


Figure 7. Map of Vernon Field showing locations of cored wells and their respective cored intervals.

Facies Name	Physical Attributes	Depositional Interpretation	
F1	Grey to Brown Mudrock, > 50% Clay, 20-40% Quartz	Mud-Flats and Mixed-Flats	Upper Intertidal
F2	Grey/Brown/Tan - Mud/Siltstone, Heavily Burrowed to bioturbated, Matrix Supported, Only sample was 40% Clay & 50% quartz		Lower intertidal to shoaling-barrier-bars of channel-fill
F3	Grey/Brown/Tan Siltstone, Grain Supported, 13-25% Clay, 35-50% Quartz		
F4	Very fine to fine Sandstone, Grey to Tan, Mottled Texture, Burrowed, Horizontal and inclined laminations,60-75% Quartz, 5-18% Clay	Sand-Flats	
F5	Very fine to fine "clean" Sandstone, Grey to Tan, Contains most Sedimentary Structures, Horizontal and inclined laminations, Cross-bedding, 65-75% Quartz, 5-15% Clay	Mixed-Flats and Sand- Flats	Sub-tidal channel-filling pointbars
F6	Lt. grey carbonate cemented sandstone, Strong Reaction to HCl, Very brittle, Low to 0% Porosity, 50% Quartz, 35-40% Clay	Biogenically and Diagenetically Controlled Diagenetic Phenomenon	Biogenically and Diagenetically Controlled Diagenetic Phenomenon

Table 2. – Bulk Mineralogy of samples from the Cotton Valley interval as determined by X-Ray Diffraction. Provided by Core Lab.

Depth	Sample ID	Quartz	K-Feldspar	Plagioclase	Calcite	Dolomite & Fe-Dolomite	Apatite	Siderite	Pyrite	Total Clay	Illite/ Smectite *	Illite & Mica	Kaolinite	Chlorite	%Gypsum Removed	%Barite Removed	%Halite Removed
13193.00	C1-02	75.2	0.2	6.9	1.2	11.3	0.0	0.0	0.6	4.5	0.0	2.7	0.0	1.8	0.0	1.2	0.0
13209.00	C1-04	70.9	0.6	13.6	1.0	1.2	0.0	0.0	0.9	11.8	0.0	8.3	0.0	3.5	1.4	0.0	0.2
13234.00	C1-05	73.0	0.5	12.2	3.9	1.9	0.0	0.0	0.9	7.5	0.0	5.1	0.0	2.4	0.3	0.8	0.0
13240.00	C1-06	74.9	0.0	10.0	3.4	5.1	0.0	0.0	1.1	5.6	0.0	3.3	0.0	2.2	0.0	0.0	0.0
14019.00	C2-01	50.8	0.2	10.7	18.4	3.2	1.1	0.0	2.2	13.3	0.0	9.1	0.0	4.2	0.6	0.0	0.0
14033.00	C2-02	38.0	0.7	6.3	4.5	1.2	0.0	0.0	2.1	47.2	0.0	29.7	0.0	17.6	0.8	0.0	0.0
14050.00	C2-03	36.5	0.5	6.6	10.1	17.9	0.0	0.0	3.5	24.9	0.0	18.9	0.0	6.0	1.1	0.0	0.0
14076.00	C2-05	40.5	0.9	7.5	8.3	1.4	0.0	0.0	2.4	38.8	0.0	25.1	0.0	13.7	0.0	0.0	0.0
14083.00	C2-06	39.2	0.9	6.8	19.2	1.7	0.0	0.0	3.5	28.6	0.0	19.6	0.6	8.5	1.1	0.0	0.0
15062.00	C3-02	48.6	0.8	15.0	25.1	2.7	0.0	0.0	2.3	5.5	0.0	2.9	0.0	2.6	0.0	0.0	0.0
15065.00	C3-03	45.7	0.6	9.1	6.4	0.2	0.0	0.0	2.1	35.8	0.0	23.5	0.0	12.3	0.3	0.0	0.0
15101.00	C3-04	66.4	0.3	16.4	1.1	2.7	0.0	0.0	1.4	11.8	0.0	8.3	0.2	3.3	0.5	0.0	0.0
15109.00	C3-05	61.8	0.5	14.8	4.3	4.4	0.0	0.0	1.3	12.9	0.0	8.9	0.0	4.0	0.6	0.0	0.0
15124.00	C3-06	40.1	0.5	7.7	7.0	0.6	0.0	0.0	2.6	41.4	0.0	27.5	0.0	13.9	1.0	0.0	0.0
13125.00	C4-01	48.6	0.4	9.7	38.3	0.0	0.0	0.0	0.5	2.6	0.0	1.9	0.0	0.7	0.0	0.0	0.0
12424.00	C6-01	41.7	1.0	5.9	0.0	0.0	0.0	0.0	0.8	50.6	0.0	37.8	1.2	11.6	0.0	0.0	0.0
12423.00	C6-02	17.6	0.3	1.1	1.5	0.0	4.8	7.3	0.0	67.4	0.0	5.4	5.2	56.8	0.0	0.0	1.0
12453.00	C6-04	76.7	0.0	8.9	3.3	0.8	0.0	0.0	1.1	9.1	0.0	7.1	0.0	2.0	0.0	0.0	0.0
12483.00	C6-06	64.4	0.3	14.4	6.5	0.5	0.0	0.0	1.6	12.3	0.0	7.6	0.0	4.7	0.2	0.8	0.0
12500.00	C6-07	49.2	1.6	5.4	0.3	0.0	0.0	0.4	2.9	40.1	0.0	33.9	0.6	5.6	2.8	0.0	0.0
13083.00	C7-01	49.2	0.7	10.9	36.5	0.0	0.2	0.0	0.6	1.9	0.0	1.4	0.0	0.5	0.0	0.0	0.0
13095.00	C7-02	68.6	0.6	14.0	1.5	0.0	0.0	0.0	3.6	11.7	0.0	8.2	0.0	3.5	1.4	0.0	0.0
13118.00	C7-03	63.9	0.3	13.5	5.5	0.3	0.0	0.0	2.1	14.3	0.0	8.4	0.0	6.0	0.0	0.0	0.0
13121.00	C7-04	63.8	0.7	11.9	4.4	4.9	0.5	0.0	2.0	11.8	0.0	8.1	0.0	3.7	0.3	0.0	0.0
13131.00	C7-05	46.2	0.8	8.5	3.9	0.2	0.0	0.0	2.3	38.1	0.0	28.8	0.0	9.4	0.6	0.0	0.0
13139.00	C7-06	62.8	0.5	15.3	1.7	0.3	0.0	0.0	0.9	18.3	0.0	8.7	0.0	9.6	0.5	0.0	0.0
13672.00	C8-01	67.6	0.0	10.1	3.0	3.3	0.0	0.0	1.3	14.7	0.0	10.0	0.0	4.6	0.0	0.0	0.0
13684.00	C8-02	67.7	0.0	11.3	6.6	1.3	0.0	0.0	1.6	11.5	0.0	6.8	0.0	4.7	0.4	0.0	0.0
13696.00	C8-03	71.1	0.4	13.7	3.0	0.4	0.0	0.0	1.0	10.3	0.0	5.7	0.0	4.6	0.0	0.0	0.0
13704.00	C8-04	75.1	0.0	10.5	1.5	0.7	0.0	0.0	0.5	11.6	0.0	5.2	0.0	6.5	0.0	0.0	0.0
	averages	64.8	0.3	11.9	3.7	1.4	0.1	0.0	1.5	16.3	0.0	10.2	0.0	6.1	0.2	0.0	0.0

C10-001: Carbonate concretions

C5-003: Calcareous Mudstone, Fossil hash

C3-005: Calcareous Mudstone

C6-005: Oxidized colored concretions in mudstone

C3-002: Preserved Bedding

C2-002: Carbonate Concretions

C2-003: Fossil Hash

C11-002:
Polychaete
Burrows

C11-001:
Polychaete Burrows

C4-008:
Mottled Texture

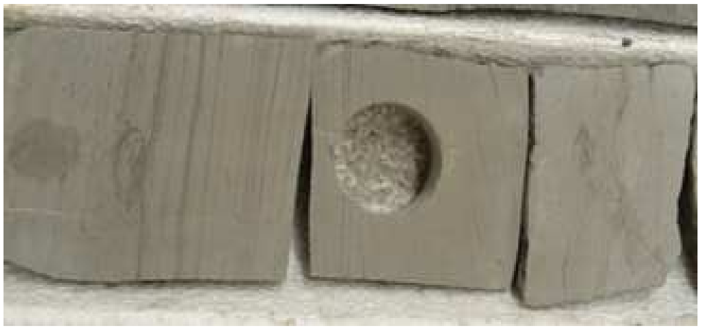
C1-006:
Approx. 18% detrital clay

C3-003:
Large Vertical Burrow

C4-005:
Floating oyster shell, fossil hash

C1-005: Cleanest Sandstone

C4-002: Trough Cross-bedding

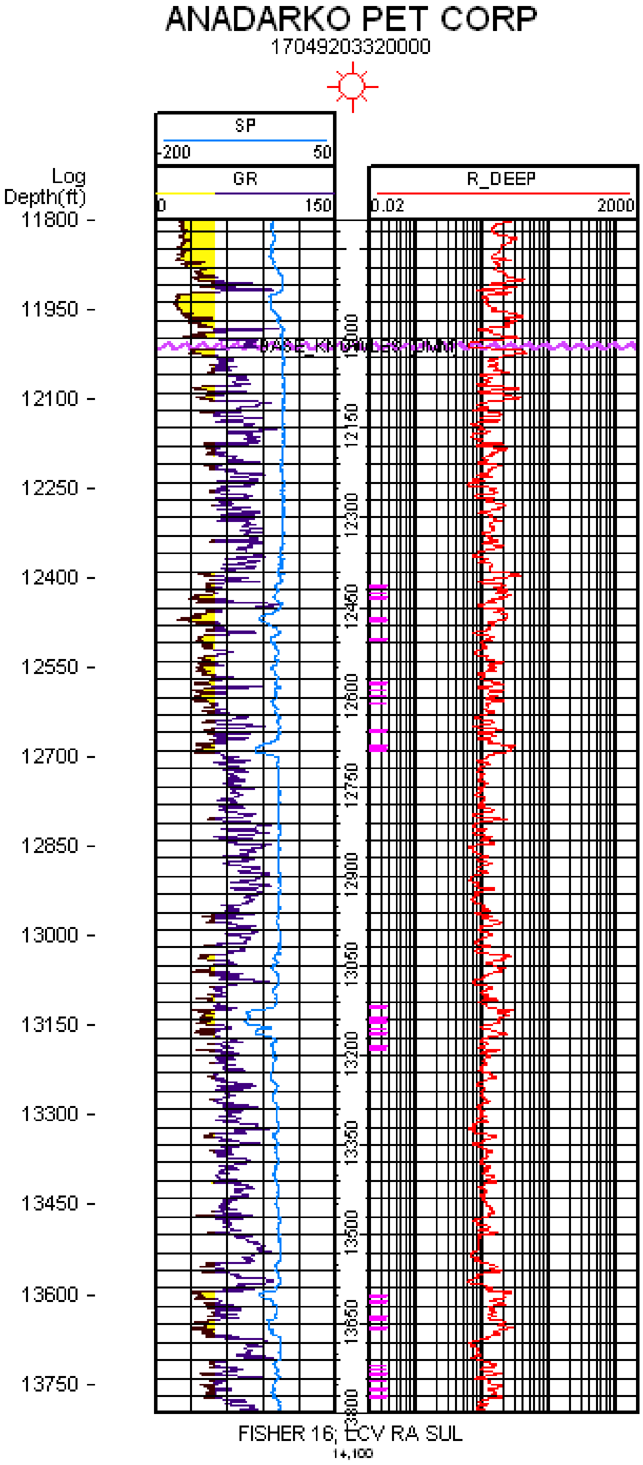


C8-003: Preserved bedding

C4-004: Preserved deformation, tilted bedding, possible large scale cross-bedding

C7-002:
Fossil Hash in Facies 6

C1-008:
Carbonate Cemented Sandstones

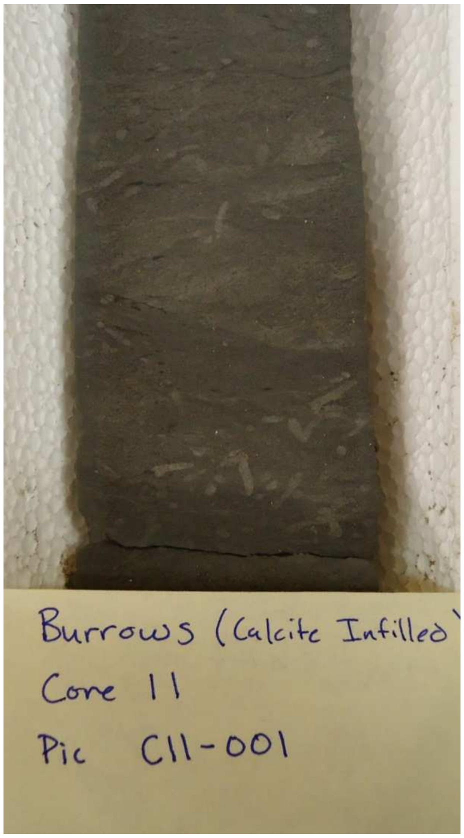

ANADARKO PET CORP
17049203320000
SP
-200
50
GR
0
150
R_DEEP
0.02
2000
Log Depth(ft)
11800
11950
12100
12250
12400
12550
12700
12850
13000
13150
13300
13450
13600
13750
12000
12150
12300
12450
12600
12750
12900
13050
13200
13350
13500
13650
13800
BASE_KNOWLES_LMM
FISHER 16; LCV RA SUL
14,100

Facies	Gamma Ray			Deep Resistivity		
	Mean	Median	Standard Deviation	Mean	Median	Standard Deviation
1	84.88	82.44	20.45	3.57	2.36	3.29
2	68.06	65.35	18.41	4.01	3.29	2.41
3	60.58	55.97	17.82	5.04	4.01	3.44
4	56.67	53.80	14.67	5.10	4.42	2.82
5	63.48	63.49	14.22	4.81	4.21	2.52
6	-	-	-	-	-	-

C6-006:
fossil hash

C1-003:
Oyster Bed

C4-005:
Floating oyster shell



C11-001:
Polychaete Burrows

C1-002:
Large Burrow

C4-008:
Bioturbation

C6-004: Horizontal Bedding Planes

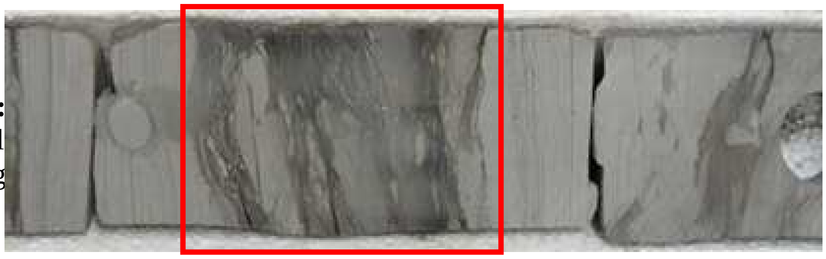
C4-007: Tilted Bedding planes

C4-002: Trough Cross-bedding

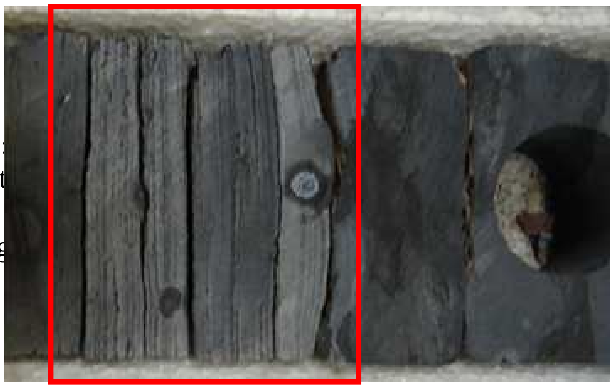
C4-004: Adjacent opposed tilted bedding

C6-007: Flaser bedding

C8-004: Lenticul Bedding



C3-002: Alternat g Bedding



C5-004: Rip up clasts

C1-004: Sediment Deformation

C4-006: Sediment deformation, paused injection event, Facies 4 type

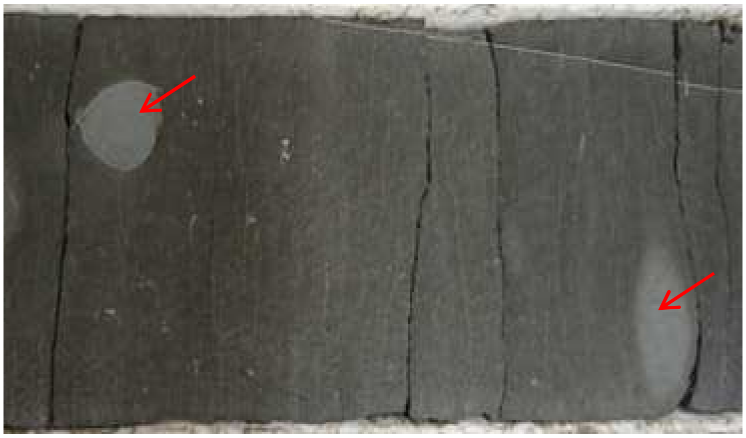
C6-002: Soft sediment deformation, Pillow of calcareous mud injected into non calcareous mudstone

C7-001: Mud injection, sharp change from clean to mottled texture

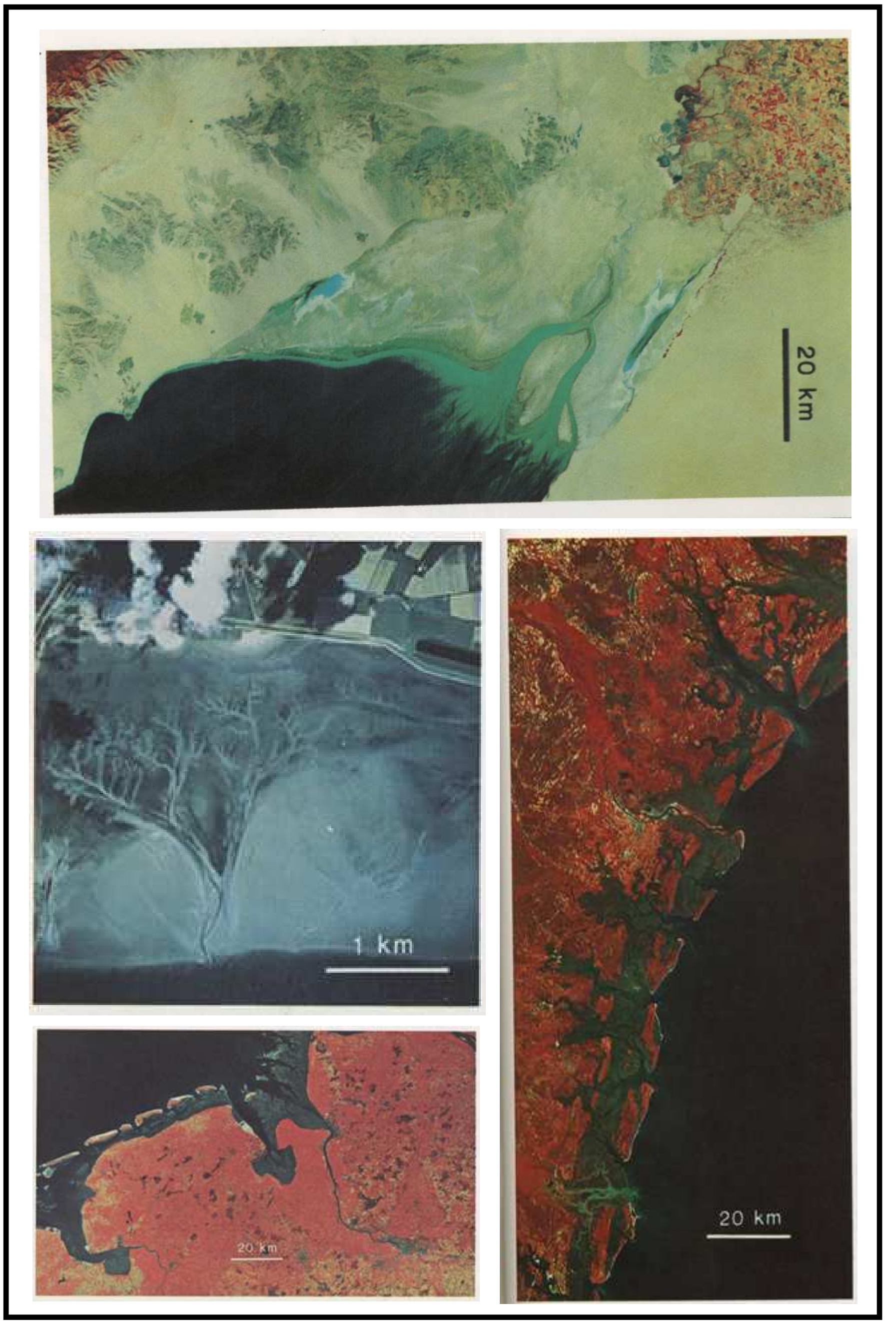
C11-003: Calcite filled vertical fracture

C1-001: Coal Spar

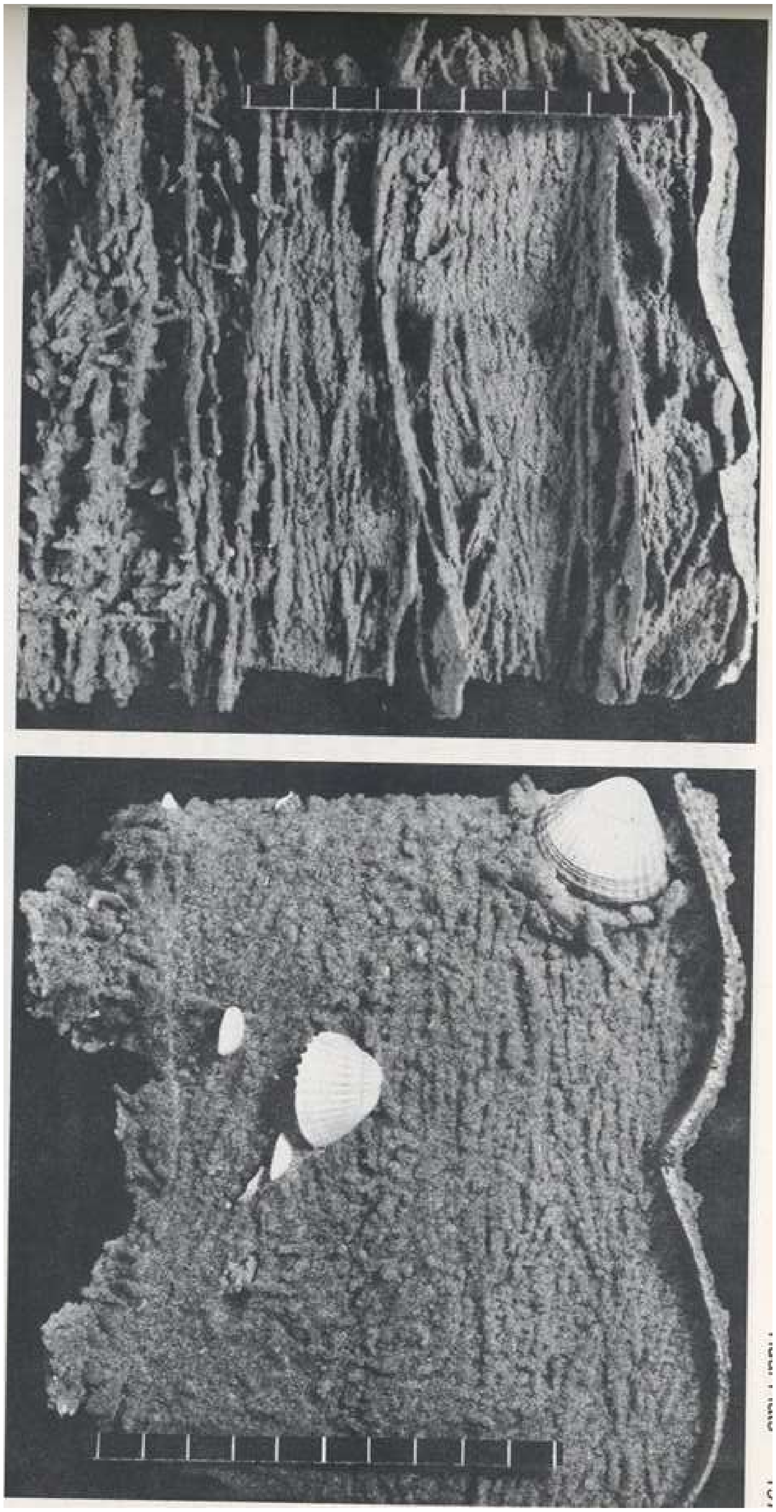
C10-001: Carbonate concretions

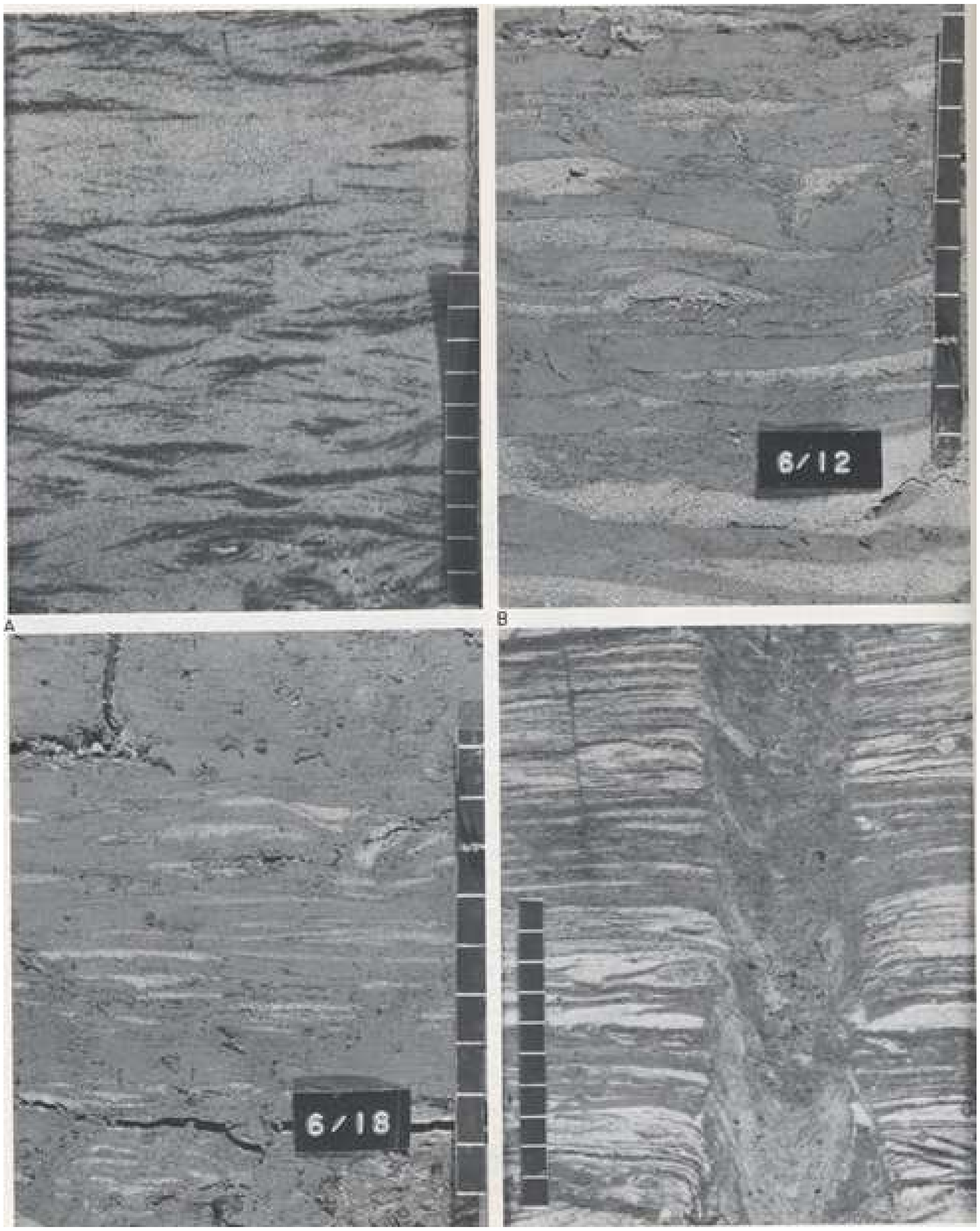


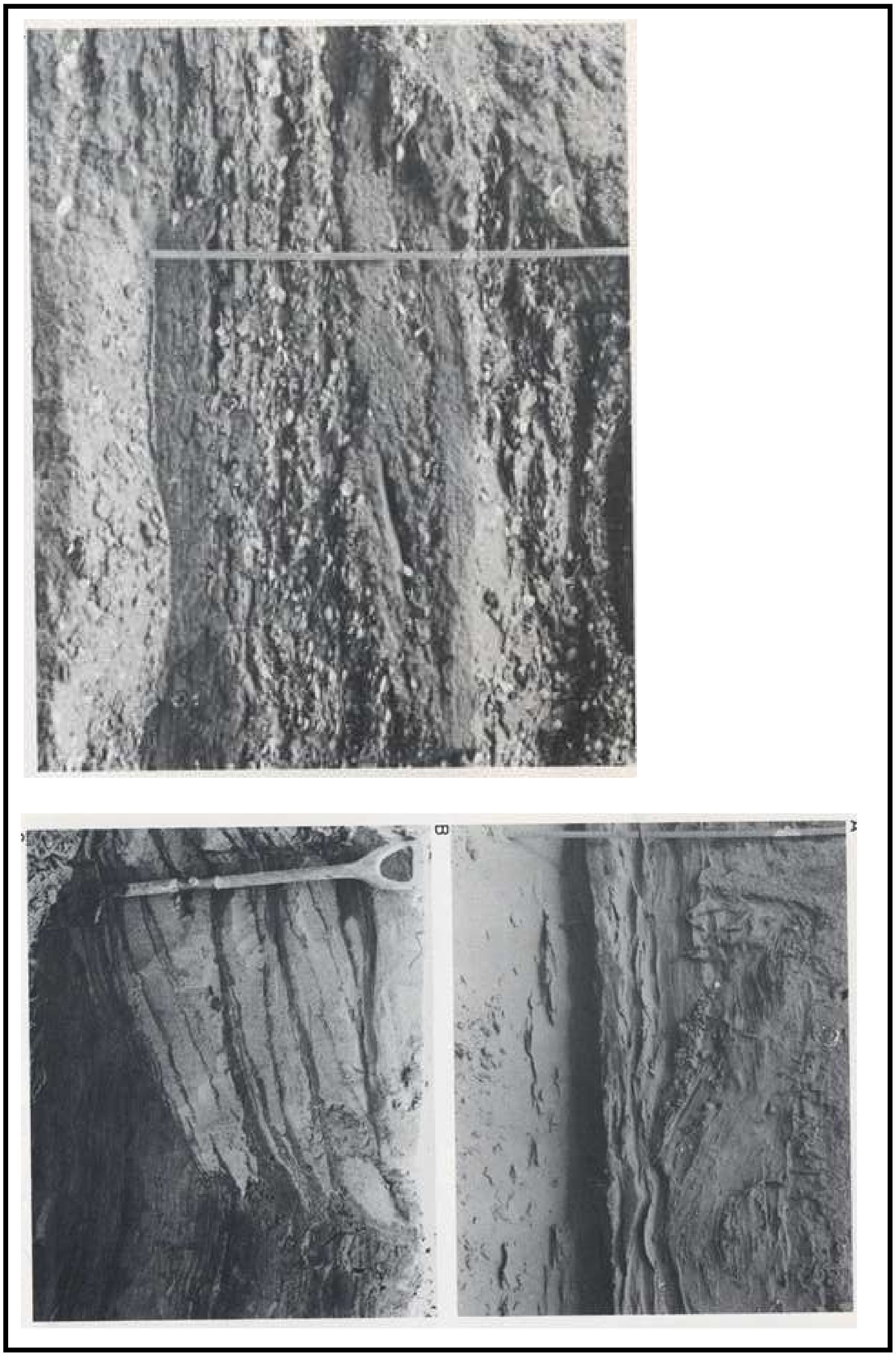
C6-005: Oxidized colored concretions

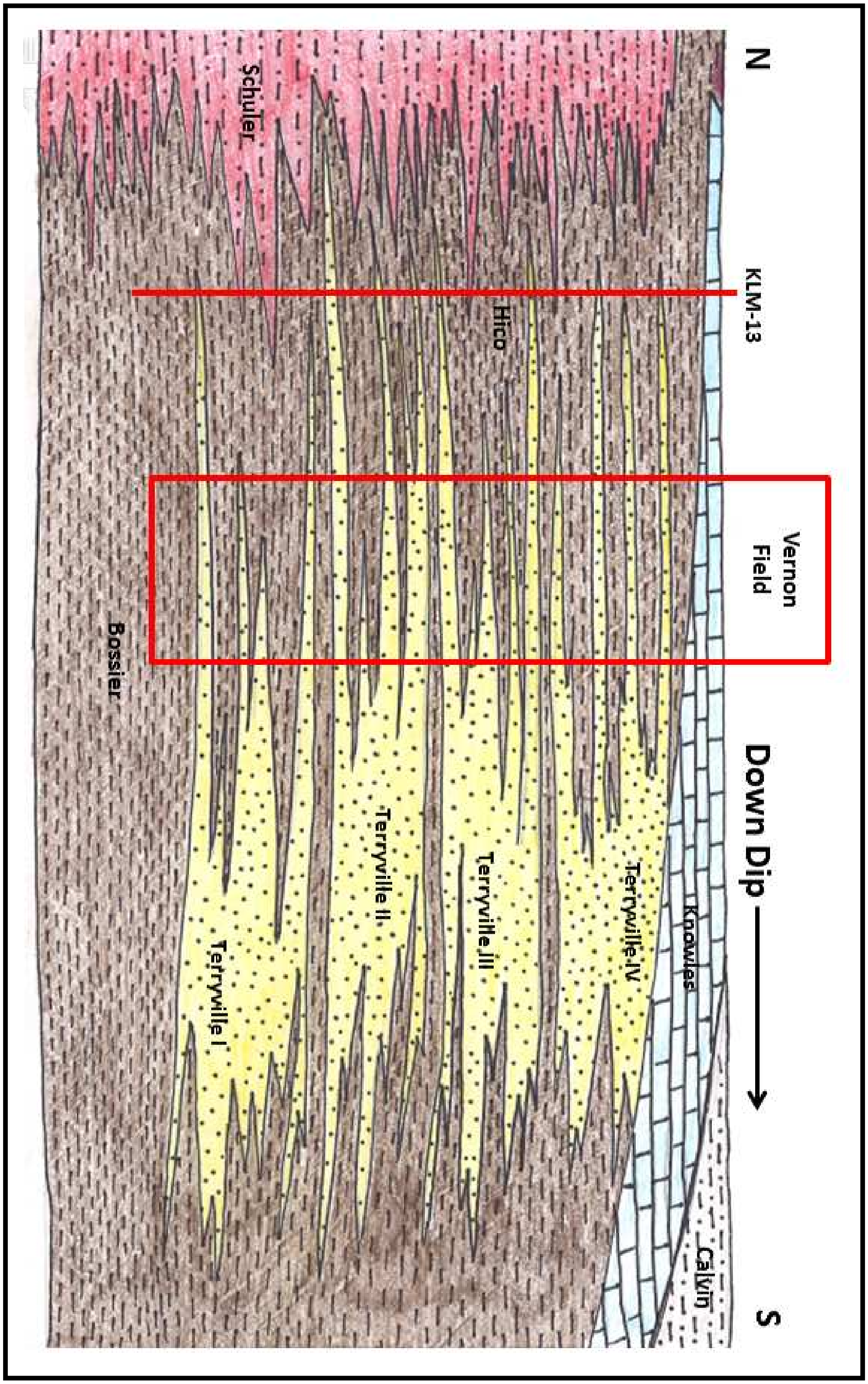

20 km
1 km
20 km
20 km

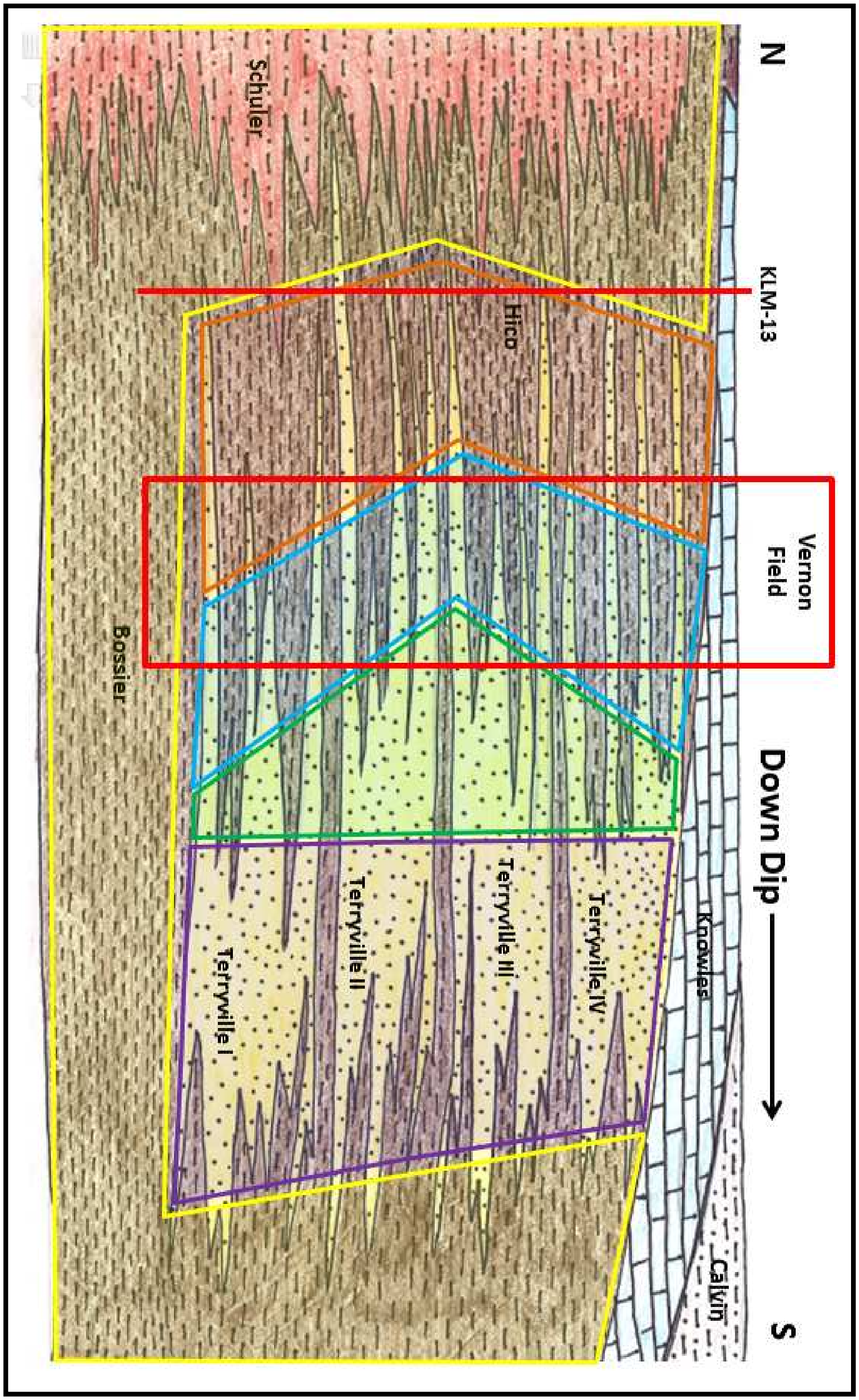

Subtidal deposition
Intertidal deposition




A
B
6/12
6/18


B


N
S
KLM-13
Vernon Field
Down Dip
Schuler
Hico
Bossier
Terryville I
Terryville II
Terryville III
Terryville IV
Knowles
Calvin


N
S
KLM-13
Vernon Field
Down Dip
Schuler
Hico
Bossier
Terryville I
Terryville II
Terryville III
Terryville IV
Knowles
Calvin

CHAPTER V

PETROLOGY, POROSITY, AND DIAGENESIS

Thin Section Analysis

A total of twenty three thin sections were prepared from the cores in this study: one from (core) Facies 1; one from Facies 2; two from Facies 3; twelve from Facies 4; five from Facies 5; and two from Facies 6. Each thin section was point counted for 600 sample points (100 in each location), with the exception of the one from Facies 1. This slide was omitted because it sampled an oddly colored concretion that was not representative of the facies.

Thin sections were examined and photographed at Boone Pickens School of Geology. A Nikon Optiphot-POL Research Microscope was used for examination and point counting, and an Olympus BX51 with Color View Soft Imaging System and Olympus MicroSuite software were utilized for photomicrographs.

The major detrital components (Table 4) in the samples are quartz, rock fragments, plagioclase feldspar, clay matrix, chert fragments, and muscovite mica. A conventional Folk (1964) ternary diagram is shown in Figure 28. Nineteen of the samples plot in the quartz arenite quadrant while the other three plot as sublitharenite.

More than 98% of the quartz was monocrystalline, with the remainder being polycrystalline. The rock fragments include carbonates (26% of total rock fragments), metamorphics (8%), volcanics (22%), and plutonics (43%). Other detrital grains occurring in trace amounts include: biotite mica, hornblende, sphene, and fossil fragments.

The authigenic components (Table 5) observed in thin section include: quartz and calcite cement, and pyrite. These will be discussed further in the section on diagenetic history.

Thin section photomicrographs of a sample of Facies 1 (slide C6-02) are shown in Figure 29**.** It is characterized by small angular detrital grains of dominantly quartz floating in a matrix of finer detrital grains, and clays. This slide was not included in the point counting, and very little porosity or cement is present in this tight mudstone facies.

Thin section photomicrographs of Facies 2 (slide C6-07) are shown in Figure 30. Facies 2 is characterized by matrix-supported detrital grains, but with a higher grain/matrix ratio. Pyrite occurs in this slide in the form of round to elongated partially opaque patterns. Microfractures are evident as thin blue lines and may contribute to total porosity, but could be resultant of coring, cutting, sampling, or thin section processing. Intragranular porosity occurs in an incompletely dissolved volcanic rock fragment in the upper left quadrant of the field of view. Partial dissolution of metastable minerals within rock fragments and other grains is a common form of secondary porosity in CVG sandstones.

Figure 31 is composed of thin section photomicrographs of Facies 3 (slide C2-03). Facies 3 is very similar to F2, but is grain supported (this sample is perhaps transitional between F2 and F3). A small patch of quartz cement is evident. Quartz cement is common in these rocks, however it is typically found only in small disconnected patches. Another microfracture is evident, but it likely is the result of stress induced during sampling.

The Facies 4 photomicrographs (slide C3-05) are shown in Figure 32. Facies 4 is characterized by quartz- and calcite-cemented sandstones with limited porosity that is the result of dissolution of metastable grains and calcite cement. Pore-lining clays are pervasive in places, but some porosity remains (blue). Pyrite (opaque) is also evident.

Photomicrographs of Facies 5 (slide C1-05) are shown by Figure 33. Facies 5 is characterized by low levels of clays, high percentages of quartz, no apparent primary porosity, and common quartz and calcite cements. Some secondary dissolution porosity can be found, but it appears to have little connectivity.

Facies 6 (slide C4-01) is shown in thin section photomicrographs by Figure 34. Facies 6 is characterized by heavy calcite cementation of relatively clean fine-grained sandstone. In thin section, it appears to be genetically similar to Facies 5, but contains abundant calcite cement. Facies 6 may have originated as Facies 5, with relatively high porosity and permeability that allowed the necessary fluids to permeate and cement the sandstones.

X-Ray Diffraction (XRD) data (Table 2) is supportive of the constituents found in thin sections. XRD results indicate that the main constituents of these rocks are quartz, plagioclase feldspar, illite, chlorite, and calcite.

Porosity and Permeability

The summary of average porosity and permeability values grouped by facies is shown in Table 6. Primary porosity is not readily evident and compaction features are common including: fused, broken and crushed quartz grains, and a scarcity of quartz cements. Detrital matrix is common and also appears to have reduced primary porosity. Secondary porosity is mostly moldic and intragranular, and presumably created by the dissolution of calcite cements and unstable to meta-stable grains present in the detritus (Figures 35 & 36). There is evidence of fracturing in the thin sections. The fractures are narrow, and their origin is debatable.

Facies 1was not point counted. The one thin section of Facies 2 contained 0.5% porosity. Average porosity increases to 2.68% for Facies 3, and again to 6.14% for Facies 4. Average porosity dropped to 4.66% for Facies 5. Facies 6, which is the fully cemented with total apparent porosity occlusion indeed displayed 0% porosity. Although the core plug study data shows generally higher average porosities, the changes from facies to facies, including the lowered porosity for Facies 5, are reflected in this data set as well.

Permeability was also measured using conventional analysis, the results of which are shown in Table 6 along with the porosity data. All facies have K values < 0.1mD except for Facies 4 which averaged 0.286mD for 12 samples. This highest permeability value correspond to the highest porosities; all were from Facies 4. Figure 37 shows crossplots of porosity versus permeability for the individual 5 facies that were tested and a composite plot of all tested facies. All permeability data was provided by EXCO resources.

Diagenetic History

The earliest phase of diagenesis involved the expulsion of pore water as compaction commenced. During the early parts of compaction, shell debris was partially dissolved and reprecipitated as calcite cement. Evidence for this includes the proximity of Facies 6 rocks to shell zones. During compaction, some quartz cements were also facilitated by pressure dissolution along siliceous grain boundaries. Quartz cement is found in core Facies 4 and 5. Framboidal pyrite may have also precipitated during this stage of diagenesis, as they form diagenetically in muddy sediments on the seafloor, usually in shallow water under reducing conditions.

The next diagenetic event was the maturation of kerogen into hydrocarbons. The increasing pressure created by kerogens cracking to natural gas may have caused microfracturing in the rock, which increased the porosity and permeability of the section. Maturation of hydrocarbons in the rocks also generate organic and inorganic acids (Al-Shaieb and Shelton, 1981) that dissolve or partially dissolve metastable grains. This porosity and permeability may have augmented existing primary porosity and facilitated the migration of corrosive fluids through the rock dissolving previous calcite cement, and partially dissolving rock fragments and feldspar grains. The secondary porosity generated during this stage of diagenesis accounts for the majority of the pore space present currently in the current CVG. A product of secondary dissolution by hydrocarbon associated fluids is authigenic clays. Precipitated authigenic clays line pore walls (illite and chlorite) and occlude pore throats (kaolinite).

A paragenetic sequence for the Cotton Valley Group sediments of Vernon Field in this investigation can be found in Figure 38**.**

Reservoir Properties and Petroleum Geology

Development of Vernon Field has gone through two main periods of drilling. The first began with the discovery well in the Vernon Field in 1967. Only a handful of wells were drilled until resource development was pursued from 1980-1987. The second major period of drilling began in the mid-1990s and ramped up significantly from 2000-2008 when Anadarko Petroleum owned the leases; a majority of the wells in Vernon field were drilled during that time period (see Figure 39).

Production from Upper Jurassic tight-gas reservoirs in northern Louisiana is typically only possible through massive hydrofracturing techniques because the porosities and permeabilities are generally low, averaging about 7% and 0.2md respectively (Table 6) in the productive facies - dominantly core Facies 4. These relatively low values are interpreted as the result of an interpreted diagenetic history of heavy compaction, quartz and calcite cementation, and authigenic clays lining grains and choking pore throats (Trojan, 1985). McBride (1982) observed that low resistivity values due to pyrite mineralization cause common techniques of water saturation calculation to be inaccurate. The tight-gas reservoirs are a challenge to produce, but often what these sandstones lack in reservoir quality, they make up for in cumulative thickness and high reservoir pressure resulting in large volumes from individual vertical wells.

Vernon field is an over pressurized gas field (Puckette, 2009) (Figure 42) with negligible oil production. The Upper Jurassic tight-gas sandstones form stacked pays that are produced using multiple perforations. The CVG ranges from approximately 11,000 – 14,000 feet deep, and these stacked reservoir sandstones are generally vertically drilled and hydrofractured. The average well has an Estimated Ultimate Recovery (EUR) of 2285 Mcf as calculated by Samson Resources (Figure 40) (Dulaune, 2010).

TOC analysis indicates that the kerogen found in the CVG sandstones and Bossier shales of Vernon field is type III, and a visual inspection of the rocks supports this as the organic matter is often finely dispersed, oxidized amorphous material with vitrinite in varying proportions (Goddard et. al., 2008).

Furthermore, vitrinite reflectance values range from .91 to 2.62% Ro (Goddard et. al., 2008), putting Vernon within the oil and gas maturity windows. This woody continental kerogen source entered the CVG system in prodelta sediments associated with the deltas flanking the basin from the east and west, and made its way to Vernon along with larger grained clastic sediments, which are also sourced from those areas. These rocks are source rocks for the shallower Hosston or “Travis Peak” and Sligo plays in the area (Goddard et. al. 2008). Based on the ready source of TOC and maturity, the rocks of the CVG and Bossier Shale in Vernon Field show a strong potential for hydrocarbon genesis.

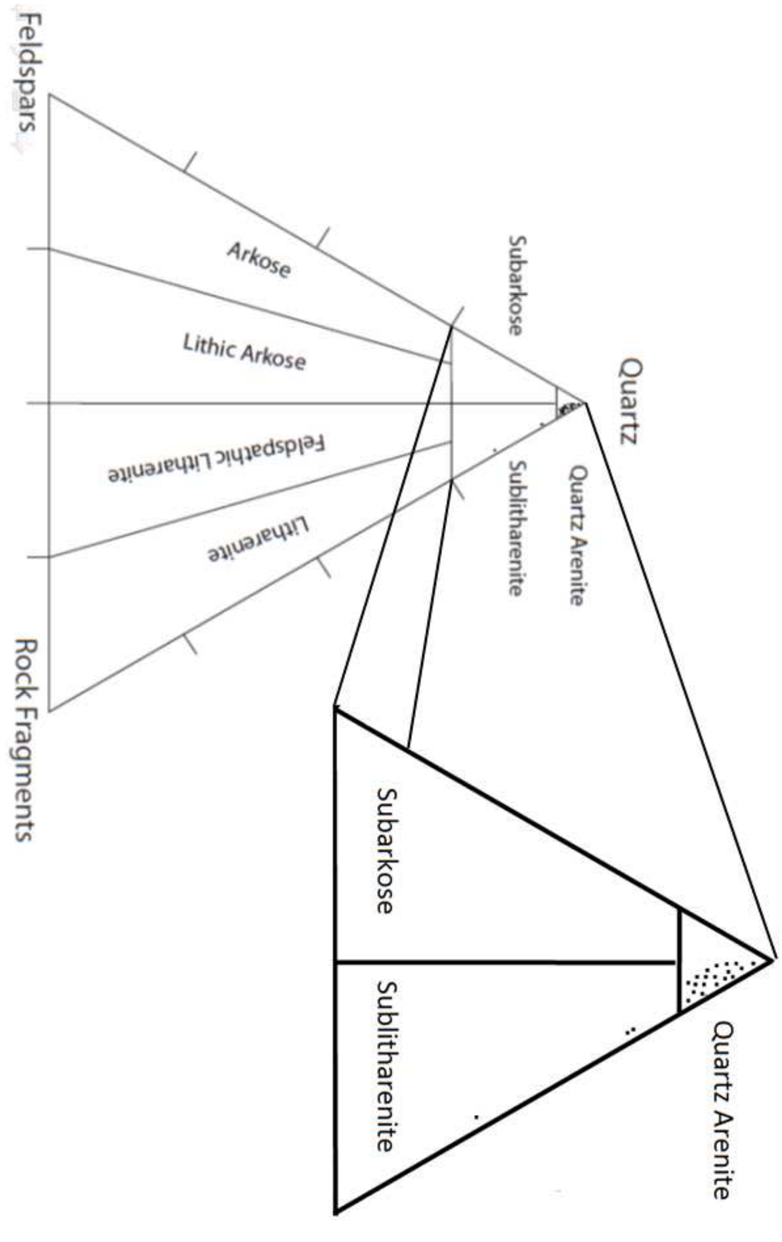
As a result of improved return on investment, many resource gas plays are drilled more aggressively when natural gas commodity prices are high (such as during the early 2000s), and Vernon field is no exception. Figure 41 shows the price of natural gas compared to a count of the number of wells drilled in Vernon field during each year. A positive relationship is evident as drilling increases when prices increase. Based on the relative shapes of the curve, wells were drilled in Vernon field only when natural gas prices hit threshold levels. It is also likely that drilling and fracturing technology and other factors also influenced economics.

A)

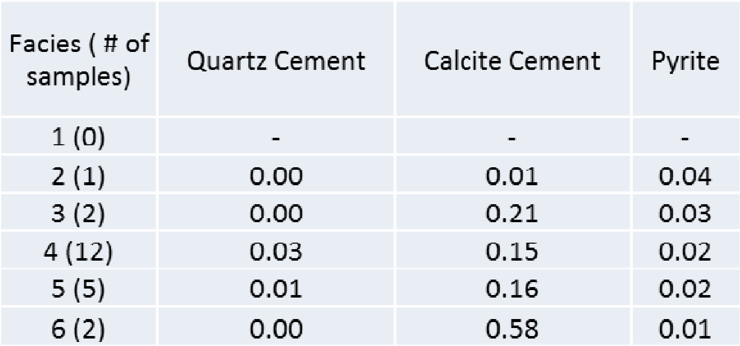
Facies (# of samples)	Total Quartz	Clay Matrix	Total Rock Fragments	Plagioclase Feldspar	Chert	Muscovite Mica
1 (0)	-	-	-	-	-	-
2 (1)	0.31	0.56	0.02	0.00	0.02	0.01
3 (2)	0.16	0.46	0.01	0.00	0.01	0.01
4 (12)	0.50	0.18	0.04	0.01	0.00	0.01
5 (5)	0.58	0.14	0.02	0.01	0.00	0.01
6 (2)	0.36	0.00	0.02	0.01	0.01	0.00

B)

Facies (# of samples)	Total Quartz	Clay Matrix	Total Rock Fragments	Plagioclase Feldspar	Chert	Muscovite Mica
1 (0)	-	-	-	-	-	-
2 (1)	0.33	0.60	0.02	0.00	0.03	0.01
3 (2)	0.24	0.71	0.02	0.00	0.02	0.01
4 (12)	0.68	0.24	0.05	0.01	0.00	0.01
5 (5)	0.77	0.18	0.03	0.01	0.00	0.01
6 (2)	0.89	0.01	0.05	0.02	0.02	0.01

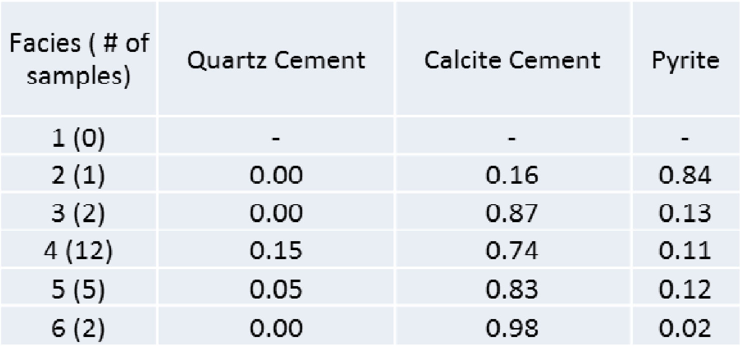

Quartz
Feldspars
Rock Fragments
Subarkose
Sublitharenite
Quartz Arenite
Arkose
Lithic Arkose
Feldspathic Litharenite
Litharenite
Quartz Arenite
Subarkose
Sublitharenite

A)

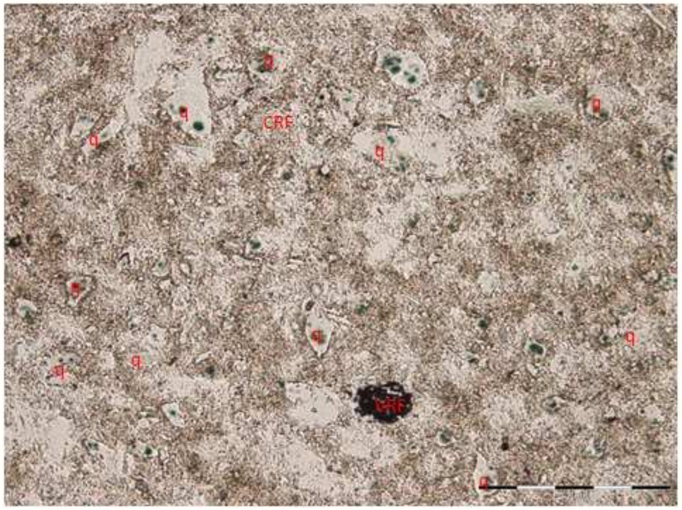


Facies (# of samples)	Quartz Cement	Calcite Cement	Pyrite
1 (0)	-	-	-
2 (1)	0.00	0.01	0.04
3 (2)	0.00	0.21	0.03
4 (12)	0.03	0.15	0.02
5 (5)	0.01	0.16	0.02
6 (2)	0.00	0.58	0.01

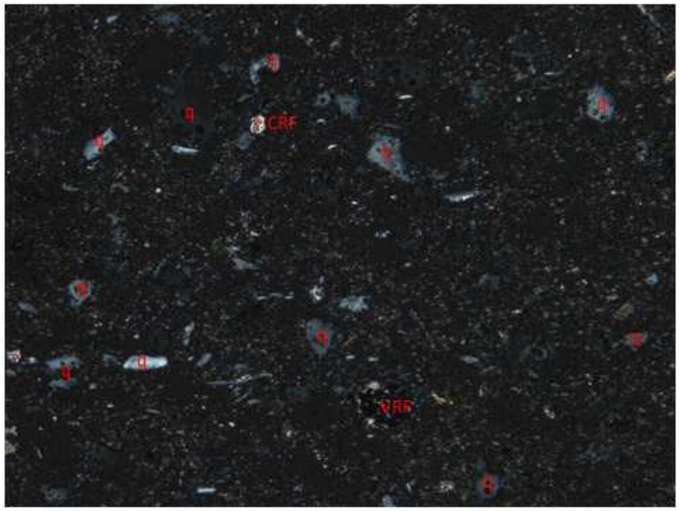
B)



Facies (# of samples)	Quartz Cement	Calcite Cement	Pyrite
1 (0)	-	-	-
2 (1)	0.00	0.16	0.84
3 (2)	0.00	0.87	0.13
4 (12)	0.15	0.74	0.11
5 (5)	0.05	0.83	0.12
6 (2)	0.00	0.98	0.02

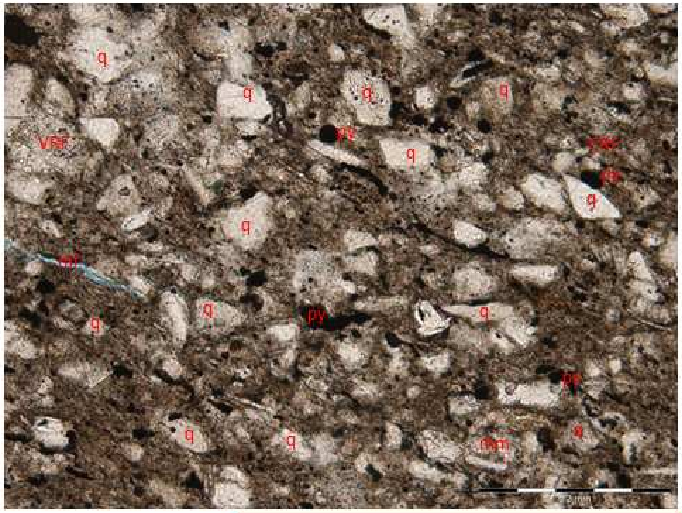


TSP-01-P



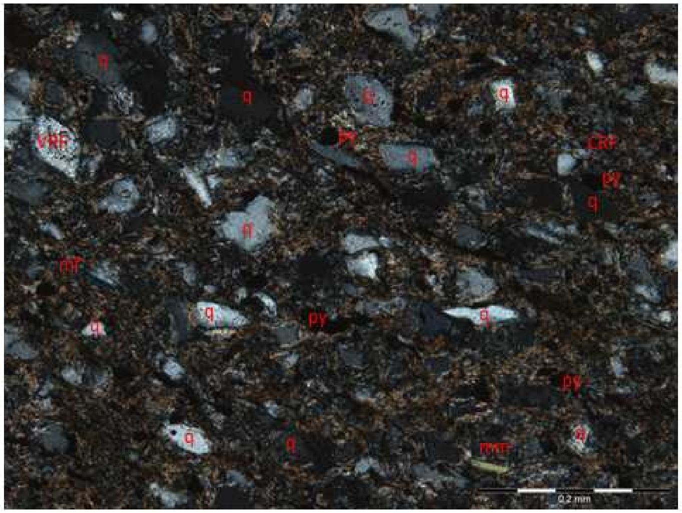
TSP-01-X

Index:
q = quartz grain
VRF = volcanic rock fragment
CRF = carbonate rock fragment

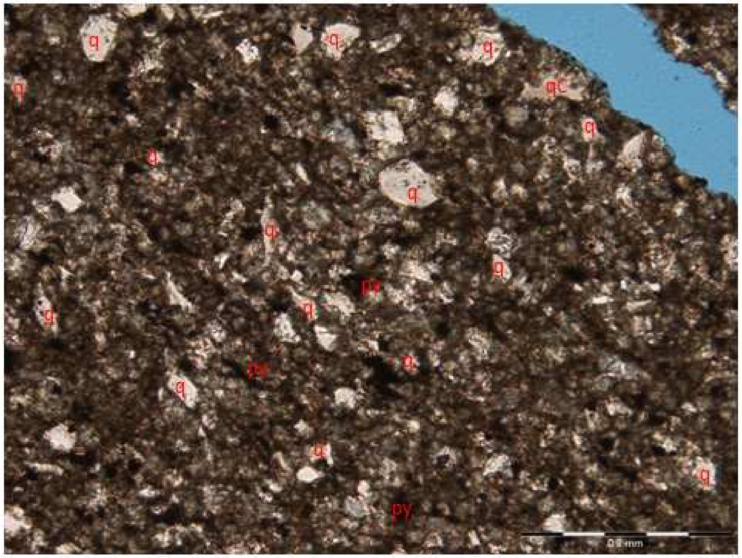


TSP-02-P

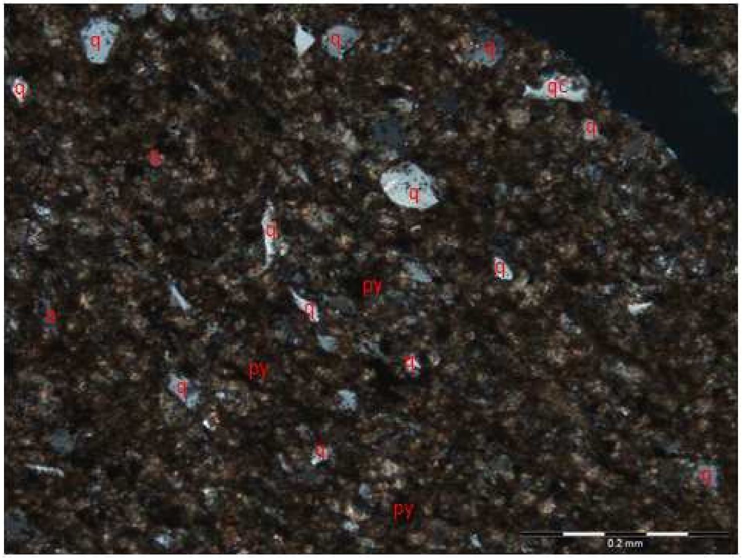
Index:
q = quartz grain
CRF = carbonate rock fragment
VRF = volcanic rock fragment
mm = muscovite mica
py = pyrite
mf = microfracture



TSP-02-X

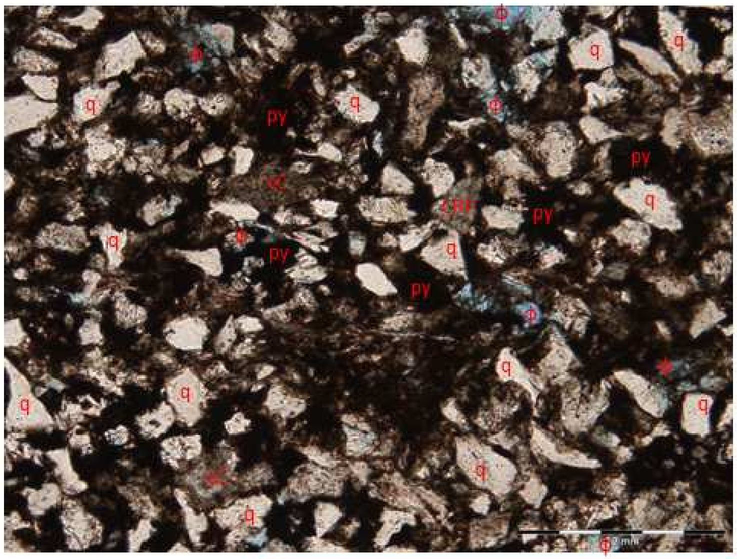


TSP-03-P



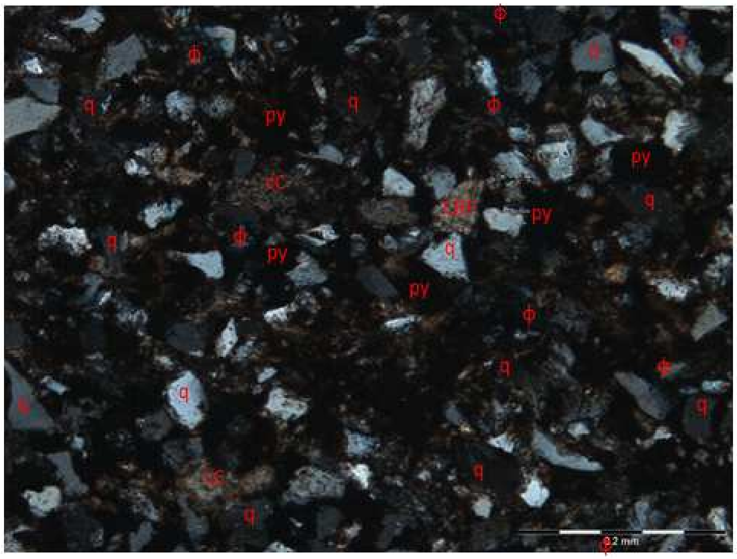
TSP-03-X

Index:
q = quartz grain
qC = quartz cement
py = pyrite

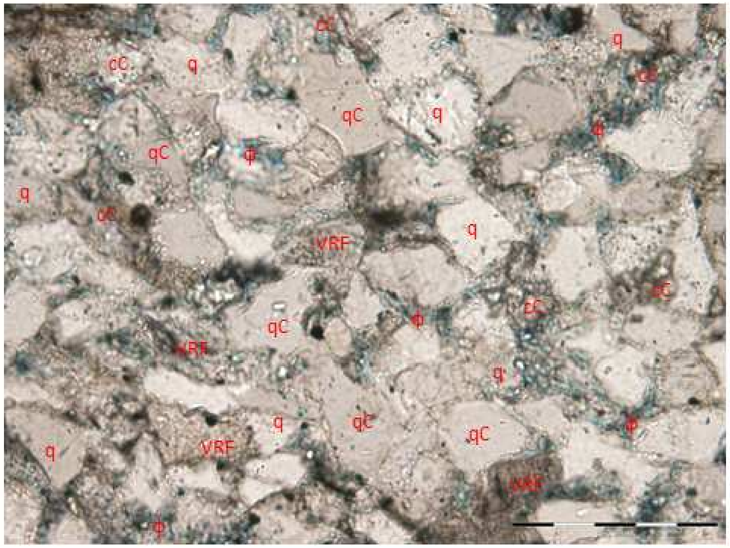


TSP-04-P

Index:
q = quartz grain
cC = calcite cement
CRF = calcite rock fragment
py = pyrite
ϕ = porosity

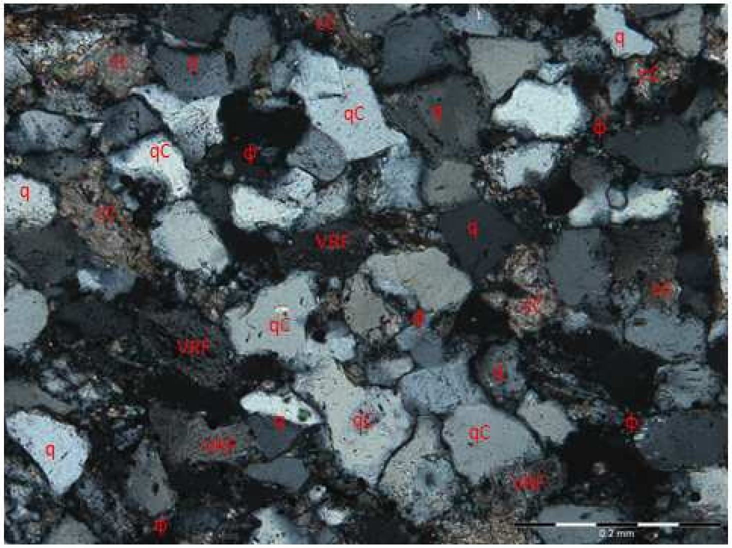


TSP-04-X

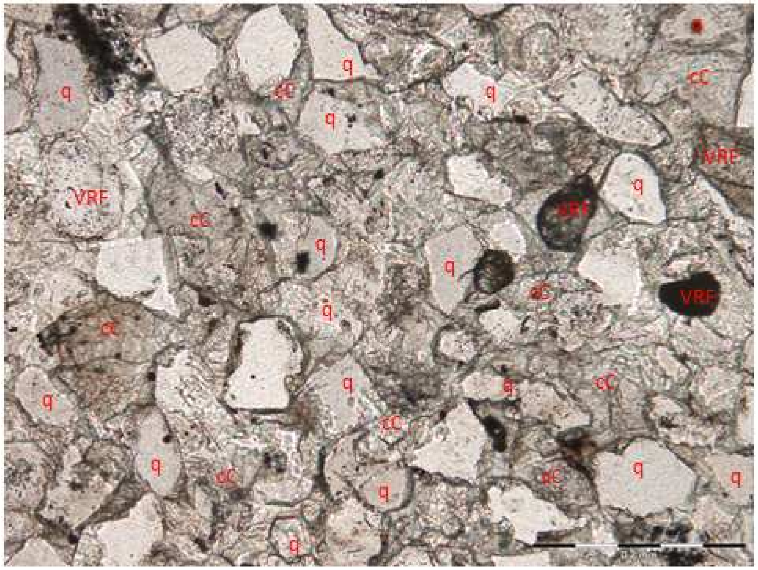


TSP-05-P

Index:
q = quartz grain
qC = quartz cement
cC = calcite cement
VRF = volcanic rock fragment
ϕ = porosity

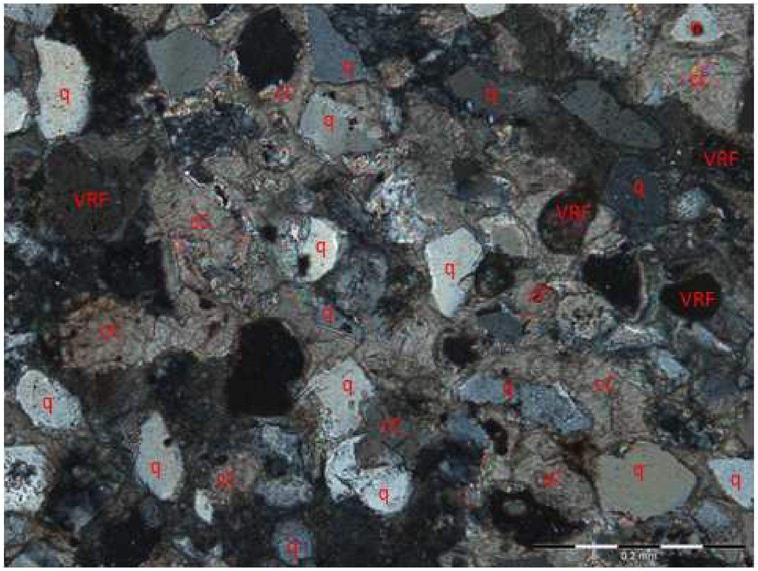


TSP-05-X

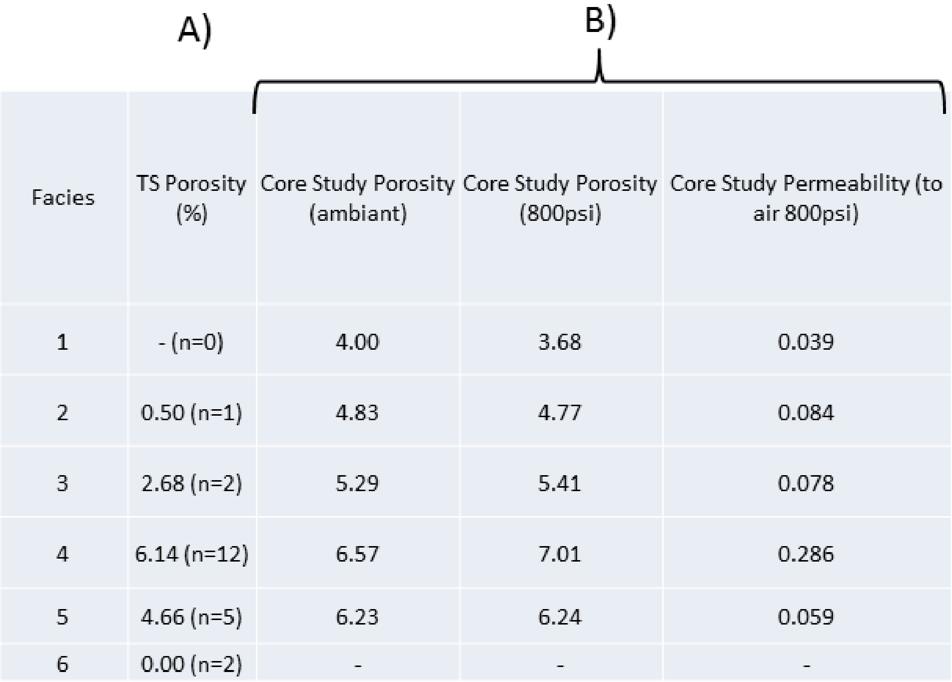


TSP-06-P

Index:
q = quartz grain
cC = calcite cement
VRF = volcanic rock fragment



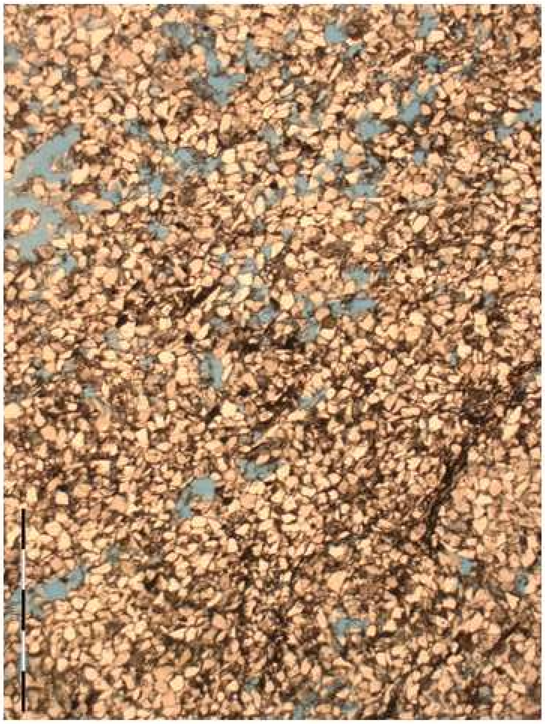
TSP-06-X



Facies	TS Porosity (%)	Core Study Porosity (ambiant)	Core Study Porosity (800psi)	Core Study Permeability (to air 800psi)
1	- (n=0)	4.00	3.68	0.039
2	0.50 (n=1)	4.83	4.77	0.084
3	2.68 (n=2)	5.29	5.41	0.078
4	6.14 (n=12)	6.57	7.01	0.286
5	4.66 (n=5)	6.23	6.24	0.059
6	0.00 (n=2)	-	-	-

Table 6. Average values for porosity and permeability by depositional facies. A) Thin Section porosity based on point counting B) Core plug study data (data provided by EXCO Resources). Sampling problems do not allow the differentiation of Facies 6 samples in the core plugs, which was completed at a different time than the core analysis and sampling for thin sections.

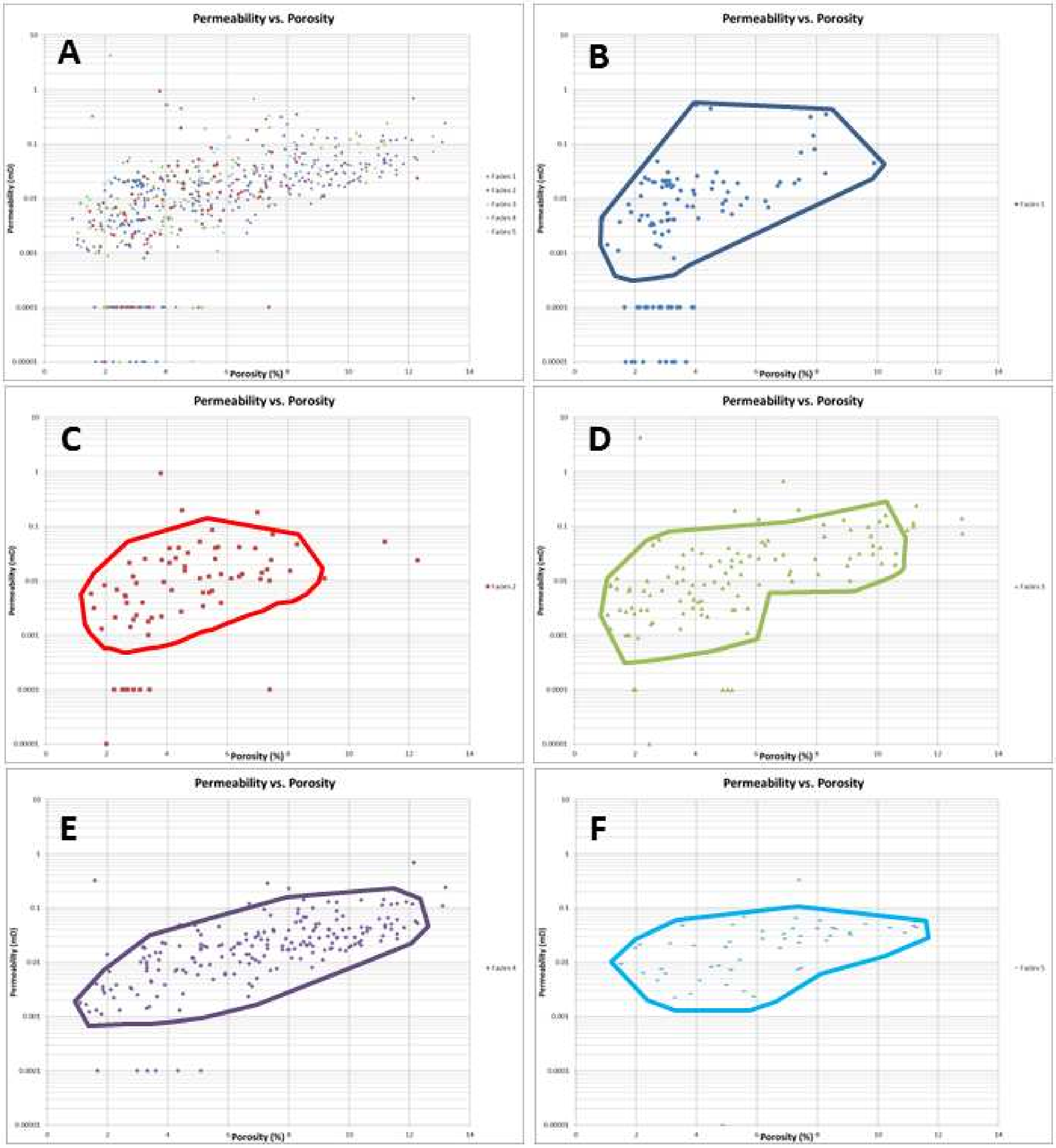
TSP-07-P



TSP-07-X

TSP-08-P

TSP-08-X


A
B
C
D
E
F
Permeability vs. Porosity
Permeability (mD)
Porosity (%)
10
1
0.1
0.01
0.001
0.0001
0.00001
0
2
4
6
8
10
12
14
Facies 1
Facies 2
Facies 3
Facies 4
Facies 5

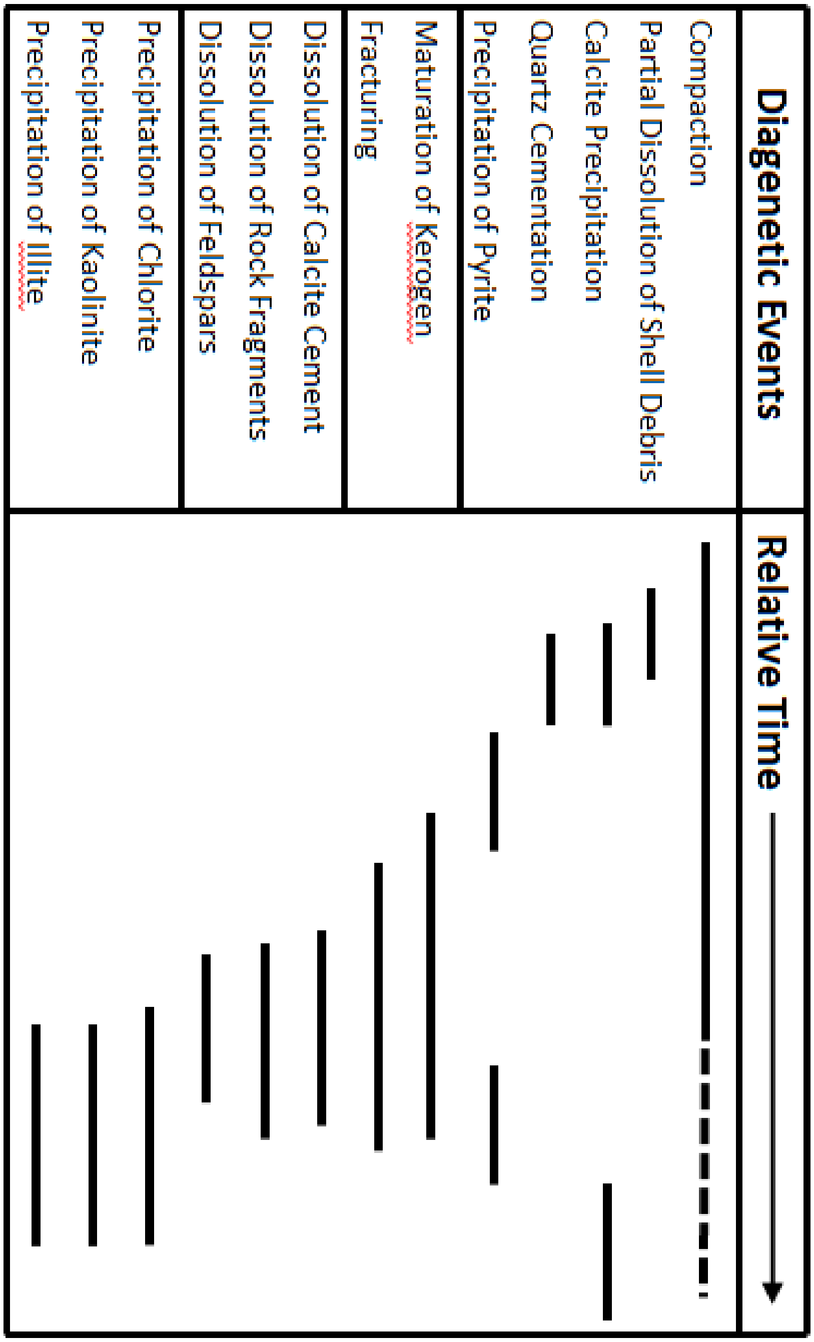


Figure 38. Paragenetic sequence of Diagenetic events

Figure 39. Estimated Ultimate Recovery (EUR) vs. Completion date for industry named reservoirs in Vernon Field (Samson Resources, 2011).

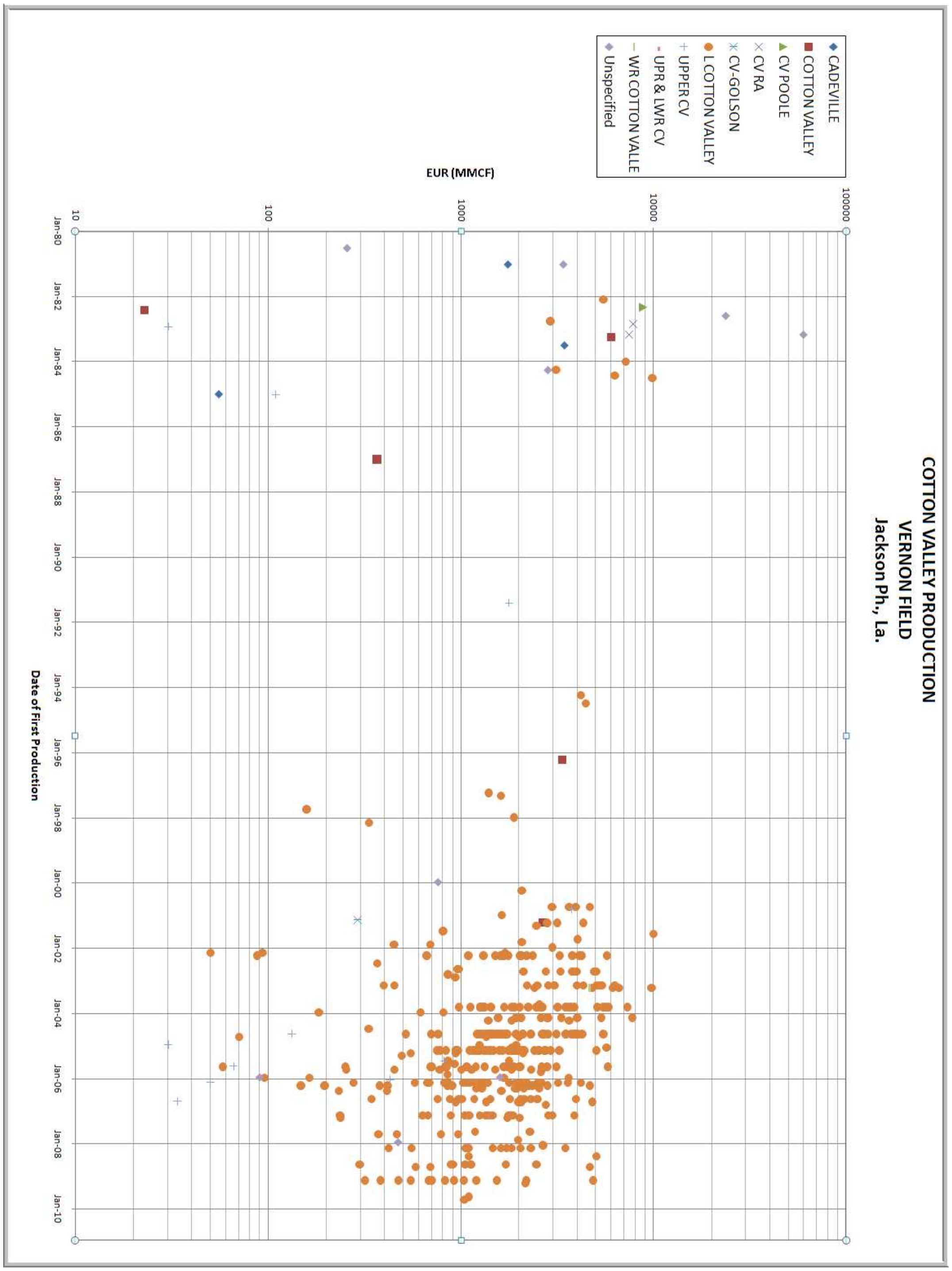


Figure 40. Distribution curve of the EUR's for Vernon field. Inset is the statistical information regarding the distribution (Samson Resources, 2011).

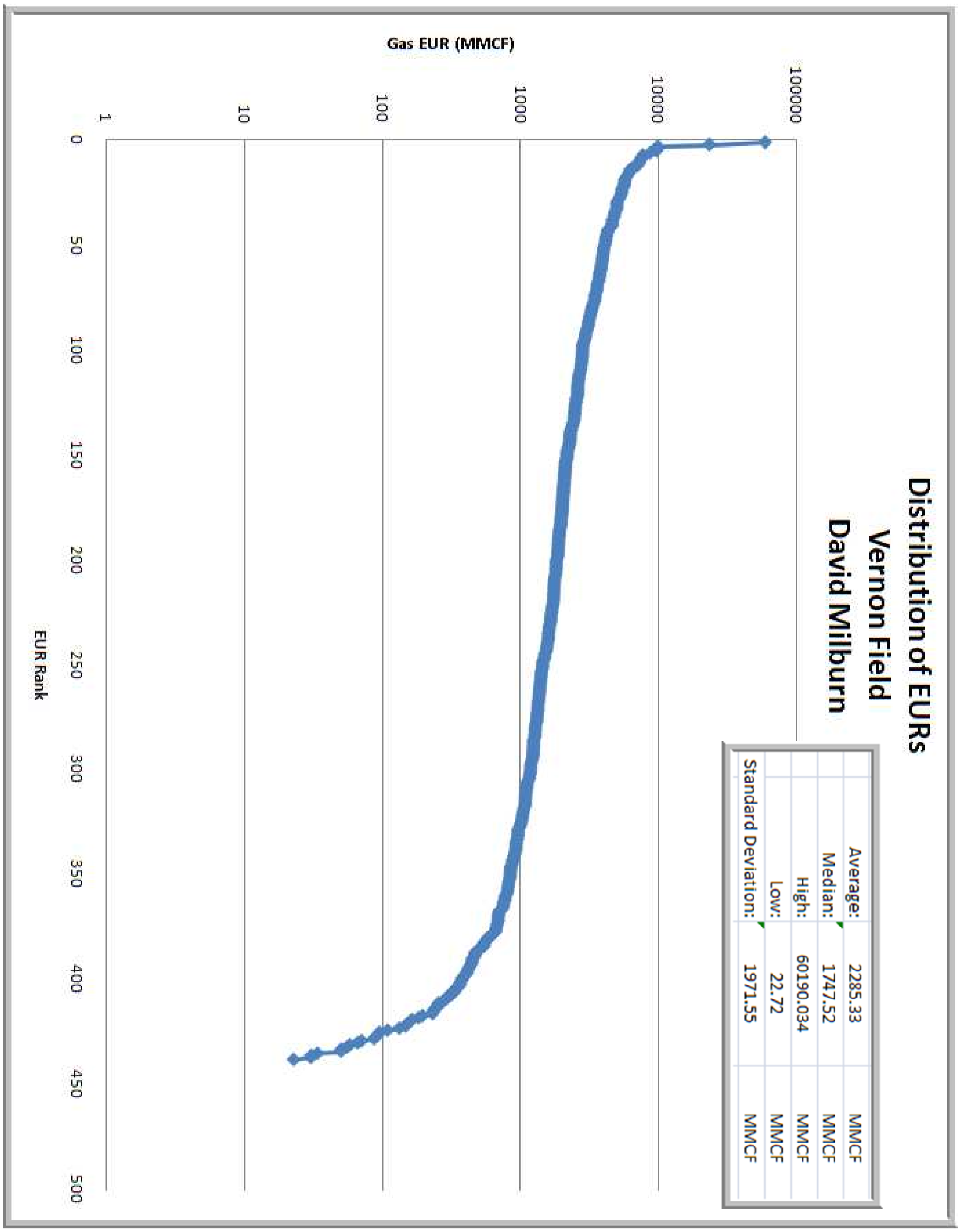
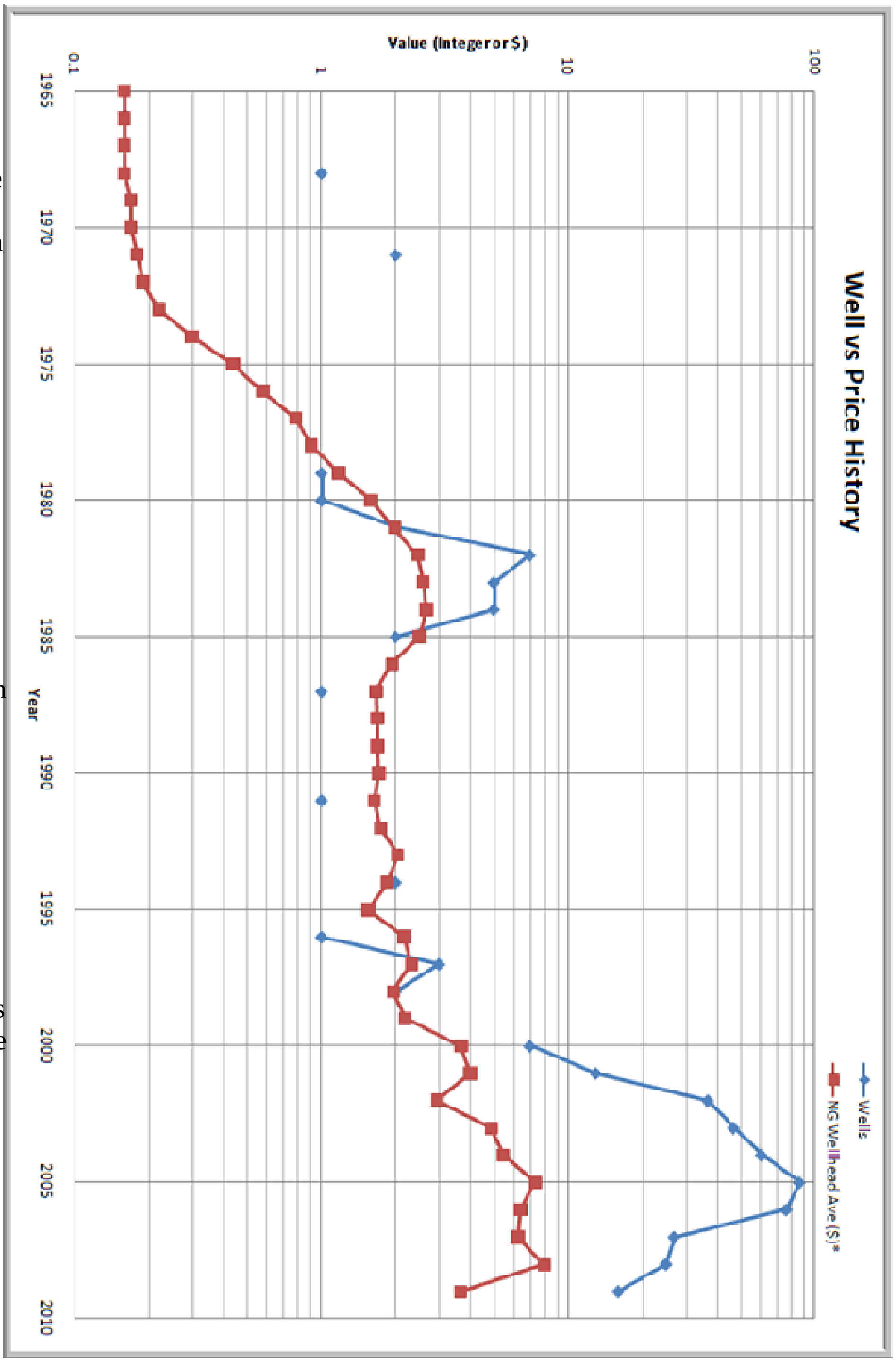
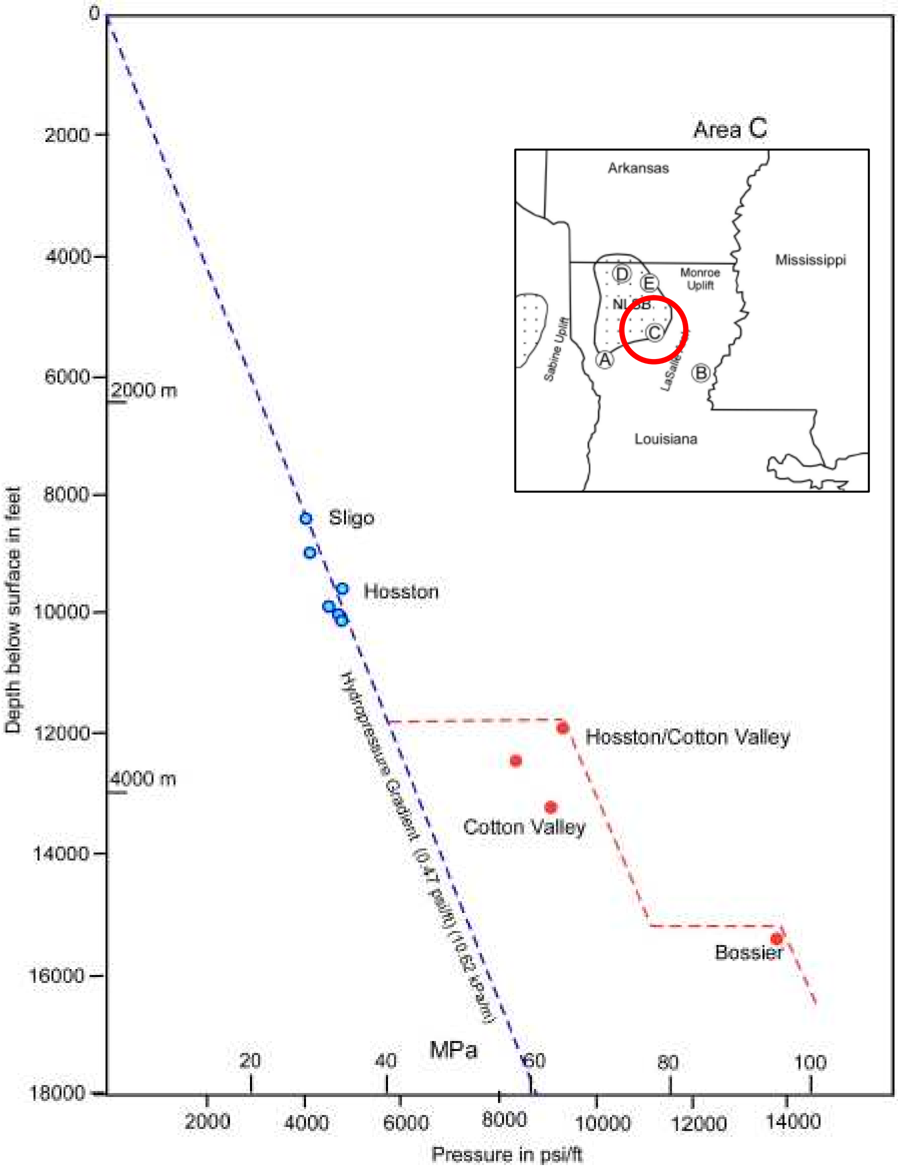


Figure 41. Comparison of natural gas prices (red) vs. wells drilled each year (blue) in Vernon Field. NG prices and well counts are from public records accessed through HIS (2011)




Area C
Arkansas
Mississippi
Monroe Uplift
NLSB
Sabine Uplift
LaSalle
Louisiana
A
B
C
D
E
Sligo
Hosston
Hosston/Cotton Valley
Cotton Valley
Bossier
Hydropressure Gradient (0.47 psi/ft) (10.62 kPa/m)
Depth below surface in feet
0
2000
4000
6000
8000
10000
12000
14000
16000
18000
2000 m
4000 m
MPa
20
40
60
80
100
2000
4000
6000
8000
10000
12000
14000
Pressure in psi/ft

CHAPTER VI

SUMMARY AND DISCUSSION

The main purposes of this study were to use available data to (1) establish the regional depositional setting of the Cotton Valley Group, (2) constrain the depositional systems present in the CVG in Vernon Field using sedimentary features in core, and (3) to reconstruct a diagenetic history and evaluate the evolution of porosity in the field.

Regional Setting

The U.S. Gulf of Mexico basin and associated sub-basins were formed by an episode of passive continental margin development which began during the breakup of Pangaea starting in the late Triassic (Atwell et. al., 2008). The U.S. gulf coast has three main basins: the East Texas Salt Basin, the North Louisiana Salt Basin, and the Mississippi Salt Basin (Figure 1). Evaporation of the early seaways in the rift left behind the first sediments, the Louann Salt, which plays a significant role in the structural styles of these basins.

The stratigraphy of the U.S. coastal basins is dominated by fine grained clastics, muddy carbonates, and occasional evaporites. The CVG is late Jurassic to early Cretaceous and represents a set of deltaic systems located in the East Texas and Mississippi Salt basins that flank an estuarine to lagoonal region in the North Louisiana Salt basin, which was protected by dividing topographic highs.

The CVG in Vernon field in Jackson Parrish, north-central Louisiana represents deposition in the North Louisiana Salt basin, which is flanked by the Monroe Uplift to the East, and the Sabine Arch to the West (Figure 1). The Cotton Valley Group (CVG) is about 12,000 – 14,000 ft. deep at Vernon field.

Core Facies

The facies classifications observed in core include six main core facies. Facies 1, 2, and 3 represent a continuum of increasing silt sized particles wherein Facies 1 is greater than 50% clays, Facies 2 is matrix supported siltstone, and Facies 3 is grain supported siltstone. Facies 1 is comprised of dark mudrocks often containing carbonate concretions and fossil hash. Facies 2, the matrix supported siltstone, and Facies 3, the grain supported siltstone, have varying levels of clay and show a variety of sedimentrary structures including preserved laminae of alternating grain sizes, polychaete worm burrows, fossil hash, carbonate concretions, and mottled textures. Facies 4 includes very-fine-grained grey to tan to brown sandstones with mottled textures and soft sediment deformation common. Facies 5 is made up of very-fine-grained sandstones that are tan to brown with soft-sediment flow features such as horizontal and tilted bedding planes, crossbedding, and alternating flow directions. Facies 4 and 5 also commonly contain beds of disarticulated fossil hash and/or whole oyster shells, and large vertical burrows which are interpreted as oyster burrows.

Depositional System

The depositional system controlling sedimentation of the CVG in Vernon Field has been interpreted as a tidal flat system based on the following lines of evidence.

CVG sandstones contain evidence of a shallow, brackish faunal assemblage of oysters and polychaete worms. Oyster shells and burrows can be seen associated with any of the facies seen in the system. Small burrows, which have been interpreted as polychaete worm burrows, are common in Facies 2, 3, and 4.. This low diversity faunal assemblage is associated with biologically rigorous, high energy, tidal flat environments.

The sedimentary structures evident in core are concordant with those found in other ancient and modern tidal flats (Weimer et. al., 1982). These include horizontal and tilted bedforms that sometimes indicate alternating flow directions and heterolithic laminations of mud and silt/sand.

Paleogeographic reconstructions from CVG times indicate Vernon to be within a lagoonal region, which supports a relatively low energy setting for CVG sandstones (Figure 6). Tidal flats occur along coasts with low wave and current energy with a measurable tidal range. The subtidal and intertidal depositional facies typically found within TF's have been identified in six core facies.

The kerogen associated with the CVG in Vernon field is type III (Goddard et. al., 2008). This indicates the possibility of a woody region and/or a plant-rich salt marsh just upstream from the sediment accumulation, which is consistent with tidal flat environments.

Depositional Facies

The core facies were interpreted within the context of a tidal flat model (see Table 1). Facies 1 is interpreted as upper intertidal zone muds, although additional study is needed to determine whether some may be deeper water muds deposited during high stands of sea level. Facies 2 and 3 are interpreted as lower intertidal mixed-tidal-flat type deposits. Facies 4 and Facies 5 are interpreted as subtidal-sand-rich zones of channel-filling point bars and shoaling-barrier-bar sediments. These facies change vertically at high frequency, and likely represent changes in relative sea level as well as temporal changes in sediment input. All of these facies were affected by burrowing to bioturbation ranging from scattered vertical oyster burrows, to pervasive bioturbation that destroyed all bedding features.

Diagenesis and Porosity

A recurring pattern of porosity reduction and enhancement is evident in the CVG sandstones and includes compaction, early calcite and quartz cements, followed by porosity being enhanced by dissolution of cements and grains, and authigenic clays that line pores and reduce throats. Quartz cement is more common in Facies 4 and 5. This is attributed to (1) the sandstones being cleaner (less clay and silt), allowing for better permeability that allowed solute-rich fluids access to grains; (2) larger grain size, which resulted in more surface area removed from grain to grain contact, which facilitated quartz nucleation; and (3) better sorting and higher volumes of pre-compaction primary porosity.

Primary porosity was not obvious in the thin sections, although it is likely some is preserved. Porosity is therefore believed to be mostly secondary, is highest in core Facies 4, and formed as the result of dissolution of feldspars grains, rock fragments, and cements after maturation of kerogens.

Porosity and permeability are both highest in Facies 4. This is believed to be the result of a proper balance of clays, cements, and detrital grains. Facies 3, 2, and 1, contain larger quantities of matrix and clays, and therefore lower permeability, which reduced fluid access to grains to generate secondary porosity. Facies 5 on the other hand, contains very little clay, was more permeable and more likely to be cemented by early calcite and quartz cements.

Production Suggestions

Core Facies 4 contains the highest values of porosity and permeability (see Table 6 and Figure 37) and as a result is considered the best reservoir rock in the CVG interval. Unfortunately, the conventional wireline suite is not capable of resolving these thin facies and therefore is not useful in delineating Facies 4 from Facies 3 and 5.

Further Study

Paleontological studies to constrain biological diversity would help determine if mudrocks in the CVG represent relatively deeper-water marine shales such as pro-delta shales or upper intertidal deposits or mud flat deposits. The determination of frequency of bioclasts in mudrocks could be used to infer if the difference in the abundance of carbonate bioclasts can explain the presence or absence of calcite cement.

Additional and better distributed core provided by future drilling activity would add much to the understanding of Vernon field and the regional picture in the CVG. Coring the shale breaks between the sandier sections could greatly add to the understanding of the stratigraphy, and contribute to understanding the source of carbonate in these rocks. These cores could help explain the spatial distribution of individual sandstone bodies, confirm or refine the interpretation of depositional environments, and improve the interpretation of the origin of these sandstones within a regional geologic context.

CHAPTER VII

CONCLUSIONS

This study attempted to establish the regional depositional setting of the Cotton Valley Group in the context of the major depositional and tectonic features of the Gulf Coast region. To accomplish this, eleven cores were examined and their features were compared to those of modern environments of deposition. Furthermore, the cored rocks were examined petrographically to establish their detrital and authigenic components. All of these data were integrated and interpreted with findings in the scientific literature to generate the following conclusions.

1. The Cotton Valley Group at Vernon field falls into a lagoonal region known as the “Hico Lagoon” during the Late Jurassic and Early Cretaceous which had low current and wave energy due to limited access to large oceans, surrounding topographic highs, and intermittent barrier islands. The Hico Shale is the unit which the sands of the CVG pinch-out into up-dip.
2. The depositional setting of the CVG sandstones is interpreted as a dynamic tidal flat ranging from mud flats, to mixed flats, to sand flats. The primary lines of evidence are oyster shells and hash accumulations, oyster and polychaete burrows, heterolithic laminae, and bidirectional flow features.

3. Depositional facies include three main groups: (1) intertidal mudstones to siltstones, (2) subtidal sandstones, and (3) diagenetically modified heavily calcite cemented sandstones. Group one includes core Facies 1 (mudrocks), Facies 2 (matrix supported siltstones), and Facies 3 (grain supported siltstones) which form a continuum. Group 2 include Facies 4 which is generally darker colored and contains more biostrutures, and Facies 5 which is generally lighter colored, appears cleaner, and contains most of the flow features. Group 3 includes core Facies 6 which are calcite cemented sandstones with no porosity typically associated with zones of shells or fossil hash.

4. Porosity is mostly secondary intragranular and moldic, and formed by partial to complete dissolution of grains by organic acids associated with the maturation of kerogen in the system. Observed primary porosity is minimal and appear to have been reduced by early calcite and quartz cement.

5. Facies 4 is considered the best reservoir in the CVG sandstones of Vernon Field because it has the highest average porosity and permeability. Facies five is also important but has slightly lower porosity and permeability. Conventional wireline logs do not have the capability of resolving individual facies.

REFERENCES

Al-Shaieb, Z., and J.W. Shelton, 1981, Migration of hydrocarbons and secondary porosity in sandstones: AAPG Bulletin V. 65., No. 11, p. 2433-2436.

Atwell, Brian W., Bo Henk, Fred C. Meendsen, and John A. Bryar, 2008, Depositional setting and petroleum production, Gray Sandstone (Upper Jurassic), Cotton Valley Field, Northern Louisiana. Gulf Coast Association of Geological Societies Transactions. Volume 58, p. 49-63.

Bretberger, Charles E., Thaddeus S. Dyman, and Steven M. Condon, 2002, Is there a basin-centered gas accumulation in Cotton Valley Group sandstones, Gulf Coast Basin, U.S.A?: U.S. Geological Survey Bulletin 2184-D, p. 1-38.

Eversull, Lori G, 1985, Depositional systems and distribution of the Cotton Valley blanket sandstones in northern Louisiana: Transactions – Gulf Coast Association of Geological Societies. Volume XXXV, p. 49-57.

Ewing, Thomas E, 2001, Review of Late Jurassic depositional systems and potential hydrocarbon plays, northern Gulf of Mexico Basin: Gulf Coast Association of Geological Societies Transactions. Volume LI, p. 85-96.

Folk, R. L., 1964, Petrology of sedimentary rocks: Hemphill Publishing Company, Austin TX 182 p.

Goddard, Donald A., Ernest A. Mancini, Marty Horn, and Suhas C. Talukdar, 2008, Hydrocarbon generating potential: Jurrassic Cotton Valley – Bossier Group, North Louisiana Salt Basin: Gulf Coast Association of Geological Societies Transactions, Volume 58, p. 305-325.

Goldhammer, R.K., and C.A. Johnson, 2001, Middle Jurassic – Upper Cretaceous paleogeographic evolution and sequence stratigraphic framework of the Northwest Gulf of Mexico Rim, *in* The Western Gulf of Mexico Basin: tectonics, sedimentary basins, and petroleum systems, C. Bartolini, R.T. Buffler, and A Cantu-Chapa (eds). American Association of Petroleum Geologists Memoir 75, p. 45-81.

Heydari, Ezat and Roger N. Townsend, 2001, Fluvial sedimentation in the Cotton Valley Group in Stringer Field, Jasper County, Mississippi: Gulf Coast Association of Geological Societies Transactions. Volume LI, p. 109-120.

Jackson, M.P.A., and B.C. Vendeville, 1994, Regional extension as a geologic trigger for diapirism: Geological Society of America Bulletin, v. 106, p. 45-81.

Judice, P.C., and S.J. Mazzullo, 1982, The Gray Sandstones (Jurassic) in Terryville field, Louisiana: basinal deposition and exploration model: Gulf Coast Association of Geological Societies Transactions, v. 32, p. 23-43.

McBride, K.C., 1982, Properties of Cotton Valley sandstone reservoirs (Upper Jurassic), Terryville field, Lincoln Parish, Louisiana: Unpublished M.S. thesis, Texas A&M University, 92 p.

Miciotto, S. A., 1980, A petrographic, stratigraphic, and structural study of the Smackover Gray Sand (Jurassic) in north Louisiana: Gulf Coast Association of Geological Societies Transactions, v. 30, p 177-182.

Moore, Tim, 1983, Cotton Valley depositional systems of Mississippi: Transactions – Gulf Coast Association of Geological Societies. Vol. XXXIII, p. 163-167.

Puckette, J., 2009, Preliminary Interpretation of the Pressure Architecture in Parts of Northern Louisiana, Southern Arkansas, and Eastern Teas: Gulf Coast Association of Geological Societies Transactions, v. 59, p. 607-620.

Reading, H.G., and M. Richards, 1994, Turbidite systems in deep-water basin margins classified by grain size and feeder system: American Association of Petroleum Geologists Bulletin, v. 78, p. 792-822.

Trojan, Michael, 1985, Effects of diagenesis on reservoir properties and log response, Upper Jurassic Taylor sandstone, Cotton Valley Group, Lincoln Parish, Louisiana: Gulf Coast Association of Geological Societies Transactions, v. 35, p. 515-524.

Turner, James R.,1997, Recognition of low resistivity, high permeability reservoir beds in the Travis Peak and Cotton Valley of East Texas. Gulf Coast Association of Geological Societies Transactions. V. 48, p. 585-594.

Weimer R.J., Howard J.D., and D.R Lindsay. 1982, Tidal flats:, *in* Sandstone Depositional Environments, P.A. Scholle and D. Spearing (eds). AAPG Memoir 31, p.191-245.

VITA

David Michael Milburn

Candidate for the Degree of

Master of Science

Thesis: REGIONAL SETTING, DEPOSITIONAL ENVIRONMENT, AND DIAGENESIS OF THE COTTON VALLEY SANDSTONE IN VERNON FIELD, NORTH LOUISIANA

Major Field: Geology

Biographical:

Education:

Completed the requirements for the Master of Science in Geology at Oklahoma State University, Stillwater, Oklahoma in December, 2012

Completed the requirements for the Bachelor of Science in Geology at Oklahoma State University, Stillwater, Oklahoma in May, 2009

Experience:

Summer Geologist Internship – Samson Resources; 2009
- Tonkawa Sandstone, Anadarko Deep, Subsurface mapping, Prospecting, Resource team experience,

Summer Geologist Internship – Samson Resources; 2010
- Cotton Valley Group, Gulf Coast, Core logging, Core Analysis, Subsurface mapping,

Contract Research Geologist – Samson Resources; Oct 2010 – Aug 2011
- Thesis research

Currently a Mud-logger at Mid Continent Well Logging Services
- NW Oklahoma, Anadarko Shelf

Professional Memberships:

AAPG, GSA