DEPOSITIONAL FACIES AND RESERVOIR QUALITY, DEVONIAN CARBONATE MOUNDS, FRISCO FORMATION, OKLAHOMA

By

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CHAPTER I

INTRODUCTION

Devonian carbonate mounds in the Frisco Formation of the Hunton Group are important petroleum reservoirs in a number of oil and gas fields in Oklahoma. Though these reservoirs have produced large volumes of petroleum, little is known about their origin, distribution and diagenetic history.

Carbonate mounds developed in a deeper-water subtidal environment, as evidenced by the lack of current features within mound structures. Mound growth usually initiated on paleotopographic highs as the dominating faunal elements of Devonian mounds, crinoids and bryozoans preferred the higher ground position because of better oxygenation and food supply. Facies in a typical mound complex include mound-core, flank and mound-crest (Wilson, 1975). In this study, carbonate mounds in the Frisco Formation were sampled and examined petrographically to establish depositional facies, describe the diagenetic history and determine the relationship between facies and reservoir quality. The datasets include cores from two widely separated oilfields and one outcrop.

Objectives

The primary objectives of this study are to identify and characterize carbonate mound facies in the Frisco Limestone. These objectives include:

(1) Establish lithofacies of mound rocks and adjacent beds,
(2) Determine rock constituents and paleoenvironment based on biotic and lithic composition,
(3) Examine diagenetic history and establish a paragenetic sequence of diagenetic events,
(4) Evaluate the relationship between rock fabric and the evolution of oil and gas reservoirs,
(5) Examine the distribution of mound rocks and initial oil production rate for the Hunton reservoir in the Fitts Field.

Methodology

During the course of this study, an outcrop and cores were described, sampled and analyzed petrographically to establish mound lithofacies and determine post-depositional diagenetic modification of the mound carbonates. An expectation of this study is a better understanding of the types of organisms associated with mounds, the impact of these biota on mound growth, and the resulting abundance and distribution of mound facies. Integrating petrography allowed the development of a sequence of paragenetic events and furthered the insight into the evolution of these important carbonate reservoirs. Specific tasks included:

(1) Describe mound geometry: Massive lime mudstones containing skeletal fragments of crinoids and bryozoans usually form lens shape buildups. In the project area, Devonian mounds are believed to be 500 meters to a kilometer in diameter (Rechlin, 2003). There is one prominent outcrop of a Devonian mound along Bois d'Arc Creek south of Ada in

Pontotoc County, Oklahoma. This mound and adjacent beds were measured laterally and vertically and systematically sampled.

(2) Wire log Analysis: Approximately five miles south of the Bois d'Arc Creek outcrops Devonian mounds produce oil and gas in Fitts Field. Cores and wire-line logs in the field were correlated to cores to determine if mound facies can be recognized by their wireline log signature. The distribution of mound facies in Fitts Field was mapped.

(3) Core Analysis: Cores of mound facies were analyzed to identify the depositional features. Cores were sampled for thin sections. Standard thin sections were prepared and analyzed for mineral composition and relative abundance of bioclasts, cement and porosity. Porosity and permeability of core samples representing individual facies were measured in the laboratory.

(4) Petrography: Facies changes across mounds can occur abruptly across boundaries between the grain-rich flanking and capping facies to micritic bafflestone core (Wilson, 1975). Major facies changes identified in outcrop were sampled for thin section petrography. Samples were collected in a systematic fashion to cross mound-core, complex flank and mound-crest as well as laterally and vertically adjacent beds, to establish facies changes.

(5) XRD: X-ray diffraction of selected samples of mound facies was used to determine the mineralogy of the Frisco Limestone.

Location:

In central and south-central Oklahoma, Hunton oil and/or gas production is reported to be primarily from the Lower Devonian Frisco Formation, Bois d'Arc Formation and Ordovician Keel Limestone of the Ordovician-Silurian Chimneyhill subgroup. The type locality for the Bois d'Arc Formation is on Bois d'Arc Creek in the northern Arbuckle Mountains, where it is overlain by the Lower Devonian (Deerparkian) Frisco Formation (Amsden, 1960). This outcrop, which is one of the primary foci of this investigation, is located approximately five miles south of the municipality of Ada in Pontotoc County, Oklahoma. The other study areas are oil fields in which the Frisco Limestone is a producing reservoir. The first is the Fitts Field located approximately five miles southeast of the Bois d'Arc Creek outcrop. Several cores from wells drilled in the Fitts Field were examined, sampled and correlated to the wireline log data. The second oil field is the Mustang field in Canadian County, where additional cores were available.

The Hunton Group contains carbonate mound lithofacies. Conodont data indicate that these mounds are part of the Frisco Formation (Rechlin, 2005). The Frisco is lower Devonian in age and separated from the underlying Hunton carbonate by an unconformity (Barrick et al., 1990). In most cases, Frisco Formation is the uppermost producing unit within the Hunton Group and much of the Hunton production in Seminole and Pontotoc counties, not previously assigned to specific formations may have produced from Frisco reservoirs. Several types of subsurface data were integrated to determine stratigraphy, depositional facies and estimate reservoir type, size and quality. The location of the subsurface core samples are Sec.27, T.2N, R.7E Pontotoc County, OK and Sec.19,T.11N., R.5W Canadian county, OK (Figure 1).

The Fitts Field is classified as a major oil and gas field in the Hunton Group (Hyatt, 1936). The field is located in T.2N. , R.6E. & R.7E. Pontotoc County, Oklahoma. The Frisco Formation in Fitts Field was mapped because well density was believed to be sufficient to define mound distribution and geometry. The thickness of the Frisco Formation was correlated with the production data to determine the impact of mound development and distribution on initial oil production rate.

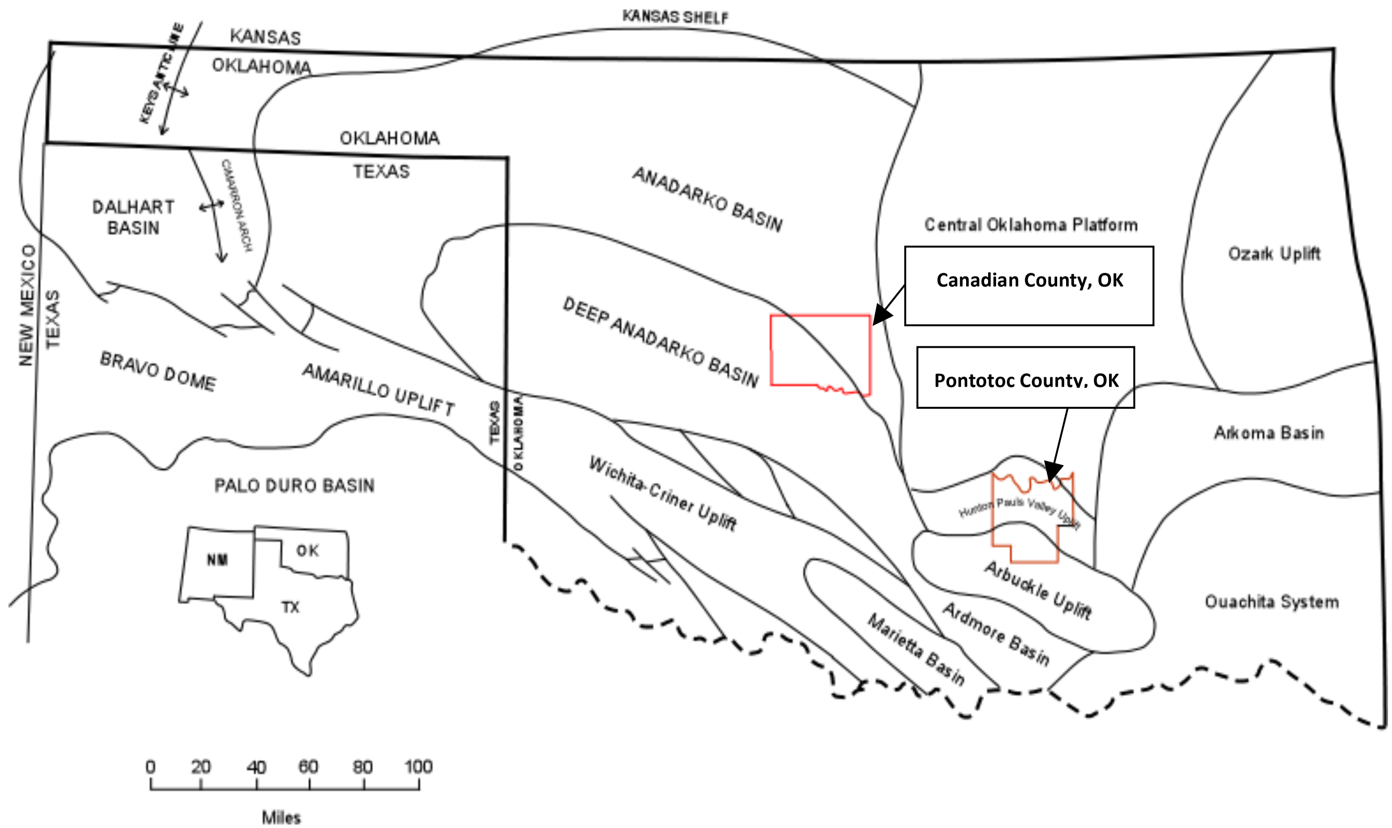


Figure 1: Location of Frisco Formation study area in Pontotoc and Canadian Counties, Oklahoma in relationship to the tectonic provinces of the southern Midcontinent region. Modified from Hentz (1994); Rechlin (2003).

Previous Work

The Frisco Limestone was first named by Reeds and described as "coquina like limestone" (Reeds, 1911). Fritz and Medlock (1993) portrayed the sequence stratigraphy of the Hunton Group in the Southern Midcontinent, with very limited focus on Devonian Frisco mounds. Morgan, et al. (1981) addressed subtle porosity and traps within the Frisco Formation in the Anadarko Basin. Al-Shaieb and Puckette (2000, 2001), Matthews (1992), Manni (1985), and Beardall (1983) described the depositional environments and diagenetic processes that affected the Hunton Group, emphasizing the oil/gas producing reservoirs. Very limited work is published concerning the geometry, facies and depositional setting of Devonian mounds in Oklahoma. Medlock (1984) first described the depositional environment of Devonian mounds on the Lawrence Uplift in Pontotoc County. Rechlin (2005) described mounds in the Frisco Formation in the subsurface of Seminole County, established their age using conodont biostratigraphy and compared them to the outcrop in Pontotoc County.

Wilson (1975) proposed, that regardless the origin, mounds show a vertical and lateral sequence of textural and organic facies. According to Wilson (1975), the ideal mound usually shows seven distinctive textural and organic facies. Rechlin (2005) used wireline logs from oil and gas exploration wells in Seminole and Pontotoc County to correlate the Frisco Formation, described the outcrop using the Wilson (1975) model and sampled "flank" and "micritic bafflestone core" facies of the mound buildup along Bois d'Arc Creek. Rechlin (2005) did not recognize any additional facies within the mound outcrop.

CHAPTER II

GEOLOGIC SETTING

General Structure:

The Hunton Group comprises a sequence of fossiliferous carbonate strata ranging in age from Late Ordovician to Early Devonian. Deposition of the Hunton Group was closely related to development of the southern Oklahoma aulocogen. The southern Oklahoma aulacogen underwent rifting, subsidence, and deformation stages. The Hunton Group was deposited during transition from the subsidence stage to the deformation stage (Adler, 1971). During Early to Late Cambrian, the rifting stage included uplift and igneous activity. During the subsidence stage a passive continental margin formed. Thicker stratigraphic sections are contained in the basins than on the more stable shelf areas adjacent to the aulacogen. Deposition of the Ordovician-Silurian-Devonian Hunton Group marked the end of the subsidence stage of the southern Oklahoma aulacogen (Amsden, 1980). Several unconformities are present within the Hunton Group. These unconformities are the result of nondeposition and erosion. Uplift and erosion of the Hunton Group took place along the Nemaha Ridge, in the Wichita Mountains and in the Northern Oklahoma (Adler, 1971). The unconformity above the Hunton resulted from partial erosion of the Group (Amsden, 1980). Upper Devonian Woodford sediments were deposited on this eroded surface.

Hunton Stratigraphy

The name Hunton was proposed by Taff for a type section (Sec.8,T.1S, R.8E.) named for the town of Hunton in Coal County, OK (Taff, 1902). The Ordovician-Silurian-Devonian Hunton Group consists of a sequence of fossiliferous marine carbonate strata that are separated by unconformities. The Devonian part of Hunton group consists of three formations, Haragan, Bois d'Arc and Frisco in ascending order. The Haragan-Bois d'Arc Formation is Lower Devonian System and Lockovian Stage (Rottmann, 2000). The type locality for Haragan-Bois d'Arc Formation is along Haragan Creek in Murray County, Oklahoma (Amsden, 1960). Reeds (1911) named all upper Hunton strata as the Bois d'Arc Formation for exposures along Bois d'Arc creek on the Lawrence Uplift, Pontotoc County. In 1926, he separated the upper massive bedded limestone from the Bois d'Arc and called it the Frisco Formation (Reeds, 1927). In 1960 Amsden designated the exposure along Bois d'Arc Creek (NE ¼ sec. 11, T.2N, R. 6E.) Pontotoc County, Oklahoma as the type section for the Frisco Formation (Amsden, 1960).

The Frisco Formation is Lower Devonian system Pragian Stage (Rottmann, 2000). The Frisco is relatively thin and lithologically and faunally distinct from underlying Helderbergian strata (Amsden, 1960). The major lithologic difference between the Frisco and Bois d'Arc is an increase in siliciclastic content in the Bois d'Arc (Medlock, 1984). The Frisco strata are believed to be separated from the Helderbergian by an unconformity and there is some evidence of minor pre-Frisco erosion (Amsden, 1960). In other areas, the unconformity represents a period of maximum erosion that truncated the pre-Frisco Hunton over a time period of one or two million years (Fritz et al., 1993). The Frisco is overlain by the Woodford Shale, which is easily identifiable as a hot shale marker bed by its radioactivity that results in high gamma-ray log readings. There is an erosional unconformity of post-Hunton and pre-Woodford time that separates the Woodford and the Hunton group at some magnitude. Figure 2 illustrates the stratigraphy of Hunton Group in southern Oklahoma.

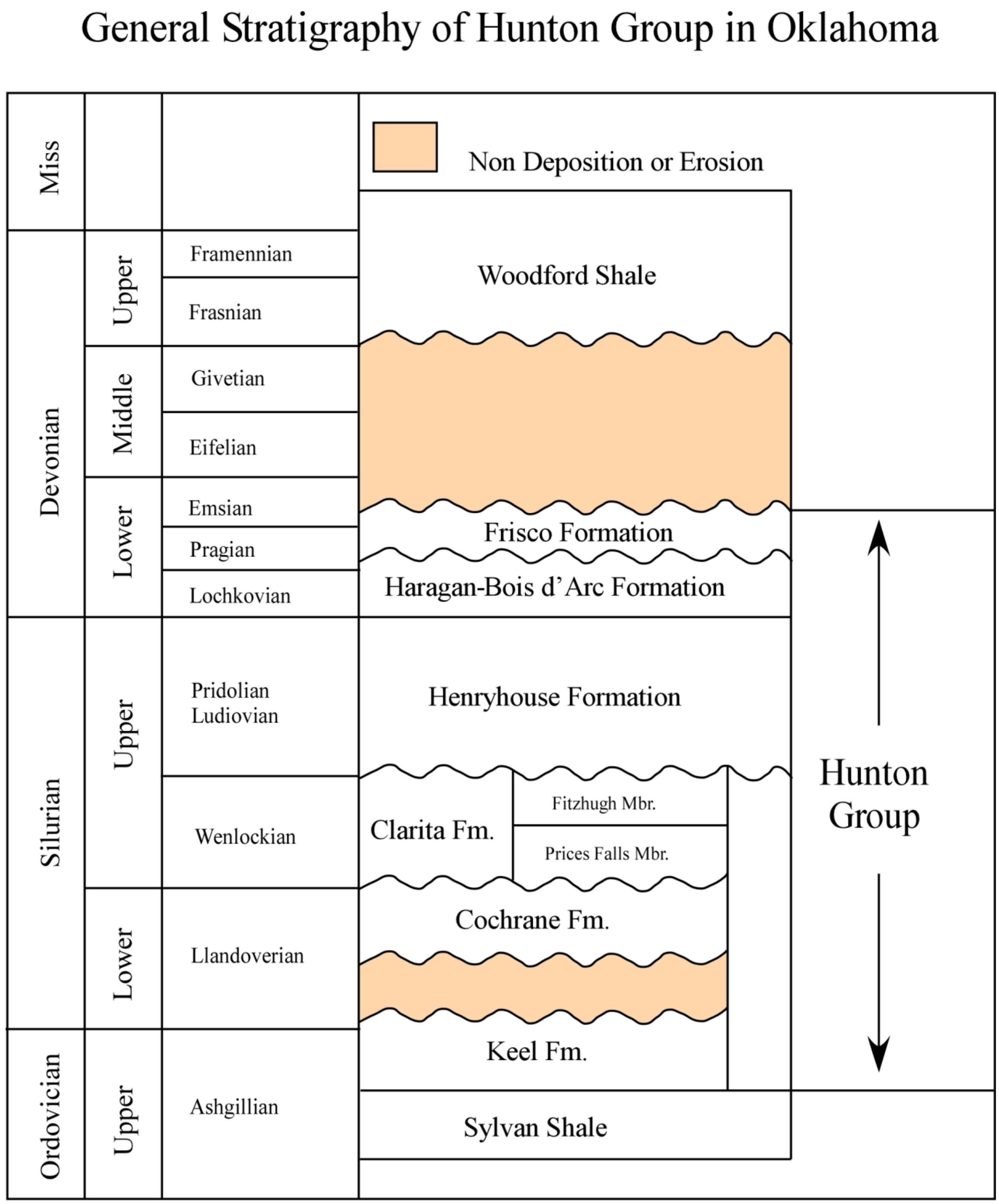


Figure 2: General Stratigraphy of Hunton Group in Oklahoma. Modified from (Barrick et al., 1990).

Conodont Biostratigraphy

Many early wells were interpreted to have thick Bois d'Arc section if the wireline log signature contained a robust deflection of the spontaneous potential at the top of the Hunton interval. However, based on the biostratigraphy of Hunton Group, it is now known that in many wells these porous zones are the Frisco Formation. The detailed Hunton Group biostratigraphy was conducted by Amsden and reported in a series of publication (Amsden, 1956, 1960; Amsden, 1962, 1967, 1980; Amsden et al., 1988; Amsden et al., 1958). Amsden and Barrick (1988) identified conodonts for the Bois d'Arc as elements of *Belodella* and *Dvorakia* that occur in the Haragan. Conodonts from coarse calcarenites are abundant, but badly fragmented (Amsden, et al., 1988). Rechlin (2005) identified *Icrodius, Claudia* and *Dvorkia* genus in the Frisco Formation. It has been suggested that sea level changes can be linked to carbon isotope variation in sediments as well as to conodont and other biozone boundaries (Ripperdan et al., 1992). The representatives of the conodont genus *Icriodus* occur in larger proportions within shallow-marine facies and their increase in proportion within the conodont assemblage are interpreted as a drop in sea-level (Sandberg, 1976). Rechlin (2005) linked the conodont biozones with sea level changes and used biozones to interpret and correlate wire-line log signatures to stratigraphic boundaries (Figure 3). These zones are considered to correlate with the Pragian of the Barrandian area (Klapper et al., 1978). Biostratigraphic analysis concluded that much of the oil and gas production from the top of Hunton that was previously allocated to the Bois d'Arc Formation is actually from the Frisco Formation (Amsden et al., 1971; Morgan et al., 1981; Rechlin, 2003). The stratigraphic relationship between older Hunton Group formations and the Frisco Limestone is illustrated in Figure 4 from Amsden and Barrick (1988).

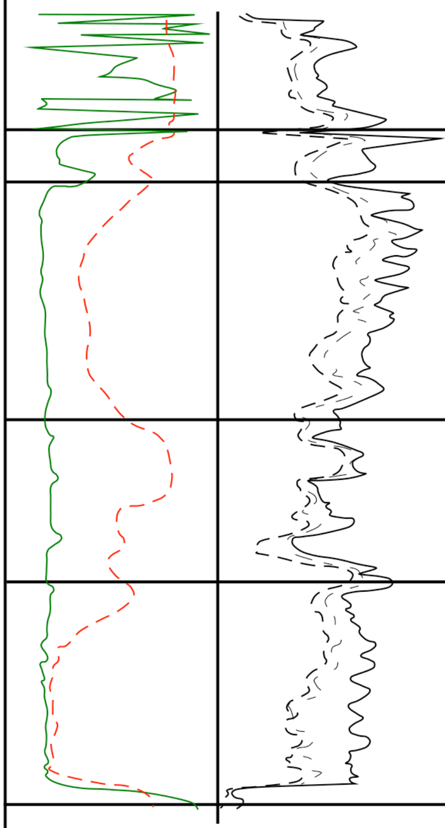
Typical Log Signature	Conodont Species Recovered	Stratigraphy
	Not Examined	Woodford Shale
	Not Examined	Misener Sandstone
	Icriodus claudiae *Dvorakia sp.*	Frisco Formation
	Panderodus unicostatus *Walliserodus sancticlairi*	Silurian (middle) Possibly Henryhouse Formation
	Ozarkodina excavata *Ozarkodina sp.* *Panderodus unicostatus* *Walliserodus sancticlairi* *Dapsilodus obliquicostatus*	Clarita Formation
	Not Examined	Sylvan Shale

Figure 3: Biostratigraphic framework of the Hunton Group and wireline log response (Rechlin, 2005). Gamma-ray is the solid curve in the track 1. Spontaneous potential is the dashed curve in track 1. Track 2 contains resistivity log. Total Hunton thickness is approximately 180 feet.

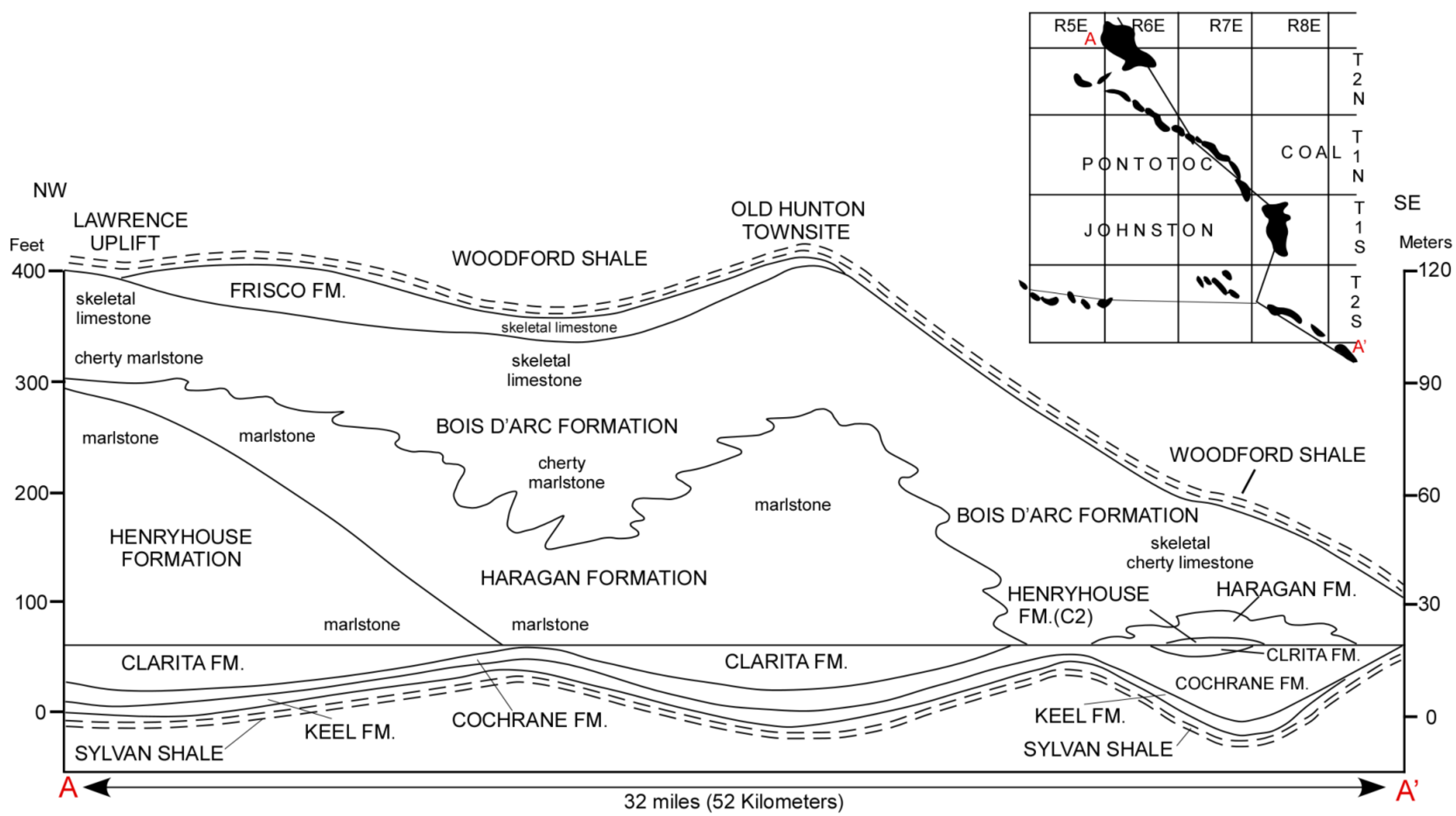


Figure 4: Northwest-southeast stratigraphic section showing Bois d'Arc and Frisco relationship along the northeastern margin of Arbuckle Mountains. Modified from Amsden & Barrick (1988).

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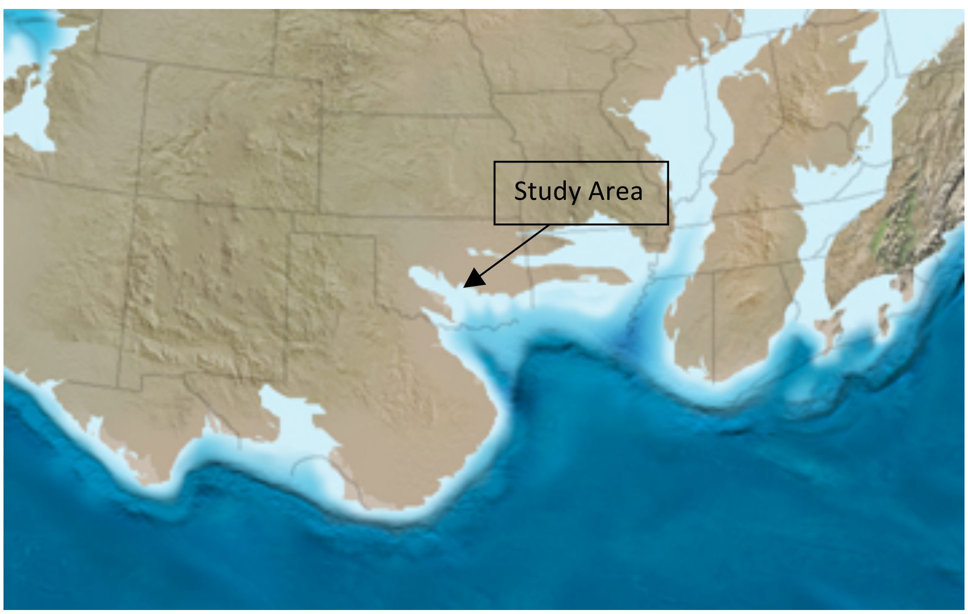
Depositional Environment

The Hunton Group formed across a stable, shallow epicontinental shelf during a time of relative tectonic quiescence (Stanley, 2001). During this period, warm shallow seas covered most of the North America and facilitated the deposition of shoal and moderately shallow water carbonate sediments across most of the cratonic shelf. The Hunton Group contains examples of cyclic sedimentation that reflect periods of sea level fluctuation.

Frisco mounds were deposited during Early Devonian time in a restricted open marine environment. During this period the sea was calcitic in origin. In calcitic seas, low-magnesium calcite is the primary inorganic marine calcium carbonate precipitate; which leads the calcitic cement precipitates from sea water as primary cementing materials. Figure 5 illustrate the approximate relationship of depositional setting and ocean bathymetric range during Early to Middle Devonian time at study area. Amsden (1961) concluded that the Frisco was deposited in an outer sublittoral environment. The wide range in size of skeletal fragments suggested that the grains were not transported long distance (Morgan, 1982). As a result of pre-Woodford uplift and erosion, the widespread flooding and associated Frisco deposition that appears to culminate Hunton deposition may not have been preserved (Al-Shaieb et al., 2000).

(a) Middle Devonian (385 M)



(b) Early Devonian (400 M)

Figure 5: Paleogeographic maps of Early and Middle Devonian showing the depositional settings and bathymetry range of the Hunton Group during deposition. After Blakey (2010).

CHAPTER III

CARBONATE MOUND BUILDUP

Introduction

Carbonate mounds are unique organosedimentary features found in environments ranging from freshwater lakes to deep marine slopes (Haywick et al., 2001). The processes of mound build-up and mound nucleation are not yet completely understood. Mounds usually grow over extended time periods and paleogeographical, palaeoclimatological and palaeoceanographic changes mainly control mound growth. Mounds are regarded by many researchers as diverse complexes that overlap in composition, primary physical characteristics, and diagenesis with ‘‘ecological’’ reefs like modern tropical shallow water coral reefs (Longman, 1980; Pratt, 1981; Webb, 1996; Wood, 1999). A number of factors may have influenced the development of these fauna-rich communities, including elevation from the surrounding sea-bed, a suitable surface for attachment and shelter among the branching structure of the corals can all play a part. These interactions of biota and sedimentary processes play an important role in carbonate mound generation.

Mound Characteristics

Carbonate mounds usually developed on the foreslope of the shelf margin with upslope sand beaches and islands. The slope usually varies from one to two degree to as much as twenty five degrees, and on steeper slopes carbonate mounds can develop below the photic zone (Wilson, 1975). Wilson (1975) proposed that carbonate mounds formed in shallow shelf environments and develop a vertical and lateral sequence of textural and organic facies. Wilson (1975) followed the Dunham classification (Dunham, 1962) (Figure 8) and suggests that regardless of the origin, typical mounds commonly show seven distinct facies (Figure 6).

The sequence of mound facies develops when the accumulation grows into the wave base and is controlled by varying rates of sediment accumulations. Mound cores are massively bedded, with thicknesses ranging from less than 1 to 35 m (Wilson, 1975). This part of the mound consists of organisms capable of trapping fine lime sediments. When the mound core reaches to a certain height (wave base), the soft sediment serve as a seat for organic crestal boundstone. The flanking beds lap up the sides of mounds and are composed of exclusively bioclastic debris. If sea level remains stable and intermound areas are filled by sediments, a single bedded capping grainstone forms across the top of the mounds. Organic veneer and talus are rare but widespread facies. If frame-producing organisms decline or are absent, the upper surface of the mound may be coated with a thin veneer of a variety of encrusting organisms. Talus is typically local lithoclastic conglomerates. These lithoclasts represent chunks of partly or wholly lithified micrite that were collapsed by wave action or carried down by current along the sloping side of normal flank beds (Wilson, 1975).

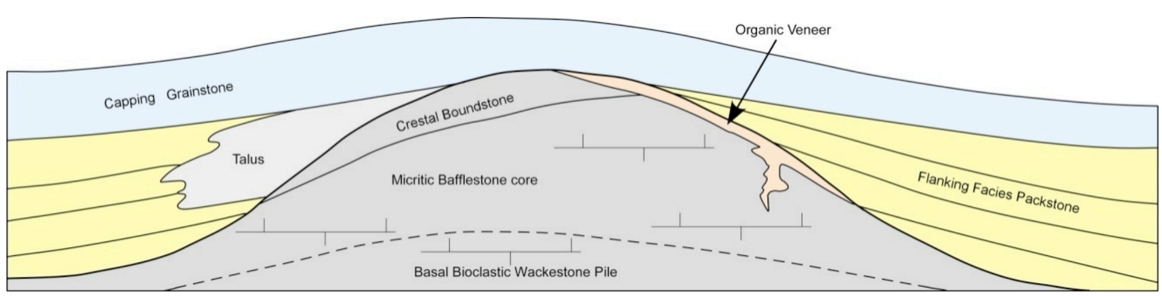


Figure 6: Typical facies of a mud mound. This model is believed to be an analogue for the Devonian Frisco mounds, after Wilson (1975)

Allochthonous carbonate original components not organically bound during deposition				Allochthonous or Autochthonous		Autochthonous limestone original components organically bound during deposition		
Less than 10% >2mm components				Greater than 10% >2 mm components		Boundstone		
Contain Lime mud (<0.20mm)			No lime mud	Matrix supported	>2mm component supported	By organisms that act as bafflers	By organisms that encrust and bind	By organisms that build a rigid framework
Mud Supported		Grain Supported						
Less than 10% grains (>0.02 mm to <2mm)	Greater than 10% grains							
Mudstone	Wackestone	Packstone	Gainstone	Floatstone	Rudstone	Bafflestone	Bindstone	Framestone

Figure 7: The Dunham (1962) classification of limestone according to depositional texture, as modified by Embry and Kolvan (Embry et al., 1971).

Devonian Frisco Mound

Carbonate mounds in the Mississippian rocks has been known for decades. Due to lack of extended Devonian mound outcrops, the recognition of Devonian carbonate mounds came later, when subsurface data became more abundant. The type locality of the Devonian Frisco Formation is along Bois d'Arc Creek in Pontotoc County, Oklahoma (Amsden, 1960). The type section outcrop is approximately four miles south of Ada, Oklahoma (Figure 9). And based on this outcrop, individual Frisco Formation mounds can have a very limited areal extent. Deposition of Frisco mounds was initiated with advance of the lower Devonian sea over the previously deposited Hunton carbonates. Hunton deposition ceased with the withdrawal of Frisco seas from this area (England, 1961). According to Stanley (2001), Frisco mounds developed in the subtidal open shelf portion of the carbonate ramp environment. This facies zone forms down slope of the moderate to high energy zone, below effective wave base, but not below the storm base (Figure 9). Facies developed in these zones are primarily grain supported with very limited mud-supported texture. Grains in this facies zones are exclusively fragmented (not rounded) fossil materials (bioclasts). This facies belt is occasionally reworked by storm currents (Stanley, 2001).

Frisco mound facies formed from the both activities of crinoids and bryozoans that produced a local accumulation of carbonate sediment (Fritz, et al., 1993; Medlock, 1984). Mound building crinoids and bryozoans acted as a baffle to longshore currents allowing for the accumulation of mud and other fine grained materials below the wave base, thus initiating mound development (Figure 10-a). This lime mud-rich core supports the bulk of the mound facies.

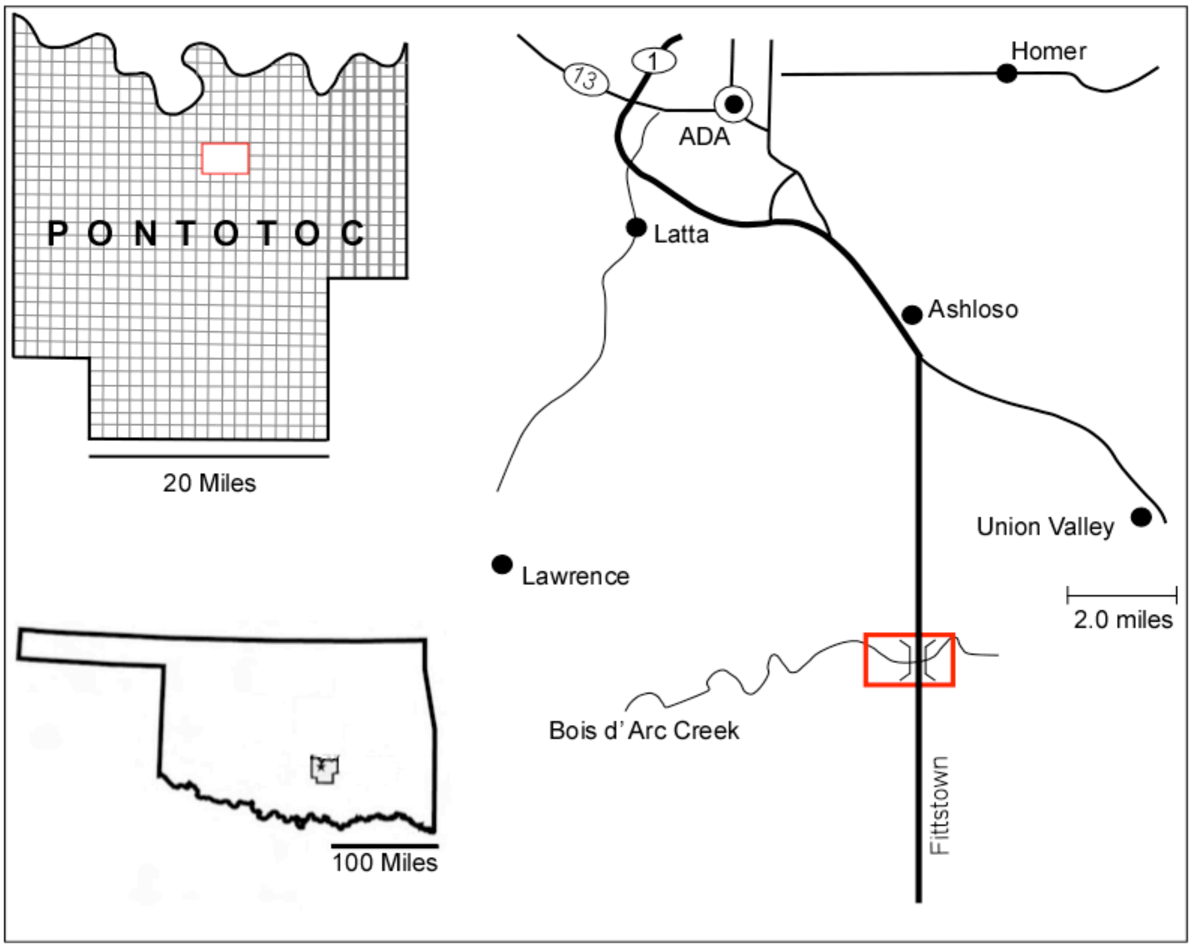


Figure 8: Location of Frisco Formation outcrops along Bois d'Arc Creek, Pontotoc County, Oklahoma.

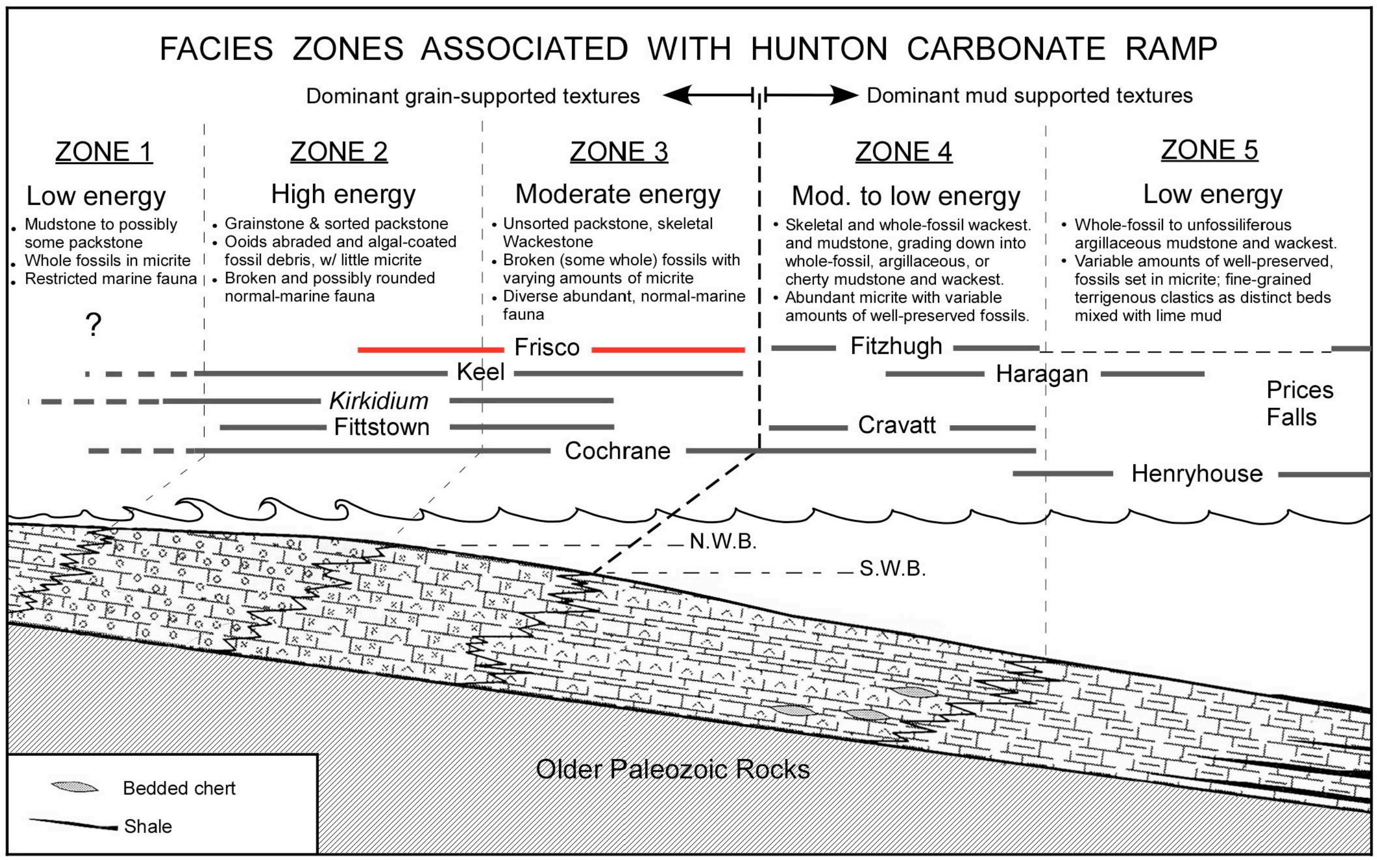


Figure 9: Standard facies model of the Hunton Group, based on a carbonate ramp model deposition. Modified from Stanley (2001).

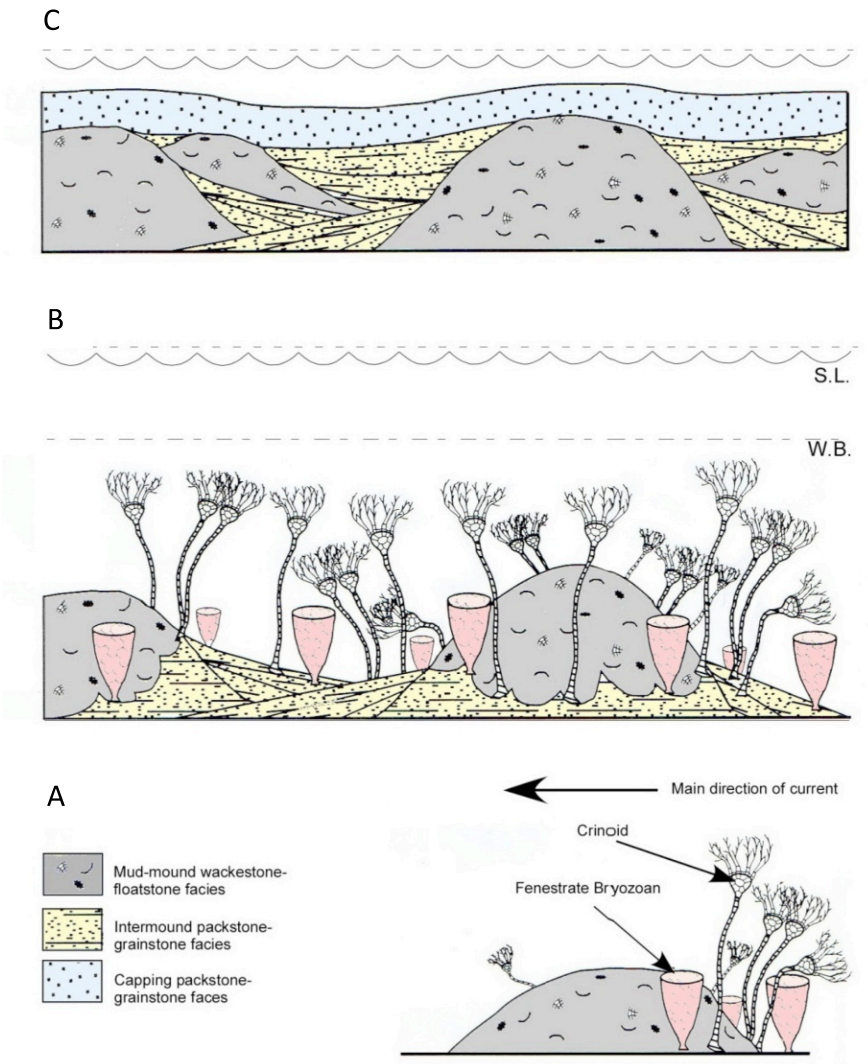


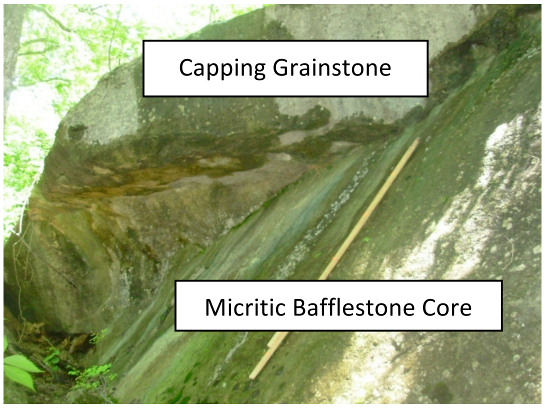
Figure 10: Diagram illustrating hypothetical development of the Frisco mound, intermound and capping facies. A-progressive colonization of current-induced pile of lime mud on lee side of crinoids-bryozoans thickets. B- Rising sea level allows lime mud to accumulate below wave base (W.B.), C- lowering of sea level (S.L.) brings mound and intermound facies into intertidal zone where they become reworked by waves, forming the coarser- grained capping facies. Modified from (Stanley, 2001).

Mounds accumulate on the leeward current side of crinoid and bryozoan thickets, from the actual baffling of sediment by these organisms (Wilson, 1975). Bioclastic debris may have drifted outside of the protection of crinoid and bryozoans thickets. Exposed to mild current, this bioclastic material is washed of the fine mud fraction, leaving only the coarser bioclastic material behind to form intermound packstone-grainstone facies (Wilson, 1975) (Figure 10-b). At final stage, Frisco mounds were exposed to the wave energy due to sea level drop; and constant wave action of the littoral zone caused washing and reworking of the mound and intermound sediment. The increased wave current activities formed the capping grainstone facies that blanket older Frisco facies (Fritz, et al., 1993; Medlock, 1984) (Figure 10-c).

Frisco mound lithofacies

Medlock (1984) defined the Frisco mound at the type location in Pontotoc County, Oklahoma as containing three specific rock textures and assigned them as specific facies: mound core, flanking and capping. Based on outcrop study of the same section along Bois d'Arc Creek a depositional facies model for the Devonian Frisco mounds was constructed (Figures 11).

Along Bois d'Arc Creek preserved mound facies unconformbly overly the older Bois d'Arc limestone. Figure 11 shows the weathering profile of Frisco facies along Bois d'Arc Creek. The overhanging ledge is interpreted as the capping grainstone facies that is more resistant to weathering than the underlying carbonate-mud-rich core. The micritic bafflestone of the core is the thickest part of mound (Figure 11) and contains of micritic limestone that is rich in bioclastic debris. Remains of baffling organisms are uncommon in this bed. The mound-core is dominantly subtidal micritic bafflestone, but contains small patches of packstone and wackestone. The flanking facies (Figure 11) developed as a result of accumulation of bioclastic sediments (crinoid and bryozoan fragments) off the mound, and deposited as a packstone/grainstone depending on the wave current energy which controlled mud accumulation.



(a) South of Bois d'Arc Creek

(b) North of Bois d'Arc Creek

(Jacobs's staff is approximately 5.5 feet or 1.6 meters)

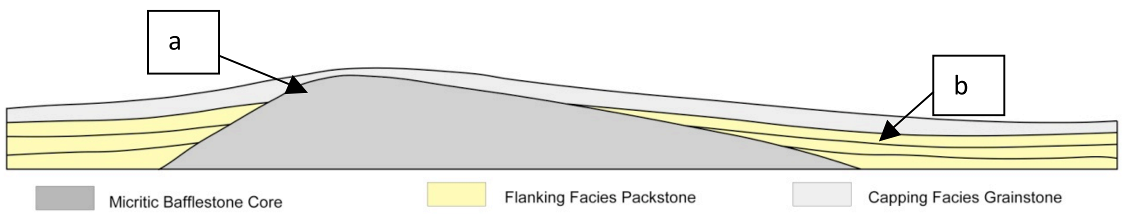


Figure 11: Devonian Frisco mound buildup at Bois d'Arc Creek, Pontotoc County, Oklahoma

The capping facies is dominantly grainstone. Capping facies blanket the mound core and flanking facies and can be distinguished by its relative stratigraphic position. The position of the pre-Woodford unconformity allows for the interpretation that the capping facies were likely exposed to meteoric water, which resulted in weathering and chemical diagenesis. Outcrop observation of the texture and composition were corroborated using thin section microscopy. The carbonates were classified using the Dunham (1962) classification shown in Figure 8 and porosity was classified using Lonoy (2006) carbonate porosity classification.

Petrographic Analysis of Mound Outcrop

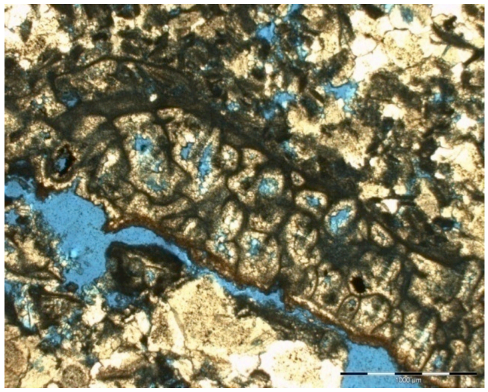
The mound samples are primarily composed of crinoid and bryozoans fragments. Faunal assemblages occurring within the mound core environment include sediment bafflers (bryozoans) and niche dwellers. Accessory fossil fragments identified include brachiopods, trilobites, corals, and gastropods, which are present in relatively small amounts. The crinoid fragments are of sufficient abundance to form grain contacts to support the framework. Abundant bryozoans are associated with buildups and constitute a considerable fraction of biotic components. Fenestellid types are the most common. Niche dwellers include brachiopods, echinoids and ostracodes.

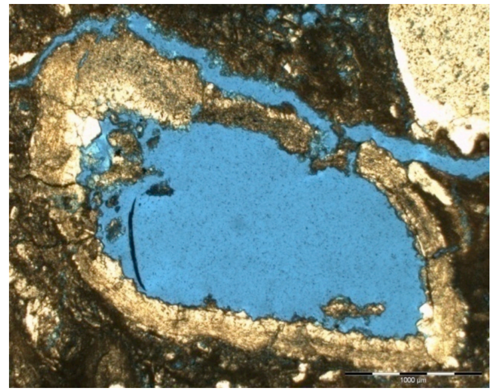
Micritic core lithofacies: Micrite or carbonate mud increases in the micritic bafflestone core of the Frisco mound. Bioclasts in the core have smooth outer surfaces that lack evidence of abrasion (Figure 14C). Ostracodes within the mud rich beds of the core are complete and contain evidence of shelter porosity (Figure 14d). Bioclast rich intervals occur in the mound core at the centimeter scale. Syntaxial calcite cement is generally absent.

Flanking facies: Bioclastic flanking lithofacies deposits are composed of bioclastic debris derived from fauna living on the mounds, along with lime mud. Packstones and wackestones are the predominant associated lithologies; however, grainstones may also occur. Crinoid and bryozoan debris formed aureoles around bioherm flanks, as the delicate long stemmed crinoids preferred the deeper, quieter lower flank environment. Easily recognized by thin section analysis, crinoid components are rigid with syntaxial calcite overgrowths and show little destructive alteration from diagenetic processes of corrosion and dissolution. Disarticulated pieces of crinoids were abundant in flanking facies; these commonly occurred along with bryozoan bioclasts.

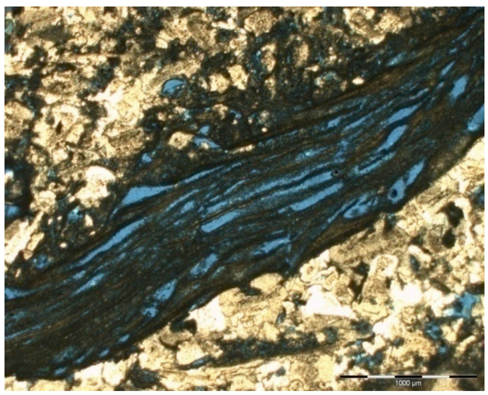
Capping facies: In capping facies abraded bioclastic debris indicates wave reworking of older deposits. Carbonate mud is less common in capping facies and crinoidal grainstone and packstone are dominant. Calcite cement in the form of syntaxial overgrowth is common and as a result, the capping facies is resistant to weathering and forms a ledge that extended beyond the face of the underlying less resistant mound core.

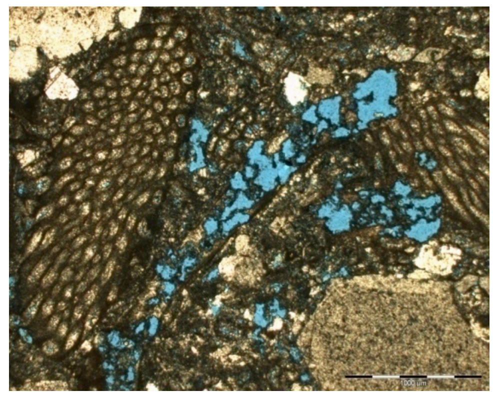
Thin section analysis was used in the classification of the different types of porosity. Primary intraparticle porosity is dominant in mound outcrop samples from flanking facies (Figures 12- a, b, c & d). The micritic mound core shows some intraparticle porosity preserved within axial canals of crinoid fragments (Figure 14-c). Secondary intergranular porosity is evident in grain-rich beds of the micritic bafflestone core (Figure 13-c &d). Capping facies contains preserved interparticle/intraparticle porosity as well as some enlarged-fracture and vuggy porosity (Figure 14 a, b, c &d).





(a) (b)





(c) (d)

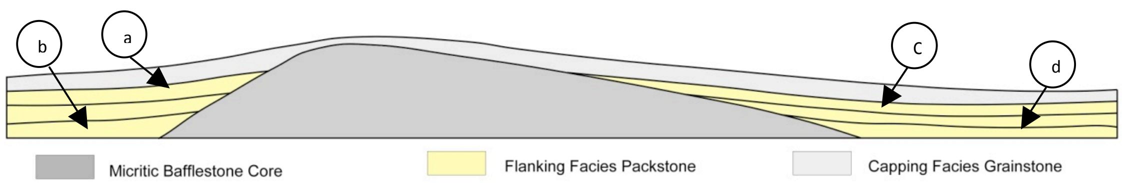
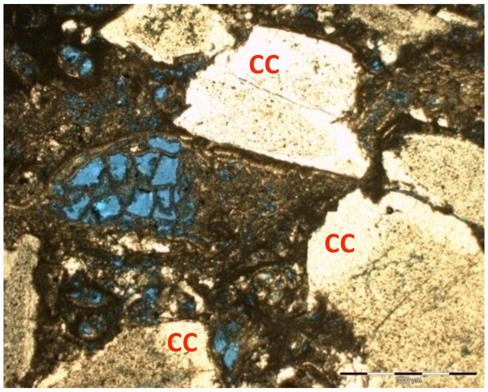
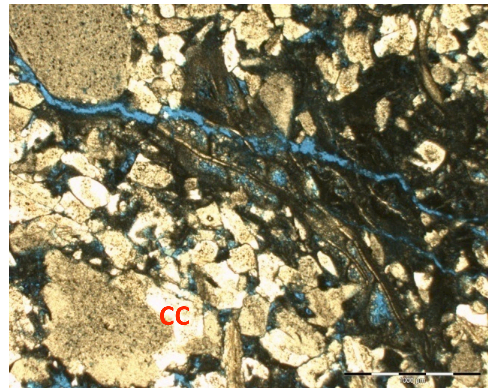
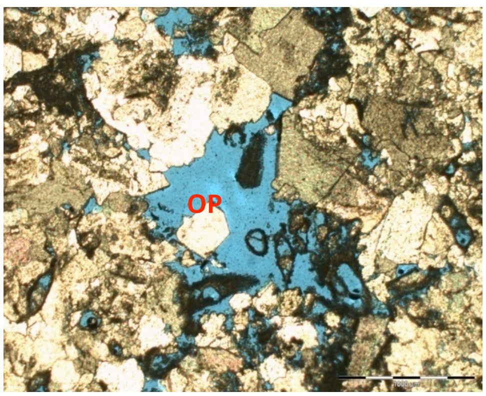


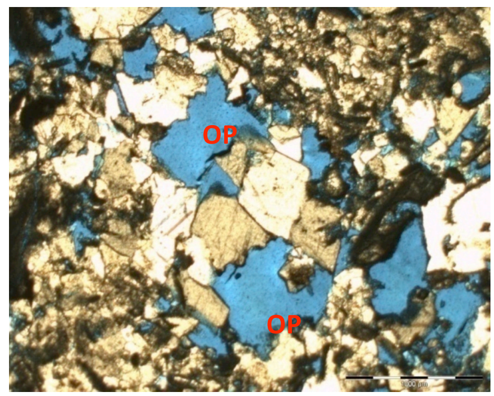
Figure 12: (a) Remnant primary porosity within zooecia of bryozoan fragments. (PPL) (flanking facies packstone). Note early pore-lining calcite cement within zooecia. (b) Dissolution of unknown grain with algal coating rim intact and micro-fracture developed along the grain (PPL); (flanking facies packstone). (c) Primary porosity within collapsed zooecia of bryozoans' branch. (PPL); (flanking facies packstone); (d) partially dissolved bryozoan fragments. (PPL); (flanking facies packstone). Scale bar in all photomicrographs is 1mm. Field of view is 2.5mm by 3.5mm.





(a) (b)





(c) (d)

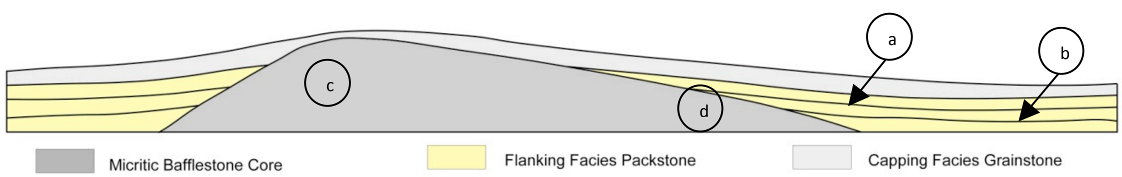


Figure 13: (a) Primary porosity within zooecia of bryozoans fragments. (PPL); (flanking facies packstone); (b) Micro fracture development along the unidentified fossil fragments. (PPL); (flanking facies packstone). Echinoderm fragments are surrounded by syntaxial calcite cement (cc), which reduces porosity and permeability in Frisco limestone mound facies. (c &d)Secondary porosity as oversized pores (OP) formed by the dissolution of carbonate grains and calcite cement. Scale bar in photomicrographs is 1mm. Field of view is 2.5mm by 3.5mm.

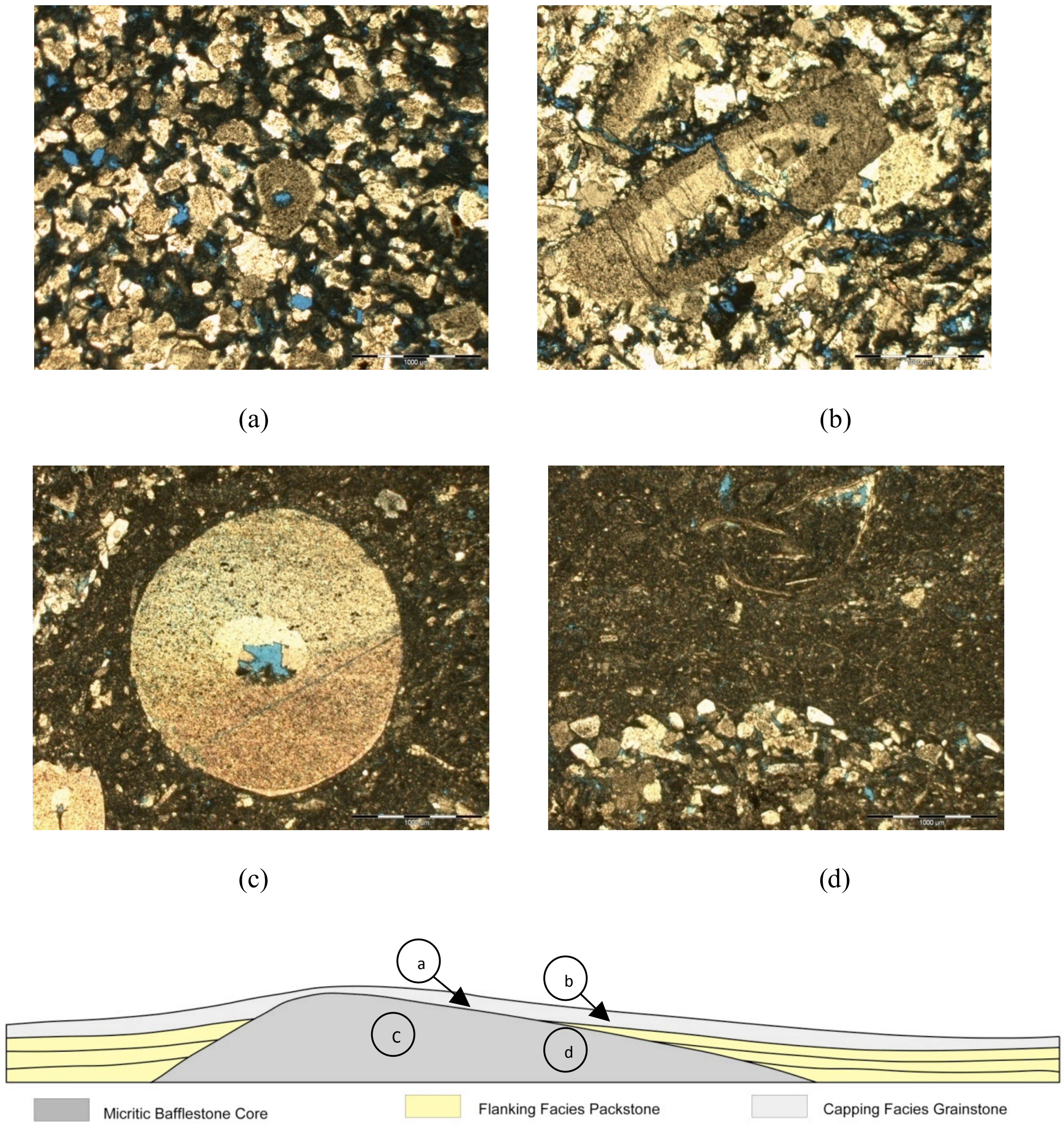


Figure 14: Echinoderm bioclasts in the capping facies that are fragmented and abraded (a) Fossil fragments containing secondary porosity in capping facies grainstone (PPL). (b) Microfracture within capping facies grainstone that provides porosity and permeability (PPL). Scale bar in photomicrograph is 1mm. Field of view is 2.5mm by 3.5mm. (c) Porosity within the axial canal of crinoids fragments. (PPL); (d) Ostracode with sheltered primary porosity. (PPL); (upper part of micritic bafflestone core). Larger bioclasts in the core wackestone are relatively intact and lack evidence of abrasion. Scale bar in photomicrographs is 1mm. Field of view is 2.5mm by 3.5mm.

A strong positive relationship between bryozoan content and porosity is apparent. Within flanking facies, porosity ranges from 15 to 20%; whereas mound core and capping facies generally have porosities of less than 4 percent. Average bryozoan content in flanking facies is 35 to 50 %. Two types of primary porosity originally occurred in Frisco mounds. The first type was the intrabiotic cavities of fossil components, mainly crinoids and bryozoans (Figure 12). A second type of primary porosity represents intergranular voids in grainstone lithofacies (Figure 13). Almost all primary porosity was occluded by the precipitation of calcite cement. This cementation took place in meteoric environments. Secondary dissolution porosity was observed in grain-rich intervals of the mound cores. Bioclastic fragments were dissolved to form oversized pores (Figure 13 c& d).

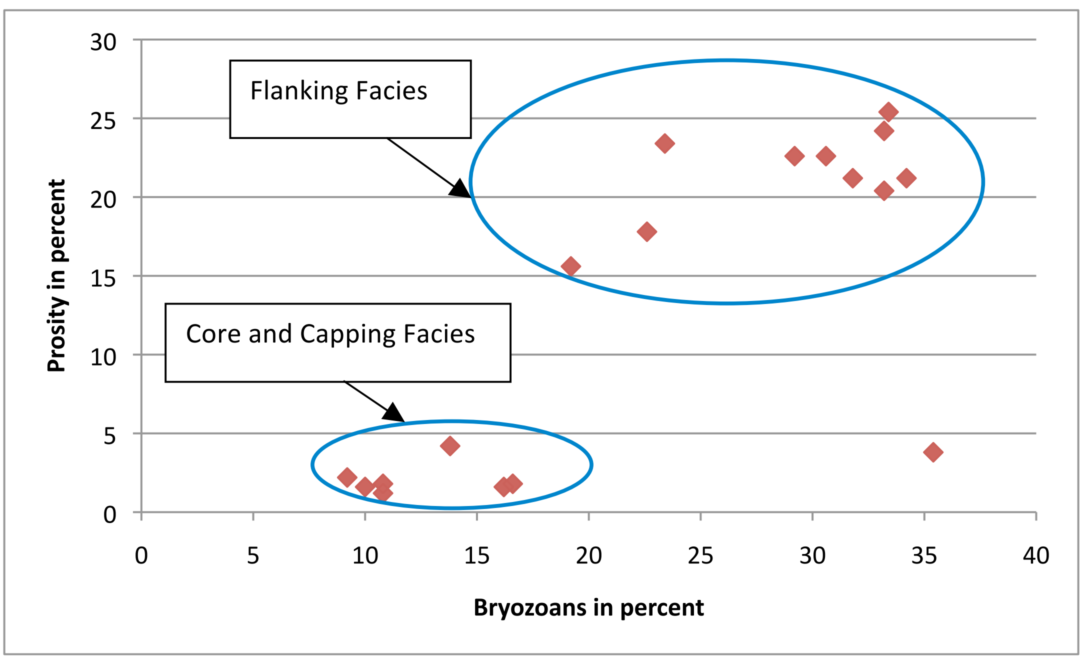


Figure 15: A positive correlation between porosity and bryozoan contents.

CHAPTER IV

PETROGRAPHIC ANALYSIS OF FRISCO MOUND CORES

Introduction

Thin-section analysis of outcrop and core samples allowed for the recognition of the lateral and vertical facies changes in lithofacies within the Frisco mounds. Thin sections were prepared for petrographic study from outcrop samples (described in previous chapter) and cores of mounds in the subsurface from Pontotoc County and Canadian County. Lithofacies in cores was used to define petrophysical facies. Pore system types established using petrographic analysis and the diagenetic history were components of reservoir characterization.

Choquette and Pray (1972) proposed a widely accepted carbonate porosity classification that emphasizes fabric selectivity. This classification is well suited to geological models that integrate depositional processes with early to late diagenetic processes in order to understand porosity evolution through time. Two major porosity types (intraparticle and interparticle/intercrystalline) were identified in thin sections. Each porosity type is distinctive to a given unit in the Frisco mound formation.

Petrographic Analysis

The petrographic analysis of cores of mound lithofacies shows that the dominant bioclasts are crinoid and bryozoan fragments. The most abundant bioclasts are crinoid fragments.

<table>
<tr><th colspan="3">Porosity Classification System</th></tr>
<tr><th>Pore Type</th><th>Pore Distribution</th><th>Pore Size</th></tr>
<tr><td rowspan="6">Interparticle</td><td rowspan="3">Uniform</td><td rowspan="2">Macropores (>100 µm)</td></tr>
<tr></tr>
<tr><td rowspan="2">Mesopores (50-100 µm)</td></tr>
<tr><td rowspan="3">Patchy</td></tr>
<tr><td rowspan="2">Micropores (10-50 µm)</td></tr>
<tr></tr>
<tr><td rowspan="6">Intercrystalline</td><td rowspan="3">Uniform</td><td rowspan="2">Macropores (>60 µm)</td></tr>
<tr></tr>
<tr><td rowspan="2">Mesopores (20-60 µm)</td></tr>
<tr><td rowspan="3">Patchy</td></tr>
<tr><td rowspan="2">Micropores (10-20 µm)</td></tr>
<tr></tr>
<tr><td>Intraparticle</td><td>---</td><td>---</td></tr>
<tr><td rowspan="2">Moldic</td><td>---</td><td>Macropores (>20-30 µm)</td></tr>
<tr><td>---</td><td>Micropores (10-20 µm)</td></tr>
<tr><td>Vuggy</td><td>---</td><td>---</td></tr>
<tr><td rowspan="2">Mudstone Microporosity</td><td>Patchy</td><td rowspan="2">Micropores (10-20 µm)</td></tr>
<tr><td>Uniform</td></tr>
</table>

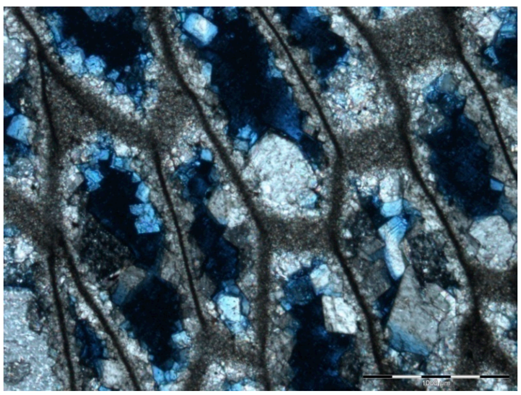
Figure 16: Lonoy porosity classification (Lonoy, 2006)

Crinoids are sufficiently abundant to have enough grain contacts to form a supporting framework, but framework organisms such as corals are not evident. The other dominant fossil fragments are bryozoans. Brachiopods, trilobites, ostracodes, and gastropods occur in lesser amounts

The Frisco crinoidal skeletal packstones are dominated by intraparticle porosity. Primary intraparticle pores form from the decay of organic material and are associated with medium-to high-energy depositional systems (Lonoy, 2006). Intraparticle pores are mostly preserved within the zooecia of bryozoans and central canal of crinoid fragments. The effect of the crinoid fragments on the original porosity of the rock is usually to reduce the porosity because the solid crinoid fragments and syntaxial-calcite overgrowths take up space which would otherwise be occupied by bryozoan fragments with intraparticle porosity.

Core samples from both Pontotoc and Canadian Counties show porosity and permeability are variable in carbonate mound rocks that are interbeded grainstone and packstone. The grainstones are low porosity, clean limestone with sutured, medium- to high-amplitude stylolites (Figure 26-a). The packstone facies are more porous, contain clay and are stylolite free. Stylolites result from compaction and pressure solution during diagenesis and may be enlarged by subsequent fluid flow. They are usually absent in limestone containing more than 5 to 10% clay (Tucker et al., 1990). Stylolites are a good indication of a clean (clay free) limestone (Figure 26-a). Dissolution progresses through complete removal of some interstitial materials and partial removal of fossil particles. All intercrystalline pores identified in the studied cores and outcrop samples are interpreted as beings secondary in origin and are recognized mostly by calcite recrystallization within larger pores (Figure 17).

Two generations of calcite commonly occluded primary void spaces. The first episode of cement was typically a crust of calcite crystals lining voids along echinoderm fragments followed by a second episode of blocky rhombic calcite (Figure 17). Patchy cement distributions are generally controlled by the selective precipitation of syntaxial calcite cement overgrowths on a single crinoid grain (Figure 18). Dissolution porosity is believed to connect the low permeability intraparticle and intercrystalline porosity. Intercrystalline micropores are 10-20 µm in diameter, mesopores are 20-60 µm and macropores are greater than 60 µm. The permeability of intercrystalline porosity increases with pore size. Figure 17 shows intercrystalline macropores in the Frisco mound facies from the Frank Horlivy JR#1 well, Canadian County, Oklahoma.



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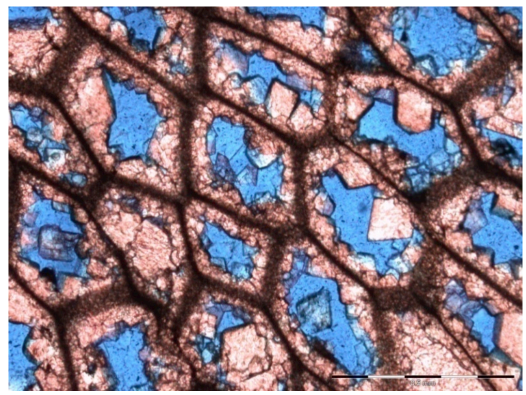

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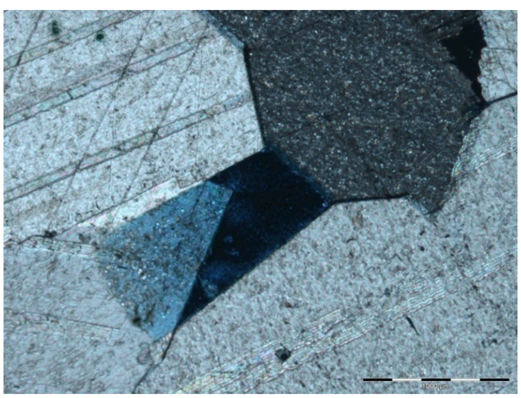

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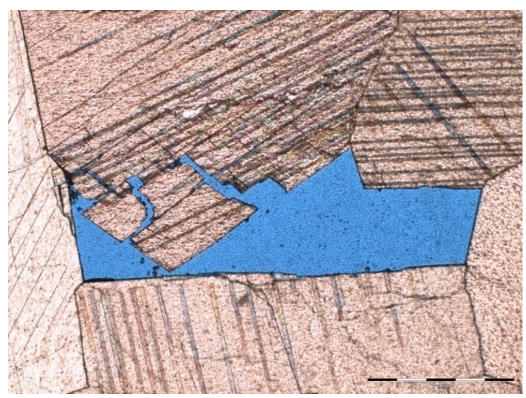
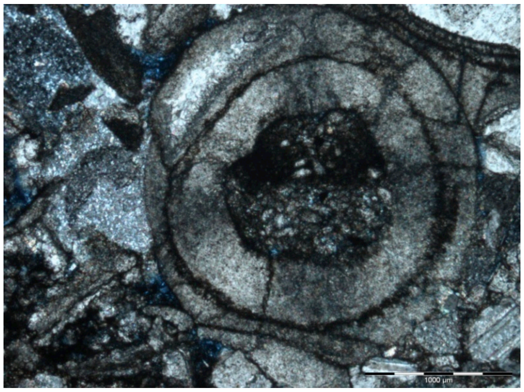
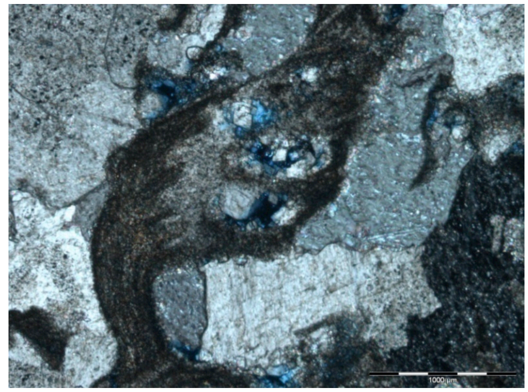


(d)

Figure 17: (a & b) Photomicrographs of primary intraparticle porosity in the zooecia of a bryozoan fragments. Early marine cement in the form of rhombic calcite lines pores. Sinclair Frank HorlivyJR#1, Canadian County, OK; depth 8805 feet. (a) Plane polarized light (PPL), (b) Stained with alizarin red solution. Scale bar in photomicrograph is 1mm. (c & d) Photomicrograph of secondary porosity that is partially occluded by sparry calcite crystals. Sinclair Frank Horlivy JR#1, Canadian County, OK. Depth 8807 feet. Scale bar in photomicrographs is 1mm. Field of view is 2.5mm by 3.5mm.



(a)



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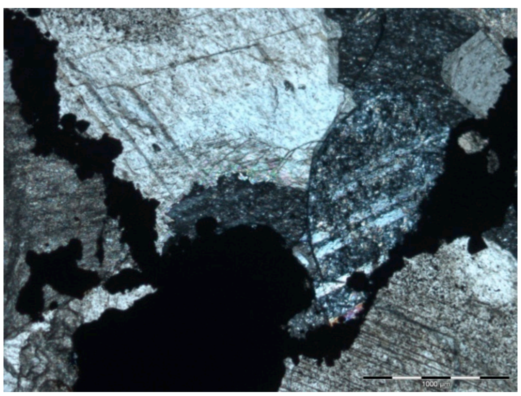

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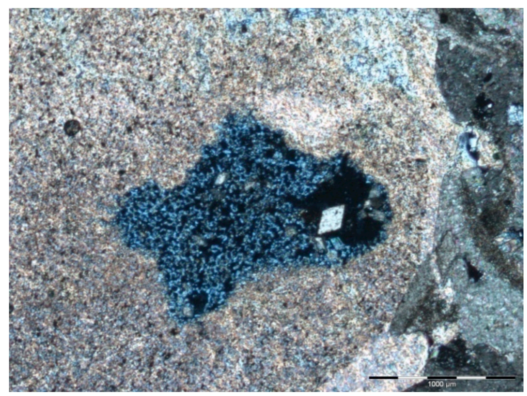
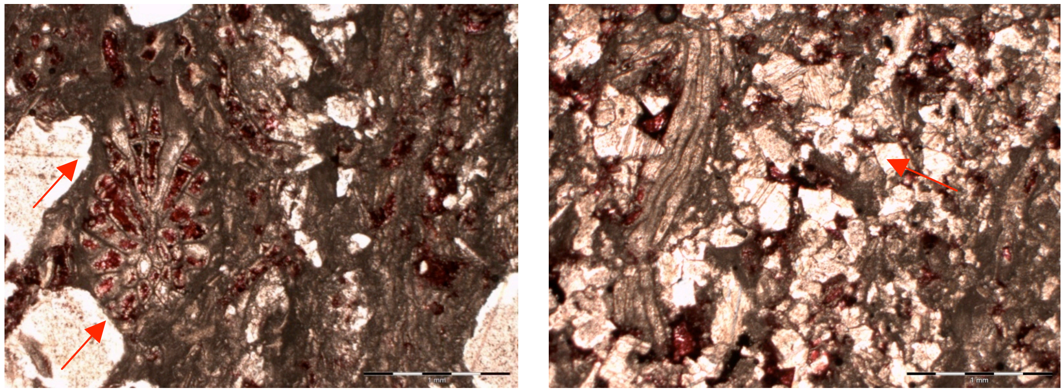


(d)

Figure 18: Photomicrograph of remnant primary intraparticle porosity preserved as microporosity within (a) crinoid fossil fragment & (b) zooecia of bryozoan fragments. Crinoid fragments in image (b) shows extensive syntaxial calcite overgrowth. (PPL); Sinclair Frank Horlivy JR#1, Canadian County, OK. Depth 8820 feet. (a) PPL (b) PPL. (c) Photomicrograph of stylolites resulting from pressure dissolution of crinoid-rich rocks with extensive syntaxial calcite overgrowth. In some instance stylolitization increases porosity and permeability (d) Dissolution pore in crinoid fragments that hosts a secondary rhombic calcite crystal. Sinclair Frank Horlivy JR#1, Canadian County, OK. Depth 8825 feet. (a) PPL (b) PPL. Scale bar in photomicrographs is 1mm. Field of view is 2.5mm by 3.5mm.



(a) (b)

Figure 19: (a) Photomicrograph of primary porosity within the zooecia of bryozoan fragments. Isolated crinoid fragments (arrow) show syntaxial calcite rims. (b) Intraparticle porosity within fossil fragments with rhombic calcite cement. Mobil East Fitts Unit , 9-40, T. 2 N., R. 7 E, Pontotoc County, OK; Core depth (a) 3452 feet; (b) unknown. (PPL). Scale bar in photomicrographs is 1mm. Field of view is 2.5mm by 3.5mm.

Diagenesis

The diagenetic history of Frisco Mounds was dominated by early calcitic cement, subaerial exposure and meteoric influences. During the Devonian period the sea was calcitic and early calcitic cement precipitated from sea water line primary pores. Variations of the diagenetic overprints were due primarily to differences in preservation of these sequences. The Frisco mound at outcrop along Bois d'Arc Creek is approximately 40+ feet thick and a mile in width. The mound is composed of dm-to-m-scale silty fossil wackestone-floatstone and bafflestone. The core matrix consists of roughly equal amounts of calcareous fossils and micritic cements. The comparison of mound rocks in outcrop with core samples from Pontotoc County (3000+ feet deep) and Canadian County (8000+ feet deep) indicates that the final product of burial diagenesis will be a comparatively low-porosity body in which fossil framework builders are largely cemented by sparry calcite.

Micritization

Practically all skeletal grains observed were influenced by an early stage of diagenesis. Dark outer coatings or rinds formed as a result of the boring and infilling habits of the blue-green alga. Micritization occurs in shallow marine waters where the accretion rate is slow and the substrate is relatively stable.

Early Meteoric Cements

Initial porosity in these uncompacted sediments ranges from 40 percent to 70 percent (Bathurst, 1975). Upon exposure to fresh meteoric waters, the original mineralogic components become unstable and undergo alteration and conversion to more stable forms. This process results in the significant reduction of primary porosity and the formation and/or occlusion of secondary porosity. Frisco mound rocks have porosities ranging from 2 percent to 25 percent. Various studies have shown that the diagenetic stabilization of a carbonate is a differential process related to the mineralogic composition of the sediment and to the diagenetic environment.

In associating differential stabilization rates to diagenetic environments based upon study of Pleistocene carbonates of Bermuda, Land (1970) observed that stabilization and cementation in the meteoric phreatic zone was very fast as compared to that occurring in the meteoric vadose zone. Frisco mound deposits in the study area were subjected to diagenesis in the meteoric environment. The following generalized criteria were observed as being indicative of meteoric diagenesis.

1. Precipitation of calcite cement in primary voids and secondary dissolution molds (Figure 17, c & d) (Land, 1967).

2. Epitaxial precipitation of sparry cements on echinoderm components. (Lucia, 1963).

Occurrences of Dolomite

No true dolostones were recognized as occurring in the Frisco carbonates; however, numerous examples of trace amount of dolomite were observed at XRD analysis (Figure 21). These minor amounts of dolomite are likely associated with the neomorphic replacement of lime mud matrix material (Longman, 1980).

Paragenesis

Frisco mounds were deposited on a restricted shallow shelf. As originally deposited in the marine environment, the carbonates predominantly consisted of calcite components. Micritization and initial organic binding of skeletal grains occurred at the sediment-water interface. Algae were the primary encrusting organisms. Extensive submarine cements were developed in many bioclastic grainstone intervals and early marine cement is evident in intraparticle pores (Figure 17, a & b).

Lithification and stabilization of the Frisco deposits was accompanied by subaerial exposure and meteoric processes. Calcium-carbonate ions derived from dissolution were locally precipitated as cements. Most pore-occlusions calcite was precipitated as sparry cements preferentially emplaced within bioclastic grainstone deposits. In nearly all intervals, mineralogic stabilization was completed in the meteoric phreatic environment as evidenced by the growth of calcite crystals lining all sides of inter-granular pores. When vuggy porosity formed, it was often cemented by calcite cement. The paragenetic sequence of diagenetic events is summarized in Figure 21.

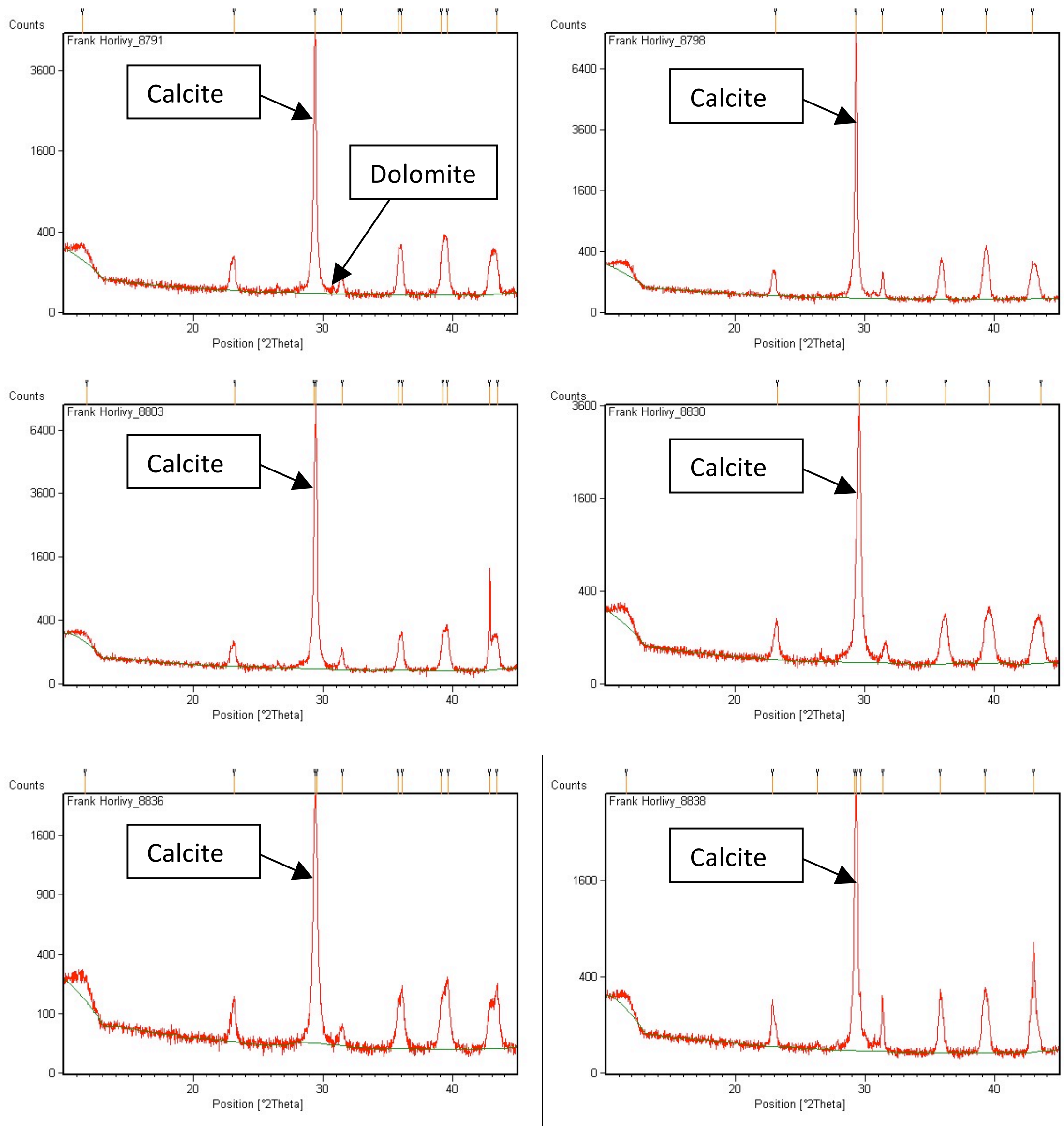


Figure 20: Representative bulk analysis x-ray diffractograms of samples of the Frisco Limestone from Frank Horlivy Jr#1, Canadian County, Oklahoma. The most intense peak of 2-theta is 29.4 indicates calcite. Only minor amount of dolomite peaks were detected. X-ray analysis of the Frisco Limestone in outcrop and core from the Fitts Field yielded similar results as the Frisco limestone is low-magnesium calcite and dolomitization is minimal.

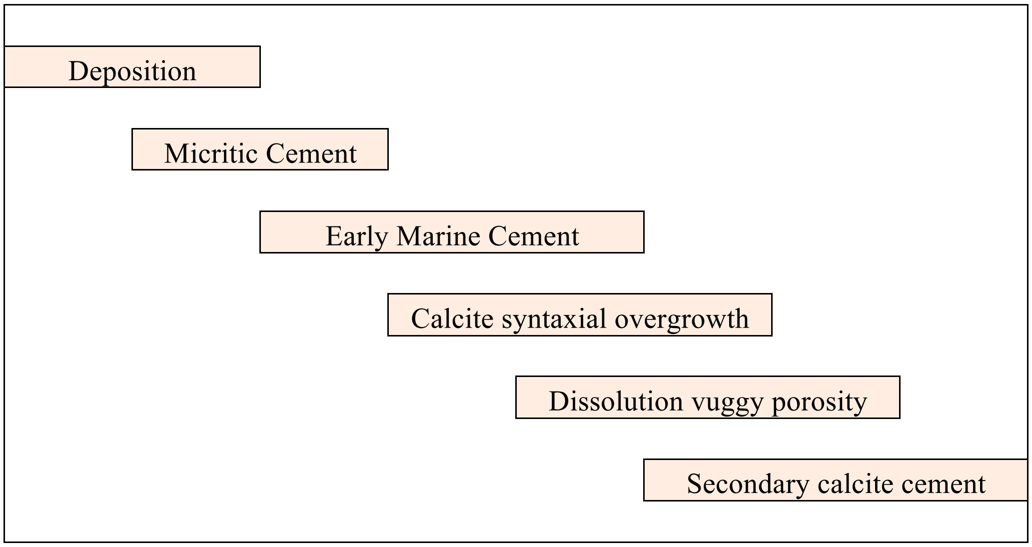


Figure 21: Paragenetic sequence of diagenetic events.

CHAPTER V

FITTS FIELD FRISCO MOUND RESERVOIR STUDY

Location

The Fitts field is located in the southeastern part of Pontotoc County, including the southeastern part of T. 2 N., R. 6 E., and the southwestern part of T. 2 N., R. 7 E (Figure 29). The field is approximately 5 miles long and 1½ miles in width. The first Hunton Group oil well in the Fitts Field was completed in July 1933, in Sec. 29, T. 2 N., R. 7 E. and produced approximately 20 million cubic feet of gas and 30 barrels of oil a day. Subsequently several hundred Hunton wells were drilled in Fitts Field. However, only two cores containing Frisco Formation were available for reservoir quality analysis.

Geological Setting

The general structure of the Franks Graben is a tilted block dipping northeast. The graben is triangular in shape, converging toward the west; it is bounded on the north by the Stonewall fault and on the south by the Franks fault zone, diverging toward the east. It is controlled on the west by a cross fault; on the south by a major east-west fault zone; and on the north by dip of more than 500 feet per mile on the subsurface formations. The eastern boundary is not yet defined, but will be controlled by normal dip or faulting (Northcutt, 2002). Fitts field is a faulted anticline within the Franks Graben (Northcutt, 2002). The depth to the top of the Hunton Group in Fitts field varies from 3045 ft to 3820 ft. Hunton Group thickness ranges from approximately 160 feet to 400 feet (Northcutt, 2002).

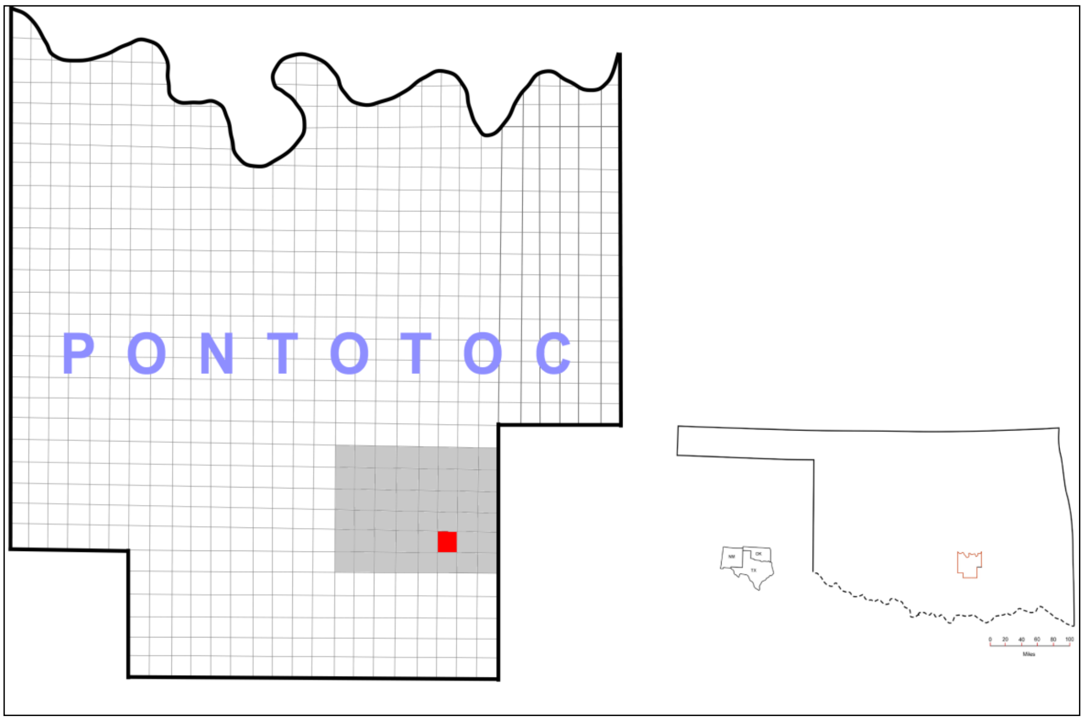


Figure 22: Location of Fitts Field and a representative wire line log, Pontotoc County, Oklahoma.

Petrophysical Analysis with Associated Core

The representative log for Fitts Field (Figure 23) is from a well located in Sec 27. T.2N. R.7E. Core to log correlation shows that changes in log signature can be interpreted to identify the Frisco Formation. As shown in the Figure 23, several distinctive changes occur at the top of the Hunton Group. These changes, which can also be identified on vintage logs include:

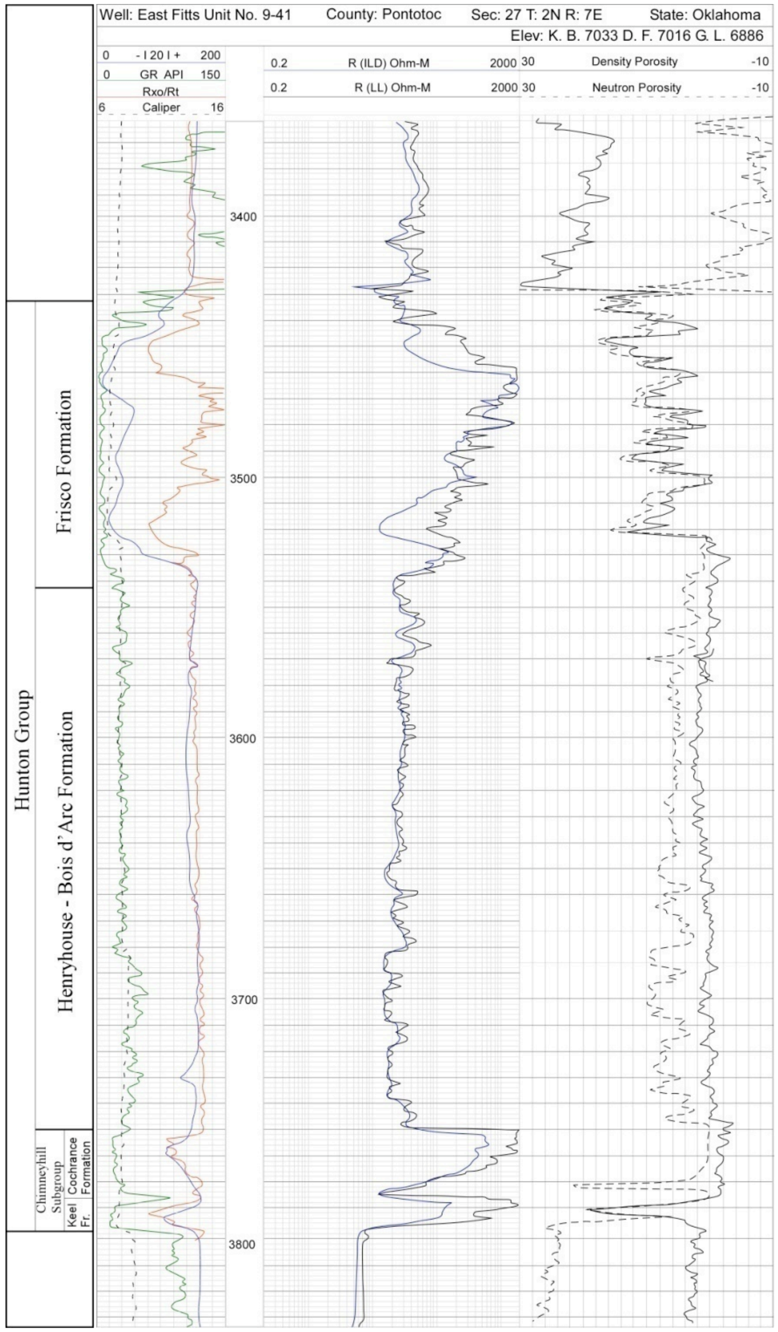


Figure 23 : Representative log for Hunton Group in Fitts Field. Mobil East Fitts Unit 9-41 (Sec. 27. T.2N., R.7E. Pontotoc County, OK).

(1) A robust negative spontaneous potential (SP) deflection from the shale baseline that typically increases from < 20 millivolts in underlying argillaceous carbonate to >150 millivolts in the Frisco Limestone.

(2) Decreased clay content as expressed by lower gamma-ray values across the same interval with the robust, negative- SP deflection. Gamma ray values in the underlying argillaceous carbonate rock average 30 API units; whereas gamma ray values in the Frisco Limestone average approximately 12 API units.

(3) Caliper logs indicate borehole diameter decreased in the Frisco Limestone. The caliper indicates borehole size across the Frisco Formation is 8 inches. The pre Frisco argillaceous carbonate has borehole diameter >8 inches.

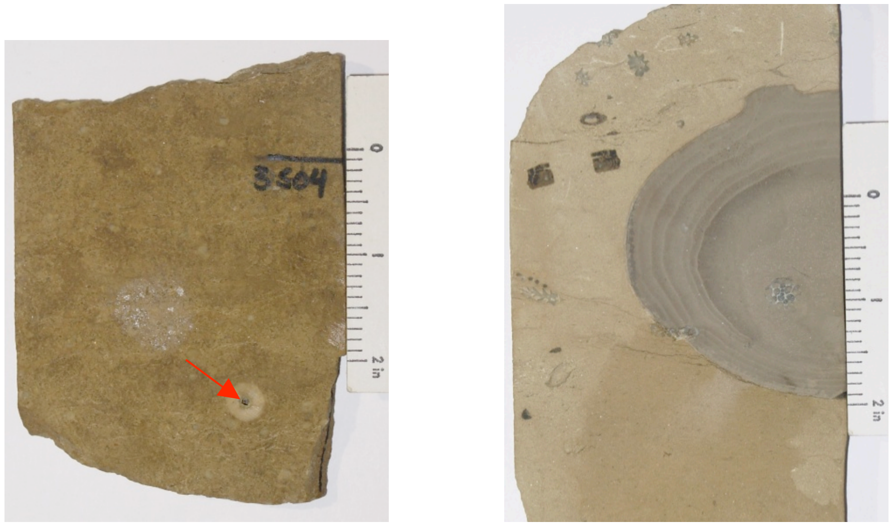
(4) Separation between shallow and deep resistivity curves increases across the Frisco Formation. These resistivity curves track or mimic each other in the argillaceous carbonate.

Formations of the Hunton Group below the Frisco Limestone interval display no positive filter cake until the Ordovician Keel Formation is encounter near the base. The porous and permeable zone of the Keel Formation at 3790 feet is oolitic grainstone (Figure: 23).

Wireline porosity measurements (which are not available with vintage logs) indicate a corresponding increase in porosity across the Frisco Formation, which has an average density porosity of approximately 14%. In this well, the subjacent Henryhouse Formation has an average porosity of 2%. Woodford Shale with high gamma-ray value exceeding 150 API units unconformbly overlies the Frisco Formation. The high gamma ray values of the Woodford Shale contribute to its value as a marker bed and help identify the contact between the Woodford Shale and subjacent units.

In this well, the Chimneyhill Subgroup contains the Ordovician Keel limestone and Silurian Cochrane Formation (Figure 23). The Henryhouse Shale, which overlies the Chimneyhill in the study area, consists of argillaceous limestone and marly beds with intercalated shale (Stanley, 2001).

The thickness of the Frisco Formation in this representative log is 108 feet (3426' to 3534') (Figure 23). Examination of cores reveals that crinoids (Figures 24 & 25) and bryozoa contain preserved primary porosity in the Frisco mounds. Early marine cement in the mound rocks largely occluded depositional porosity and reduced permeability. These low-permeability zones are evident in core by their lack of oil staining (Figure 24) and on the wireline logs as thin (< 4 feet) intervals of higher resistivity and low porosity values of <4% (Figure 23).



(a) (b)

Figure 24 : (a) Crinoid fragments with porosity in axial canal (arrow); (b) Silica replacement of micritic bafflestone. Dark bioclasts are bryozoan fragments. Brown color is oil staining. Mobil East Fitts Unit, 9-41, Pontotoc County, Oklahoma. Depth (a) 3504 feet (b) 3517 feet

(a) (b)

Figure 25: (a) Bryozoans fragments micritic bafflestone; (b) Micritic bafflestone with secondary sparry calcite cement that filled early vuggy porosity. Mobil East Fitts Unit, 9-41, Pontotoc County, Oklahoma. Depth (a) 3518 feet (b) 3519 feet

(a) (b)

Figure 26: (a) Contact between the Frisco Formation and the underlying argillaceous Henryhouse Formation (arrow); (b) Ooid grainstone: Keel Formation, Chimneyhill Subgroup. The brown color is oil stain. East Fitts Unit 9-41, Pontotoc County, Oklahoma. Depth (a) 3523 feet (b) 3786 feet.

Core samples from a well in Sec.27, T.2N, R7E. Pontotoc county, OK contain more complex facies relationship than those evident in outcrop. The vertical facies changes within this core are interpreted as overlapping facies of nearby mounds. The scarcity of core samples from this field makes it difficult to determine the size and shape of mounds. Because of the lack of well data, the horizontal dimensions of individual buildups could not be determined. Based on core and thin-section analyses, cored Frisco lithofacies from the subsurface were classified as follows:

F1- Moderate to poorly sorted grainstone or packstone with fine crystalline (micritic) layers.

F2- Well sorted finer grained bioclastic grainstone with occasional larger bioclasts.

F3- Muddy wackestone with occasionally floating bioclasts.

F4- Echinoderm pelmatozoan crinoidal grainstone (marble texture) with low porosity, stylolites and occasional fractures with/without $CaCO_3$ filling.

The compelexity of mound lithofacies preserved in core is in stark contrast to the outcrop mound. As a result of this complexity, porosity and permeability changes over short vertical distances are evidenced by wireline log characteristic and core measurements. No well logs were available for the Mobil East Fitts Unit 9-40 but logs from nearby wells were examined. Based on the thin section analysis, porosities fluctuated slightly within depositional facies, cored in the Mobil East Fitts Unit 9-40. However porosity measurement between facies contrasted sharply. The nearby Mobil East Fitts Unit 9-41 was cored and logged (Figure 23). Core porosity relationship evident in the E.Fitts Unit 9-40 were confirmed by analyzing porosity and permeability measerment taken across the Frisco Formation in the E.Fitts Unit 9-41.

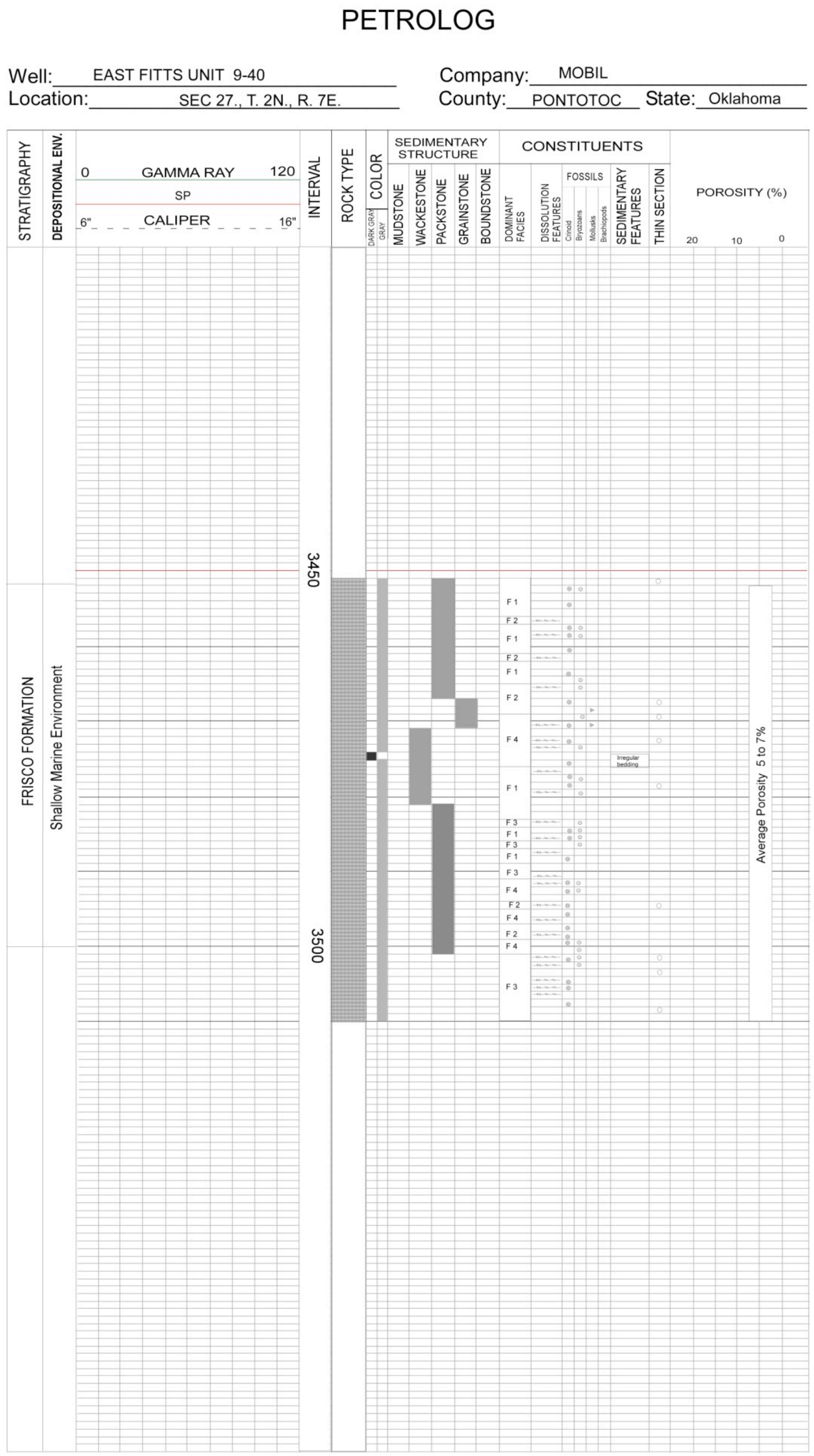
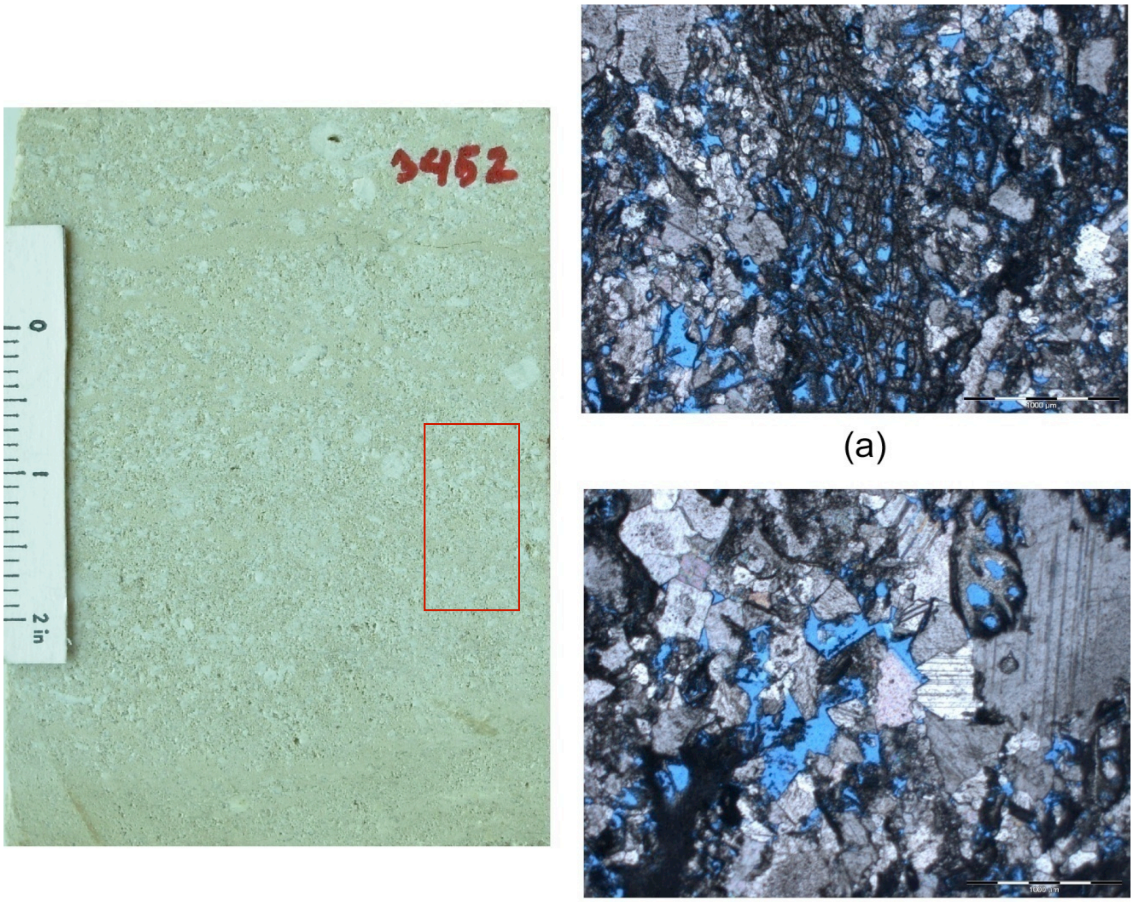


Figure 27: The cored interval of Frisco Formation core from the Mobil E Fitts, 9-40, Sec.27, T.2N., R.7E, Pontotoc County, OK.



(b)

Figure 28: Photograph of core hand specimen and thin section photomicrograph of the Frisco Limestone. (a) well sorted finer grained bioclastic grainstone with occasional larger bioclasts. Primary porosity preserved within the bryozoan fragments; (b) secondary dissolution porosity. Brown color of core is oil staining. Mobil, E Fitts, 9-40, Sec.27, T.2N., R.7E, Pontotoc County, OK.

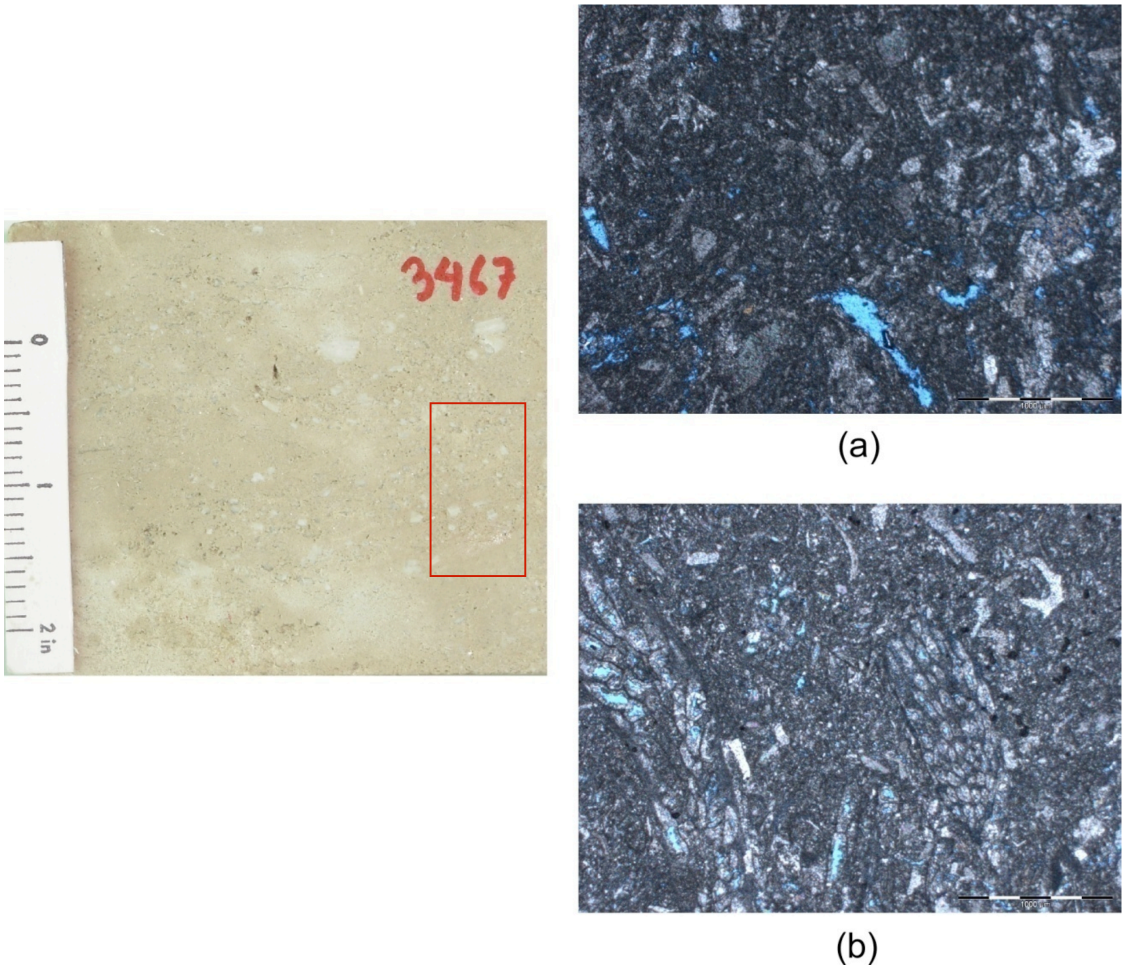
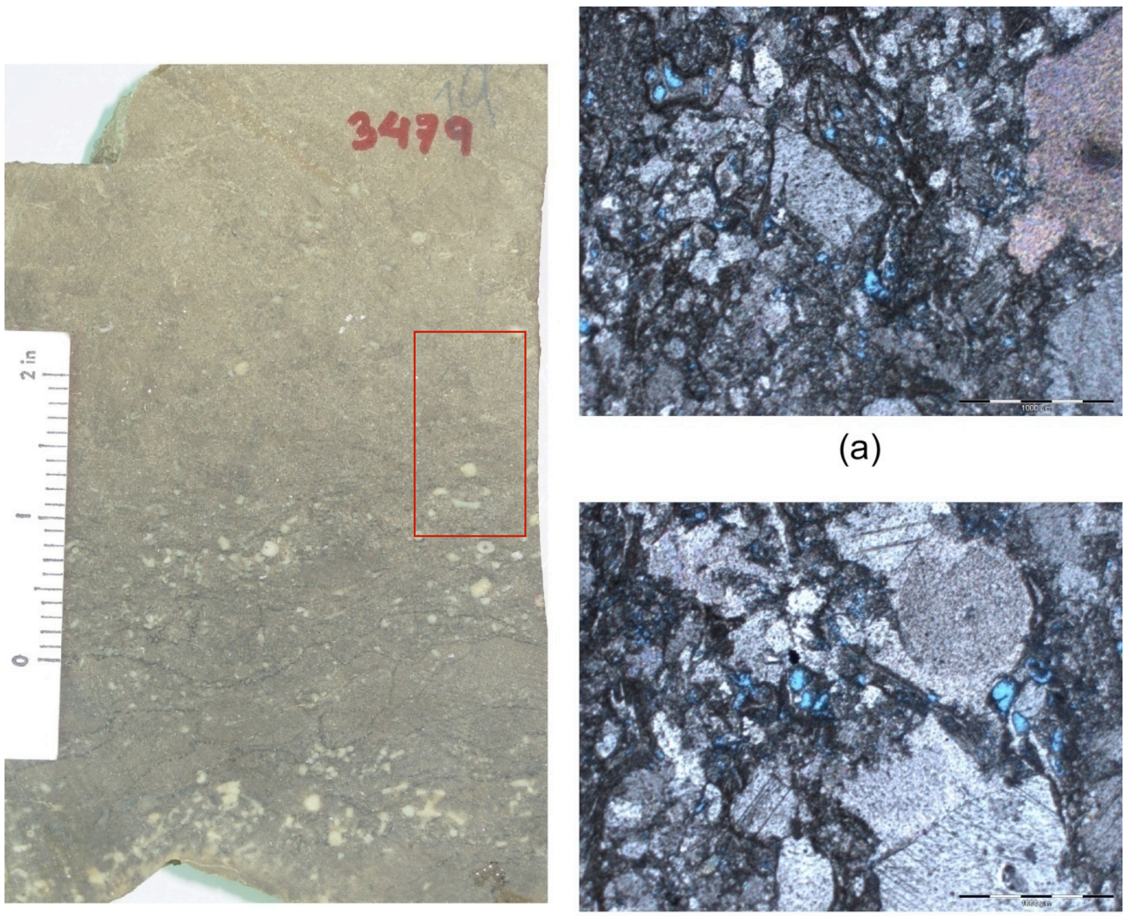


Figure 29: Core photograph and thin section photomicrographs of the Frisco Limestone. Moderate to poorly sorted packstone with baffled muddy layers. Primary porosity preserved within the fossil fragments, especially bryozoans. Brown color is oil staining. Mobil, E Fitts, 9-40, Sec.27, T.2N., R.7E, Pontotoc County, OK.



(a)

(b)

Figure 30: Core photograph and thin section photomicrographs of Frisco Limestone. (a) Pelmatozoan rich packstone with minimal porosity, (b) Argillaceous pelmatozoan packstone. Mobil, E Fitts, 9-40, Sec.27, T.2N., R.7E, Pontotoc County, OK.

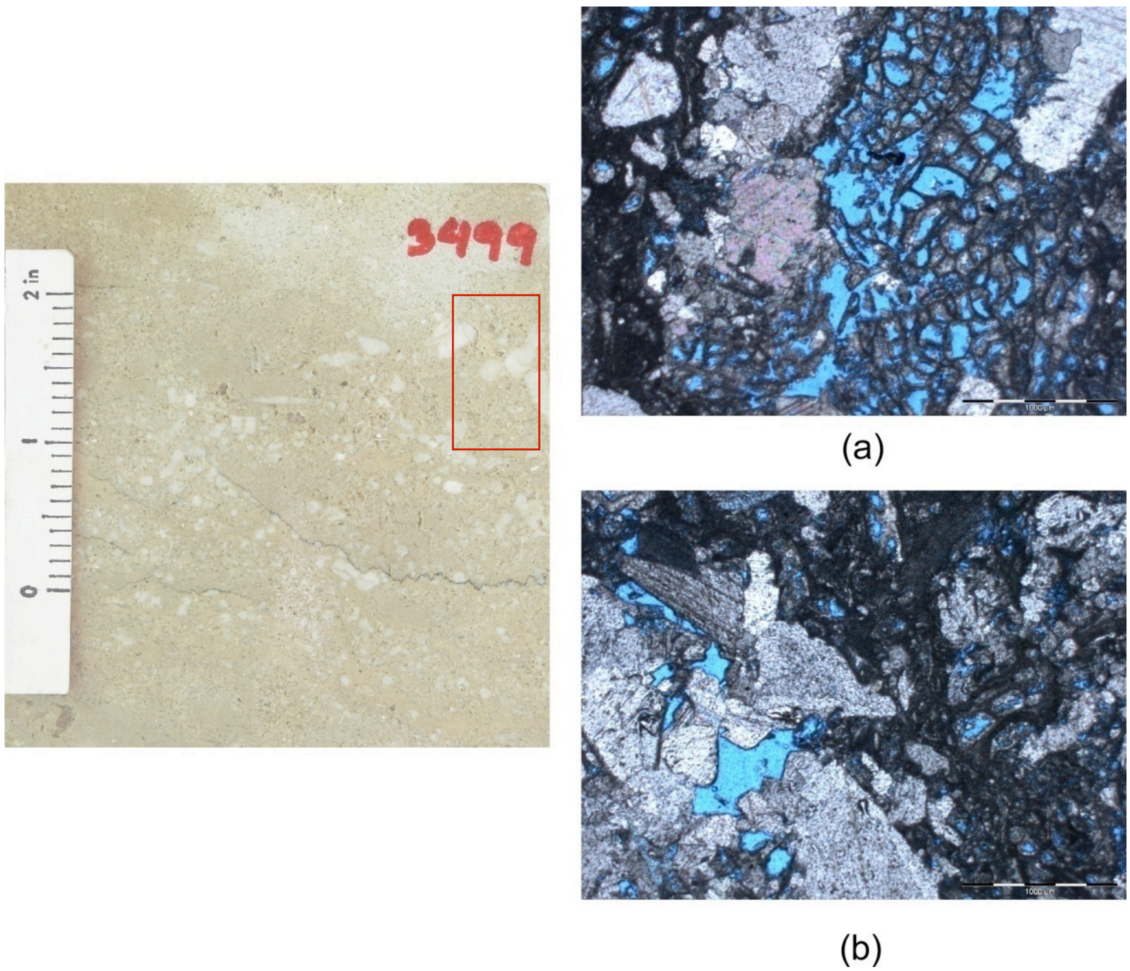


Figure 31: Core photograph and thin section photomicrographs of Frisco Limestone. Cored interval is lightly oil stained. (a) Primary porosity preserved within the bryozoan fragments and (b) secondary dissolution porosity developed by dissolution of bioclasts. Mobil, E Fitts, 9-40, Sec.27, T.2N., R.7E, Pontotoc County, OK.

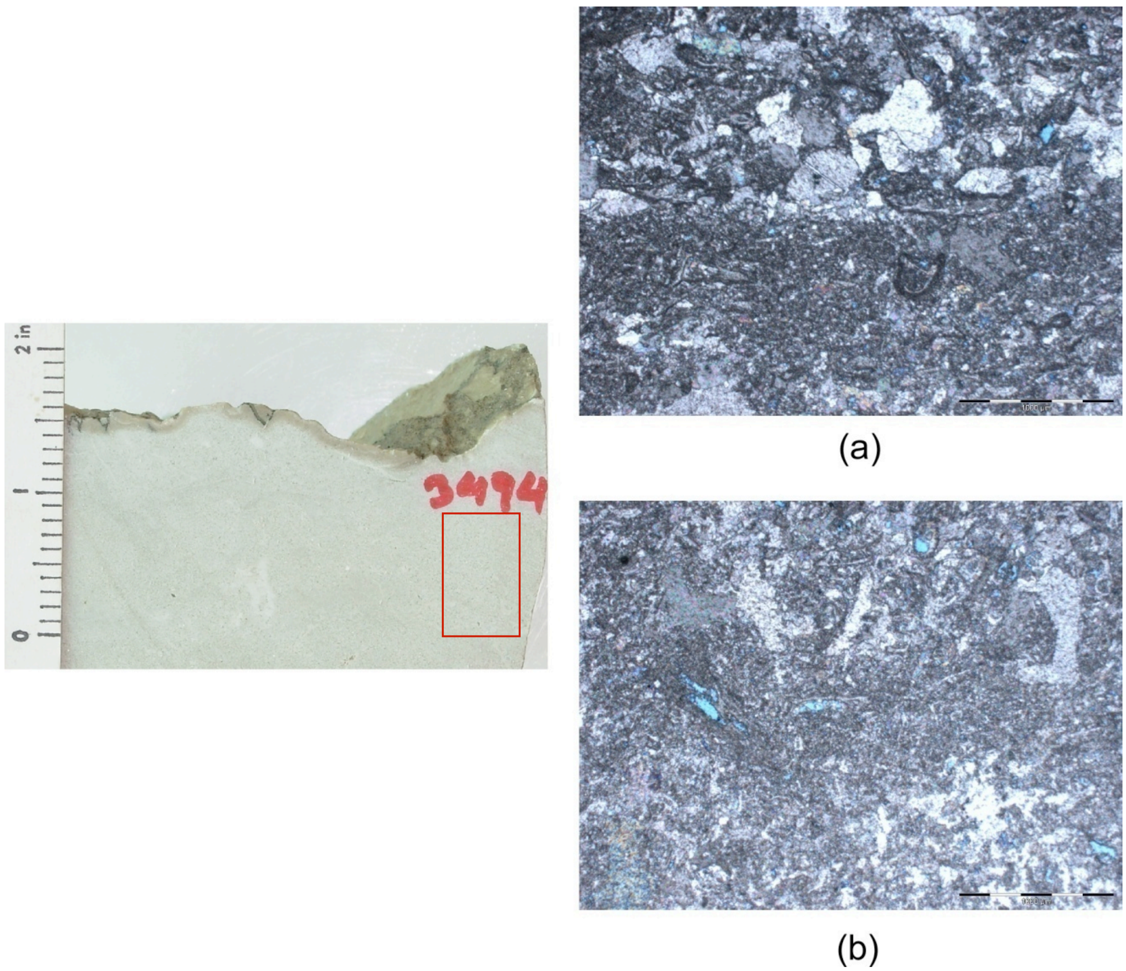
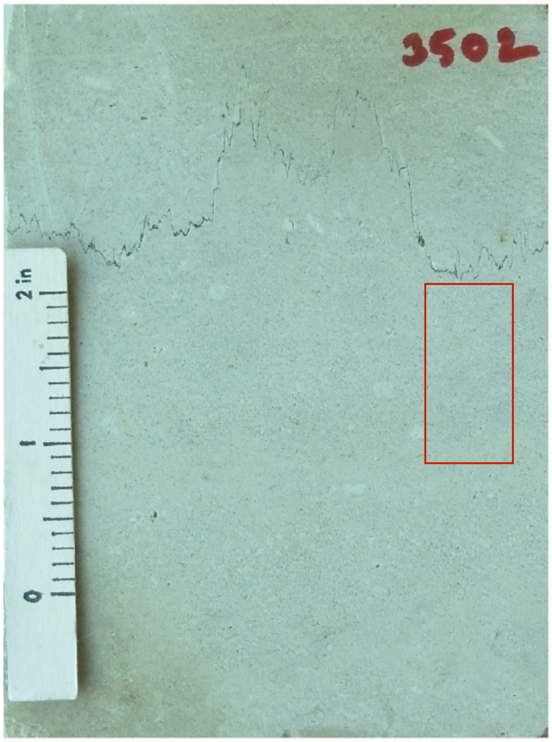
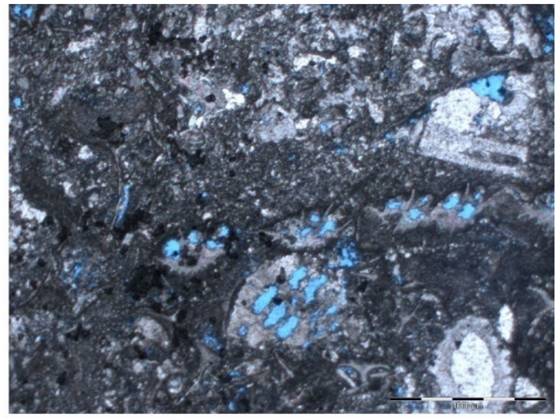
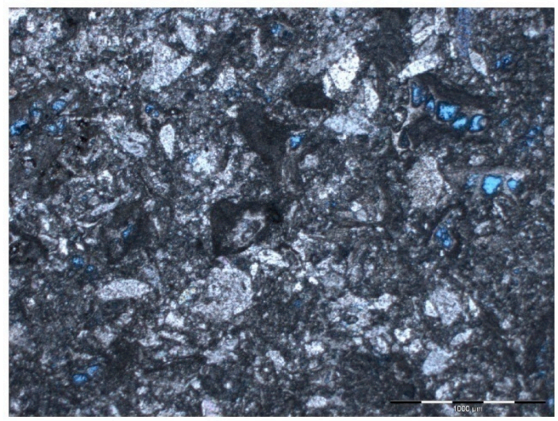


Figure 32: Core photograph and thin section photomicrographs of muddy wackestone with occasionally floating bioclasts and minimal porosity.(a) Contact between mud-rich and bioclast-rich intervals, (b) bioclasts rich zone. Mobil, E Fitts, 9-40, Sec.27, T.2N., R.7E , Pontotoc County, OK





(a)



(b)

Figure 33: Core photograph and thin section photomicrographs of pelmatozoan grainstone with extensive calcite overgrowth. Visual low porosity, stylolites and secondary fracture filling CaCO3 cement. (a) cemented pelmatozoan (crinoid) fragments, (b) fine grained packstone-grainstone with extensive $CaCO_3$ cement. Mobil, E Fitts, 9-40, Sec.27, T.2N., R.7E. Pontotoc County, OK.

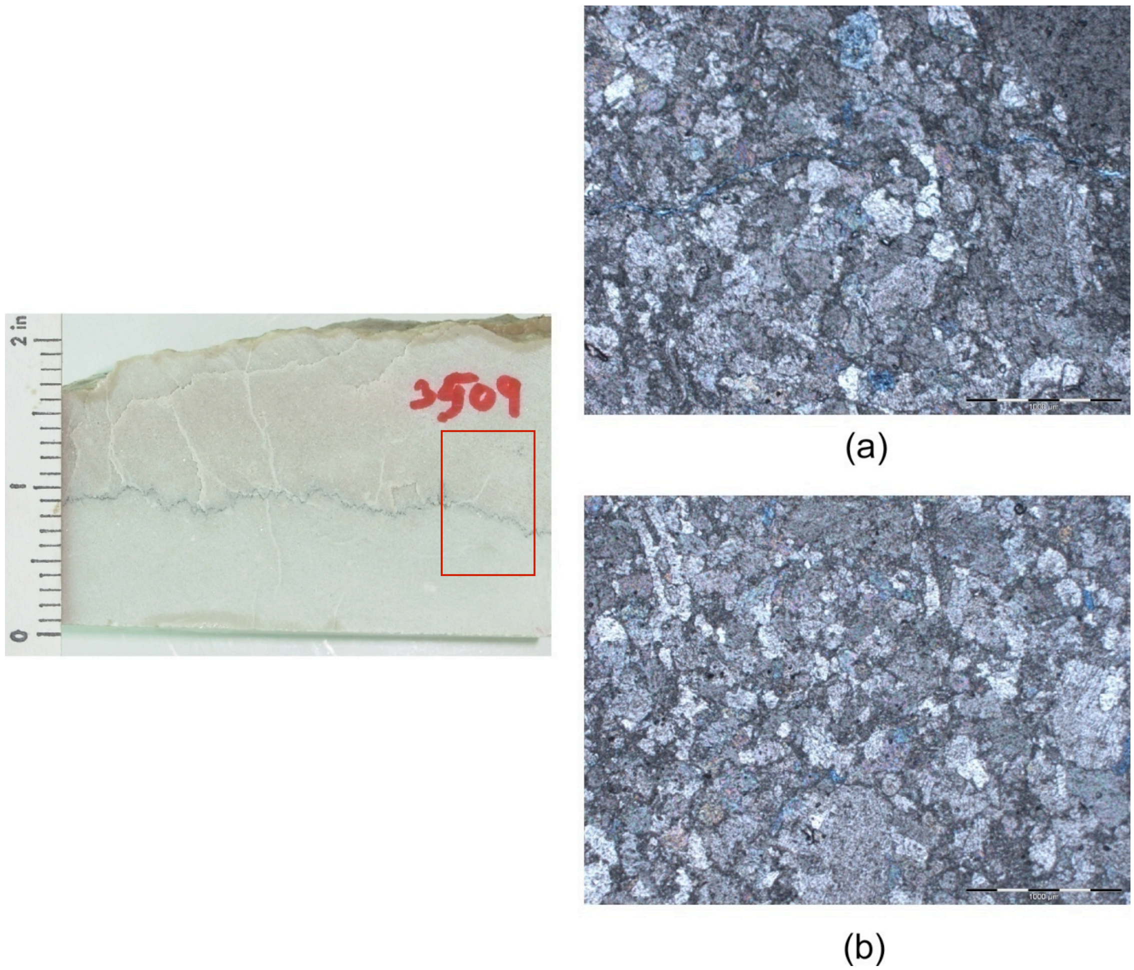


Figure 34: Core photograph and thin section photomicrographs of pelmatozoan grainstone with stylolites and cemented vertical fracture. (a) pelmatozoan grainstone with extensive CaCO3 cement. (b) grainstone with extensive recrystallization that has occluded all visual porosity. Mobil, E Fitts, 9-40, Sec.27, T.2N., R.7E. Pontotoc County, OK.

Porosity and Permeability

Porosity and permeability measurements were obtained using conventional core plug analysis so that porosity estimation provided by the thin section analysis could be verified. Selected core pieces were drilled using a one inch internal diameter core bit, dried and analyzed at the Devon Energy rock lab in the Boone Pickens School of Geology. Porosity for the selected samples was determined using a Core Lab PORG-200 gas porosity meter. Permeability was calculated using a Core Lab PERG-200 gas permeameter. The PORG-200 porosity meter is designed to measure the grain volume of core plugs of known bulk volume.

Porosity and permeability measurements indicate that these two properties are highly variable. For instance, measurement data indicates at depth 3452 feet and 3472 feet mound rocks have high porosity (8-14%) and high permeability (22md). In contrast the sample from 3483 feet depth contains some interpartical porosity, but the clay content reduced the permeability to as low as 0.1 md. The core sample at depth 3509 feet is interpreted as the contact between the Frisco Formation and Bois d'Arc Formation. This sample contains intrapartical porosity by thin section analysis, but very low permeability. Core sample at depth 3510 feet is within the Bois d'Arc Formation. The sample is crinoid rich, fossiliferous carbonate with a smooth marble- like texture and no apparent porosity in hand specimen. Core plug analysis confirmed the low porosity and permeability for this zone.

Sample Depth (feet)	Length (inches)	Radius (inches)	Bulk Volume (CC)	Grain Volume (CC)	Porosity %	Permeability (md) at psig app. 19
3452	1.182	0.495	14.96	12.84	14.16	81.50
3467	1.174	0.497	14.83	12.87	13.27	89.20
3472	1.238	0.498	15.81	14.46	8.51	19.20
3473	1.181	0.498	15.10	14.11	6.49	0.20
3483U	1.172	0.498	14.96	14.76	1.35	0.10
3483D	1.183	0.496	14.98	14.24	4.94	2.60
3493	1.345	0.497	17.13	15.79	7.81	26.2
3494	1.221	0.497	15.61	14.92	4.39	0.00
3499	1.210	0.492	15.11	13.21	12.56	62.40
3502	1.134	0.497	14.44	13.49	6.63	1.90
3504	1.271	0.497	16.18	15.44	4.56	0.00
3508	1.113	0.498	14.21	13.49	5.06	1.40
3510	1.149	0.497	14.64	14.59	0.31	0.20

Table 1: Porosity and Permeability measurements of core sample from the Mobil E Fitts, 9-40, Sec.27, T.2N., R.7E. Pontotoc County, OK.

Porosity and permeability measurements from core plug analysis were obtained for the Frisco Limestone and Pre-Frisco limestone samples and compared with thin section measurements. Samples containing higher percentage of bryozoans fragments were found to have higher porosity and permeability values than the samples that are composed of mostly pelmatozoan bioclasts (Table-2). At core depth 3504 feet, the thin section shows approximately 22% bryozoa; but the carbonate mud occluded the primary porosity within the zooecia of bryozoans, reducing porosity and permeability (Table-2). This relationship was verified with multiple measurements.

Well: Mobil 9-40	**Thin Section Analysis**				**Core Plug Analysis**	
Sample Depth (feet)	**Echinoderm (%)**	**Bryozoans (%)**	**Others (%)**	**Porosity (%)**	**Porosity (%)**	**Permeability (md) at Psig 19**
3452	24.4	53.6	7	15	14.16	81.50
3467	19.4	46.8	22.8	11	13.27	89.20
3470	84.2	2.4	11.4	2	--	--
3473	80.8	2.6	11	5.6	6.49	0.20
3479	33.2	3.4	61.8	1.6	--	--
3494	62.6	7.2	23.4	6.8	4.39	0.11
3499	24.2	54.6	6.2	15	12.56	62.40
3502	31.2	27.6	34.4	6.8	6.63	1.90
3504	4.0	21.0	70.6	4.4	4.56	0.00
3508	--	--	--	--	5.06	1.40
3509	60.60	0.4	38.60	0.40	--	--
3510	--	--	--	--	0.31	0.20

Table 2: Comparison of porosity and permeability using thin section and core plug analysis. (Sample depths without bioclast percentages were not thin sectioned)

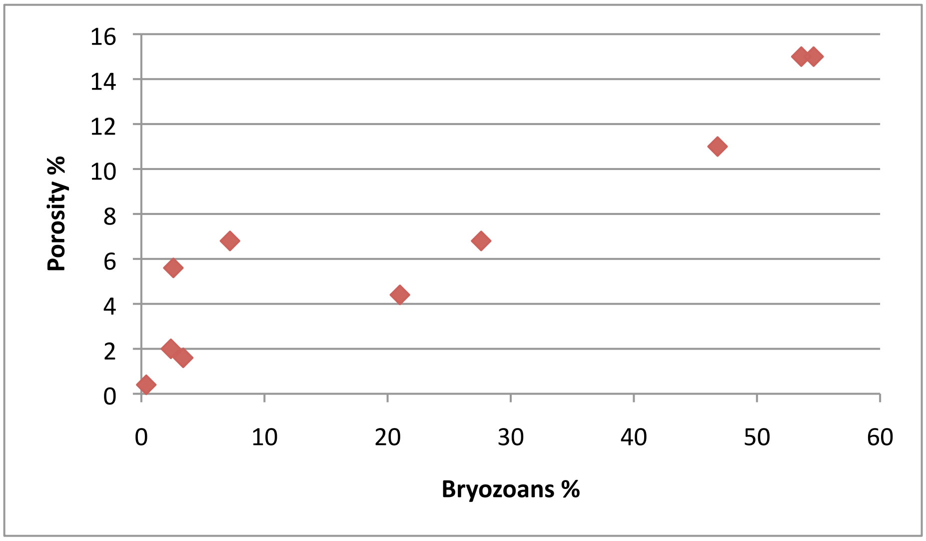


Figure 35: Plot of bryozoa concentration in % vs. porosity for the Frisco Formation. A positive relationship between the abundance of bryozoa and porosity is evident.

Discussion of Petroleum Geology of Frisco Formation in Fitts Field Field

The Frisco Formation is the primary producing unit in the Hunton Group in many fields in south central Oklahoma. Many early wells were interpreted to have a thick Bois d'Arc section of Formation if a robust negative spontaneous potential deflection developed at the top of the Hunton interval. Based on the biostratigraphy of Hunton Group, it is now known that many of these porous zones are the Frisco Formation (Rechlin, 2003).

The Mobil E Fitts, 9-41 well in, Sec.27, T.2N., R.7E. Pontotoc County, OK cored the entire zone of robust spontaneous potential, part of the less robust interval below, and a small interval at the base of the Hunton Group.

(1) Based on the texture and composition of the recorded carbonate units, the wireline log signature across the Hunton Group, and nearby outcrop of the Frisco Limestone, the upper porous section of the Hunton Group in the Mobil E Fitts 9-41is interpreted as the Frisco Limestone. Using this wireline log as a guide, it was possible to map the Frisco Limestone across the Fitts Field. In addition based on this log calibrated core and well completion record it is

apparent that oil production from the Hunton Group in the Fitts field is from the Frisco and Keel Formations with the largest volume coming from the thick Frisco Formation reservoir. The mapped thickness of the Frisco mound facies varies from 0 to 125 feet (from wireline logs and completion records). In areas of the Fitts Field where log control is more abundant an attempt was made to estimate size of the Frisco mounds. For instance, the interpreted Frisco facies in sec. 36, T.2N, R.6E is approximately 2000 feet wide and 12 feet thick. In comparison, the mound exposed at Bois d'Arc Creek is approximately 600 feet wide and 40 feet thick. Based on these observations, the thick Frisco limestone to the east of the Fitts Field appears to represent stacked mounds facies of adjacent mounds. This interpretation was confirmed by the stacked facies in the Mobil East Fitts Unit 9-41 core.

(2) The difficulty in estimating mound morphology is compounded by post-Hunton uplift and erosion prior to the Woodford deposition. The lowermost Woodford units thicken and thin in response to thickening and thinning of the underlying Hunton Group (Blackford, 2007). It is expected that the uppermost unit in the Hunton, the Frisco Limestone would be most impacted by the pre-Woodford erosion. However, it should be noted that the thickening of the interpreted Frisco Formation influences the rate of initial oil and gas production from the Hunton Group. An isoproduction map in barrels of oil per day from the Hunton Group reservoirs was constructed on data collected from completion reports. The initial production rate of oil from the Frisco reservoirs was posted on a map of Fitts Field and contoured to determine if a relationship exists between the thickness and production. The initial production rates in barrels per day were collected from vintage production reports and scout data. Only data for wells drilled in the mid 1930's were used to avoid decreased production rate attributed to reservoir depletion. Production data for more than 400 wells were screened for age, single zone completion in the Frisco Formation and proper time period for an initial production test. Wells were selected and incorporated in the Iso-production map.

(3) A comparison of the Frisco Limestone isopach map (Figure 46) and Frisco Isoproduction Map (Figure 36) allows the inference initial production rate that exceeding in 4000 barrels of oil per day aligns with the trend of thicker Frisco reservoir. The production rate falls off quickly in areas where the Frisco is mapped as less than 25 feet thick.

(4) The lack of thick mound core and capping facies in cores of the Frisco Limestone in Fitts Field and Mustang field may reflect the sparse nature of core data. Micofacies evident in the core may be the results the core penetrating the flanking facies. It is not known if the thickening evident in outcrop is preserved in Fitts Field or if the thickness in the subsurface was more affected by pre-Woodford erosion.

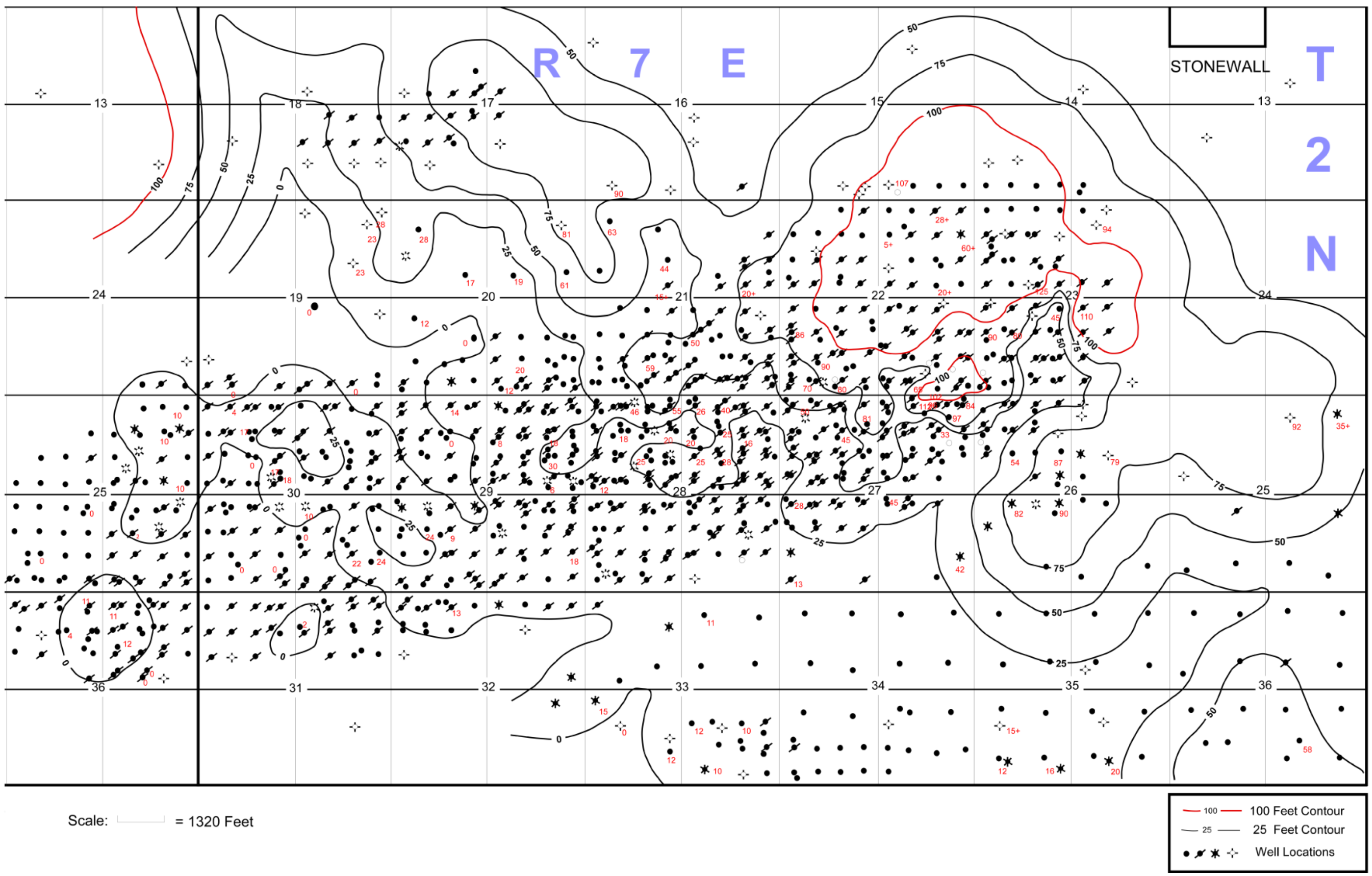


Figure 36: Isopach map of Frisco Formation based on well logs and vintage drilling and completion reports, after (Stewart et al., 1989).

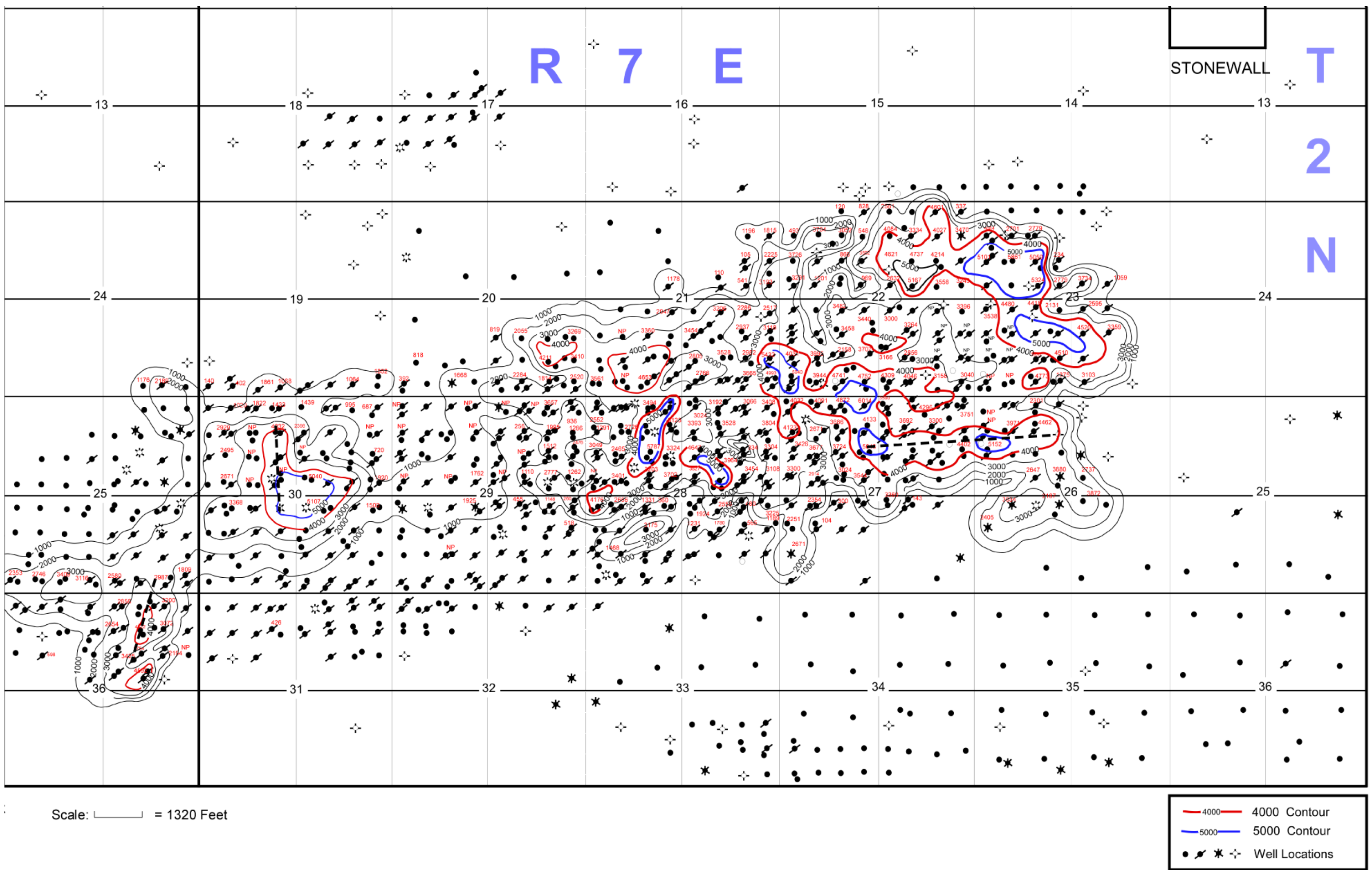


Figure 37: Isopach map of production data of Fitts Field; indicates maximum gross production follow the Frisco mound trend , after (Stewart, et al., 1989).

CHAPTER VI

CONCLUSION

The collection and analysis of core data and observation of the evidence from the outcrop of the Frisco Limestone provided an opportunity to interpret the morphology, petrology and reservoir properties of the carbonate mounds. Some evidence was stronger and allowed for the confident interpretation of features such as mound facies and morphology in the outcrop, the relationship between the composition of the carbonate and evaluation of reservoir and non reservoir facies and wireline log signature of the Frisco Limestone. Other evidence was tenuous or too spare to allow for the confident interpretations.

Based on the consideration of all evidence the following conclusions are proposed.

1. Facies within and proximal to the Frisco carbonate mound complex include (1) bafflestone (cement rich variants) within mound-core regions, (2) packstone (skeletal rich debris) within mound-flank regions, and (3) Capping grainstone formed across the top of the mounds.
2. In order to explain all the features found in the Frisco mound buildup a depositional model has been proposed. The central massive part of the mounds consists of dark to light grey colored micrite; macrofossils are rare but well preserved. The flank facies in contrast consists of coarse and densely packed crinoidal and bryozoan rich wackestone to packstone. The tops of the mounds are usually covered with grainstone caps of abraded bioclasts. The position pre-Woodford unconformity supports the interpretations that the top of the Frisco mounds were eroded, complicating their interpretation.

3. Petrographic observations and XRD results indicate that cementing materials and bioclasts are calcite in Frisco mounds and that dolomitization is not evident or minimal.
4. Primary porosity is preserved within fossil fragments, whereas secondary porosity developed due to dissolution that may have occurred during post Frisco subaerial exposure. Secondary dissolution porosity is more common in mound-flank positions.
5. The thick mound core and thinner mound facies evident in the outcrop were not clearly evident in cores of subsurface sections. Instead cores contain alternating thinner beds of grainrich and mud-rich facies that are interpreted as stacked flanking facies and core facies.
6. There is a noticeable positive relationship between the abundance of bryozoans fragments and porosity. Bryozoan- rich rock with sparce carbonate mud tends to become reservoir facies.
7. Echinoderm- rich facies with <20% bryozoans tend to cement with syntaxial calcite overgrowths that greatly reduce porosity and permeability.
8. The comparison of mapped thickness of the Frisco Limestone and initial oil production rates from early wells in the Fitts Field reveals a positive correlation.
9. The petrography of the Frisco Limestone allows for the inference that the cored facies represent stratified reservoirs of the flanking facies. In contrast, the mound core is lower porosity and permeability. Early marine cement filled intergranular porosity, whereas carbonate mud occluded primary porosity in bryozoans by infilling the zooecia.
10. The variable porosity and permeability evident in cored Frisco Limestone was confirmed by thin section analysis and core plug porosity and permeability measurements. Low-porosity and low-permeability zones were cemented by extensive $CaCO_3$ cement or contained argillaceous carbonate mud. These zones were also evident on wireline logs and may serve to enhance compartmentalization in the Frisco reservoir.

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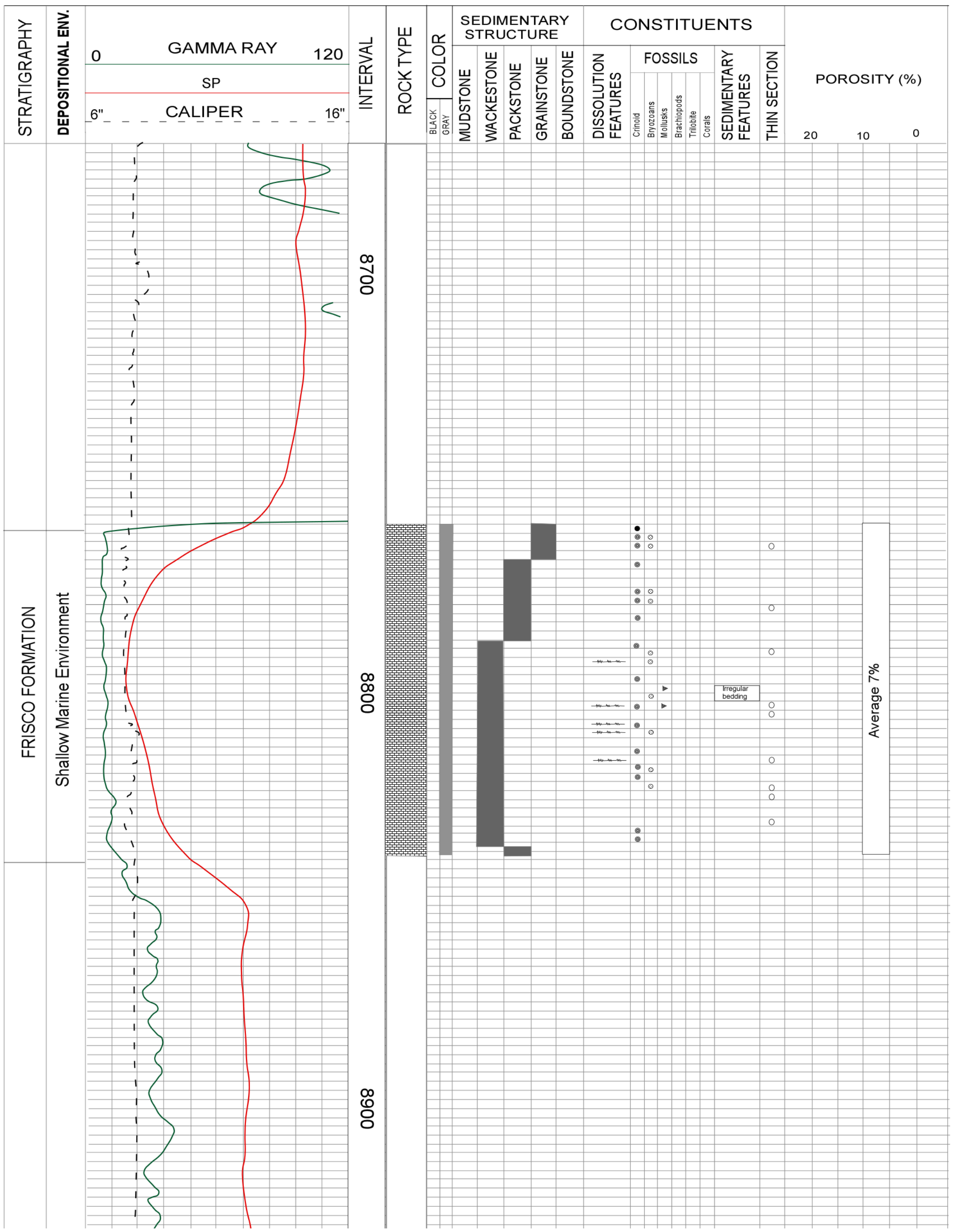
APPPENDICES

PETROLOG

Well: Frank Horlivy, JR. # 1
Company: Sinclair Oil & Gas Company
Location: 19-11N-5W
County: Canadian
State: Oklahoma



Well: Sinclair Oil & gas Co, Frank Horlivy, JR # 1 (8780' to 8837')

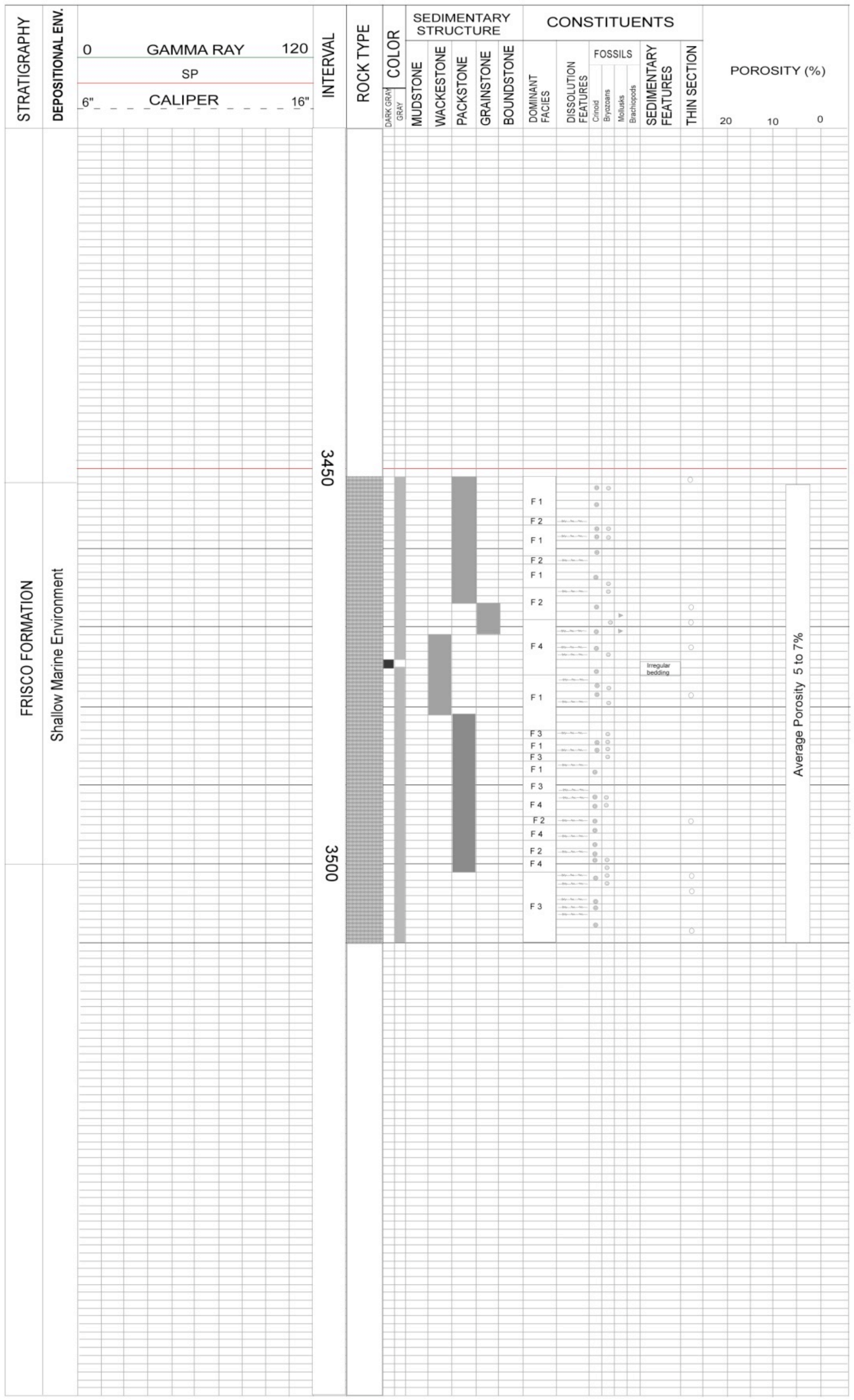
Unit: Lower Devonian Frisco Formation - Light- gray wackestone, packstone and grainstone.

Description: the Frisco limestone is muddy limestone with abundant crinoids and fragmented shelly debris, including a considerable quantity of bryozoa from 8780' to 8791'. Visible porosity is evident in thin sections, mostly occupying center of hollow fossils and matrix surrounding fossils. Some irregular bedding with abundant bioclast and low porosity occurs at depth 8795' to 8807'. This bed may represent storm deposit. Several stylolites were enlarged by dissolution, resulting in higher permeability. A well-defined lithostratigraphic contact at 8837' marks the boundary between Frisco Formation and Fittstown Member of the Bois d'Arc Formation.

PETROLOG

Well: EAST FITTS UNIT 9-40 Company: MOBIL

Location: SEC 27., T. 2N., R. 7E. County: PONTOTOC State: Oklahoma



Well: Mobil East Fitts Unit (EFU) 9-40 (3452' to 3510')

Unit: Lower Devonian Frisco Limestone.

Description: Core from the Frisco Limestone consists of stacked alternating muddies and grain-rich limestone. Based on hand sample description and thin section petrography study mound facies in this core were divided into four micro facies.

F1- Moderate to poorly sorted grainstone or packstone with fine crystalline (micritic) layers.

F2- Well-sorted finer-grained bioclastic grainstone with occasional larger bioclasts.

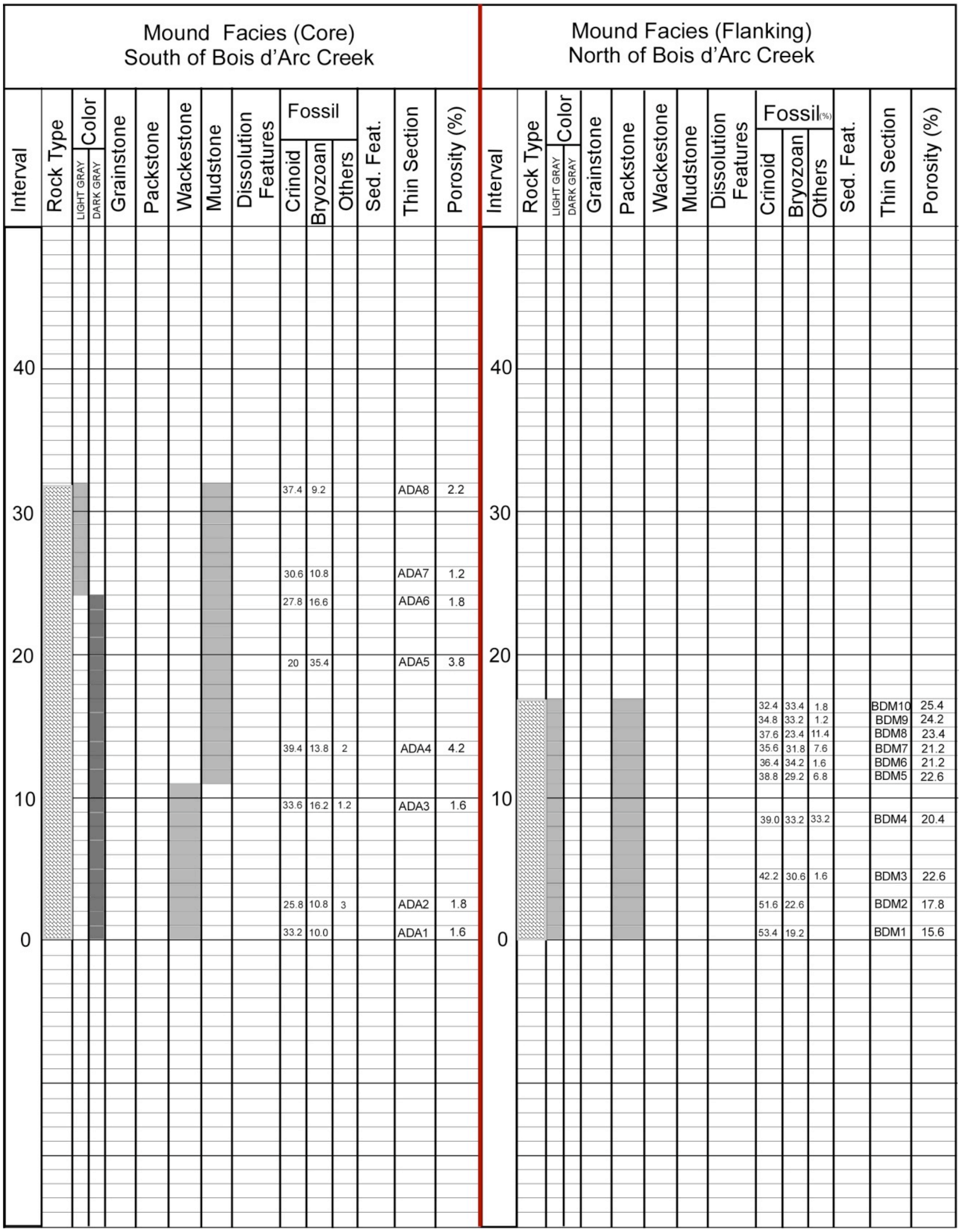
F3- Muddy wackestone with occasionally floating bioclasts.

F4- Echinoderm pelmatozoan crinoidal grainstone (marble texture); low porosity, stylolites, occasionally fractured with/without $CaCO_3$ filling.

The compelexity of mound lithofacies preserved in core is interpreted as indication of high frequency changes in water energy and /or overlapping /coalescing mounds. As a result of this complexity, porosity and permeability change occurs over short vertical distance. No well logs were available for the Mobil E Fitts Unit 9-40, but porosity and permeability measurements were collected using conventional core plugs and traditional steady-state pressure measurement techniques. F3 is interpreted as mound core, where as F6, F2 and F4 are interpreted as flanking facies.

Outcrop Petrolog

Location: Bois d'Arc Creek
County & State: Pontotoc County, Oklahoma
Stratigraphic Interval: Frisco Formation, Hunton Group



VITA

Monjur Rahi Siddique

Candidate for the Degree of

Master of Science/Arts

Thesis: DEPOSITIONAL FACIES AND RESERVOIR QUALITY, DEVONIAN CARBONATE MOUNDS, FRISCO FORMATION, OKLAHOMA

Major Field: Geology

Biographical:

Education:

Completed the requirements for the Master of Science in Geology at Oklahoma State University, Stillwater, Oklahoma in December, 2009.

Completed the requirements for the Bachelor of Science in Geology at University of Dhaka, Dhaka, Bangladesh in 2003.

Experience:

Chesapeake Energy: Associate Geologist (June' 2010 to Current)

ConocoPhillips: Summer Internship (summer' 2009)

Teaching Assistant : Florida Atlantic University, Boca Raton, Florida.

Teaching Assistant: Boone Pickens School of Geology, Oklahoma State University.

Research Assistant: Boone Pickens School of Geology, Oklahoma State University.

Professional Memberships: AAPG, GSA, OCGS, HGS

Name: Monjur Rahi Siddique
Date of Degree: December, 2010*

Institution: Oklahoma State University
Location: Stillwater, Oklahoma

Title of Study: DEPOSITIONAL FACIES AND RESERVOIR QUALITY, DEVONIAN CARBONATE MOUNDS, FRISCO FORMATION, OKLAHOMA

Pages in Study: 73
Candidate for the Degree of Master of Science

Major Field: Geology

Scope and Method of Study:

Devonian carbonate mounds of the Frisco Formation in Oklahoma are important petroleum reservoirs in a number of oil and gas fields that produce from Hunton Group carbonates. Though these reservoirs have produced large volumes of petroleum, little is known about their origin, distribution and diagenetic history.

Outcrops and cores were described, sampled and analyzed petrographically to establish fabric and mound lithofacies and determine post-depositional diagenetic modification. The preservation and evolution of mound porosity was controlled by depositional facies. Post depositional alteration reduced primary porosity. Syntaxial calcite cement on pelmatozoan grains occluded primary porosity, whereas fine granular cement reduced the porosity in bryozoan zooecia. Some primary porosity is preserved in the axial canals of crinoid stems and zooecia of bryozoan fragments. Primary porosity provided conduits for corrosive fluids that formed secondary dissolution porosity during pre-Woodford subareal exposure. Core analysis reveals Fitts Field is producing from stacked mound deposits. Stratified bryozoa-rich reservoir of flanking facies preserves the best reservoir quality. In contrast, the muddier beds of the mound core and pelmatozoan-rich beds in flanking facies can be low porosity and low permeability.

ADVISER’S APPROVAL: Dr. James Puckette