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Deposition, Diagenesis And Porosity Of Birdbear Formation, Williston Basin, North Dakota

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DEPOSITION, DIAGENESIS AND POROSITY OF BIRDBEAR FORMATION, WILLISTON BASIN, NORTH DAKOTA

by

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This thesis, submitted by Nwachukwu Francis Chidi in partial fulfillment of the requirements for the Degree of Master of Science from the University of North Dakota, has been read by the faculty Advisory committee under whom the work has been done and is hereby approved.

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This thesis is being submitted by the appointed advisory committee as having met all of the requirements of the School of Graduate Studies at the University of North Dakota and hereby approved.

Wayne Swisher
Dean of the School of Graduate Studies

april 29, 2016
Date

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Title Deposition, Diagenesis and Porosity of Birdbear Formation, Williston Basin, North Dakota

Department Harold Hamm School of Geology and Geological Engineering

Degree Master of Science

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Nwachukwu Francis Chidi
May 16, 2016

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ABSTRACT

The Birdbear Formation in Williston Basin of western North Dakota is a carbonate-evaporite sequence that has been the subject of much research over the past decades. This study looks at the depositional environment and the diagenetic characteristics of the formation, and their relation to production characteristics. Much has been done over the years on the Birdbear Formation, but most of these studies were restricted to eastern Montana (USA), southern Manitoba and south western Saskatchewan (Canadian province). The approach of integrating the role and effects of deposition, diagenesis, and porosity of the Birdbear Formation (Upper Devonian) Williston Basin in McKenzie County, North Dakota was the main purpose for this research. A detailed study was carried out through physical core descriptions, thin section analysis, wireline log correlations, and nuclear magnetic resonance (NMR) spectroscopy measurements to determine if the effects of diagenesis have been critical enough to alter or create adequate porosity and permeability within rock fabrics for the migration of generated hydrocarbons. Results from core analysis showed that two units were recognized, first being a lower carbonate dolomite-limestone of uniform lithology (boundstone to wackestone classification) with abundant organic material that could have served as self-sourcing in production and the second, an upper anhydrite-carbonate lithology (packstone classification), that has the ability to entrap migrating fluids within the study area. Sediments of the upper section of the lower carbonate unit exhibited high diagenetic activities that enhanced porosity

and overall permeability through observed intra-crystalline, inter-granular, and moldic vuggy porosities that were confirmed by NMR analysis. These sediments also showed marked selective or partial dolomitization, micritization and dissolution of calcite cements from inclusion of brines that were effective in creating what could be excellent reservoir rock qualities in the potential for the Birdbear Formation as a hydrocarbon producer within the Williston Basin.

CHAPTER I

INTRODUCTION

The Williston Basin is an intra-cratonic sedimentary basin in the heart of North America that covers several thousand square miles across parts of North Dakota, South Dakota, Montana, Manitoba and Saskatchewan. The basin has lithological facies ranging from marine, non-marine and fluvial deposits that cover over four stratigraphic sequences that have oil bearing formations that have contributed significantly to the economy of these states.

In the state of North Dakota, since petroleum was discovered, production has been from formations that are limited to the western portion of the state. The Birdbear Formation is one of the producing formations in the Williston Basin that has garnered a lot of attention on its uniqueness of lithology, thickness, extent of its deposited litho-facies that are easily identifiable through wireline log signatures, distinct assemblage of fossils and potential petroleum system from a carbonate-rich source that has made it one of the talked about play systems in the basin.

Data from cumulative petroleum production indicates that the Birdbear Formation as at 2014 assessment done by the U.S. Geological Survey indicated production of about 6,711,835 Million Barrel (MBO) in McKenzie county and re-evaluation in the Saskatchewan portion of the basin highlights a spike jump in production over a short span of time. This attests that the Birdbear Formation could be more prolific by employing high technology in improved oil recovery methods.

Over the years, studies have shown that non-effective distribution of oil and gas within the Williston Basin is a multi-facet challenge in the petroleum industry with several reasons pointed out which led to diverse studies been carried out towards understanding and delineating the paleo-sedimentary environment that would generally improve oil production within the basin.

Geologic Setting

Figure 1. Extent of the Williston Basin (Wilson M. L. 1956).

The Williston Basin, an oval shaped depression that cuts across North Dakota, South Dakota, Montana, southeastern Saskatchewan and parts of Manitoba, began subsiding in early Ordovician time about 500 Ma, and continued to subside till early Cenozoic time through various events, but deposition of sediment in the basin began during the Cambrian time and peaked from the Ordovician to Devonian periods as land masses were modified and eroded during this time.

During this depositional time, accumulation of evaporates, shales, dolomite, limestone and other sedimentary clasts were laid down in the basin, with a total thickness of about 15,500 feet at the center of the basin. Limestones and dolomites constitute the lithological framework of the Birdbear Formation, deposited at about 350 Ma during the Devonian time.

The Birdbear Formation is underlain by the Duperow Formation and overlain by the Three Forks Formation, with a thickness of about 150 feet and has the characteristics of a restricted shallow marine shelf environment with a sequence of carbonate-evaporite deposits.

Deposition of the Birdbear in Devonian time was controlled largely by three shelf-wide, gradually shoaling-upwards depositional cycles that marked the beginning of a transgressive phase that produced uplifts, sea level changes and general basinal downwarping (subsidence) episodes that allowed the accommodation of successive lithological deposition of sediments in the Duperow and Birdbear Formations, punctuated by more frequent shelf-wide fluctuations in salinity (Kissling et al., 1985), with the later Laramide Orogeny a tectonic event that rejuvenated several basement complexes that produced the Nesson anticline that servers as hydrocarbon traps in the northern portion of the study area.

Purpose

McKenzie County is located at the western part of the Williston Basin North Dakota, with over 7000 wells drilled. There are about 1146 wells that penetrate the Birdbear Formation in this county. This section of the state has undergone fair share of tectonic activities which produced the Nesson anticline in the north eastern section of the study area, with the Billings and Little Knife anticlines in the southern portion of the Williston Basin that developed structural traps for the accumulation of oil and gas.

The intent of this paper is to examine the diagenetic processes on the sediments in McKenzie County and how they relate to the creation of effective porosity within the rock matrix in relation to migration of generated hydrocarbon within the basin.

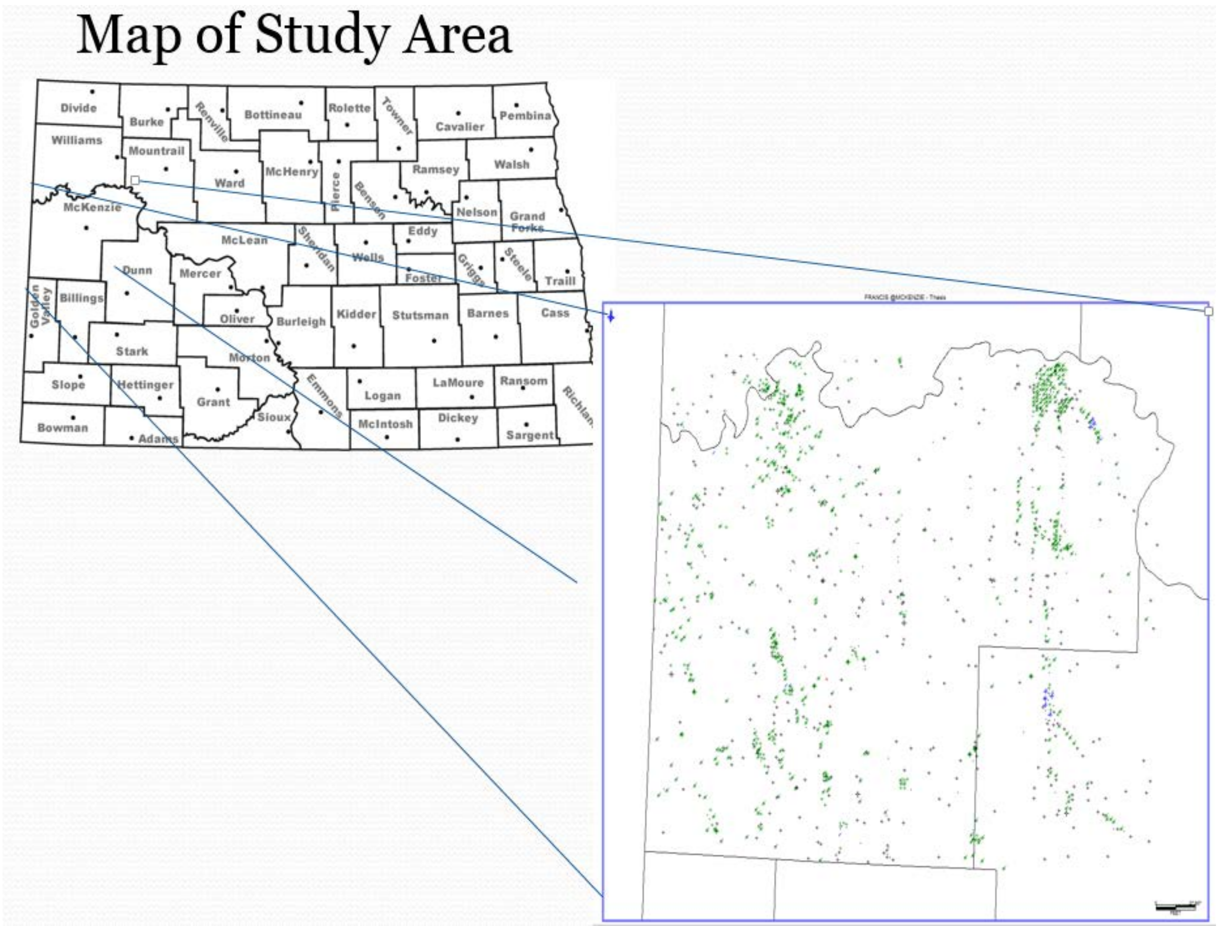


Figure 2. Location map of Wells in McKenzie County.

Previous Works

Baillie (1953), first described the Birdbear Formation in the Williston Basin. He stated that the Birdbear was correlative to the Nisku in Central Alberta from litho-stratigraphic and fossil assemblage, but with marked difference from truncations produced by erosional activities in the Alberta arc.

Sandberg (1958), formally define the Birdbear Formation in the Birdbear well No. 1, Mobil Producing Company, Dunn County North Dakota in the Williston Basin. He outlined the unique uniform lithological character, color, texture and thickness of the formation that can be traced from correlative wells within the basin.

Kent (1968), placed the Birdbear Formation in the middle Frasnian age and divided the formation into two units, a lower carbonate unit and upper evaporate unit. He also stated that beyond their lithological similarities and stratigraphic position, very little connection exists between the Birdbear Formation of the Williston Basin and the Nisku in the Canadian Province.

Halabura (1982), described the depositional environment of the upper Devonian Birdbear Formation in Saskatchewan, Canada. His study included a detailed lithofacies mapping and sedimentological characteristics as distinguishable on wireline logs throughout Saskatchewan.

Cynthia et al, (1982), described the diagenesis of the Nisku Formation and the origins of late-stage cements in formation sediments in west-central Alberta, where it was hypothesized that sediments had influxes of subsurface brine fluid-inclusions that gave rise to dissolution of calcite cements. This created porosity that enhanced migration of fluids in the subsurface and resulted in accumulation of hydrocarbons within the west-central Alberta Basin.

Martiniuk et al. (1995), interpreted the Birdbear Formation with a number of litho-facies and discussed the petroleum potential of the formation in north central North Dakota to southern Manitoba. The authors correlated the facies to determine the depositional environment. From this, potential stratigraphic and structural traps were identified.

Whittaker and Mountjoy (1995), provided an analysis of diagenesis of an upper Devonian carbonate evaporate sequence of the Birdbear Formation and southern interior plains, where they recognized a trend of diagenetic processes from the inclusion of Devonian sea waters that enhanced dolomitization, formation of micritized and calcite cements within sediments of these formations.

Burke and Sperr (2005), highlighted the fact that production in the Birdbear Formation was from an interval in the upper carbonate-anhydrite unit as against the previously held belief that production was from the lower carbonate unit, which is more plausible for production known to have been from stratigraphic traps in confining reservoir within the Formation.

LeFever (2009), characterize the Birdbear as a restricted shallow marine shelf environment with a sequence of carbonate-evaporite deposits that occurs in the Williston Basin of North Dakota, Montana, southwest Manitoba and southern Saskatchewan. The author pointed out the potential possibilities of the Birdbear Formation to be producible from two source bed points within the dolostones bed A and B zone interval from diagenetic-stratigraphic traps within the formation.

Yang Chao (2010), noted that recent study on reservoir characteristics of the Birdbear Formation reveal that different unknown source rock bed within the formation in the Williston Basin that suggests a separate petroleum system from the previous known plays that have enhanced the production of hydrocarbon in the Saskatchewan area of the basin in recent times. He found that re-evaluation of petroleum potential of the basin has generated an upswing in production rate over a short period of time.

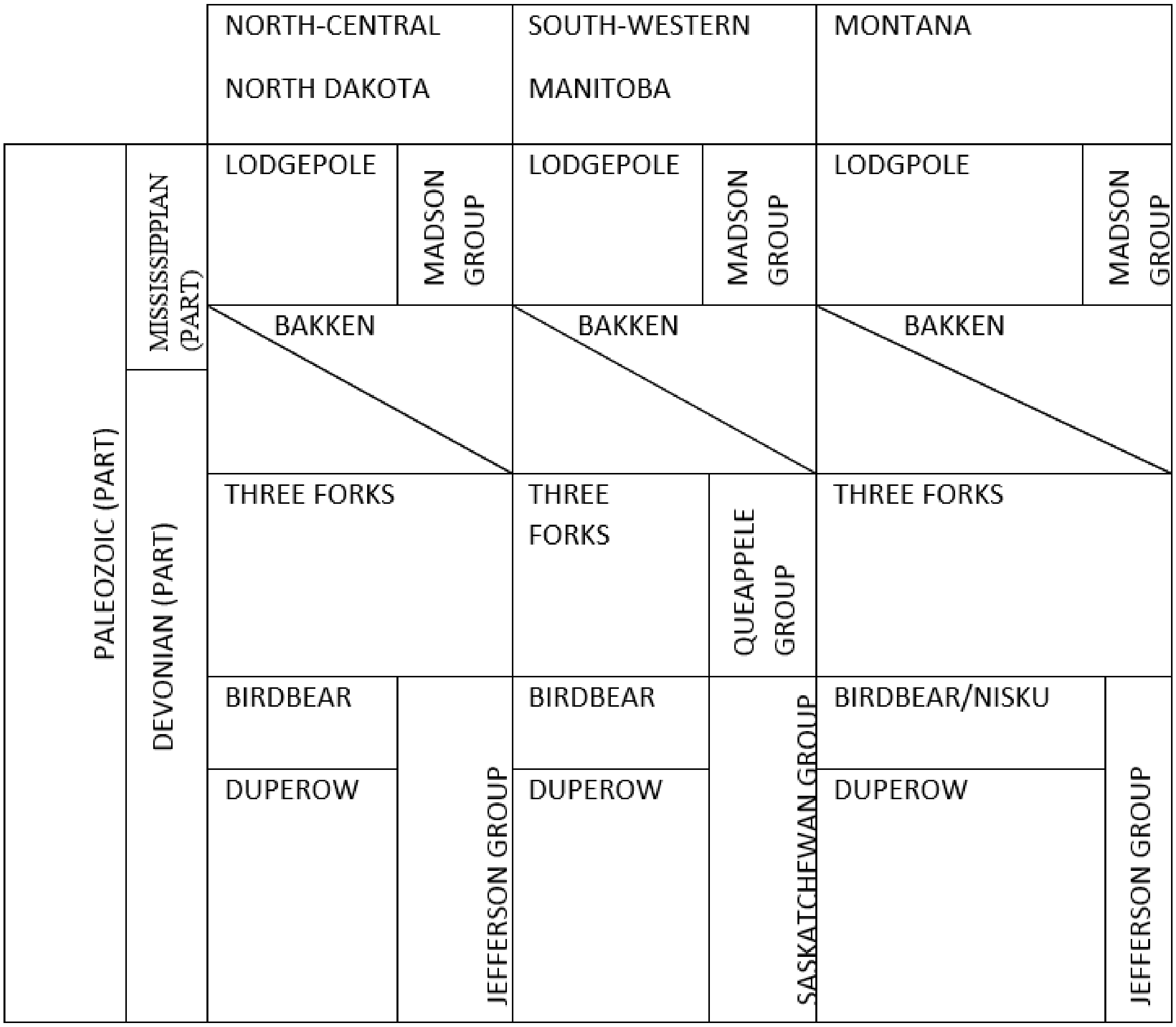


Figure 3. Stratigraphic correlation chart of the Birdbear Formation (modified after Martiniuk 1995).

CHAPTER II

METHODS

The following methods were employed to answer the purpose of this project, and they include:

Wireline Logs

Wireline logs was used to correlate lithological sections of wells with same stratigraphic unit in McKenzie County. Over 1,140 wells top that cuts across Birdbear, Duperow and Souris River Formations were picked for this paper.

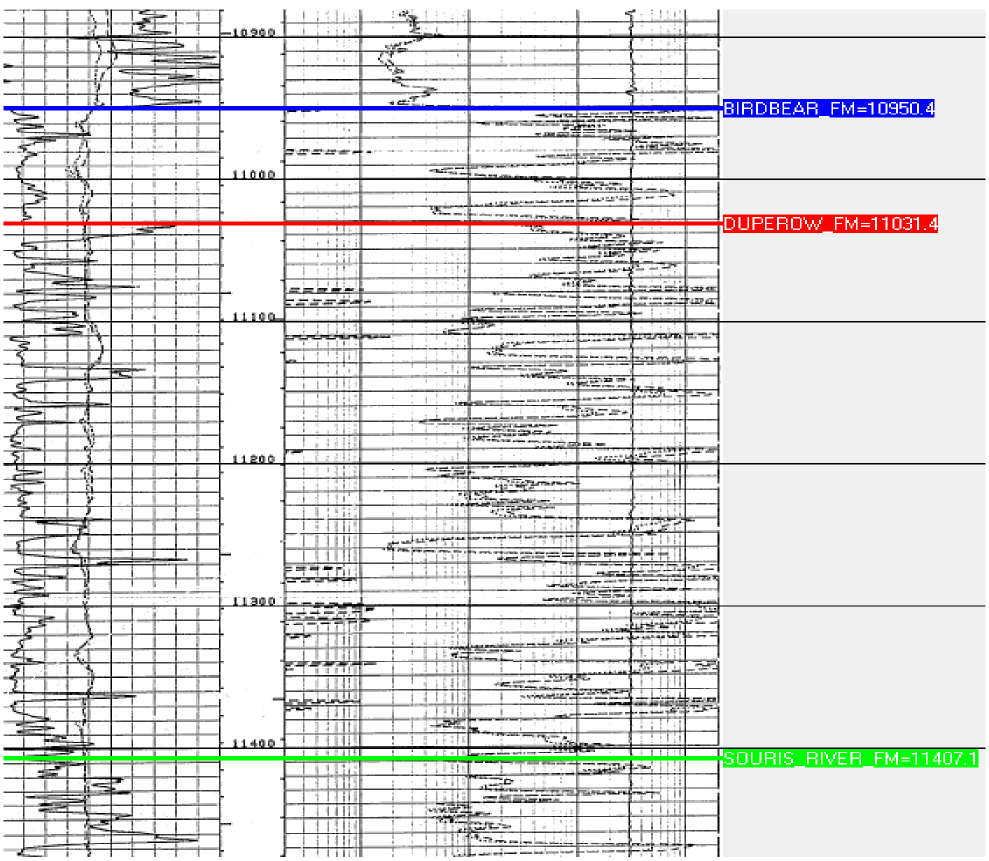


Figure 4. Lithological log displaying picks of formations tops.

Core Description

Thirteen core that penetrates the Birdbear Formation were described in detail. These cores were selected based on availability and sufficient interval thickness within the study area. Lithologic and characteristics such as sedimentary structures, post-depositional sedimentary structures, fossil contents, porosity, type of cements, diagenetic processes and rock lithology were identified and dilute hydrochloric acid was used to differentiate between limestone, dolomite and anhydrite based on the level of effervescence that these different lithologies produce. Classification based on Dunham (1962) classification scheme was used to assign rock type names.

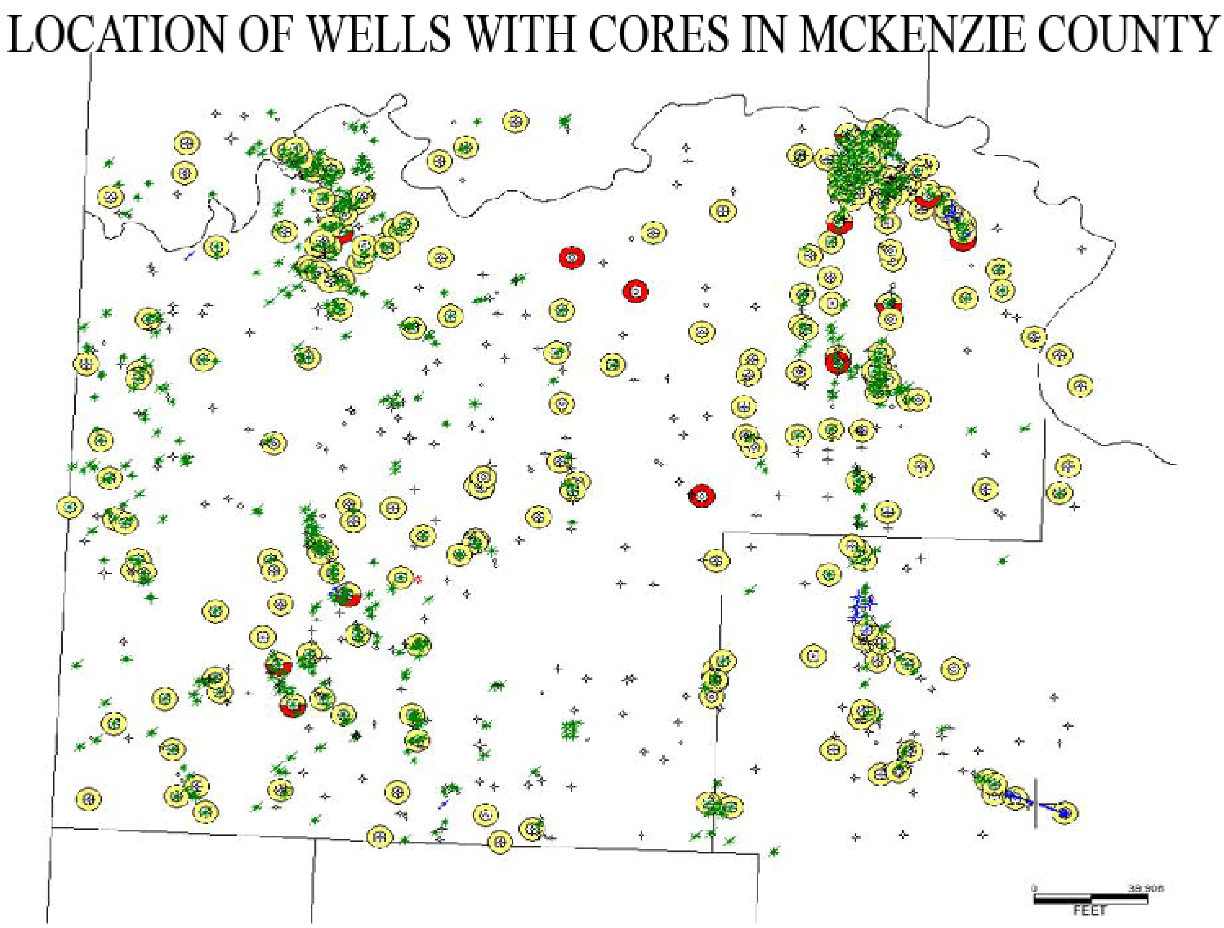


Figure 5. Location of wells marked in red with cores used for this paper from McKenzie County.

Thin Section Description

Thin section slide from seven cores that penetrates the Birdbear Formation in McKenzie County were analyzed under a Leica DFC450 high powered microscope. This was used to further expand on understanding the porosity network of rock fabric as diagenetic processes reworked these rock materials. Most of the slides were stained with blue epoxy for porosity identification and Dunham (1962) scheme were used to classify textural features within slides sample intervals.

Surfer and Petra Softwares

Specialized software applications such as PETRA was used for well–well correlations. Three correlation plots were made across McKenzie County that determined the stratigraphic inter-relationship between marked out wells as they cut across the formation within study area.

SURFER was used to make isopach, contour, cumulative production and generalized sonic porosity maps across the study area.

NMR Spectroscopy Technology

A 2-MHz Oxford instrument Nuclear Magnetic Resonance (NMR) Spectroscopy technology was used to generate porosity distribution data that provided information on porosity percentage (%) within rock matrix (fabric) of thirteen cored samples that penetrate the Birdbear Formation. The generated (T_2) uni-modal and bi-modal peak distribution graphs were used to interpret and estimate porosity percentage created from sediment reworking resulting from diagenetic processes in study area.

From this study, a general depositional environment and stratigraphic framework of facie pattern was made on the Birdbear Formation within McKenzie count in the Williston Basin, which highlight types of lithofacies present in the area, evidence of diagenetic processes within the sediments and a combined porosity network within the study area.

CHAPTER III

RESULTS

The following results are presented from methods used in this project; they were put forth from detailed reviews, descriptions, analysis and experimental fronts to give a holistic interpretation of findings in study area.

Stratigraphy of the Birdbear Formation

The Birdbear Formation previously called the "Nisku" was first proposed by Baillie (1953), described as continuous carbonate sequence with type locality in the Alberta area because of its distinct similar stratigraphic unit and lithology, but discovered that it was truncated by erosional activities in the Alberta arc which separates the Williston and Alberta Basins, therefore the drop of "Nisku" was effected in the Williston portion of the basin.

Sandberg and Hammond (1958), designated the type section for the Birdbear Formation in the Birdbear well No. 1, Mobil Producing Company, Dunn County North Dakota in the Williston Basin, which is a reference for the Birdbear and other formations in the Basin. They outlined the Birdbear Formation as unique uniformly thick-bedded light gray to medium brownish gray, porous, fossiliferous limestone and dolomite and finely crystalline within the basin.

Deposition of the Birdbear Formation was controlled by three depositional cycles in late Devonian time, within the Jefferson group at the end of the deposition of the Duperow Formation which underlain the Birdrear and the Three Forks Formation that overlain it in a shelf-wide depositional environment.

Kissling et al, (1985), concluded that the depositional cycles were marked with frequent punctuations by varying salinities of water bodies that produced anhydrites during subaerial exposures with further sequence of carbonate-evaporite. The unit has a thickness of about 150 feet, and is divided into two informal units of boundstone and limestone consisting of medium dark gray to dark gray lower unit and anhydrite-carbonate upper unit sequence of light gray to medium light gray.

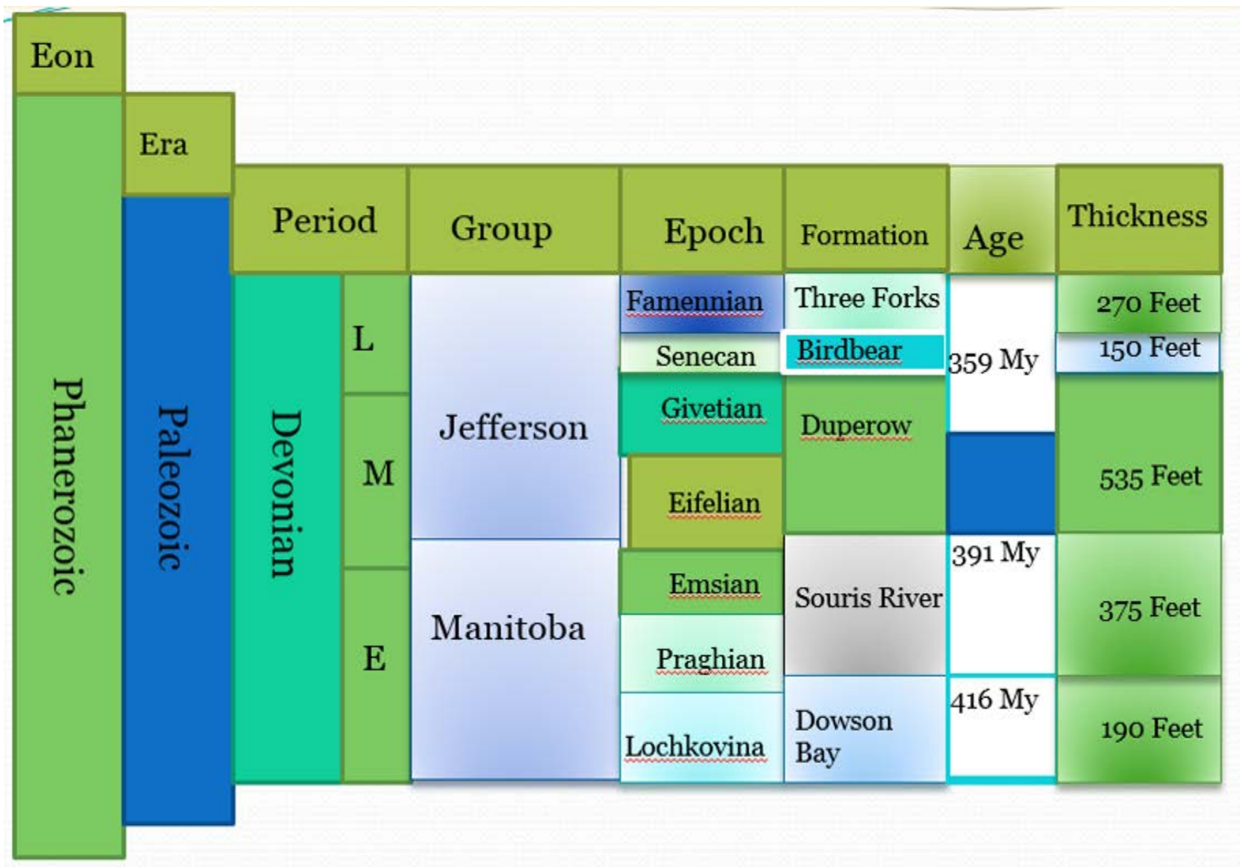


Figure 6. Geologic Time Scale of North Dakota (Modified from USGS 2010).

Core Description

Thirteen cores that penetrates the Birdbear Formation in McKenzie County were described. The formation was divided into two units designated as a lower unit 1 and an upper unit 2 respectively, according to their stratigraphic position as shown in the lithology log below (Figure 7.), and described from bottom up.

The upper section of lower unit 1 that falls within study area, is of uniformly carbonate dolomite-limestone facies of boundstone in some areas in this paper.

NDGS 12555

Pennzoil Exp. & Prod. Co.

North Branch #34-42F

SENE 34-148-102

KB 2345

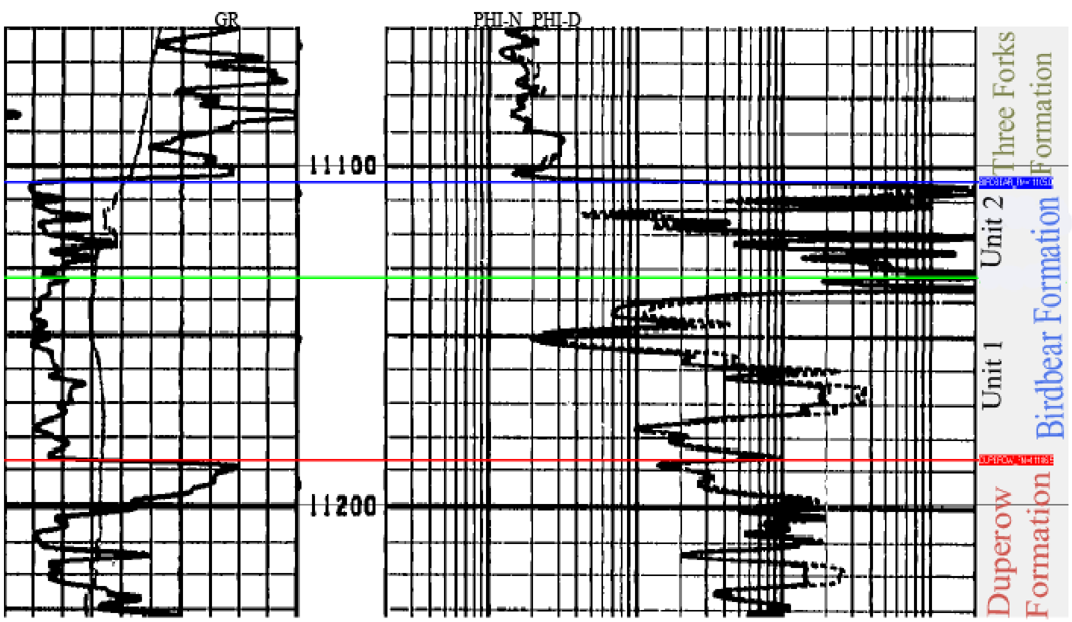


Figure 7. Typical Birdbear log displaying informal units from study area.

Classification, with medium dark grey to dark grey, very porous with medium−fine grained sediments texture that have inter-granular and moldic vuggy porosity in some sections with scattered anhydrite pockets. This section is rich in dark organic matter bands, highly bioturbated with abundant gastropods, crinoids, ostracods, stromatoporoids, rugose corals and amphiporas.

As seen from NDGS 2602 below, a limestone from the study area in unit 1, sediments here are burrowed which has destroyed previous sedimentary structures with present porosity of about 3%.

Figure 8. NDGS 2602, Texaco Incorporation Seth A. Garland #5, 6-153N-95W C NE, Limestone, fairly cemented, high porosity with anhydrite pockets, bioturbated, with abundant amphipora (stromatoporoids) and rugose corals from unit 1. (Core depth 10,068.1').

Figure 9. Limestone: very dark gray sediment rich in organic matter with trace of oil stain and slightly fractured from unit 1. NDGS 21786, SWNW, Denbury Onshore LLC. Rink 12-4ESH, 4-151N-98W. (Core depth 11,428.8' – 11,429.6')

Figure 10. Limestone, dark gray−grayish black; packstone, characteristics of unit 1 with stromatoporids. NDGS 12249, NENW, 17-146N-102W, Meridian Oil Incorporated, MOI #21-17. McKenzie County, North Dakota. (Cored interval 10,997')

NDGS 21786 (Figure 8.), and NDGS 12249 (Figure 9), are dark gray, vertically fractured, rich in organic matter, with abundant amphipora, typical facie found in the upper portion of the lower unit 1 of the Birdbear Formation. Visible oil stains on sample from (Figure 8), could be indicative of probable hydrocarbon production in that section of unit 1 within the study area. However, oil stains are restricted locally and not present in all cores observed. Thin sections showing gradual dolomitization of sediments with similar localized fossil assemblage as mentioned above, and shown below.

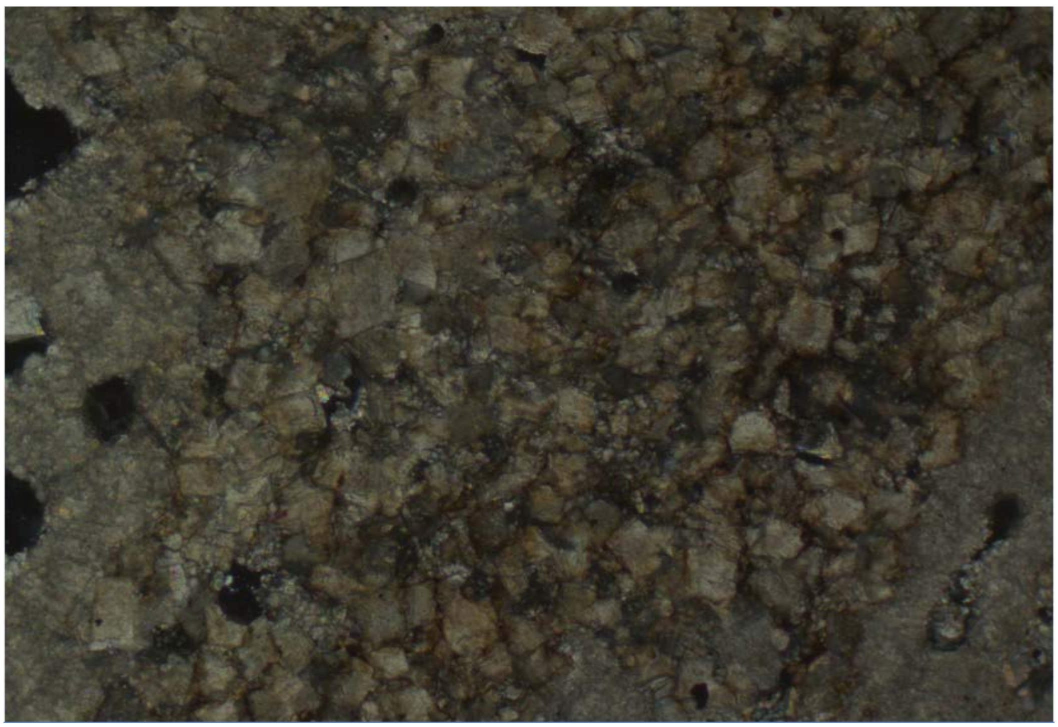


Figure 11. Limestone (packstone): showing gradual dolomitization of rock grains, dissolution of calcite cements and porous, from unit 1. (NDGS 2602, 6-153N-95W C NE, depth 10,061.8', magnification 10X, HA=0.022mm).

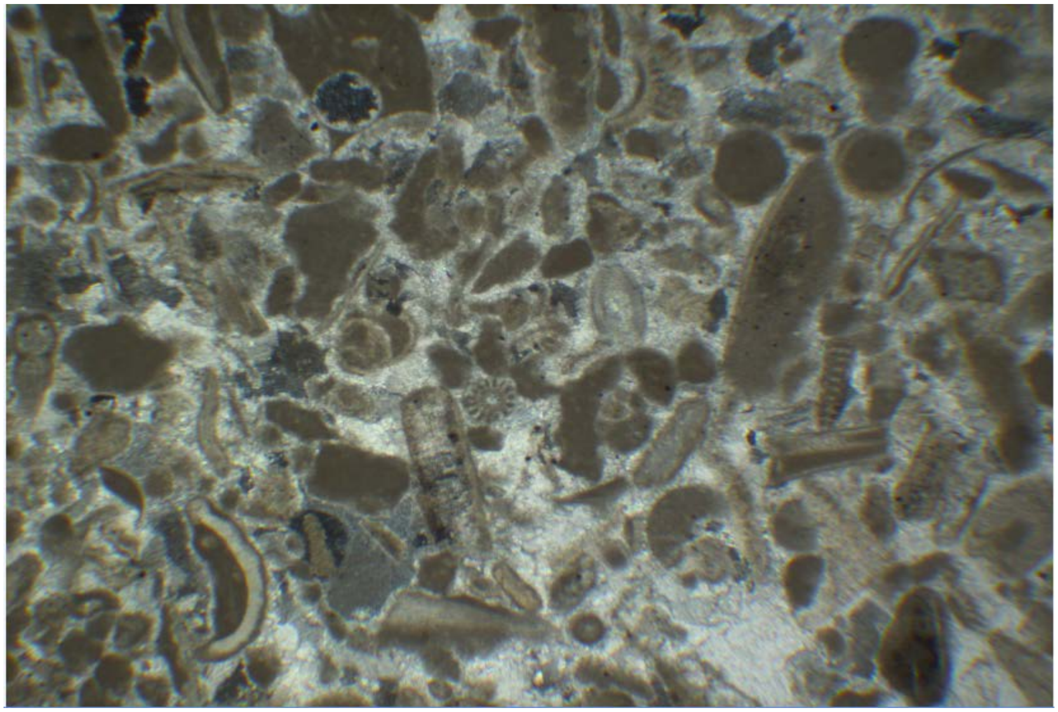


Figure 12. Limestone (grainstone), with spar cements, gastropod, ostracods, rugose corals, anhydrite from unit 2. (NDGS 3086, 1-152N-95W C NW, depth 10,553.5', magnification 4X, HA=0.10mm).

Sediments of unit 2 consist of an upper anhydrite-carbonate section that is light gray to medium light gray, fair–poor inter-crystalline porosity with medium to fine grained texture. Where this unit contacts the Three Forks Formation, it has massive anhydrite beds with varying thickness from 3 feet and above exists within study area. Beneath the massive anhydrite beds a combination of lime dolomitic facies, restricted rare organic matter with anhydrite pockets with fair to poor porosity are observed. This anhydrite beds stands out as ideal seal that could restrict the movements of fluids between the Birdbear and Three Forks Formations within the Williston Basin.

Figure 13. Anhydrite, light gray, massive and lacking bedding plane from unit 2. NDGS 12962, SWSE, 35-148N-102W, Pennzoil Exploration & Production Company, North Branch #35X-34 BN. (Core depth 10,962'–10,963').

Figure 14. Dolomite, light gray with fair porosity from unit 2, and has rare soft organic sediment laminae with anhydrite pocket. NDGS 12962, SWSE, 35-148N-102W, Pennzoil Exploration & Production Company, North Branch #35X-34 BN, (Core depth 10,967' – 10,967.9').

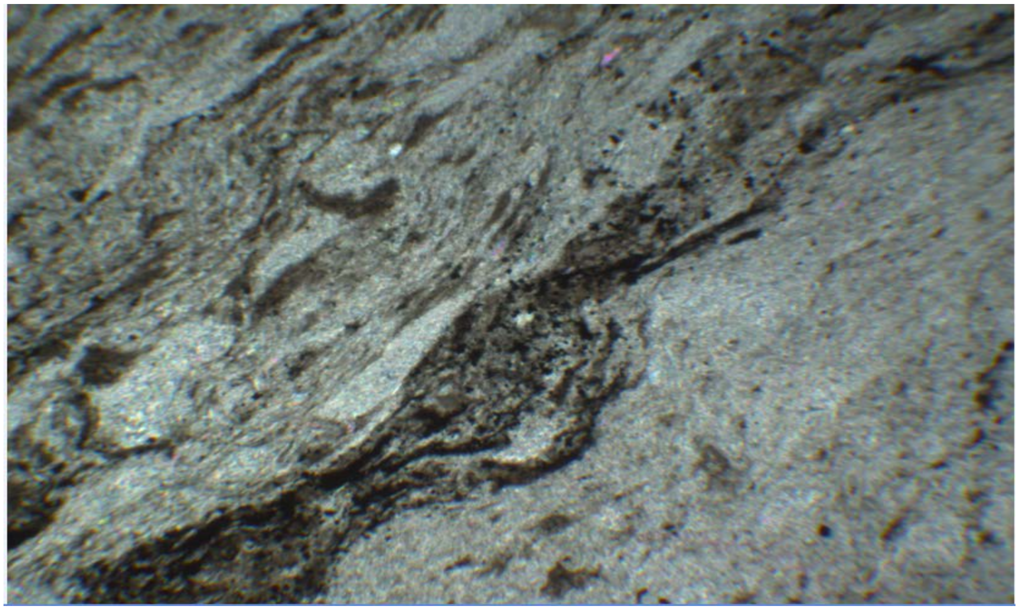


Figure 15. Anhydrite with rare laminar soft organic matter from unit 2. NDGS 3086, 1-152N-95W C NW, Amerada Petroleum Corp. Antelope Unit “B” #1. (Core depth 10,507.5' magnification 4X, MH= 0.10mm).

Thin Section Description

Thin sections were used to delineate the paleo-depositional litho-facies identified within the study area and associated thin slides are in appendix D in this paper.

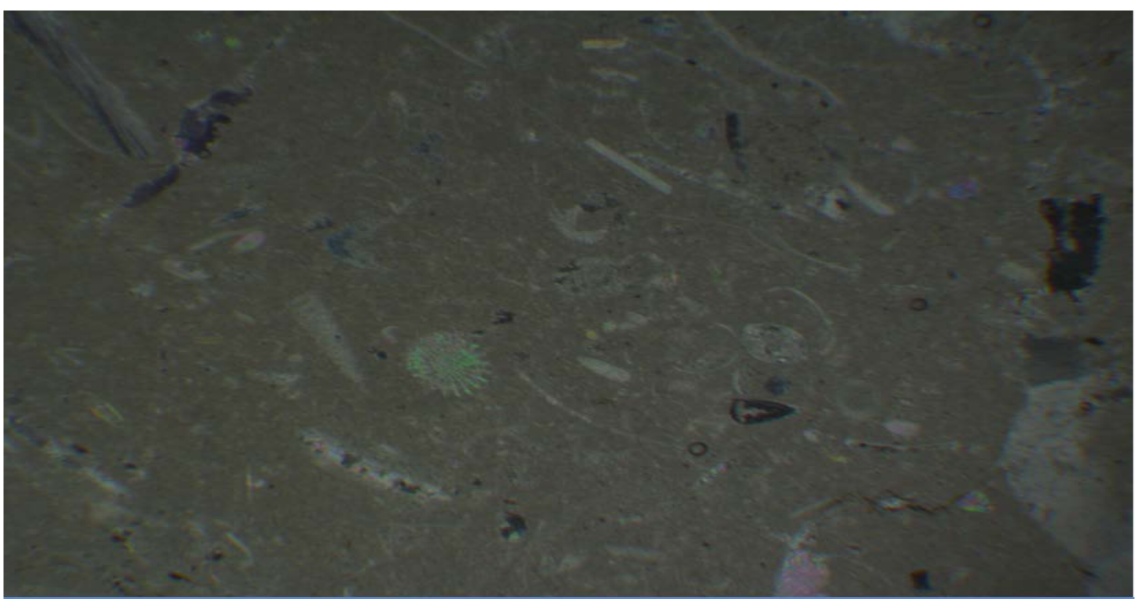


Figure 16. Packstone, a typical unit 1 limestone facie, with bryozoan, brachiopod and corals in mud matrix. NDGS 2373, NESE, 1-152N-95W, Amerada Petroleum Corp. Antelope Unit “A” #1. (Cored depth 10,459', magnification 4X, MH= 0.10).

Figure 17. Limestone (packstone), with bryozoans, tabulate coral, with stylolites in mud matrix. NDGS 2820, NWSW, 5-151N-95W, Texaco Inc. F. P. Keogh #4. (Cored depth 10,937.6', magnification 4X MH=0.10).

Both images show shallow marine deposits of packstone with abundant coral bryozoans, crinoids, amphipora and gastropods. Unit 2 has massive anhydrite in some cores or mixed dolomitic-anhydrite with laminar or rare soft organic matter as indicated on Figure 13, above.

A number of porosity types were identified with sediments of the Birdbear Formation that cuts across both units 1 and 2, and they include intra-granular, intra-crystalline, inter-crystalline, modic vuggy and fractured porosities respectively.

Porosity/Permeability

Porosity and permeability are important factors in conventional rocks that contribute to the effective migration of fluids and generated hydrocarbon in the subsurface. Although there may be effective porosity without adequate permeability in a rock matrix due to interconnectivity of pores within the rock.

Intra-Crystalline Porosity

Sediments from the study area exhibited intra-crystalline porosity developed post-depositionally. Thin sections show area where calcite cements and other allochems materials were dissolved thereby creating pore spaces. Dissolved calcite cements are further transported to form spar in unit 1 within study area.

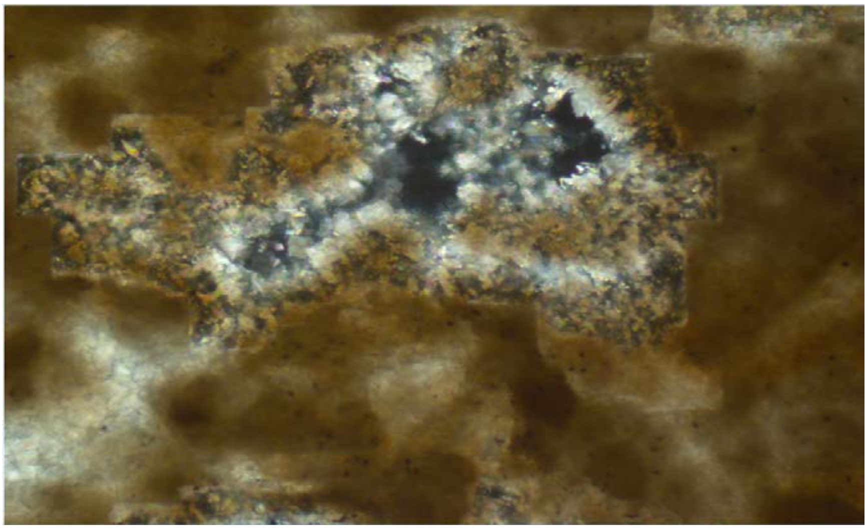


Figure 18. A limestone matrix with dissolution of calcite cement to create porosity. NDGS 12249, NENW, 17-146N-102W, Meridian Oil Inc. MOI #21-17. (Cored depth 10,975.8'-10,976.8', magnification 4X, MH= 0.10).

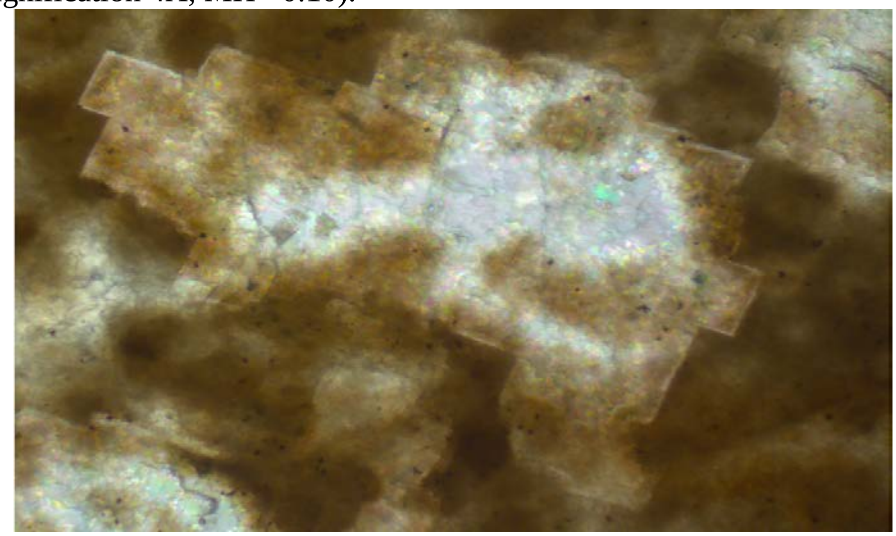


Figure 19. Limestone, magnified anhydrite crystal at right angle, within a grain matrix. NDGS 12249, NENW, 17-146N-102W, Meridian Oil Inc. MOI #21-17. (Cored depth 10,975.8'-10,976.3' magnification 10X, MH= 0.22).

Intra-Granular Porosity

Sediments of the Birdbear Formation in the study area developed local intra-granular porosity in the lower unit 1 litho-facie from incompletely cemented rock matrix of dissolved calcite cements in the post-sedimentary process. Most of this porosity allowed the movement of subsurface fluids and could serve as retention pores for holding migrating hydrocarbons.

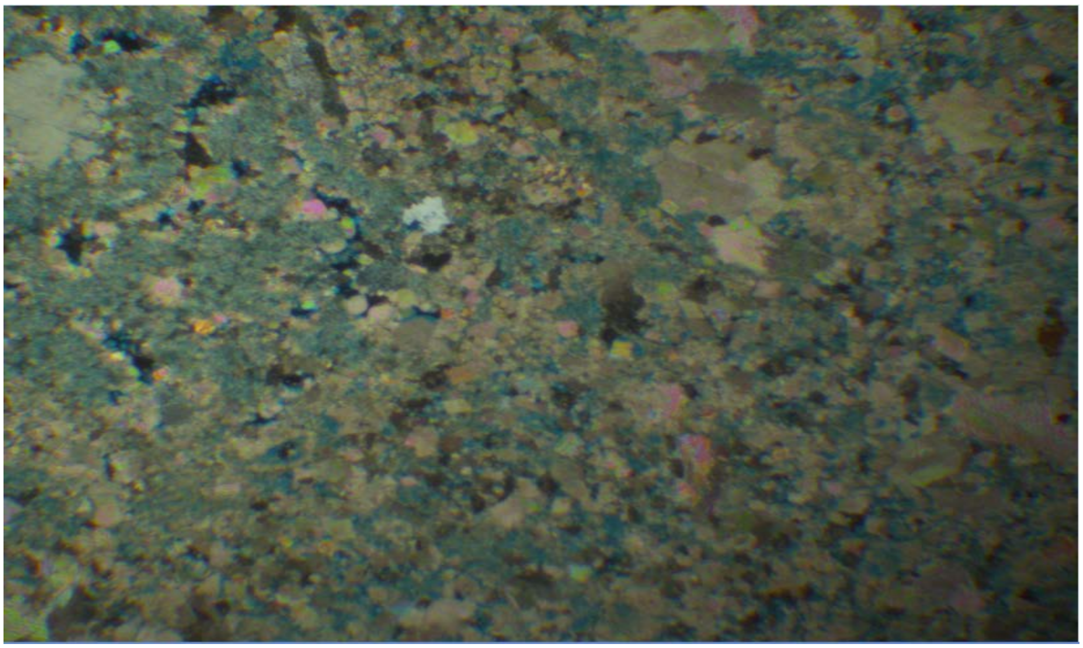


Figure 20. Limestone (mudstone) epoxy stained showing inter-granular porosity from dissolution of calcite cements in rock matrix. NDGS 2820, NWSW, 5-151N-95W, Texaco Inc. F. P. Keogh #4, (Cored depth 10,902.2', magnification 4X, MH= 0.10).

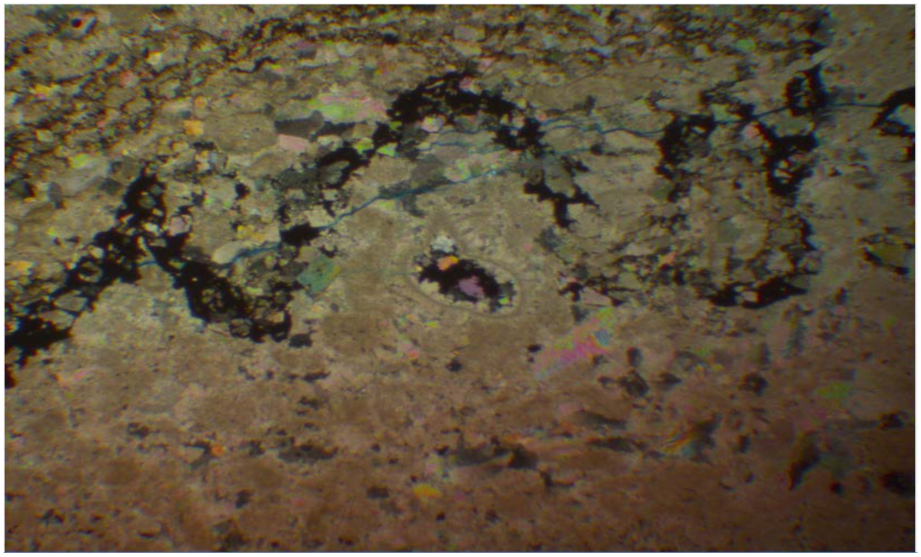


Figure 21. Limestone (mudstone-wackestone) with intra-granular porosity, soft organic matter inclusion and recrystallizing ostracod with spar forming cement. NDGS 2820, NWSW, 5-151N-95W, Texaco Inc. F. P. Keogh #4, (Cored depth 10,902.2', magnification 4X, MH= 0.10).

Vuggy Porosity

The litho-facies of the lower unit 1, developed moldic vuggy porosity from the dissolution of existing grains, and cements from probable marine sedimentary environment of deposition or brine fluid movement in the subsurface as sediments here showed.

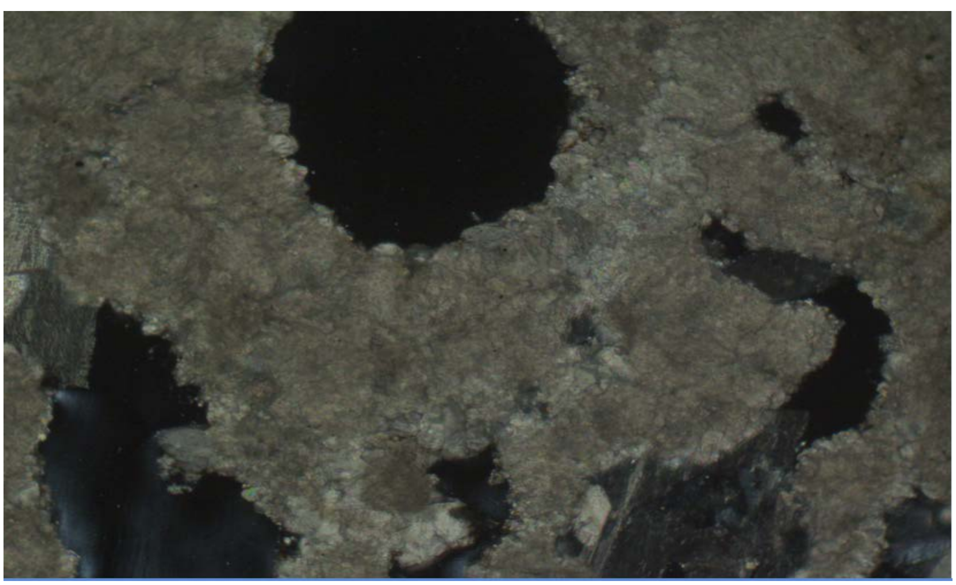


Figure 22. Limestone, showing moldic vugs as dissolving calcite cements are eroded by subsurface fluids within rock matrix. NDGS 2602, C NE, 6-153N-95W, Texaco Inc. Seth A. Garland #5 (Cored depth 10,057.9', magnification 10X, MH= 0.22).

Fractured Porosity

Sediment from study area were observed to have fractured porosity which could be as a result of overburden pressure or tectonic activities as core sample NDGS 2373, NESE 1-152N-95W, Amerada Petroleum Corp. Antelope Unit “A” #1, with cored depth 10,451' in the north eastern portion of the study area developed such porosity, and shown below,

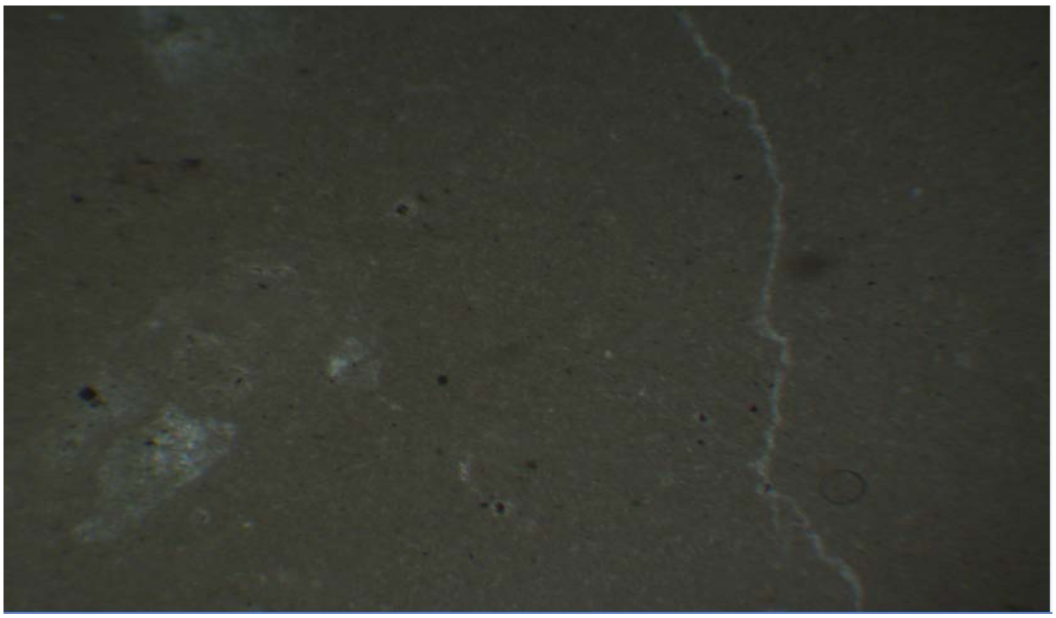


Figure 23. Dolo-mudstone with evidence of vertical fracture running on rock surface, with calcite cement infilling. NDGS 2373, NESE, 1-152N-95W, Amerada Petroleum Corporation, Antelope Unit “A” #1, (Cored depth 10,451', magnification 4X, MH= 0.10).

Most sediments from the upper lithofacies in unit 2, exhibited low porosity from the massive anhydrites found in rock matrix which are impermeable or experiencing gradual dolomitization in this section which could enhance or destroy porosity during sediment transformation.

Table 1. Porosity Values of Sedimentary Rocks (From Schlumberger Log interpretation chart, 2010).

Sediment	Porosity (%)	Permeability
Anhydrite	0	Nil
Limestone, dolomite	5 to 20	Poor to Good
Vuggy limestone	Up to 50	Excellent
Crystalline rock		
Unfractured	0 to 5	Very poor
Fractured	5 to 10	Poor

Table 2. Porosity Values of Rock Sediments in Pure Form, (Modified from Schlumberger log interpretation chart, 2010).

Sediments	Mass g/cc
Anhydrite ($CaS0_{4)}$	2.98
Dolomite ($CaC0_3MgC0_3$)	2.85
Halite (NaCl)	2.03
Limestone (calcite) ($CaC0_3$)	2.71
Sandstone (quartz) ($Si0_2$)	2.65

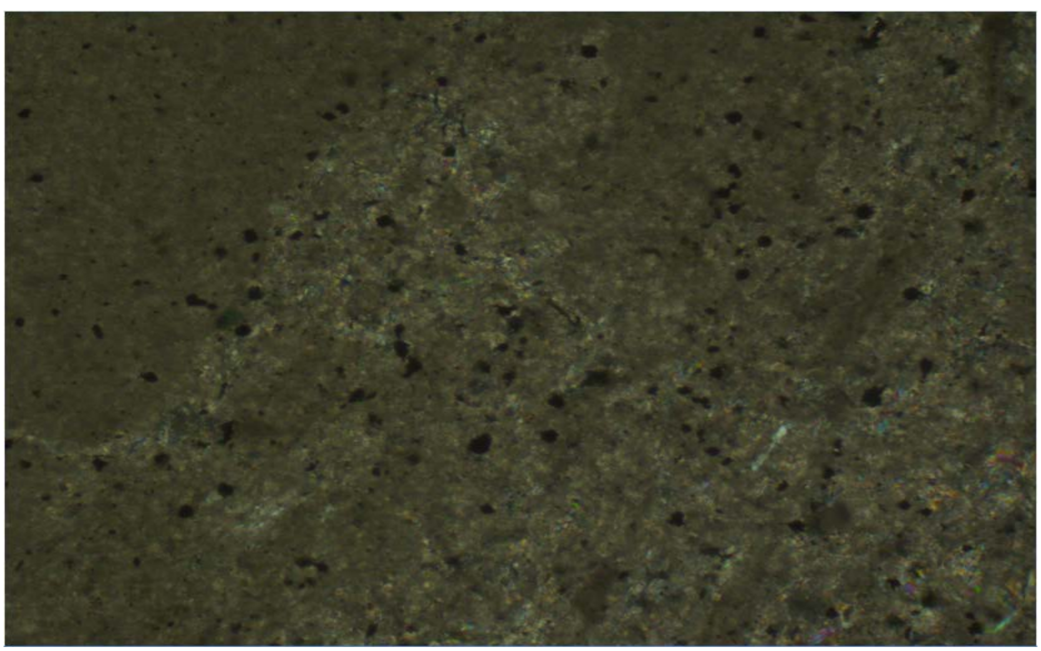


Figure 24. Dolo-mudstone, with calcite cement and anhydrite. NDGS 2602, C NE, 6-153N-95W, Texaco Inc. Seth A. Garland #5 (Cored depth 10,037'-10,040', magnification 10X, MH= 0.22).

Diagenetic Features of Sediments in the Study Area

Sediments of the Birdbear Formation in McKenzie County experienced appreciable diagenetic processes from the inclusion of brine fluids (formation waters) that were rich in Mg^{2+} ions. These fluid inclusions produced changes form chemical (biogenic) alterations, and deep burial pressures associated with geothermal temperature that were constantly modifying the sediments.

Mechanical/Chemical Compaction

The resultant high depth associated with sediments over a long period of time generates distortion, flattening, plastic deformations, brittle fractures and realignment of grains within rock fabric, including fossil allochems as shown below.

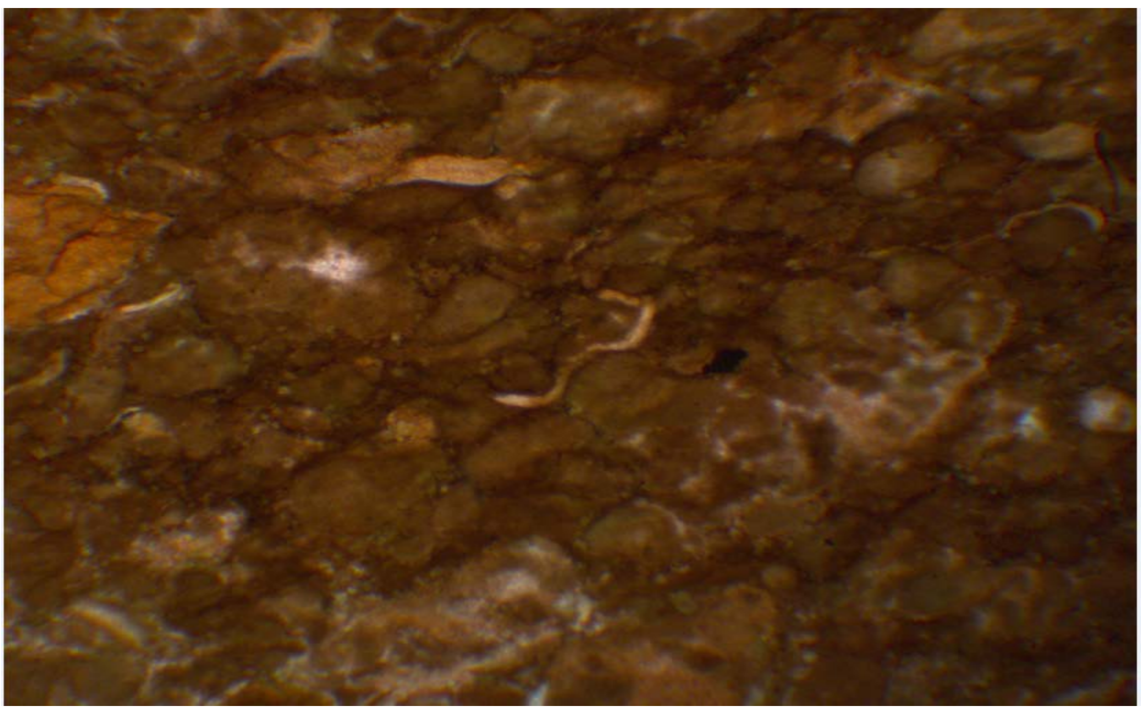


Figure 25. Limestone, overburden pressures leads to the deformation of ostracod shell, and grain realignment in rock fabric. NDGS 12249, NENW, 17-146N-102W, Meridian Oil Inc. MOI #21-17 (Core depth 10,976.9'-10,977.3', Magnification 10X, MH=0.10).

Dissolution and pressure solution in grain boundaries of calcite cements from the inclusion or in contact with formation fluids produced features like stylolites, solution seams and in rare cases veins of organic matter within rock matrix.

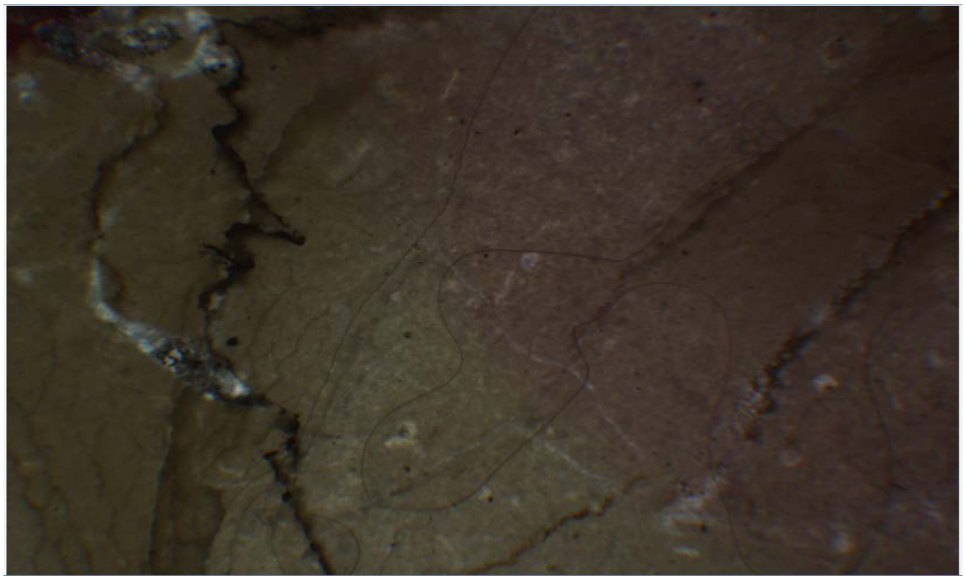


Figure 26. Limestone, showing stylolite from dissolution of cements within rock matrix. NDGS 2967, NWSE, 3-152N-96W, Texaco Inc. A. S. Wisness #2, (Cored interval 10,589', magnification 4X, MH=0.10).

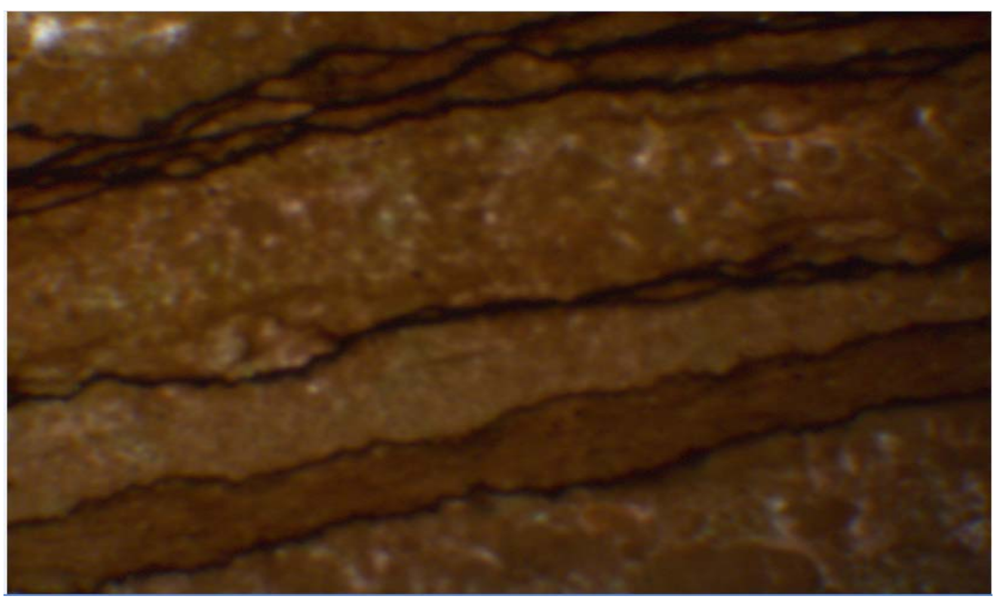


Figure 27. Limestone with veins of soft organic matter inclusion. NDGS 12249, NENW, 17-146N-102W, Meridian Oil Incorporated, MOI #21-17, (Cored depth 10,977.3'-10,977.7', magnification 4X, MH=0.10).

Bioturbation and Micritization

Sediments from the study area were marked with bioturbations at various intervals or locally, which obliterated initial pre-depositional porosity. Actions from boring algae and fungi on the outer shells of fossil remains aids micritization that occurs and envelopes the outer rims of remains as shown below.

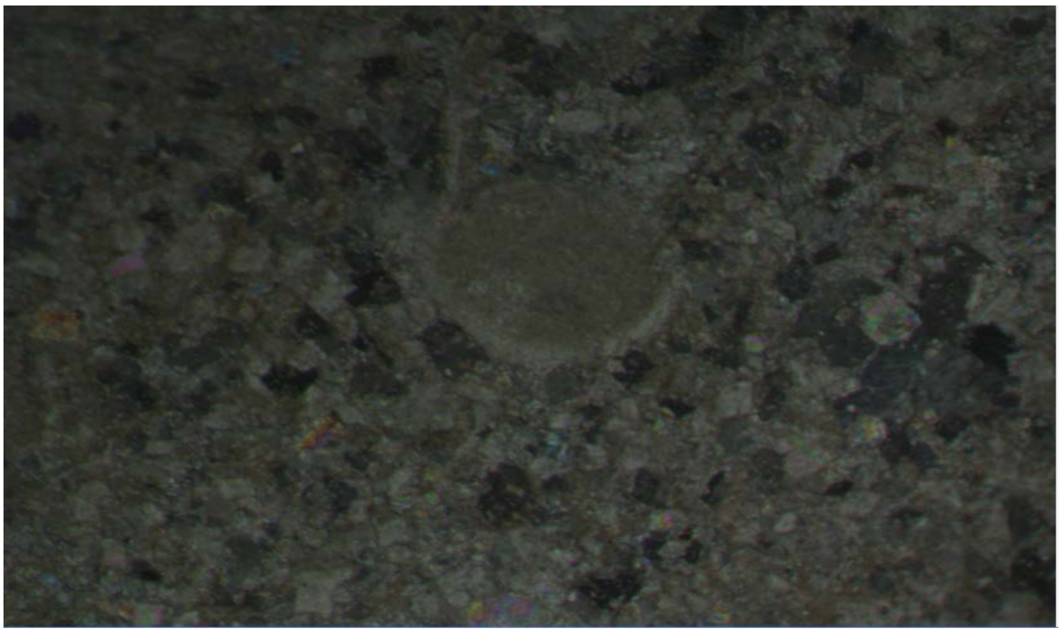


Figure 28. Limestone (packstone), micritizing brachiopod remains in dolomitizing rock matrix. NDGS 2373, NESE, 1-152N-95W, Amerada Petroleum Corp. Antelope Unit “A” #1, (Cored interval 10,455', magnification 10X, MH=0.22).

Cementation

Burial cementation produced prismatic spar forming cements, syntaxial overgrowth or microcrystalline cements in ostracods and gastropods remains in rock matrix within the study area. This was in response to formation fluids inclusion flows and increased burial temperatures producing new precipitates in pores spaces within the marine (phreatic) environment of the Birdbear Formation sediments.

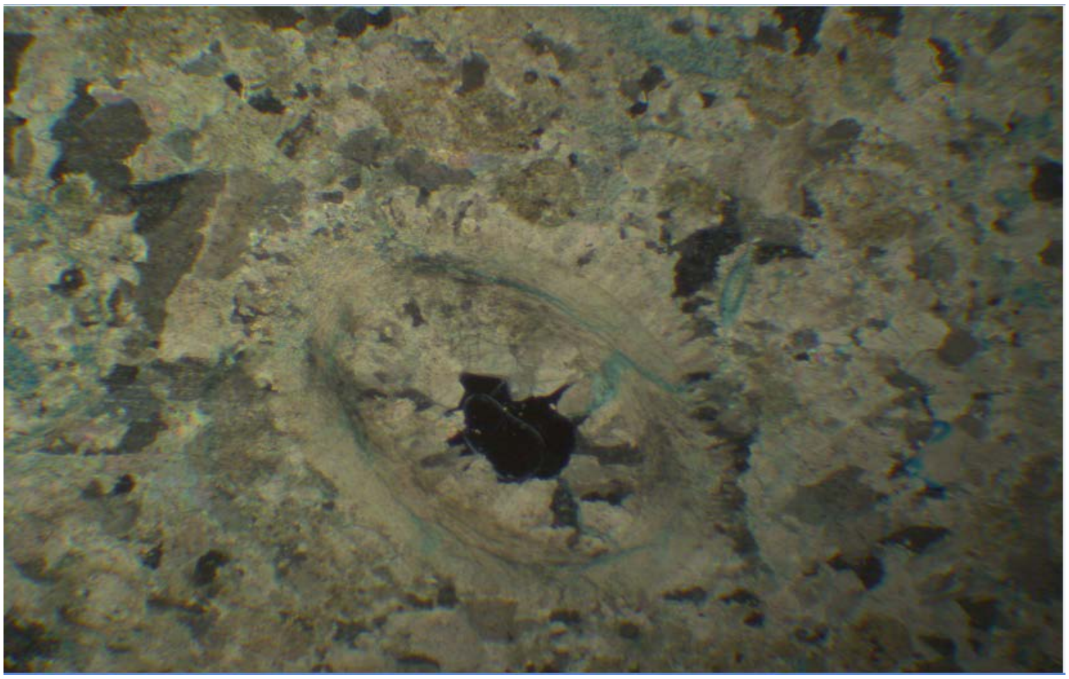


Figure 29. Limestone (wackestone), bladed crystal syntaxal growth of ostracod remains from calcite cement. NDGS 2820, NWSW, 5-151N-95W, Texaco Inc. F. P. Keogh #4, (Cored depth 10,910.2', magnification 4X, MH=0.10).

Replacement/Recrystalization

Most ostracod fossil remains experienced partial to complete recrystallization, which could be locally within some interval, as larger crystals overgrowth takes over the remains, and gastropods remains were transformed from a less stable aragonite mineral cement into a more stable calcite mineral cement in rock matrix. Some fine lime mud matrix were transformed into medium to coarse sparry calcite cements within the sediments as Figures 30 and 31 indicates.

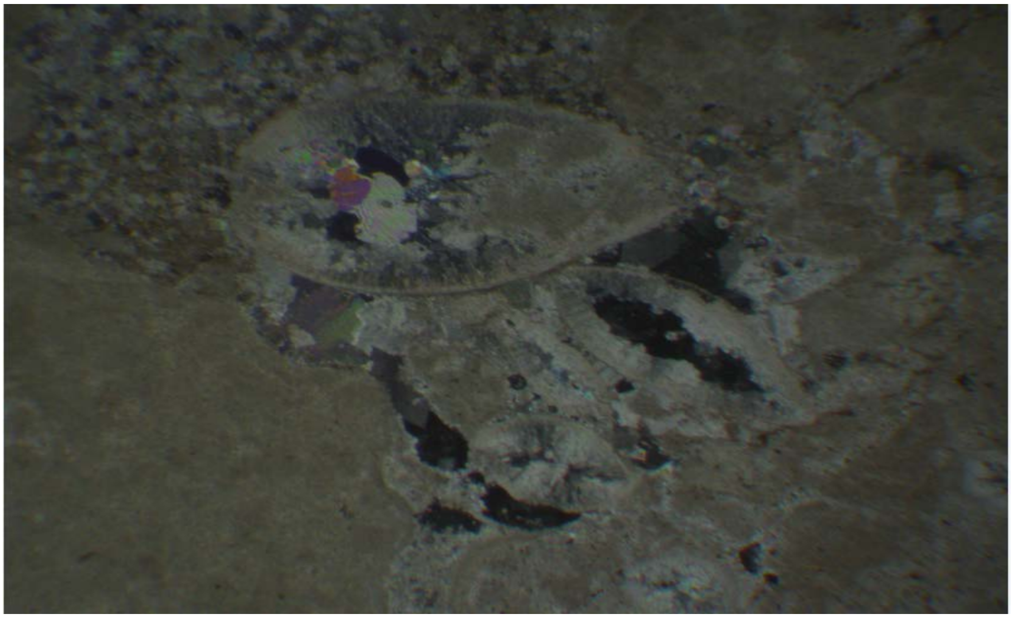


Figure 30. Limestone (packstone), recrystallization with spars forming cements on ostracods carapace. NDGS 2373, NESE, 1-152N-95W, Amerada Petroleum Corp. Antelope Unit “A” #1, (Cored interval 10,464', magnification 4X, MH=0.10).

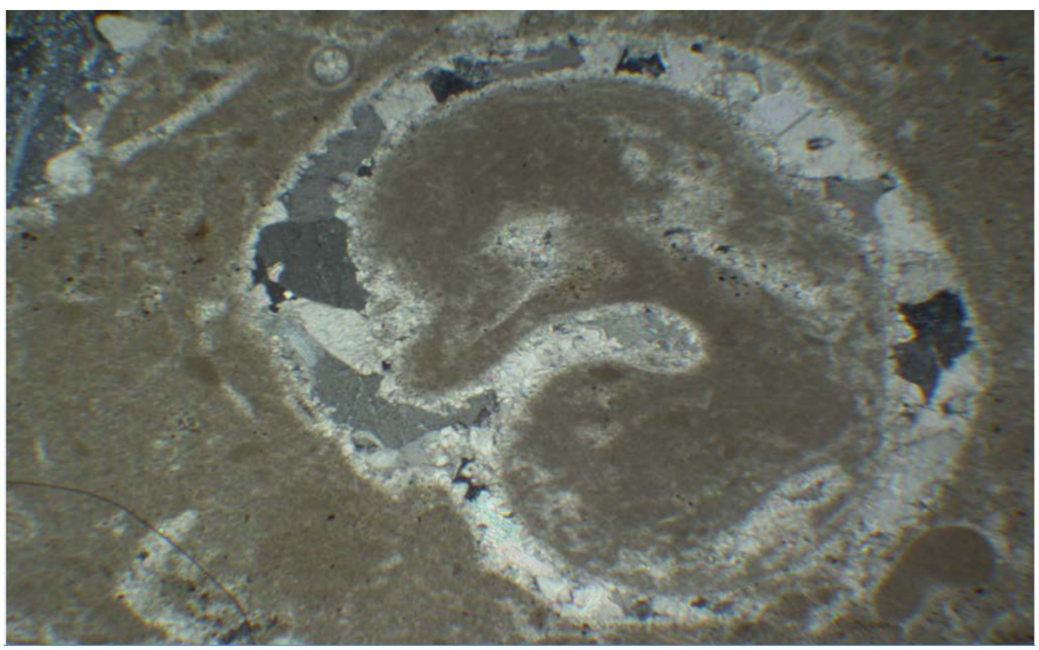


Figure 31. Limestone (packstone), recrystallizing gastropod shell indicating diagenetic transformation from aragonite to calcite. NDGS 2967, NWSE, 3-152N-96W, Texaco Inc. A. S. Wisness #2, (Cored interval 10,586', magnification 4X MH=0.10).

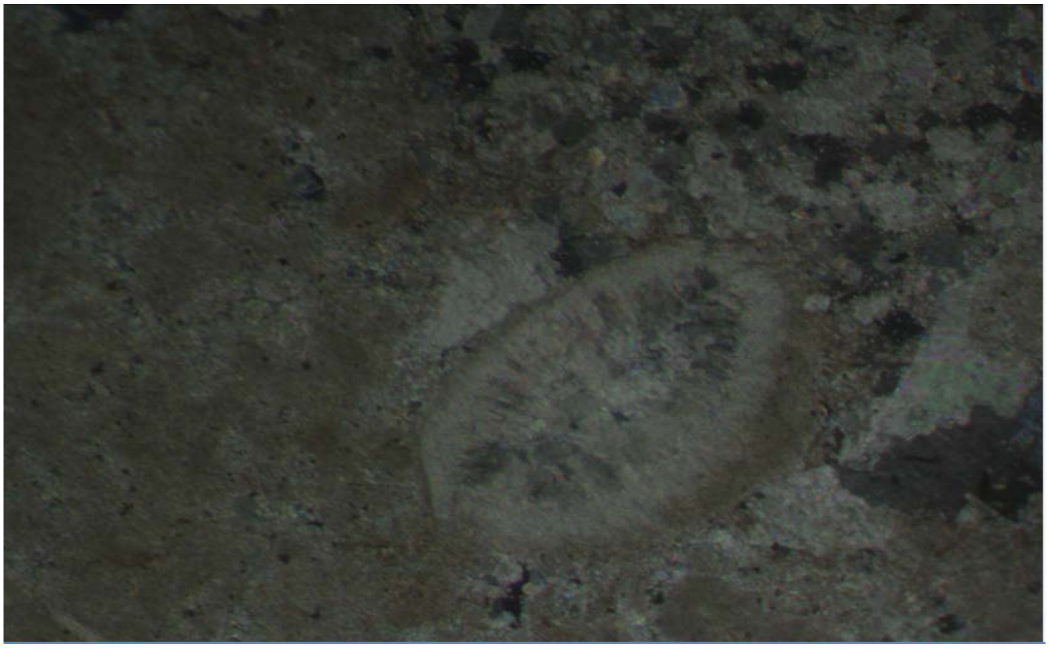


Figure 32. Limestone (packstone): recrystallization of ostracod shell, isopachus cement with fabric selective porosity. NDGS 2373, NESE, 1-152N-95W, Amerada Petroleum Corp. Antelope Unit “A” #1, (cored interval 10,464', magnification 10X, MH=0.22).

Dolomitization

Sediments of the Birdbear Formation in the study area were altered through replacement reaction of micritized dolomite facies in the subsurface from brine fluid inclusions. This fluid inclusion developed mineral transformation, dissociation and realignment within rock matrix.

$2\ CaCO_3 + Mg^{2+} \leftrightarrow CaMg\ (CO_3)_2 + Ca^{2+}$ (replacement reaction)

$Ca^{2+} + Mg^{2+} + 2CO_3^{2-} \leftrightarrow CaMg\ (CO_3)_2$ (precipitation in system)

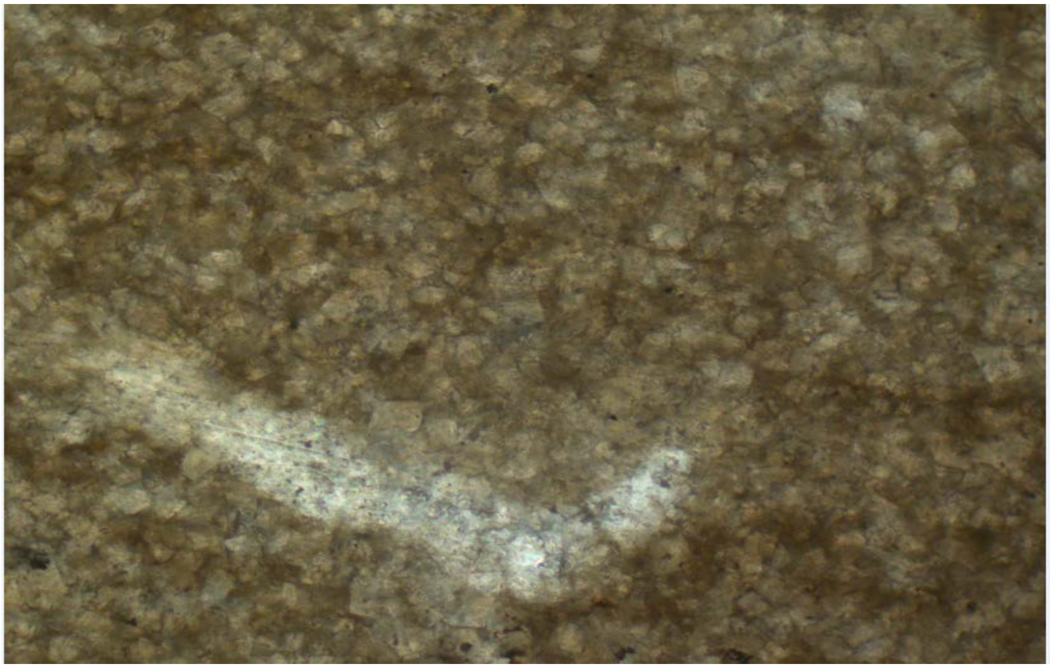


Figure 33. Dolomitizing limestone grains with anhydrite having inter-granular porosity, NDGS 12962, SWSE, 148N-102W, Pennzoil Exploration & Production Co. North Branch #35X-34 BN, (Cored interval 11,009', magnification 10X, MH=0.22).

From both reactions above in sediments within study area, dolomitization of the parent rock is produced which could be fabric selective with partial replacement of allochems, cements and change in textural characteristic as shown below in Figure 33. Some dolomites in this regard could be pore space or fracture infilling or total replacements.

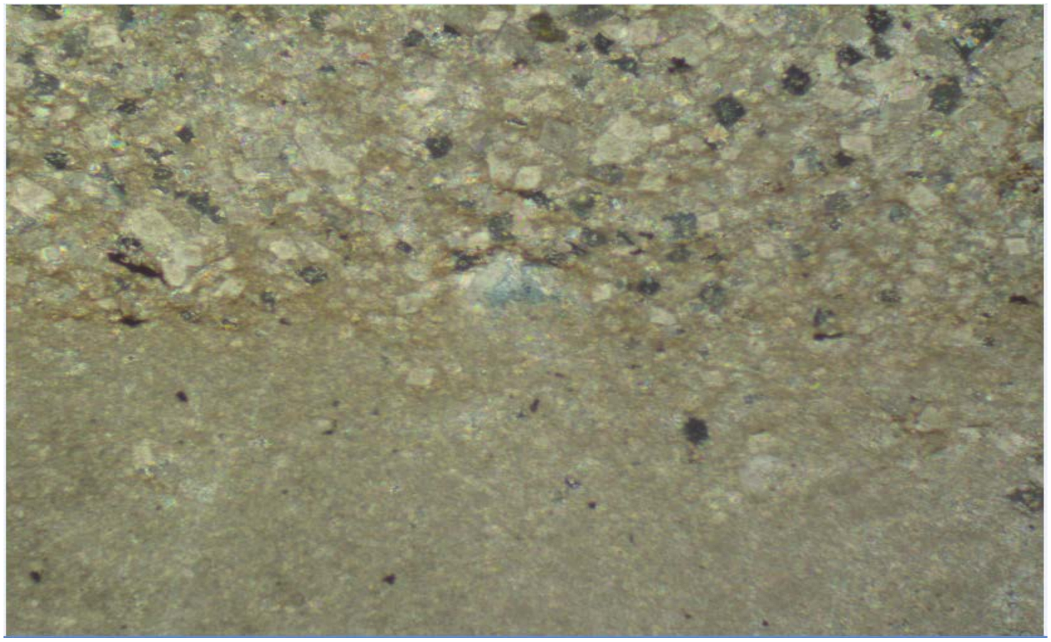


Figure 34. Limestone (grainstone), in micritized fabric selective dolomitization within rock grains. NDGS 2820, NWSW, 5-151N-95W, Texaco Inc. F. P. Keogh #4, (Cored interval 10,920', magnification 10X, MH=0.22).

Wireline Logs

Over 1140 wells logs were picked from Petra software. From the Birdbear Formation interval, a lower and upper units were identified from their log signature, characteristic lithology and correlated across wells in the study area. From total wells cluster within the study area, three cross-sectional plots were made and shown below,

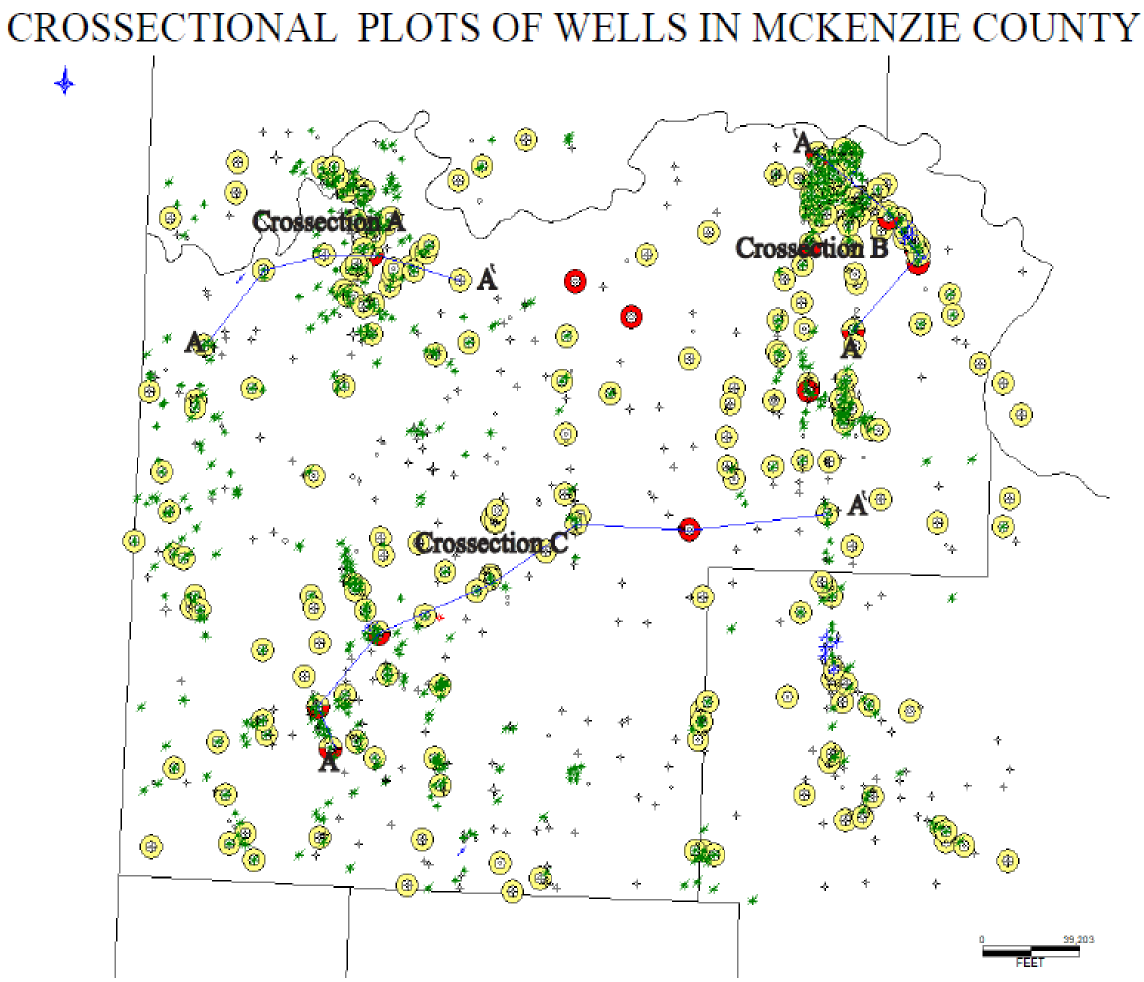


Figure 35. Cross section location of stratigraphic top plots A, B and C of wells in McKenzie County.

Other correlated cross-sectional stratigraphic plots are in appendix B.

An isopach map of the Birdbear Formation was constructed (Figure 36), depicting that stratigraphic maximum thickness within the study area increases 5 feet interval from the south west towards the center of the study area with a maximum thickness of about 100 feet. This follows the trend that the center of the Williston Basin is at the heart of the study area, but sedimentation drops in the north eastern flank of the study area and then peaks to maximum as you move further in the north eastern direction towards the Nesson anticline area. This sediment thickness undulations could be as a result of anticline formation activity or reef build up during time of sediment deposition within the study area.

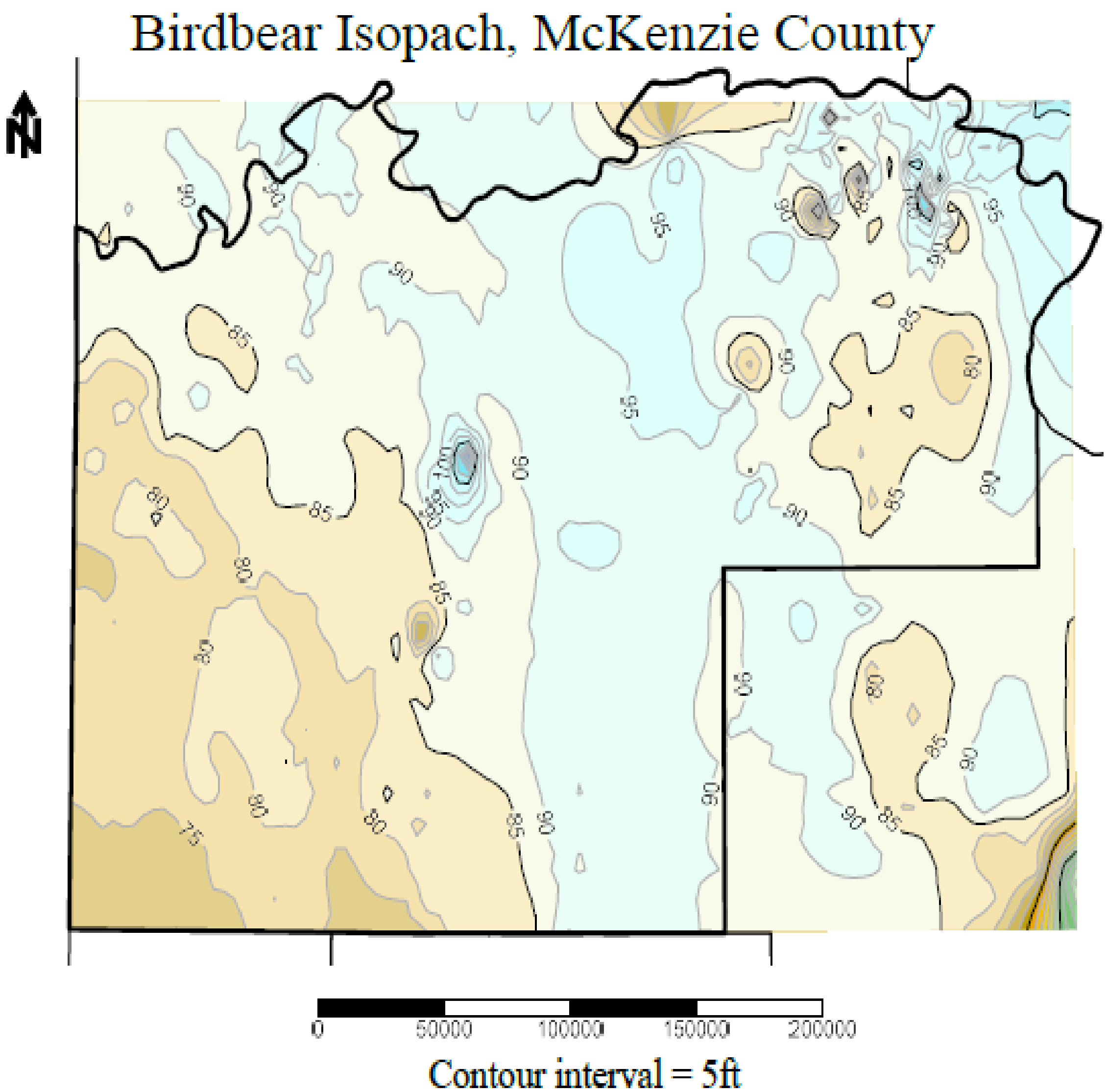


Figure 36. Birdbear Isopach, McKenzie County.

From the Kaskaskia sequence of sea level rise and subsidence in the Devonian time that produced change in sediment influx into the basin and further deposition in shallow marine environments with carbonate and evaporite deposits within the study area could be an inferred explanation to varied localized thickness of anhydrite and carbonate facie across study area.

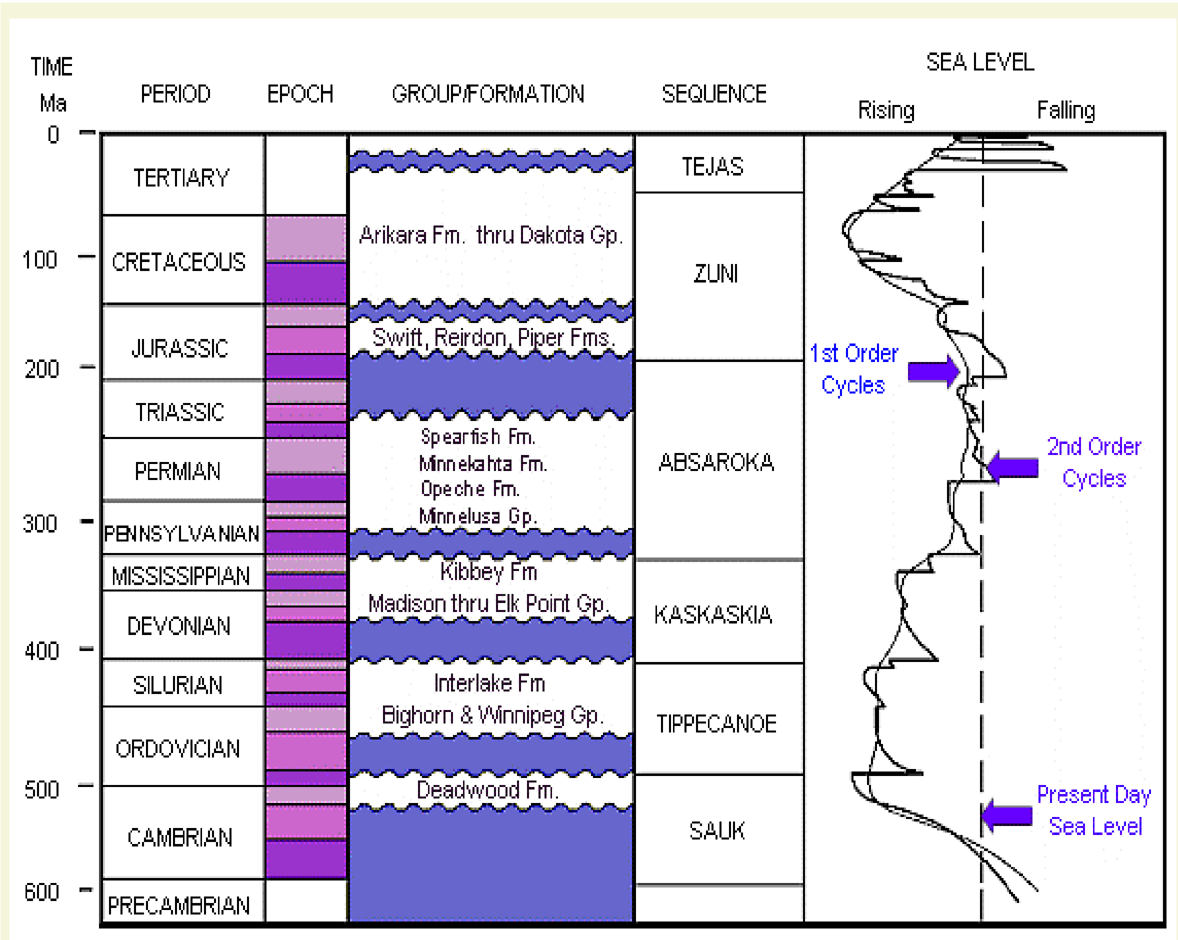


Figure 37. Time-stratigraphy column of the North Dakota Williston Basin with first and second order sea level curves of Vail, et al. (Modified after Fowler and Nisbet, 1985).

A contour map produced for the study area, indicates that depositional interval reduces basin wards from the south western part of the study area with 100 feet interval. The center of study the area with elevation of about 9100 feet below sea level marks the deepest, and confirms the general sediment supply, sea level fluctuations and basin subsidence that was in motion in the Kaskaskia sequence in the Devonian time as the Williston Basin was being formed.

High elevations experienced in the south west and north eastern portions of the study area could be resultant Billing’s anticline and Nesson anticline activities of structural modification within the affected areas as shown in Figure 37 above.

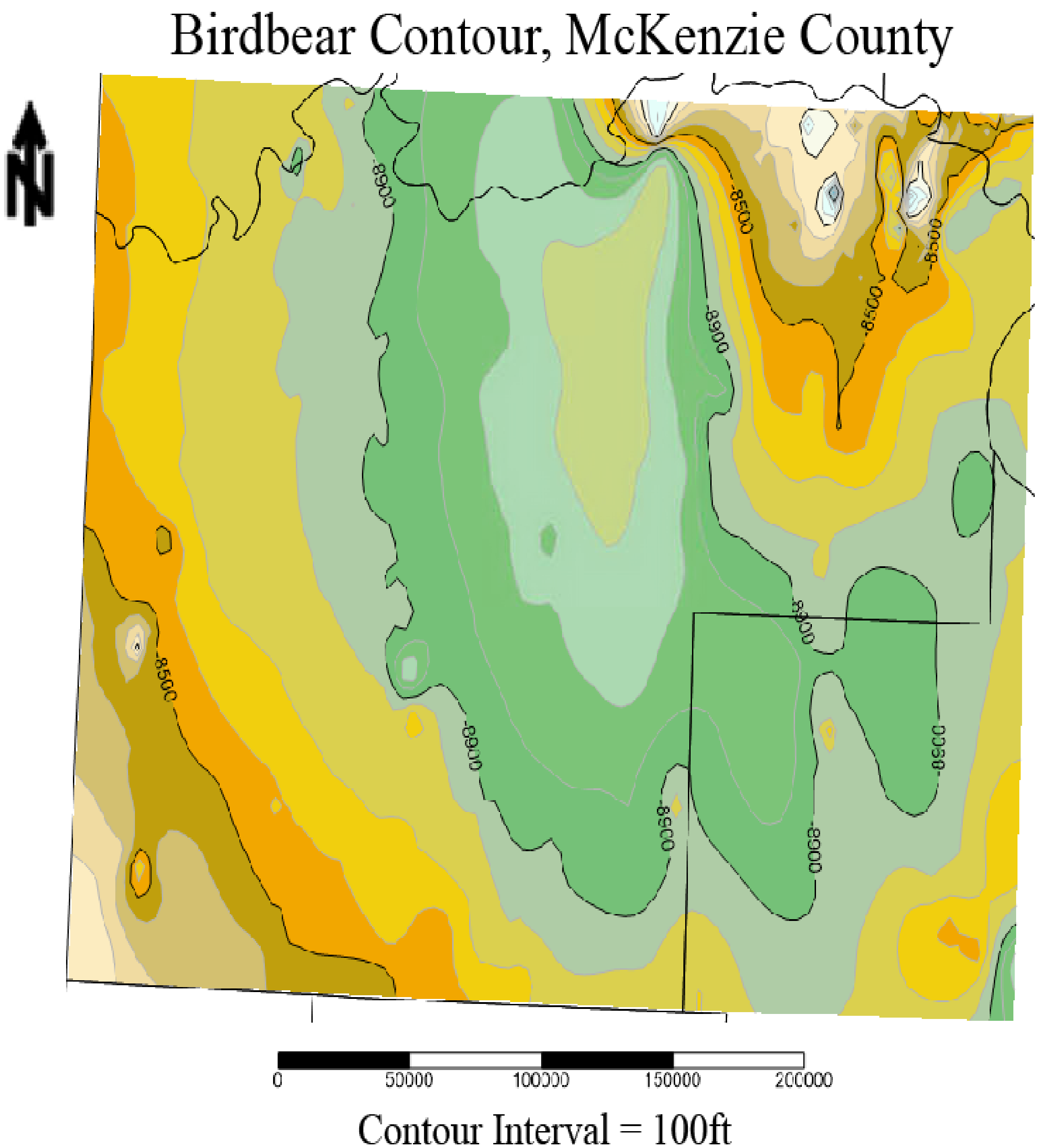


Figure 38. Birdbear Contour, McKenzie County.

Log Porosity of Study Area

Digitized wireline logs were extrapolated to get a generalized view of porosity percentage across the study area. Sonic logs data were exported into Microsoft Excel spread sheet and further data converted to porosity percentages using the equation below:

$$\varphi_{sonic} = \frac{\Delta t_{log} - \Delta t_{ma}}{\Delta t_f - \Delta t_{ma}} \quad \text{…. (Eq. 1)}$$

Where Δt_{ma} is the matrix transit time; Δt_{log} is the formation transit time; and Δt_f is the mud transit time (after Wyllie et al, 1958). Matrix transit time Δt_{ma} value used in the report was 47.6 assumed for limestone lithology and mud transit time Δf_f value used was 185.

From this conversion, data averages of generalized sonic porosity values were taken to produce a map of average porosity across McKenzie County.

The produced map was used to enhance our understanding on the porosity network within the study area and also make inference about the potential reservoir characteristics of the localized stratigraphic producing units distributed within the formation.

Figure 39 below, map of porosity across study area, indicates that porosity within the study area increases from the center of the basin towards the flanks. This could further explain the lateral migratory paths of generated hydrocarbons that have been discovered in structural traps in the south western portion of the study area. Similar trend holds in the north eastern portion of the study area as hydrocarbons have been discovered in structural traps along the Nesson anticline.

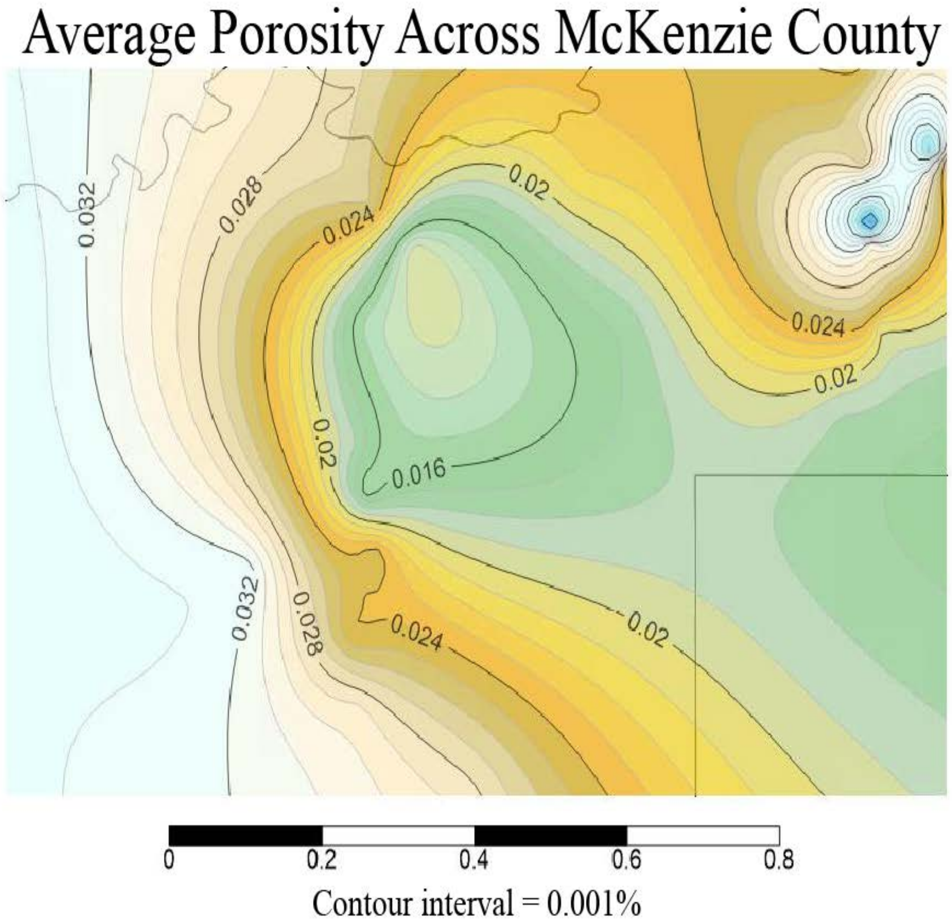


Figure 39. Average Porosity across McKenzie County.

Some cores have oil stains (NDGS 3614, 34-151N-96W NENE, Calvert Drilling & Production Corporation, Alfred Brown #1, depth 11,087' −11,088' and NDGS 21786, 4-151N-98W SWNW, Denbury Onshore LLC, Rink 12-4ESH, depth 11,426.2' – 11,428.5'). NMR porosity data for both limestone and dolomite lithologies produced values of 2.03% and 12.77% for NDGS 3614 and porosity values of 1% and 6.5% for limestone and dolomite from NDGS 21786 respectively.

From a porosity stand point, sediments in the study area appear to be capable of producing hydrocarbons. Comparing isopach and average porosity maps across the study area, the trend of localized porosity increase is associated with a similar increase in sediment interval thickness, but it should be noted that these are not predictive of production in all cases.

Nuclear Magnetic Resonance (NMR) Spectroscopy

Thirteen cores of the Birdbear Formation were used for NMR analysis. From these thirteen, two samples of limestone lithology and dolomite lithology were taken from each well.

Measurements of dry mass, saturated mass, bulk volume and density were made of these different rock samples. Saturating fluid was standard water at room temperature and pressure over two weeks' time. Samples were run in a 2-MHz Oxford instrument at different relaxation times between six minutes to twelve hours, depending on the nature of rock (lithology and mineral composition), to generate a (T_2) relaxation curve time for each sample.

From distribution data analysis generated, average porosity values for limestone and dolomite were 1.8% and 7.2% respectively. These results indicates that dolomite lithology of the Birdbear Formation in McKenzie County is porous enough to have allowed the migration of fluids within the study area. This information further enhances our understating that the dolomite facies within the study area could be good reservoir rocks within the localized producing intervals. .

Below are results from the analysis of (T_2) graph plots from the nuclear magnetic resonance (NMR) spectroscopy.

Table 3. Summary of Results from NMR (T_2), Transverse Relaxation Time on Porosities of Rocks with Different Lithology.

Well	Lithology	Depth (ft)	Dry mass (g)	Saturated mass (g)	Bulk volume (ml)	Density (g/ml)
NDGS 1343	Limestone	10551	30	31	11.339	2.646
	Dolomite	10565	20	20	7.118	2.809
NDGS 2373	Limestone	10507	27	28	10.308	2.619
	Dolomite	10482	10	10	4.074	2.455
NDGS 2602	Limestone	10068	26	28.5	10.308	2.522
	Dolomite	10046	42	42	13.008	3.229
NDGS 2820	Limestone	10928	20	20	8.345	2.396
	Dolomite	10897	10	10	5.4	1.852
NDGS 2967	Limestone	10577	26	26.2	10.308	2.522
	Dolomite	10542	22	22.4	7.118	3.091
NDGS 3086	Limestone	10519	36	37	13.008	2.767
	Dolomite	10508	67	67.5	21.217	3.157
NDGS 3614	Limestone	11076	25	25.4	10.063	2.484
	Dolomite	11087	22	23	10.063	2.186
NDGS 5742	Limestone	10678	16	19	6.038	2.649
	Dolomite	10682	36	37.8	14.235	2.529
NDGS 12249	Limestone	10977	19	20	7.118	2.669
	Dolomite	11004	12	14	5.4	2.222
NDGS 12962	Limestone	10993	10	10.2	6.136	1.629
	Dolomite	10972	15	16	3.436	4.365
NDGS 19918	Limestone	11572	33	34.8	13.205	2.499
	Dolomite	11568	14	15.3	5.007	2.796
NDGS 21786	Limestone	11416	17	18.5	6.136	2.771
	Dolomite	11428	13.5	16	5.105	2.644
NDGS 24123	Limestone	11375	55	56.8	20.028	2.746
	Dolomite	11379	24	27.5	12.223	1.964

NDGS 1343, 7-152N-94W NWSW, Amerada Petroleum Corporation, Helen G. Price.

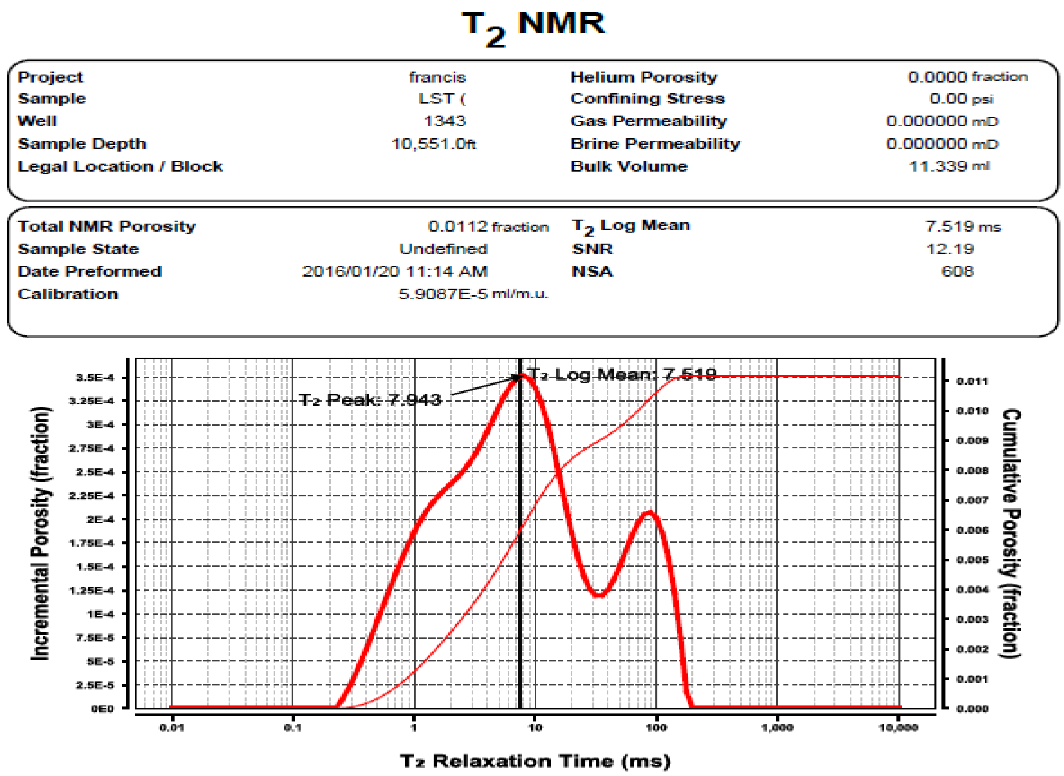


Figure 40. NDGS 1343 limestone lithology generated a bi-modal (T_2) distribution value, with porosity of 1.12%, depicting its sediments having average fractured porosity as evident from core and thin section observation, showing free water in the system.

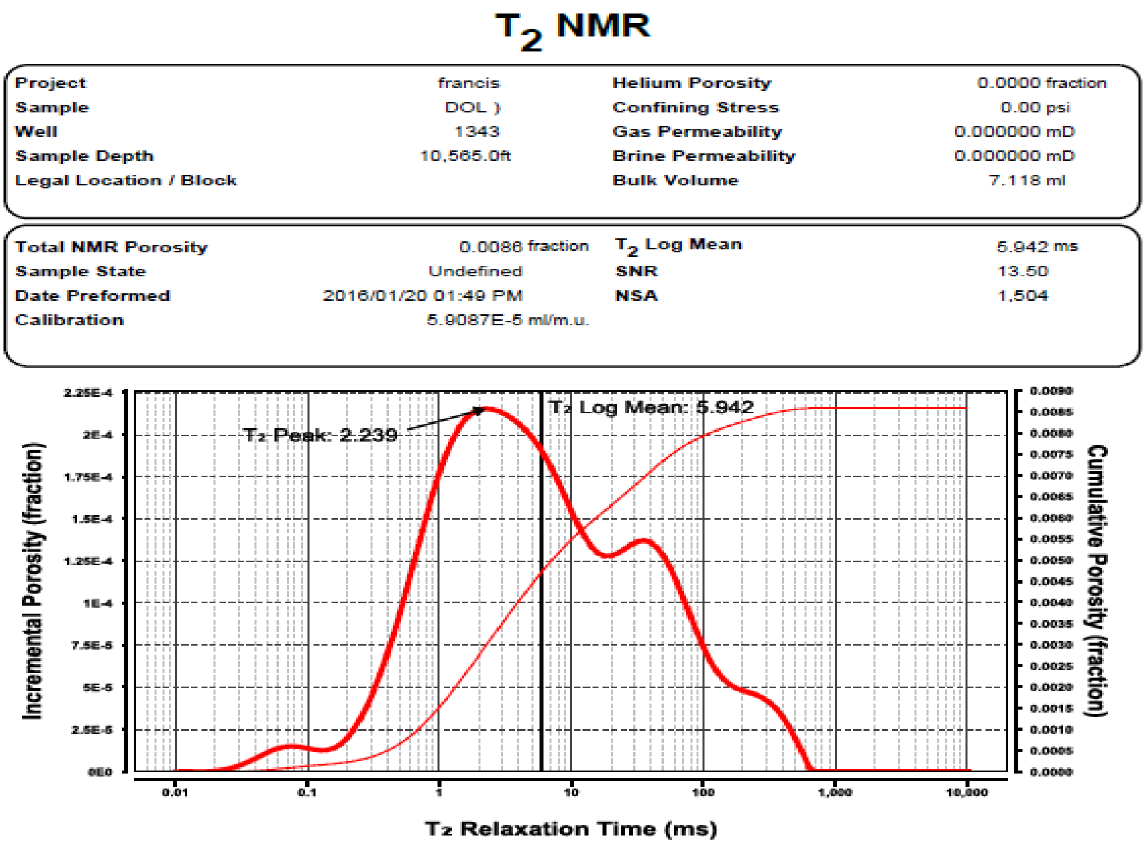


Figure 41. NDGS 1343 dolomite lithology generated bi-modal (T_2) distribution value, with porosity of 0.86% which indicates that sediments here are not porous with low free water in the system.

NDGS 2373, 1-152N-95W NESE, Amerada Petroleum Corporation, Antelope Unit "A" #1.

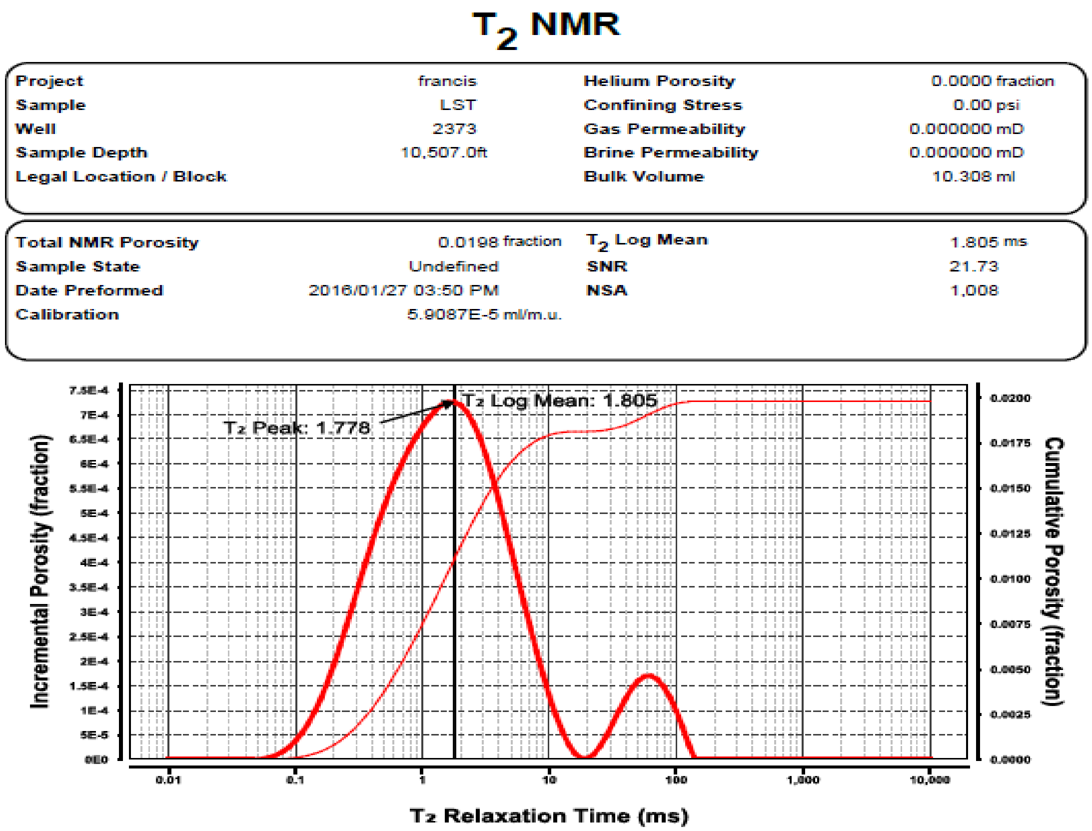


Figure 42. NDGS 2373 limestone lithology generated a bi-modal (T_2) distribution value, with porosity of 1.98%. This corresponds to that observed from thin section and core which gave less free water in the system.

T_2 NMR

Project	francis	**Helium Porosity**	0.0000 fraction
Sample	DOL	**Confining Stress**	0.00 psi
Well	2373	**Gas Permeability**	0.000000 mD
Sample Depth	10,482.0ft	**Brine Permeability**	0.000000 mD
Legal Location / Block		**Bulk Volume**	4.074 ml

Total NMR Porosity	0.0516 fraction	**T_2 Log Mean**	7.229 ms
Sample State	Undefined	**SNR**	18.40
Date Preformed	2016/01/27 04:04 PM	**NSA**	608
Calibration	5.9087E-5 ml/m.u.		

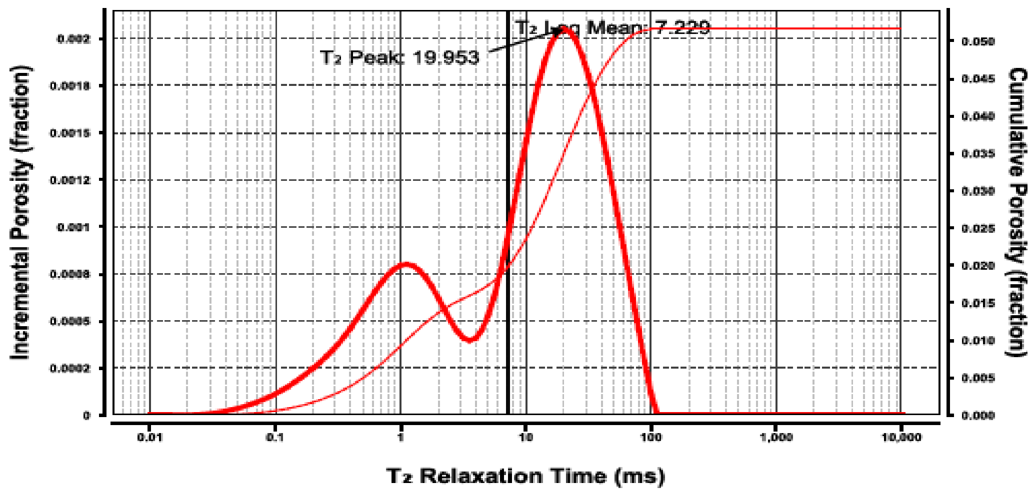


Figure 43. NDGS 2373 dolomite lithology generated a bi-modal (T_2) distribution value, with porosity of 5.16%, which is resultant from selective dolomitization prevalent at this depth giving rise to high porosity in the rock matrix and high free water in the system.

Other graphed results on the (T_2) relaxation times are in appendix E.

CHAPTER IV

DISCUSSIONS AND INTERPRETATION

Depositional Environment of the Birdbear Formation

Observations from wireline logs, core and thin section analysis, indicates two units within the study area. A uniformly carbonate dolomite-limestone facies characterize the upper section of unit 1 and an anhydrite-carbonate facie characterize the upper unit 2. From the Kaskaskia sequence that marked a time of sediment supply, sea level fluctuations and basin subsidence during early Devonian to late Mississippian time was part of depositional sequence cycles in the Williston Basin. This marked the influx of sediments that characterized the depositional environment of the Birdbear Formation in the study area.

Deposition of the late Devonian carbonate-evaporite sequence was controlled largely by three shelf-wide, gradually shoaling-upwards depositional cycles in the Duperow and Birdbear Formations that were punctuated by more frequent shelf-wide fluctuations in salinity (Kissling et al., 1985). The depositional environment of the Williston Basin is representative of about several thousands of feet of sediments, with the Birdbear Formation having a maximum of about 150 feet of locally distinct facies.

Upper Section of Lower Carbonate Unit 1

The lithofacies of the upper section of the lower carbonate unit, are interpreted as representation of moderate energy environment to restricted shallow-marine shelf wide deposits from a receding sea level rise (Julie A. LeFever, 2009). In McKenzie County, this carbonate rich medium light gray to dark gray, with nodular limy dolomitic mudstone to boundstone characterize this section of the unit. These dolomitic limestone intervals with rare inclusion of clasts debris (bioclasts), locally interbedded peloidal packstone indicative of bank facies environment of deposition with carbonate muds and patchy anhydrite cements recrystallized in some sections. This section of the lower carbonate unit lithofacies are rich with diverse faunal assemblage such as, crinoids, brachiopods, bryozoans, rugose and tabulate corals, gastropods, and locally restricted amphiporas and algae stromatoporoids that are indicative of a subtidal depositional environment. Sediment facies here show evidence of laminations with prominent vertical fractures, moldic vuggy, and intra-granular porosities and strong bioturbation.

Abundant carbonate muds present in unit could be indicative of low energy conditions (Martiniuk et al., 1995) based on the recognition of low to moderate energy conditions on mud matrix in sediments of this unit.

Upper Anhydrite-Carbonate Unit 2

The occurrence of massive, laminated and nodular anhydrite interbedded sequence with medium to light gray color and inclusion of dolomitizing carbonate facies characterized this unit. Receding waters and warmer climate created a supratidal or sabkha conditions with increasing salinity, which precipitated anhydrites and other carbonates that are prevalent in the study area Halabura (1982).

Mg^{2+} rich fluids that moved basin wards in the subsurface dolomitized sediments in this unit in laminated nodular matrix with rare organic matter from algae mats associated with supratidal to shallow intertidal environments that were restricted locally. This section is devoid of calcareous fossil remains as conditions were not favorable for their preservation.

Diagenesis

Understanding the diagenesis of sediments of the Birdbear Formation in the subsurface within the study area follows the steps out-lined below from personal observation. Note that this may not present the general path for diagenesis within the formation and could vary from an individual point of view or formation to formation.

Diagenetic Events

Dissolution of sulfate and calcite cements. Inclusion of hydrothermal subsurface fluids within the study area were instrumental in the dissolution of calcite cements and anhydrite cements. Dissolution of carbonate mud rock materials that were filled with calcite cements not strongly bounded or cemented in the subsurface is controlled by the movement of these subsurface fluids within the depositional environment. This dissolution could be linked with transformation of aragonite mineral from gastropods remains that is influenced by solubility of $CaCO_3$ in sediments of the upper section of the lower carbonate unit of the study area. Local porosity is formed from this event and if on a large scale with trapping structures in place, could been instrumental in trapping migrating fluids. Sulfate cements from anhydrite $CaSO_4$, patchy cements were dissolved out from rock matrix, also creating porosity in rock fabrics.

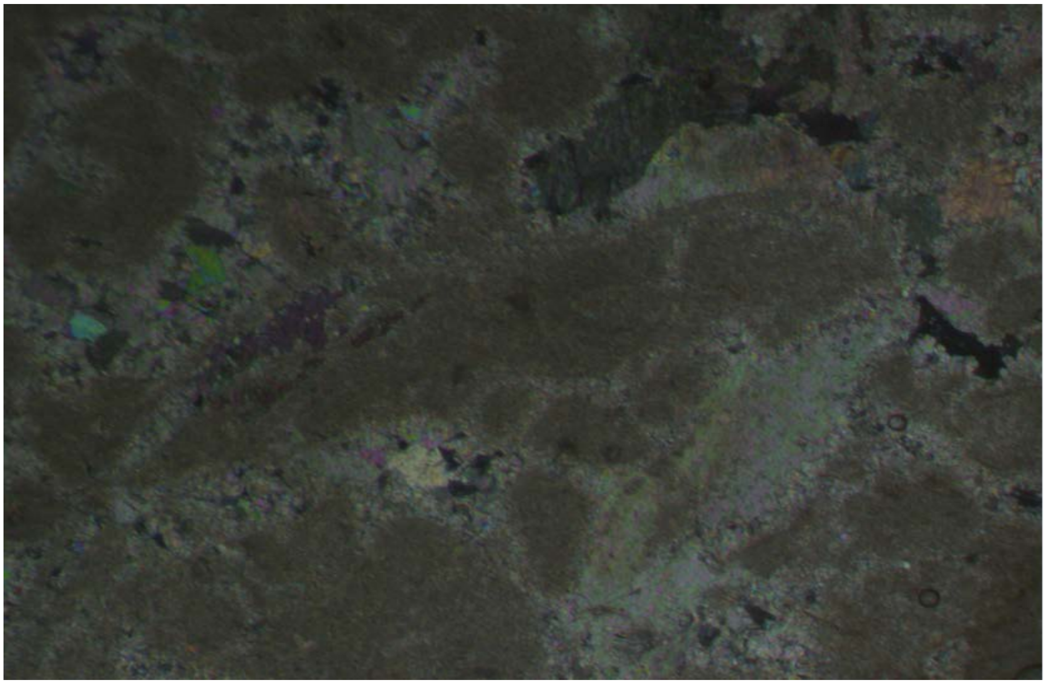


Figure 44. Limestone, dissolution of calcite cements within rock grains and fabrics creating porosity. NGDS 2373, NESE, 1-152N-95W, Amerada Petroleum Co. Antelope Unit “A” #1. (Cored depth 10,496.2', Magnification 10X, MH=0.22).

Dolomitization. From chemical replacement of unstable ca^{2+} rich elements from sediments within study area, into Mg^{2+} rich elements through dolomitization of these sediments, as dolomite was one of the most common rocks observed within the Birdbear Formation in both units 1 and 2. These dolomite resulted from inclusion of migratory fluids in the subsurface through various channels mentioned in this paper, and has average porosity of 7.2%. Dolomite is mixed with carbonate mudstone and shows partial dolomitization or selective dolomitization within rock fabric.

Dolomite from upper section of unit 1 within the study area showed marked porosity enhancement with typical void spaces, which have further enhanced the reservoir quality of the formation in study area.

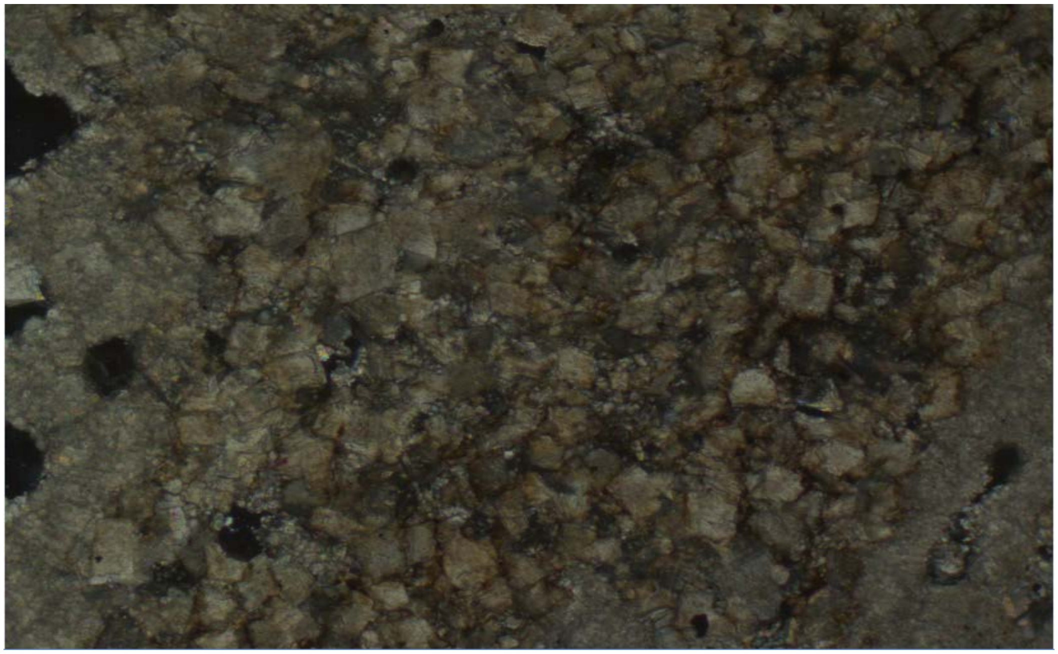


Figure 45. Limestone, gradual dolomitization of rock grains,with void space at the top left portion of slide. NDGS 2602, NESE, 1-152N-95W, Texaco Inc. Seth A. Garland #5. Cored depth 10,061.8', Magnification 10X, MH=0.22).

Anhydrite cementation. The Birdbear Formation has nodular patchy anhydrite cements and massive anhydrites in pores. The supratidal and sabkha environmental conditions that led to the deposition of these rocks in the Birdbear Formation was widespread, with unit 2 having most of the massive anhydrite. Some nodular patchy cements in pores were locally embedded within the upper section of unit 1of the study area from the transformation of gypsum.

The massive unit 2 anhydrites could play a critical role in the petroleum play of the Birdbear Formation as these anhydrite bodies exhibit low to absent porosity.

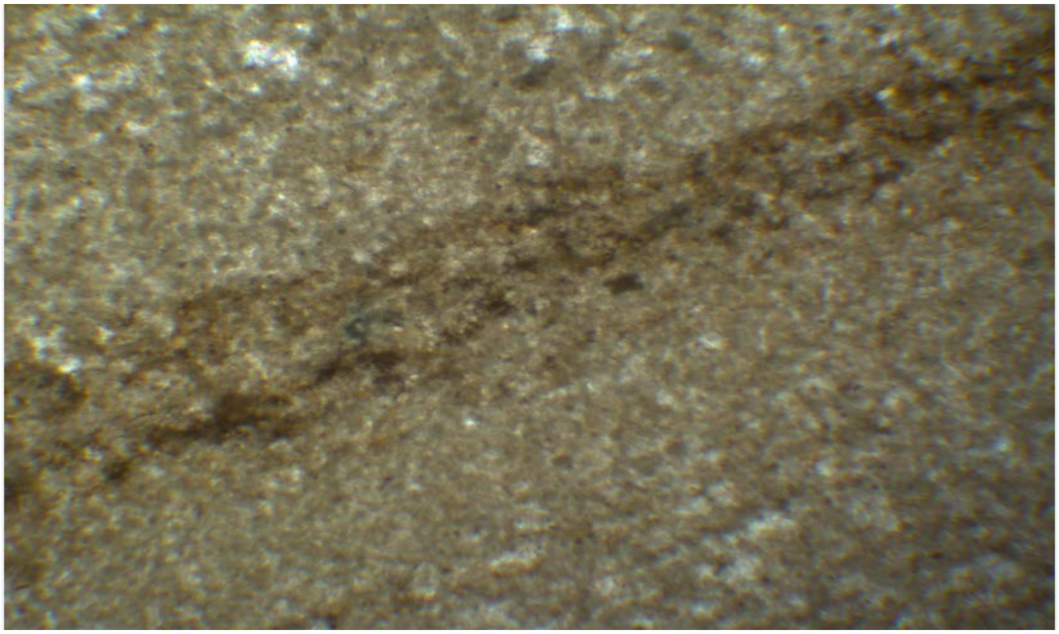


Figure 46. Massive anhydrite from unit 2. NDGS 12249, NENW, 17-146N-102W, Meridian Oil Inc. MOI #21-17. (Cored depth 10,970.8'-10,971.1', Magnification 4X. MH= 0.10).

Calcite cementation. Calcite in the Birdbear are microcrystalline calcite cements and spar replacement calcite cements from elevated salinity which are prevalent in the upper section of unit 1 and low to negligible in unit 2.

Spar forming cements developed from gastropods, ostracods and brachiopods that were recrystallizing from their initial aragonitic and calcite minerals, while microcrystalline cements filling voids or replace skeletal materials of organic remains.

Stylolites/ Fractures. Stylolites occur at various horizons within sediments in the study area. Compaction and fluid inclusion dissolution are common in sediments of the upper section of unit 1 in the form of brittle/ plastic deforms with vertical fractures rare in sediments of unit 2.

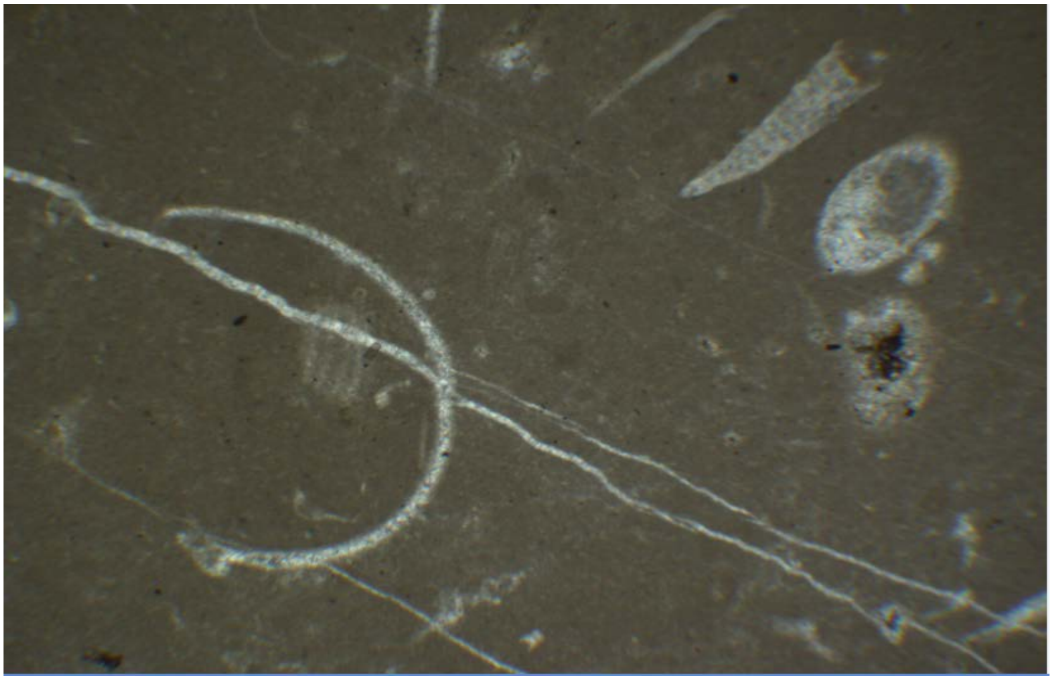


Figure 47. Limestone, patchy anhydrite cements, and calcite cements in vertical fractures with high porosity from upper section of unit 1. NDGS 3086, C NW, 1-152N-95W, Amerada Petroleum Co. Antelope Unit “B” #1. (Cored depth 10,556' magnification 4X, MH= 0.10).

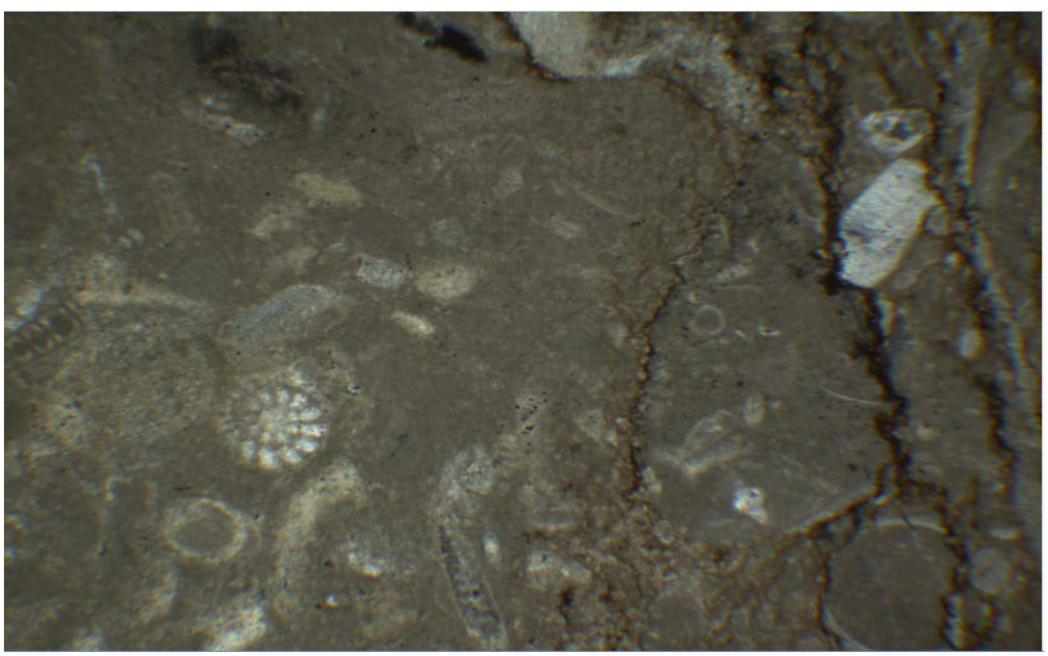


Figure 48. Limestone with crinoids, corals, ostracods, stylolites and patchy anhydrite from upper section of unit 1. NDGS 3086, C NW, 1-152N-95W, Amerada Petroleum Co. Antelope Unit “B” #1**.** (Cored depth 10,562' magnification 4X, MH=0.10).

Diagenesis and Production

Recognition of various type of lithologies within the study area from core, thin section analysis and NMR analysis on porosity stand point, indicates that the Birdbear Formation has the essential elements for a petroleum play system. This play system from a lithostratigraphic perspective has localized reservoirs (dolomites and pelodial limestones of the upper section of carbonate unit 1), that were locally sourced from scattered intervals rich in TOC of about 1.5% (personal communication with Dr Stephan H. Nordeng HHSGGE).

This was further confirmed from oil stained core intervals from the study area. Cap rocks that seal these producing intervals were the nodular anhydrites from the upper unit 2 that prevent further migration. However, production from the Birdbear Formation in North Dakota has not been prolific but a potential exists for improved production from this formation as discussed from different studies in the past and from new techniques in exploration and better understanding of sedimentary processes from sequence stratigraphy.

Assessment and reports on potential exists for production from the Birdbear from the dolostone bed A and interval B zone, as discussed by Julie A. LeFever (2009), from enhanced porosity and permeability resultant of fluid inclusion from core analysis, further elucidates that the Birdbear could make a mark in production that is enhanced from diagenetic-stratigraphic traps within the formation.

Yang Chao (2010), highlights that re-evaluation of the petroleum potential of the Birdbear Formation in Saskatchewan has generated an upswing in production rate from un-assessed stratigraphic intervals within the formation, resulting in increased production over a short time.

The inclusion of subsurface fluids accelerated diagenetic processes on sediments in the study area that produced intra-crystalline, intra-granular, moldic vuggy and fractured porosities that were characteristics of good reservoir and could have been responsible for aiding migrations of generated hydrocarbons. A cumulative production map was produced to determine if production was wide spread or restricted locally within the study area.

Cumulative production map for the Birdbear Formation in McKenzie County suggests that production is not wide spread, but were locally within stratigraphic carbonate self-sourcing intervals that are restricted to the deepest portion of the basin and declines towards the flanks of the basin. Production follows same migratory path as inferred from sonic porosity map of study area only true in the south western portion of study area, but did not conform to porosity in the north eastern portion.

Similar production trend were observed in the south western portion of Williams County as production were restricted locally, with porosity increasing in the south western direction..

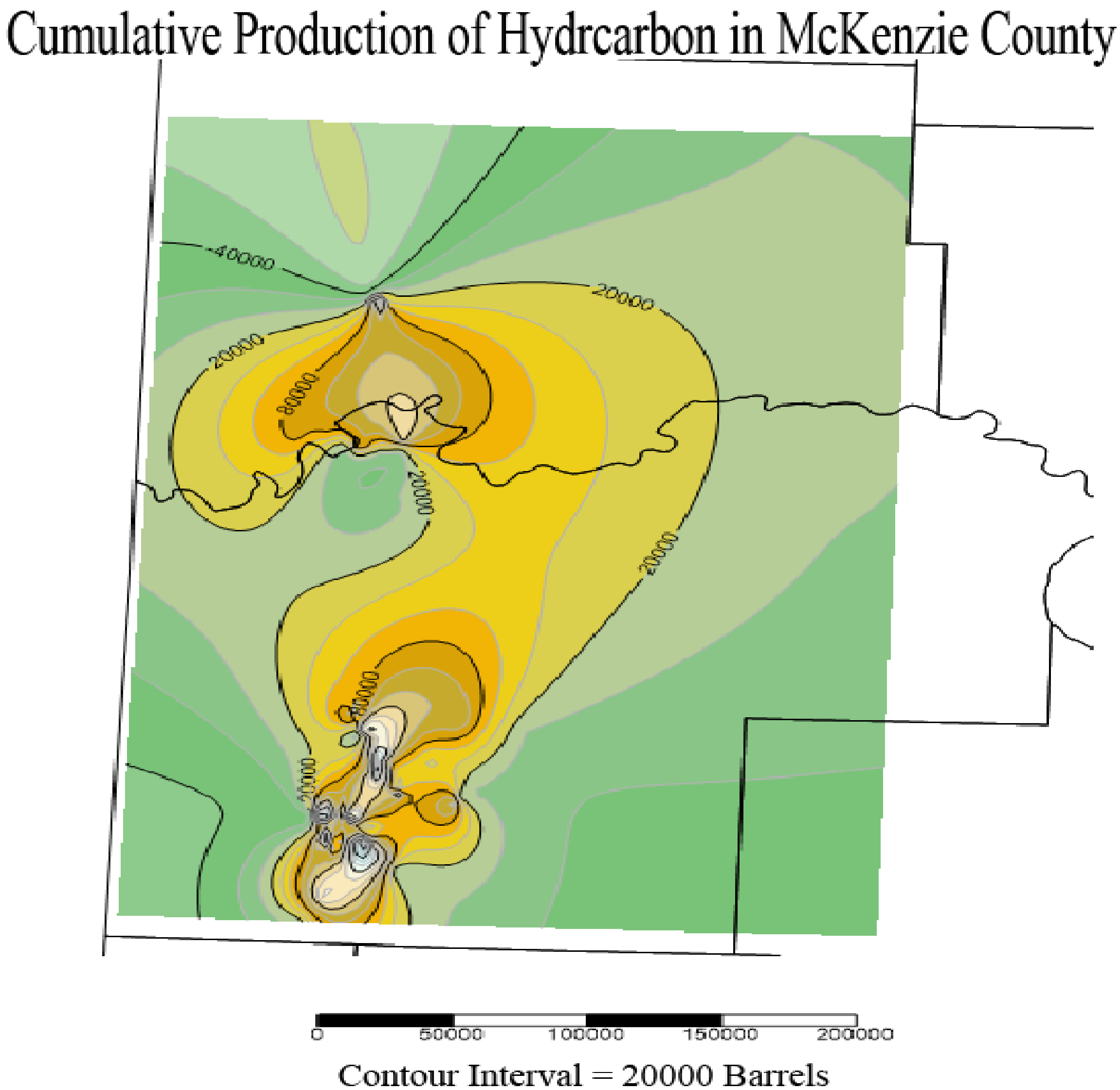


Figure 49. Cumulative Production of the Birdbear in McKenzie and Williams Counties.

Porosity not coincident with cumulative production indicating from both produced maps, could be as a result of insufficient data from cumulative production points.

Below is data from cumulative oil produced in McKenzie County in 2014.

Table 4. Cumulative oil produced in McKenzie County 2014 (NDGS Oil & Gas 2014)

Wl_Permit	Wl_Status	Pool_Nm	PoolStatus	Name_	CumOil	CumWater	CumGas
6858	A	BIRDBEAR	AL	MCKENZ	180781	9796	282159
6973	A	BIRDBEAR	AL	MCKENZ	331271	1240037	250907
7094	IA	BIRDBEAR	AL	MCKENZ	58260	245631	125068
7768	PA	BIRDBEAR	PNA	MCKENZ	16584	17973	3577
9144	A	BIRDBEAR	AL	MCKENZ	1037360	900120	632144
10985	PA	BIRDBEAR	PNA	MCKENZ	1189	17640	636
11029	A	BIRDBEAR	AL	MCKENZ	19883	21734	22866
11422	IA	BIRDBEAR	AL	MCKENZ	124961	48697	124549
12227	A	BIRDBEAR	PNA	MCKENZ	142611	342384	48483
13600	PA	BIRDBEAR	PNA	MCKENZ	288159	1046598	103406
13604	IA	BIRDBEAR	AL	MCKENZ	81256	134035	73290
14801	A	BIRDBEAR	AL	MCKENZ	1259700	2105822	824550
14976	A	BIRDBEAR	AL	MCKENZ	825959	3682228	500636
15008	A	BIRDBEAR	PNA	MCKENZ	26695	175555	18408
15029	PA	BIRDBEAR	PNA	MCKENZ	241120	2932876	171053
15065	PA	BIRDBEAR	PNA	MCKENZ	11574	50942	2404
15206	A	BIRDBEAR	AL	MCKENZ	25408	0	0
15412	A	BIRDBEAR	TA	MCKENZ	53386	32374	70508
15414	IA	BIRDBEAR	AL	MCKENZ	133188	23139	157687
15428	A	BIRDBEAR	AL	MCKENZ	32397	37535	28514
15481	A	BIRDBEAR	AL	MCKENZ	70438	5349	125917
15540	A	BIRDBEAR	AL	MCKENZ	187136	61379	292910
15579	A	BIRDBEAR	AL	MCKENZ	84818	12710	82804
15625	A	BIRDBEAR	AL	MCKENZ	76656	29470	72385
15653	A	BIRDBEAR	AL	MCKENZ	125104	27213	258059
15654	PA	BIRDBEAR	PNA	MCKENZ	491	42329	181
15752	A	BIRDBEAR	AL	MCKENZ	150945	84401	235535
15775	A	BIRDBEAR	AL	MCKENZ	71172	212529	143651
15776	A	BIRDBEAR	AL	MCKENZ	207279	39102	442902
15779	A	BIRDBEAR	AL	MCKENZ	95181	41541	152688
15800	IA	BIRDBEAR	AL	MCKENZ	25217	61907	15262
15857	A	BIRDBEAR	AL	MCKENZ	149000	56017	201619
15865	IA	BIRDBEAR	AL	MCKENZ	27979	160482	41445
15874	A	BIRDBEAR	AL	MCKENZ	62190	132724	141217
15926	A	BIRDBEAR	AL	MCKENZ	163534	60990	247328
15937	A	BIRDBEAR	AL	MCKENZ	82723	268355	139555
16039	IA	BIRDBEAR	AL	MCKENZ	17612	20151	24475
16063	A	BIRDBEAR	AL	MCKENZ	127710	117225	134842
16591	A	BIRDBEAR	AL	MCKENZ	94908	37192	255755

Basin wide cumulative production from the Birdbear Formation through 2014 stands at about 20,422,256 (MBO) from 174 wells. McKenzie County with about 6,711,835 (MBO), accounts for about 33% total basin wide production from 39 wells in the Birdbear Formation.

However, 59 wells penetrates the formation in McKenzie County, of these well, 39 wells produced oil, 7 wells are inactive, 6 wells are plugged/abandoned, while 26 wells are fully active with 20 being dry wells within the study area.

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

In this study, from a holistic approach through observations and analysis that traces the depositional environment of the Birdbear Formation in McKenzie County through the diagenetic processes that modified and enhanced the sediments that subsiquently sets out a characteristic play system within the Williston Basin.

In as much as porosity and pore size distribution are important in production planning, estimation of reservoir retention and the overall producibility in a field of any hydrocarbon bearing formation of which the Birdbear Formation is in line with the following are the conclusions:

1. The Birdbear Formation is a depositional environment with two distinct units of a lower carbonate interval and upper anhydrite-carbonate interval with characteristic lithology that can be traced on core and wireline logs across the study area.
2. Sediment classification within the study area based on the Dunham scheme reveals sediments were of boundstones (mudstones), as dominant and in some cases wackestones in the upper section of unit 1, and packstones were dominant in unit 2. The conventional sediments within the study area were subjected to a host of diagenetic processes that enhanced dissolution and precipitation of calcite cements, micritization, dolomitization within sediment fabrics and porosity.

3. NMR analysis generated average dolomite lithology porosity value of 7.2%, and average limestone lithology porosity value of 1.8%, which are favorable values for conventional rocks.
4. Porosities recognized within the study area includes intra-crystalline, inter-granular, moldic vuggy and fractured porosities.
5. Production within the study area were locally in stratigraphic traps restricted to some intervals, with porosity not coincident with cumulative production data, which may be as a result of insufficient data as cumulative production was virtually absent in the north eastern portion of the study area.

Recommendations and Future Work

More studies need to be conducted on this in the future. Effective methods like use of brine solution in saturating the samples, and centrifuging the resultant saturated samples to determine the pore throat or pore size distributions of sediments.

Future work will also include the saturation of the sediments with heavy or light hydrocarbons and further analyzing the data to differentiate between brine and hydrocarbon saturation at different stages of analysis in ascertaining the effective porosity of these sediments since they exhibit appreciable percentage porosity values.

The plotting of a potentiometric map of the county could help in determining the direction of water flow and subsequent hydrocarbon flow direction within the study area, and TOC sampling done to determine how rich in organic matter the dolomite facies in the upper section of the lower carbonate unit 1 are in serving as source rocks.

X-ray Diffraction analysis of the rock samples could be carried out to determine the chemical composition and constituent of the rocks in ascertaining the percentages of rock minerals that make up the grains to determine the level of dolomite ratio to calcite ratio in a selective dolomitizing rock matrix.

APPENDICES

APPENDIX A

LIST OF WELLS

1. NDGS 1343, Amerada Petroleum Corporation, Helen G. Price. 7-152N-94W NWSW, McKenzie County, North Dakota. (Cored Interval = 10,541'−10,570' & 10,598'−10,608').
2. NDGS 2373, Amerada Petroleum Corporation, Antelope Unit "A" #1. 1-152N-95W NESE, McKenzie County, North Dakota. (Cored Interval = 10,450'−10,508').
3. NDGS 2602, Texaco Incorporation, Seth A. Garland #5. 6-153N-95W C NE, McKenzie County, North Dakota. (Cored Interval = 10,037'−10,095').
4. NDGS 2820, Texaco Incorporation, F. P. Keogh #4. 5-151N-95W NWSW, McKenzie County, North Dakota. (Cored Interval = 10,885'−10,961').
5. NDGS 2967, Texaco Incorporation, A. S. Wisness #2. 3-152N-96W NWSE, McKenzie County, North Dakota. (Cored Interval = 10,536'−10,594').
6. NDGS 3086, Amerada Petroleum Corporation, Antelope Unit "B" #1. 1-152N-95W C NW, McKenzie County, North Dakota. (Cored Interval = 10,507'−10,565').
7. NDGS 3614, Calvert Drilling & Production Corporation, Alfred Brown #1. 34-151N-96W NENE, McKenzie County, North Dakota. (Cored Interval = 11,076'−11,088').
8. NDGS 5742, Texaco Incorporation, Devonian Unit 2 #1X. 4-153N-95W SWSW. McKenzie County, North Dakota. (Cored Interval = 10,673'−10,683').
9. NDGS 12249, Meridian Oil Incorporated, Moi #21-17. 17-146N-102W NENW, McKenzie County, North Dakota. (Cored Interval = 10,964'−11,024').
10. NDGS 12962, Pennzoil Exploration & Production Company, North Branch #35X-34 BN. 35-148N-102W SWSE, McKenzie County, North Dakota. (Cored Interval = 10,962'−11,002').

11. NDGS 19918, Continental Resources Incorporation, Charlotte 1-22H. 22-152N-99W SWSE, McKenzie County, North Dakota. (Cored Interval = 11,567'−11,572').
12. NDGS 21786, Denbury Onshore LLC. Rink 12-4ESH. 4-151N-98W SWNW, McKenzie County, North Dakota. (Cored Interval = 11,413'−11,430').
13. NDGS 24123, XTO Energy Incorporation, Marina Trust 12X-20G2. 20-149N-97W SWNW, McKenzie County, North Dakota. (Cored Interval = 11,370'−11,379')

APPENDIX B

STRATIGRAPHIC TOPS OF WELLS CROSS PLOTS

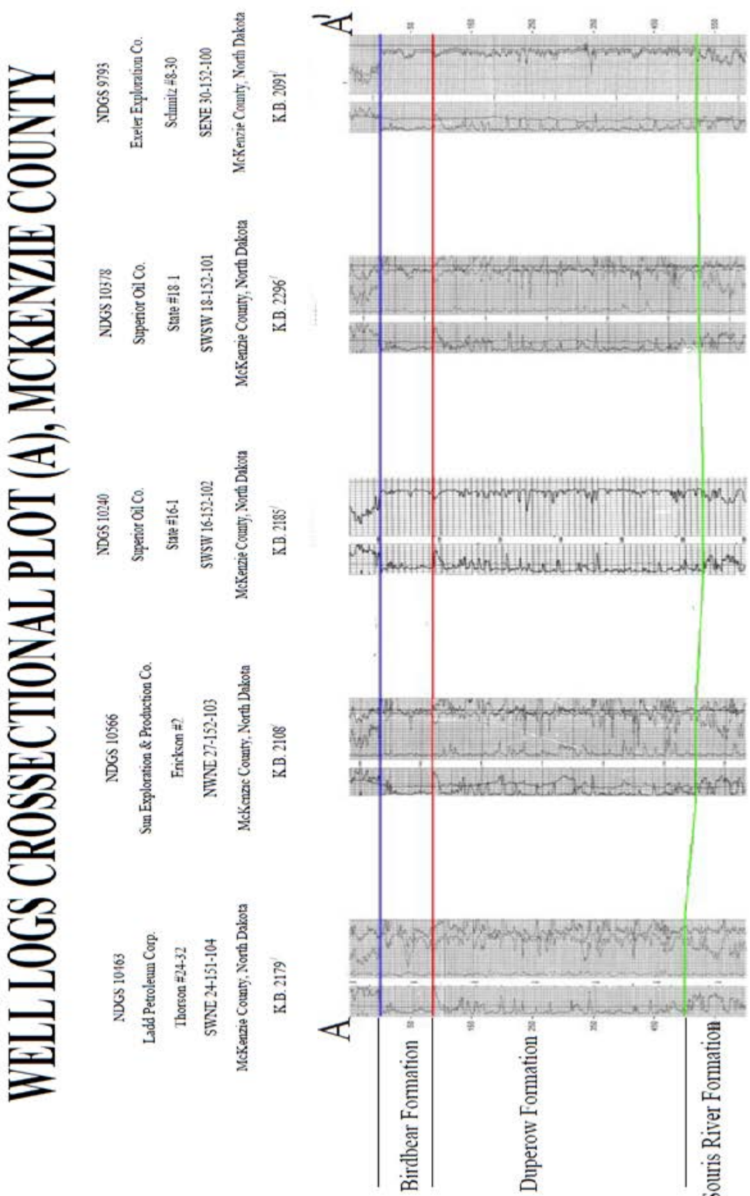


Figure 50. Well logs cross sectional plot (A).

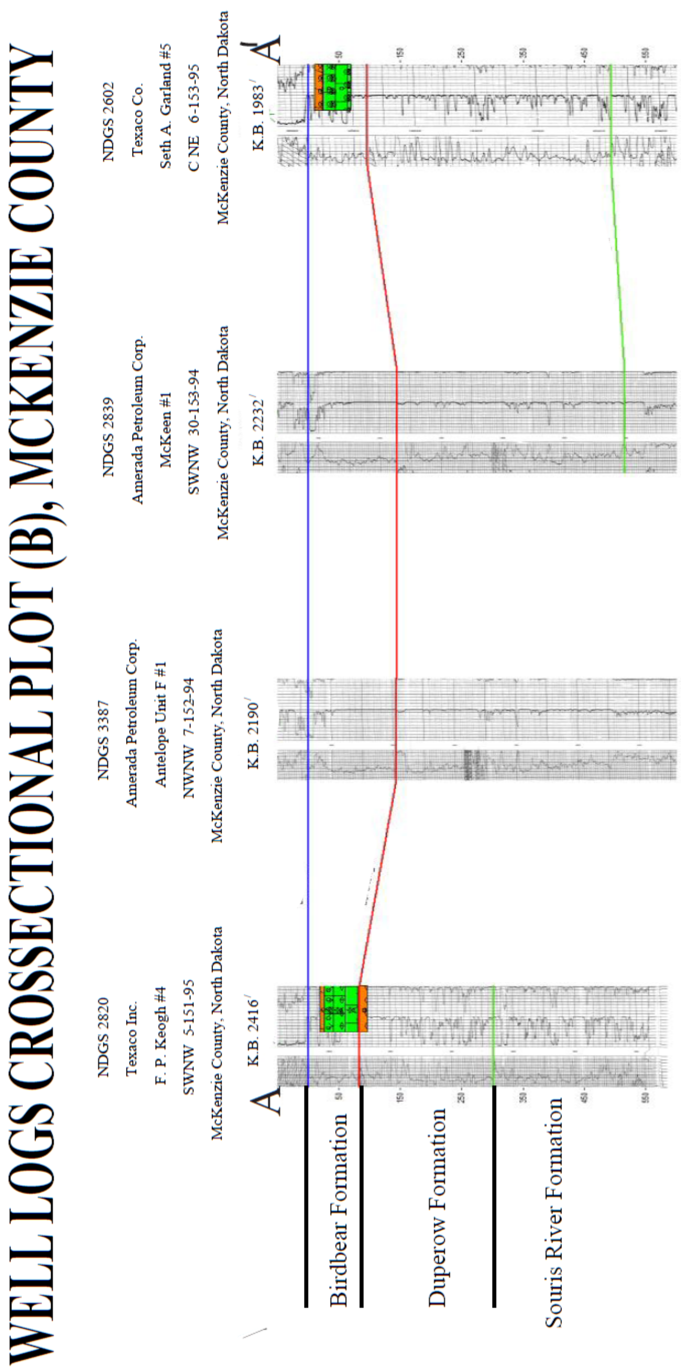


Figure 51. Well logs cross sectional plot (B).

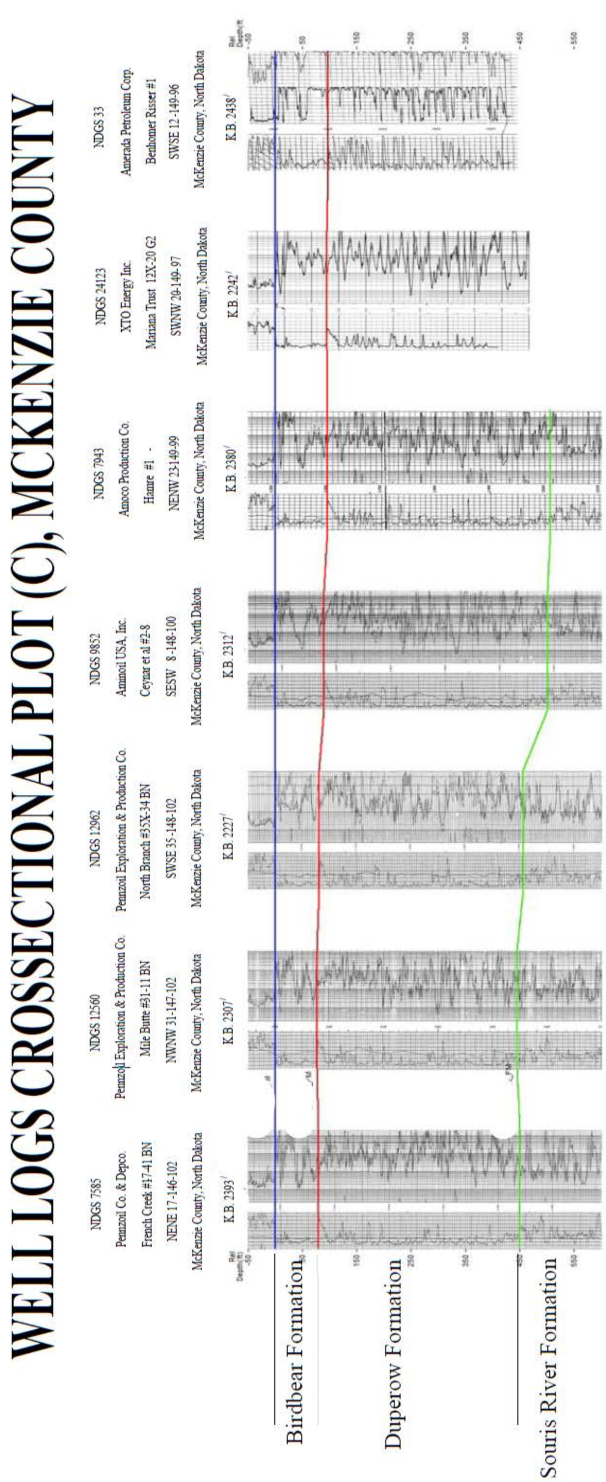


Figure 52. Well logs cross section plot (C).

APPENDIX C

CORE AND THIN SECTIONS DESCRIPTIONS

Thirteen cores penetrating the Birdbear Formation in McKenzie County were described in details with thin section slides below.

NDGS 1343
7-152N-94W NWSW.
Amerada Petroleum Corporation.
Helen G. Price.
McKenzie County, North Dakota.
(Cored Interval = 10,541'−10,570' & 10,598'−10,608')

Unit	Depth	Descriptions
1	10,540'−10,544.4'	Dolomite: medium light gray; packstone, with soft Sediment laminar beds; poor porosity. Well cemented medium−fine grained with anhydrite pockets.
2	10,544.4'−10,545'	Limestone: medium dark gray; pack stone, with bands of soft sediments laminar bands, medium−fine grained that are fairly cemented with visible bioturbations and vertical fractures.
3	10,545'−10,546'	Dolomite: light gray; packstone, medium−fine grained that are well cemented.
4	10,547'−10,548.5'	Limestone: medium dark gray; packstone, with soft sediments laminar beds; medium−fine grained, well cemented.
5	10,548.5'−10,550.2'	Dolomite: medium light gray; packstone, coarse−medium grained, fairly cemented with high porosity and bioturbations.
6	10,550.2'−10,551.6'	Limestone: medium gray; packstone, medium−fine grained, well cemented, slightly fractured having anhydrite pockets with fair porosity.
7	10,551.6'−10,561.8'	Dolomite: medium light gray; boundstone, medium−fine grained, fairly cemented having bands of soft sediments infilling' (limestone intercalation), anhydrite pockets, bioturbated with vertical fractures.
8	10,561.8'−10,608'	Limestone: medium gray−medium dark gray; medium−fine grained, fairly cemented with calcite microcrystalline growth. Soft sediments infilling bands, bioturbations, stromatoporoids, vertical fractures. Prominent bioturbations, anhydrite pockets and stylolites.

NDGS 2373
1-152N-95W NESE.
Amerada Petroleum Corporation.
Antelope Unit “A” #1.
McKenzie County, North Dakota.
(Cored Interval = 10,450'−10,508')

Unit	Depth	Descriptions
1	10,450'−10,472.5'	Limestone: medium dark gray−dark gray; packstone, medium−coarse grained, well cemented, fair porosity. Anhydrite pockets, slight vertical fractured, stylolites and bioturbated.
	T. S. 10,451'−10,464'	Limestone: boundstone−packstone, medium−coarse sub angular grained, abundant gastropods, rugose corals (10,451'), recrystallized ostracod carapace, prismatic spar forming cements, bivalve shells. Horizontal soft algae soft sediment infilling with vertical fractures are present with partial recrystallization of calcite cements.
2	10,472.5'−10,489.9'	Dolomite: light gray−medium light gray; packstone, medium−fine grained that are loose cement and anhydrite pockets.
	T.S. 10,48.8'−10,48.9'	Dolomite: highly dolomitized grainstone, 50% grains (pebbles) with dolomite rhombs forming, horizontal soft algae sediment infilling.
3	10,490'−10,491.2'	Limestone: medium dark gray−dark gray; packstone, medium−fine grained that are loose cemented with microcrystalline growth.
4	10,491.2'−10,494.5'	Dolomite: medium light gray; packstone; medium−fine grained, fairly cemented, burrowed and anhydrite pockets.
5	10,494.5'−10,508'	Limestone: medium dark gray−dark gray; packstone, medium−fine grained, fairly cemented with soft sediment infillings, highly burrowed with unidentified micro fossils. Prominent horizontal stylolites.
	T.S 10,496.2'−10,497'	Limestone: boundstone, high rate calcite cement dissolution within rock fabric, characteristics of vadoze zone diagenesis, abundant crinoid with anhydrite pockets.

NDGS 2602
6-153N-95W C NE.
Texaco Incorporation.
Seth A. Garland #5.
McKenzie County, North Dakota.
(Cored Interval = 10,037'−10,095')

Unit	Depth	Descriptions
1	10,037'−10,050'	Dolomite: medium gray; packstone, medium−fine grained, fairly cemented, exhibits high porosity, with soft sediment infilling laminations. Anhydrite pockets, slightly fractured with stylolites and bioturbated.
	T.S. 10,037'−10,048'	Dolomite: boundstone, dolomitizing micrite calcite cements and dissolution of calcite cements forming spar with mediun−fine subangular grains. Horizontal soft algae sediment infillings and vertical fractures
2	10051'−10095'	Limestone: medium gray−medium dark gray; packstone, medium−fine grained that are fairly cemented, high porosity with soft sediments infilling. Anhydrite pockets, visible vertical fractures, bioturbated, Abundant amphipora (stromatoporoids) and rugose corals.
	T.S 10,052.8'−10,093'	Limestone: packstone with calcite crystal growth, gradual dolomitizing of grains (dolomite rhombs developing), dissolution of calcite cements creating vugs, solution seams (10,076.5'), broken ostracod shells, gastropods and anhydrite pockets.

NDGS 2820
5-151N-95W NWSW.
Texaco Incorporation.
F. P. Keogh #4.
McKenzie County, North Dakota.
(Cored Interval = 10,885'−10,961')

Unit	Depth	Descriptions
1	10,885'−10,891.5'	Dolomite: light gray−medium light gray; boundstone, fine−very fine gained, well cemented, poor porosity. Visible horizontal soft algae sediment laminar infilling.
	T.S 10,886.7'−10,889'	Dolomite: mudstone, 5%−10% grains, horizontal soft algae sediment infilling with calcite cements and anhydrite pockets.
2	10,891.5'−10,907'	Limestone: medium gray−medium dark gray; packstone, medium−fine grained, high intra-particle grain porosity. Muddy anhydrite unit with probable peloids at (10,891'). Slightly bioturbated with visible vertical fractures having abundant stromatoporoids, and Amphipora (10,906.5').
	T.S 10,893'−10,902.2'	Limestone: packstone, epoxy stained showing high porous media of inter-granular porosity, 10% grains with radiaxial chalcedony chert mineral. Highly burrowed, gastropods, crinoids (10,893'). Dissolution of ostracods shell.
3	10,907'−10,947.5'	Limestone: light gray−medium light gray; packstone, medium−fine grained, with anhydrite/gypsum microcrystalline growth indicative of shallow marine (loss of water). Highly bioturbated with vertical fractures and stylolites present.
	T.S. 10,910.2'−10,37.6'	Limestone: mudstone−packstone, bladed crystal growth from calcite cements, recrystallization of ostracod shell (10,919.3') formation spar cements creating intra-particle porosity (10,916.8'). Selective dolomitization, gastropods, anhydrite, stylolites and bryozoan matty tabulate corals.
4	10,947.5'−10,961'	Dolomite: very light gray−light gray; bondstone, fine grained, poor porosity. Anhydrite mixture with soft sediment infilling laminar beds and slightly boiturbated.

NDGS 2967
3-152N-96W NWSE.
Texaco Incorporation.
A. S. Wisness #2.
McKenzie County, North Dakota.
(Cored Interval = 10,536'−10,594')

Unit	Depth	Descriptions
1	10,536'−10,537'	Dolomite: light gray−medium light gray; anhydrite mudstone, fine−very fine gained, fairly cemented, poor porosity. Visible anhydrite laminar bands and vertical fractures.
2	10,537−10,539.3'	Limestone: medium dark gray−dark gray; packstone, medium−fine grained, fair-low porosity. Calcite bands with visible vertical fractures present.
3	10,539.4'−10,545.1'	Dolomite: light gray−medium light gray; packstone/wackestone, medium−fine grained, (massive and well bounded grain contact) low−no porosity. Bioturbated, anhydrite pockets with soft algae sediment laminar infillings.
4	10,545.2'−10,567'	Limestone: medium gray−dark gray; packstone, medium−fine grained, low porosity. Soft sediment infilling laminar beds with anhydrite pockets. Stromatoporoids and vertical fractures.
5	10,568'−10,583.9'	Limestone: medium light gray; packstone, medium−fine grained, high intra-particle porosity with vertical fractures. Anhydrite pockets, highly bioturbated, abundant stromatoporoids, amphipora, rugose corals.
6	10,584'−10,594'	Limestone: medium gray−dark gray; packstone, medium−fine grained, high porosity with vertical fractures. Anhydrite pockets, highly bioturbated, with gastropods, stylolite.
	T.S 10,586'−10,589'	Limestone: packstone, fine−meduim subangular grains of calcite cement, broken ostracod shell indicative of deep burial compaction, dissolution seam, recrystallizing gastropod shell, corals, geopedal structure. Vertical fractures and stylolites with finer−medium−finer episode of deposition at (10,589').

NDGS 3086
1-152N-95W C NW.
Amerada Petroleum Corporation.
Antelope Unit “B” #1.
McKenzie County, North Dakota.
(Cored Interval = 10,507'−10,565')

Unit	Depth	Descriptions
1	10,507'−10,510'	Dolomite: medium gray; boundstone, (highly dolomitized), anhydrite with crystalline porosity, having soft sediment infilling laminations and stylolites.
	T.S 10,507'	Dolomite: boundstone, 10% grains, with vertical fracture, soft algae sediment infilling laminae.
2	10,510'−10,546'	Limestone: light gray; boundstone, micrite, medium−fine grained that are loosely cemented, scattered vug porosity with soft organic matter sediments infilling. Anhydrite pockets, bioturbated. Amphipora (stromatoporoids).
	T.S 10,511.8'−10,545.5	Limestone: boundstone, dissolution of calcite cements creating vug porosity, recrystallizing bivalve shell, abundant stromatoporoids with veins of soft organic sediments.
3	10,547'−10,565'	Limestone: medium gray−dark gray; boundstone, medium−fine grained, fairly cemented, average porosity. Anhydrite pockets, highly bioturbated, with vertical fractures.
	T.S 10,548.3'−10562'	Limestone: boundstone, 5% grains, dissolution of calcite cements creating porosity, abundant ostracods, bivalves, corals, gastropods, vertical fractures. Prominent soft algae sediment (bitumen) deformation infilling, indication of high over burden weight as ostracod carapace broken (10,553.5').

NDGS 3614
34-151N-96W NENE.
Calvert Drilling & Production Corporation.
Alfred Brown #1.
McKenzie County, North Dakota.
(Cored Interval = 11,076'−11,088')

Unit	Depth	Descriptions
1	11,076'−11,087'	Limestone: medium gray−medium dark gray; packstone, medium−fine grained with vug porosity. Soft organic sediment infilling laminations, vertical fractures, bioturbated with rugose corals, stromatoporoids and stylolites.
2	11,087'−11,088'	Dolimite: light gray−medium light gray; boundstone, medium−fine grained with soft organic matter sediment infilling bands, visible oil stains.

NDGS 5742
4-153N-95W SWSW.
Texaco Incorporation.
Devonian Unit 2 #1X.
McKenzie County, North Dakota.
(Cored Interval = 10,673'−10,683')

Unit	Depth	Descriptions
1	10,673'−10,676'	Dolomitic Anhydrite: light gray−medium light gray; boundstone, massive crystalline anhydrite with crystalline low porosity, having soft organic sediment infilling laminations.
2	10,676'−10,680'	Limestone: medium gray−medium dark gray; boundstone/packstone, micrite, medium−fine grained, calcite crystals growth, fair porosity with soft organic matter sediments infilling laminations with vertical fractures.
3	10,680'−10,682'	Dolomite: light gray−medium light gray; boundstone, medium−fine grained, fair porosity, slight vertical fractures.
4	10,682'−10,683'	Limestone: medium gray−medium dark gray; boundstone, calcite crystal growth, soft organic sediment laminations and bioturbations.

NDGS 12249
17-146N-102W NENW.
Meridian Oil Incorporated.
Moi #21-17.
McKenzie County, North Dakota.
(Cored Interval = 10,964'−11,024')

Unit	Depth	Descriptions
1	10,964'−10,965.9'	Limestone: dark gray−grayish black; packstone, with calcite or anhydrite crystal infill replacement, low-no porosity with vertical fracture veins (25.71µm), filled with probably pyrites.
2	10,965.9'−10,975.5'	Dolomitic Anhydrite: light gray−medium light gray; wackestone, deformed soft organic matter sediments infilling laminations with vertical fractures. Replacement reactions (dolomitization).
	T. S 10,970.8−10,971.1	Dolomite: packstone, 30% grains, calcite cement, epoxy stained depicting high porous medium, soft algae sediment infilling.
3	10,975.5'−10,977'	Limestone: dark gray−grayish black; packstone, medium−fine grained, fair-low porosity, slight anhydrite pockets, vertical fractures.
	T.S 10,975.5'−10,977.7'	Limestone: packstone with calcite crystals forming at (10,975.8'), 20% grains, dissolution of calcite cements creating spar forming cement, high over burden pressure compaction as ostracod shells are deformed (10,976.9−10,977.3'). Section has anhydrite pockets and veins of soft organic sediment infilling.
4	10,978'−10,994.3'	Dolomite: light gray−medium light gray; bondstone, massive anhydrite (10,796'−10,980'), dark shale band at 10,992' with slight fracture. Replacement of laminar by soft algae sediment.
5	10,994.3'−11,002.2'	Limestone: dark gray−grayish black; wackestone, medium−fine grained, fair porosity, soft organic matter sediments infilling laminations with vertical fracture extensively at depth 11,000'. Pocket anhydrite, ostracods and corals.
6	11,002.4'−11,011.5'	Dolomite: medium gray; packstone, medium−fine grained, high vug porosity, anhydrite nodular pockets, slight vertical fractures and stylolites.
7	11,011.6'−11,024'	Limestone: dark gray−grayish black; packstone, medium−fine grained, average porosity, highly bioturbated with slight fracture, stylolites.

NDGS 12962
35-148N-102W SWSE.
Pennzoil Exploration & Production Company.
North Branch #35X-34 BN.
McKenzie County, North Dakota.
(Cored Interval = 10,962'−11,002')

Unit	Depth	Descriptions
1	10,962'−10,963'	Anhydrite: medium light gray; massive crystalline, fine, no bedding planes.
2	10,963'−10,966.5'	Limestone: medium dark gray−dark gray; packstone, medium−fine grained, average porosity, anhydrite pockets with vertical fractures along surface.
3	10,966.5'−10,968.3'	Dolomite: light gray; wackestone/packstone, medium−fine grained, fair porosity with soft organic sediment laminar, anhydrite pockets.
4	10,968.3'−10,972'	Limestone: medium gray−dark gray; packstone, medium−fine grained, prominent vertical fracture
	T. S 10,969.8'	(10,969.1'−10,970'). Soft organic matter sediment laminar. Limestone: packstone, calcite cements with high dolomitization rate as dolomite rhombs are visible. Dark soft algae sediment deformation infilling, high porosity.
5	10,972'−10,975.2'	Dolomite: light gray−medium light gray; packstone, medium−fine grained, fair porosity, soft organic matter
	T.S 10,975'	sediments infilling, crossbeds and pocket anhydrites. Dolomite: packstone, epoxy stained depicting high porosity with dolomite rhombs forming.
6	10,975.2'−10,977.4'	Limestone: dark gray-grayish black; packstone, medium−fine grained, fair porosity, prominent vertical fractures and stylolites.
7	10,977.4'−10,988'	Dolomite: light gray−medium light gray; packstone, fine grained, fair−low porosity, lamination and slight vertical fracture.
8	10,988'−11,002'	Limestone: medium gray−dark gray; packstone, coarse−medium grained, high porosity (11,001'-11,007'), pocket anhydrites, bioturbations with soft organic sediment
	T.S 10,991'	lamination. Slightly fractured, ostracods and stylolites. Limestone: boundstone, recrystallization of calcite cements, high over burden pressure as ostracod shell snaps in half, anhydrite pockets and dolomitizing calcite grains.

NDGS 19918
22-152N-99W SWSE.
Continental Resources Incorporation.
Charlotte 1-22H.
McKenzie County, North Dakota.
(Cored Interval = 11,567'−11,572')

Unit	Depth	Descriptions
1	11,567'−11,570'	Dolomitic Anhydrite: very light gray−light gray; boundstone, mediun−fine grained with low porosity, having soft organic sediment infilling. Vertical fractures, bioturbations and stylolites.
2	11,570'−11,572'	Limestone: medium gray; boundstone, medium−fine grained with soft organic matter sediment infilling lamination and anhydrite pockets.

NDGS 21786
4-151N-98W SWNW.
Denbury Onshore LLC.
Rink 12-4ESH.
McKenzie County, North Dakota.
(Cored Interval = 11,413'−11,430')

Unit	Depth	Descriptions
1	11,413'−11,415.5'	Anhydrite: very light gray−light gray; massive crystalline structure, fine−muddy grained, average porosity, soft organic sediment laminar and slight vertical fractures.
2	11,415.5'−11,419.6'	Limestone: medium gray-dark gray; crystalline (shinny/luster). High porosity, soft organic sediment lamiae, anhydrite pockets and vertical fractures.
3	11,419.6'−11,421.5'	Dolomite: medium light gray; packstone, medium−fine grained, average porosity with soft organic sediment laminar, anhydrite pockets. Highly fractured vertically.
4	11,421.5'−11,422'	Limestone: medium dark gray; packstone, medium−fine grained, average porosity with vertical fracture, soft organic matter sediment laminar.
5	11,422'−11,424.6'	Dolomite: sandy medium gray; packstone, medium−fine (muddy) grained, high vug porosity (surface acts as a sponge), soft organic matter sediment infilling laminations.
6	11,424.6'−11,426.2'	Limestone: medium dark gray; organic bondstone, medium−fine grained, average porosity. Sediments rich in organic matter (probably microbial or algae mat) and prominent vertical fractures.
7	11,426.2'−11,428.5'	Dolomite: medium gray−medium light gray; microcrystalline growth (11,428'), crystalline porosity, soft organic matter lamination, anhydrite pockets. Unit has oily stain and vertical fracture.
8	11,428.6'−11,430'	Limestone: very dark gray; organic boundstone, medium−fine grained, fair porosity. Sediment in unit is rich in organic matter with trace of oil stain and slightly fractured.

NDGS 24123
20-149N-97W SWNW.
XTO Energy Incorporation.
Marina Trust 12X-20G2.
McKenzie County, North Dakota.
(Cored Interval = 11,370'−11,379').

Unit	Depth	Descriptions
1	11,370'−11,371'	Dolomitic Anhydrite: light gray; boundstone, (highly dolomitized), anhydrite nodules with low to no porosity, soft organic sediment infilling laminations.
2	11,371'−11,378.3'	Limestone: medium gray; packstone, medium−fine grained that are highly fractured, fair porosity. Soft organic matter sediment infilling, and scattered anhydrite pockets.
3	11,378.3'−11,379'	Dolomite: medium gray; packstone, medium−fine grained, high porosity (surface of rock acts as a sponge) with vertical fractures. Soft organic sediment laminar with unit having oil stain.

APPENDIX D

FIGURES FROM THIN SECTIONS OF WELLS THAT PENETRATE THE BIRDBEAR FORMATION

NDGS 2373, 1-152N-95W NESE, Amerada Petroleum Corporation, Antelope Unit "A" #1, McKenzie County, North Dakota.


Mag 4x/0.10

Figure 53. (10,451') Limestone (packstone): anhydrite cements, gastropod, rugose coral with calcite cements experiencing recrystallization and porous.

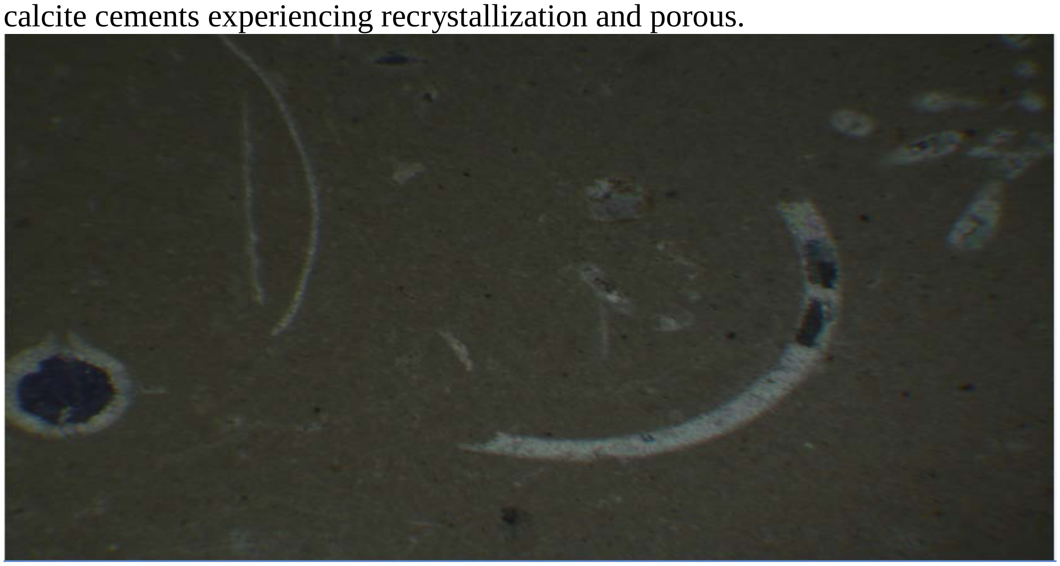

Mag 4x/0.10

Figure 54. (10,451'b) Limestone (packstone): Recrystalizing brachiopod shell, broken ostracod carapace with anhydrite.

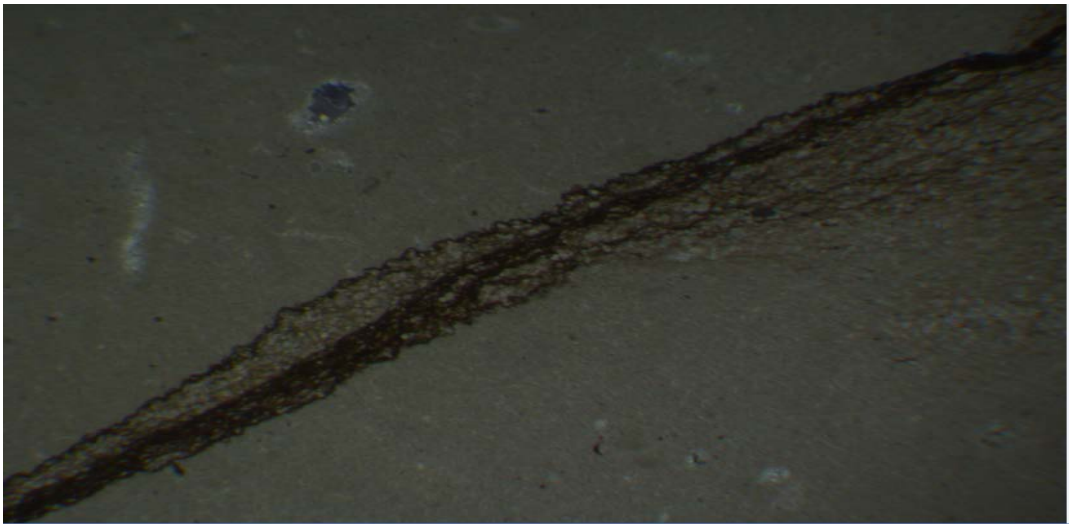
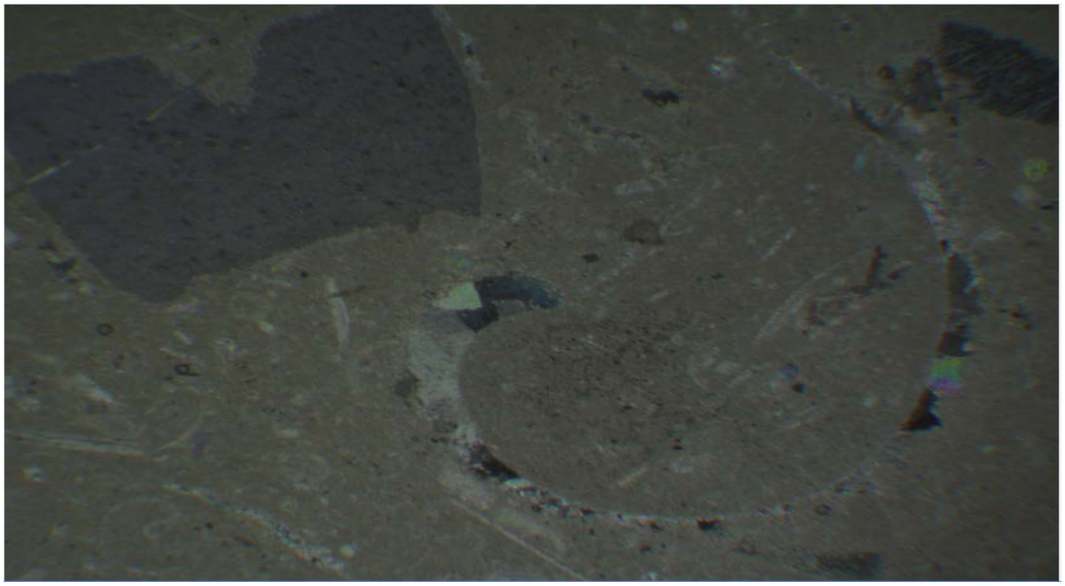

Mag 4x/0.10

Figure 55. (10,452') Limestone (packstone): Soft algae organic matter infilling or stylolite with anhydrite.

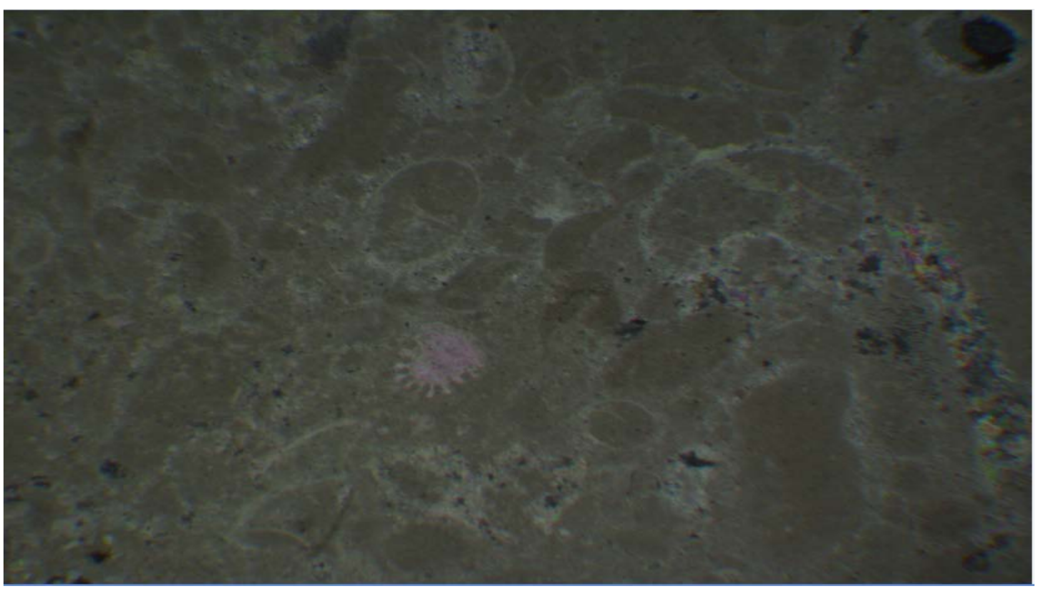

Mag 4x/0.10

Figure 56. (10,452') Limestone (packstone): amphipora, crinoid in rock matrix.



Mag 4x/0.10

Figure 57. (10,459') Limestone (packstone): crinoid, amphipora, ostracod undergoing recrystallization.



Mag 4x/0.10

Figure 58. (10,462') Limestone (packstone): rugose coral, ostracods shells, gastropods with fabric selective porosity.


Mag 10x/0.22

Figure 59. (10,488.8') Dolomite (packstone): Pebbly soft organic sediment infilling within original sediment.

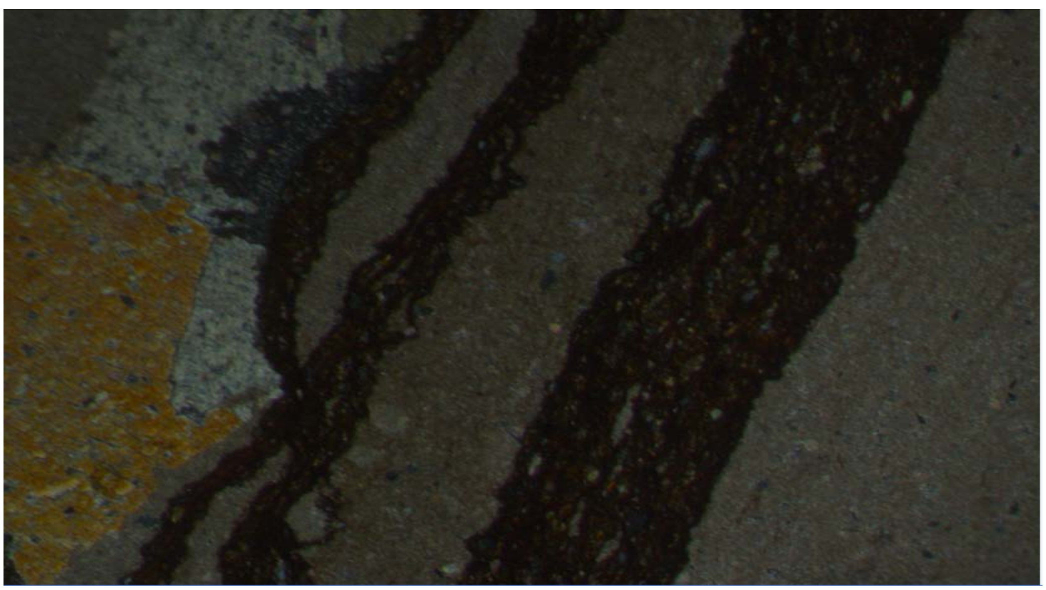

Mag 10x/0.22

Figure 60. (10,489.9') Dolomite (packstone): soft organic matter sediment infilling.

 Mag 4x/0.10

Figure 61. (10,497') Limestone (boundstone): crinoid with anhydrite.

NDGS 2602, 1-152N-95W NESE, Texaco Incorporation, Seth A. Garland #5, McKenzie County, North Dakota.

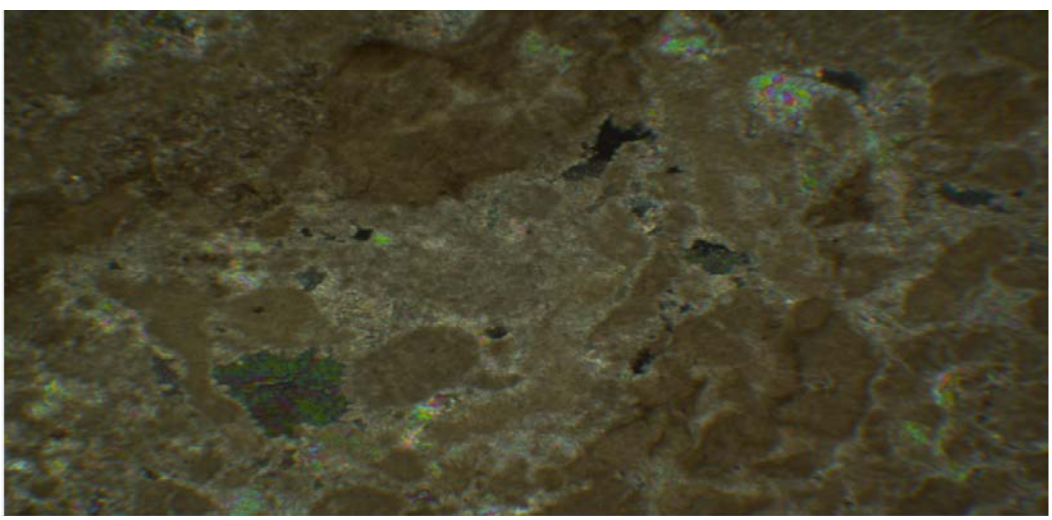
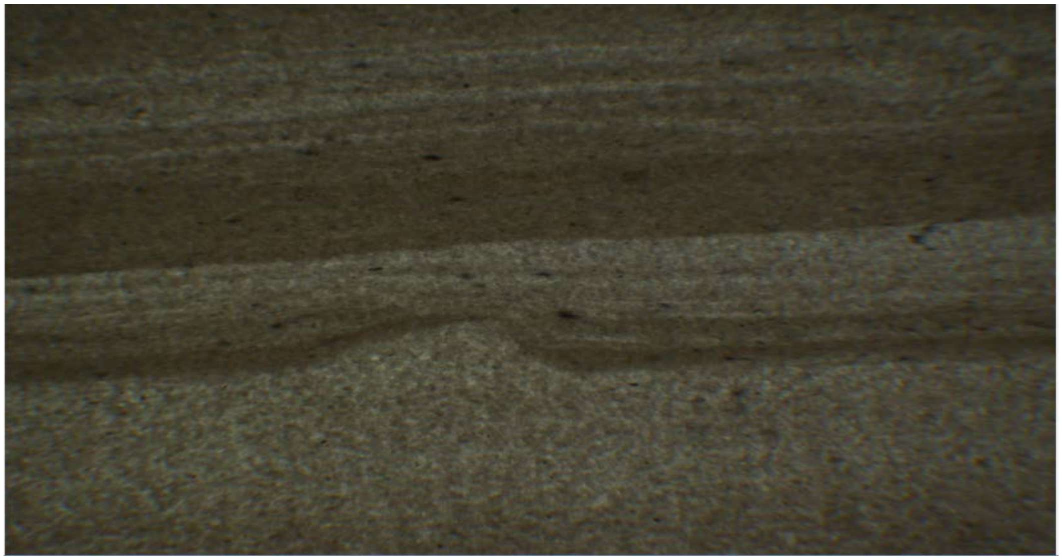
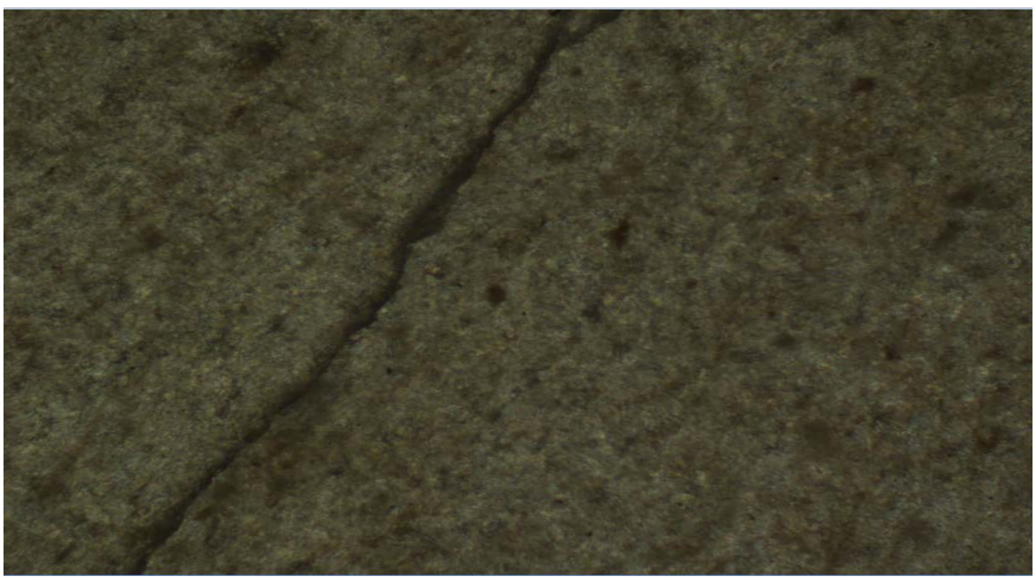
 Mag 4x/0.10

Figure 62. (10,043') Dolomite (Boundstone): calcite cements, high porosity due to dissolution of cements creating porosity with spar forming cements.



Mag 4x/0.10

Figure 63. (10,046') Dolomite (boundstone): rock framework with soft sediment laminae beds with slight deformation.



Mag 10x/0.22

Figure 64. (10,048') Dolomite (Boundstone): visible fracture running in rock surface, very porous.

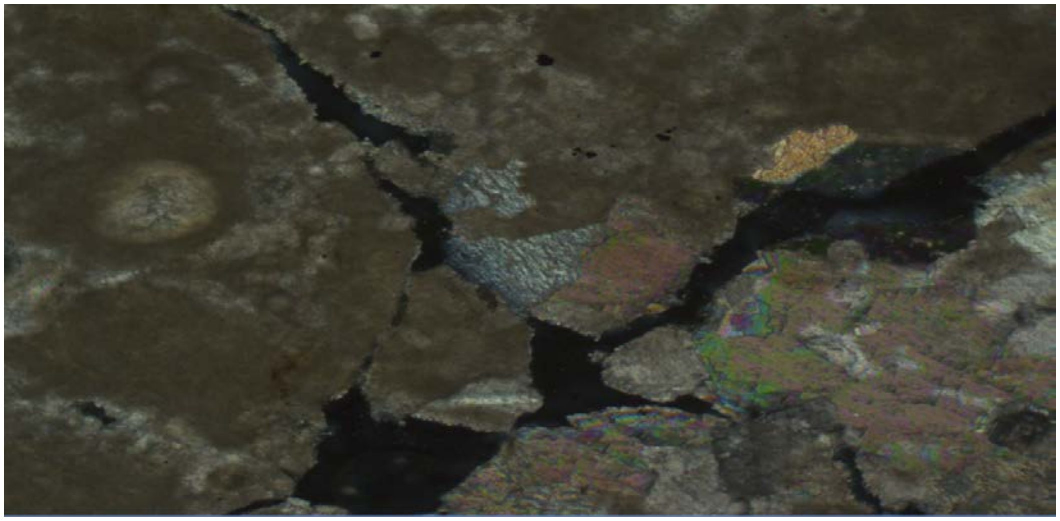

Mag 10x/0.22

Figure 65. (10,052.8') Limestone (packstone): Anhydrite, precipitation of spar forming cements and very porous.

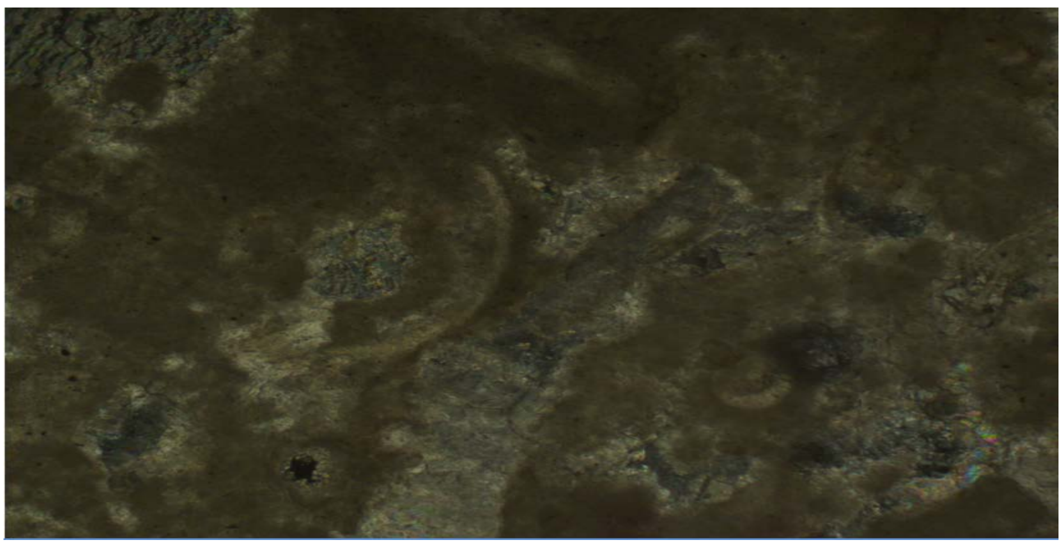

Mag 10x/0.22

Figure 66. (10,054') Limestone (packstone): recrystallizing ostracod carapace, anhydrite having calcite cements with high porosity.

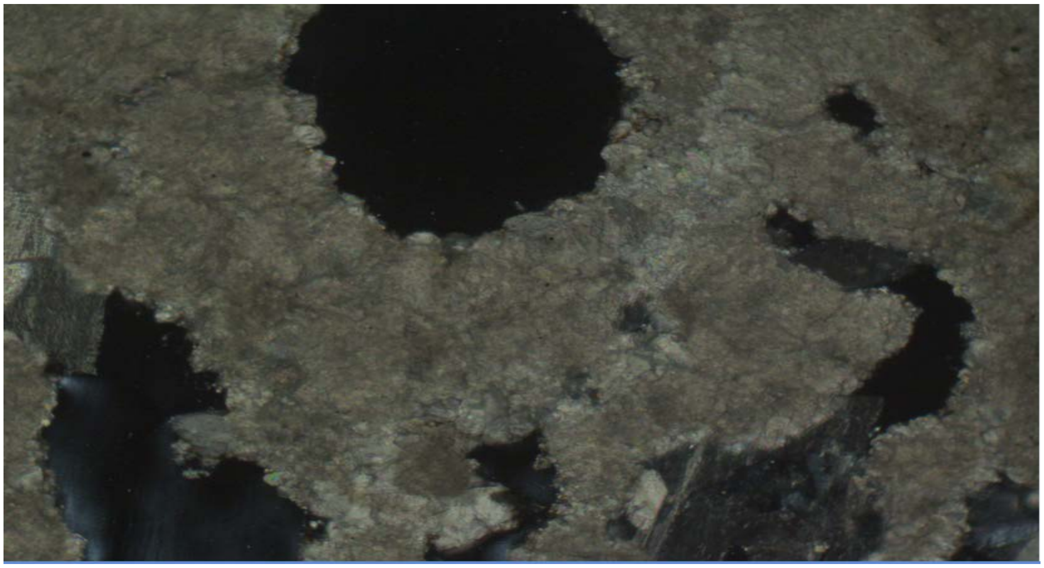
 Mag 10x/0.22

Figure 67. (10,057.9') Limestone (packstone): visible diagenetic process within rock matrix, as dissolving calcite cements are creating vug porosity.

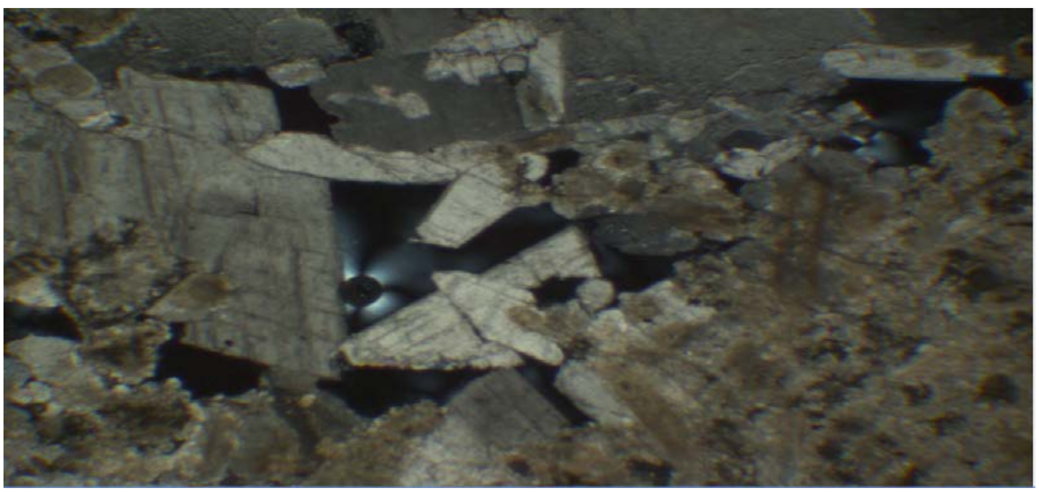
 Mag 4x/0.10

Figure 68. (10,069.9'b) Limestone (packstone): Recrystallization of rock materials and dissolution of calcite cements, developing crystals that give rise to inter-crystalline porosity.

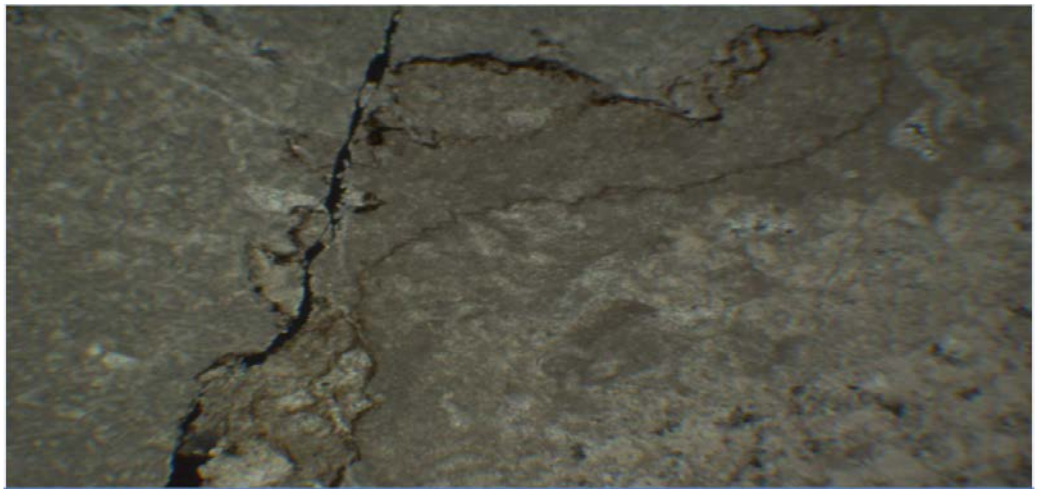
 Mag 4x/0.10

Figure 69. (10,076.5') Limestone (packstone): Anhydrite, solution seams and soft organic sediment inclusion.

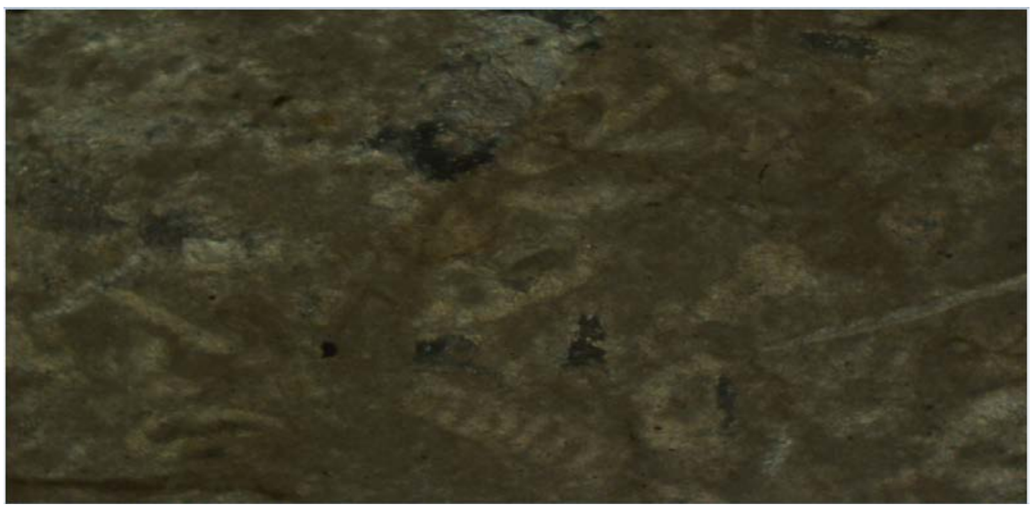
 Mag 10x/0.22

Figure 70. (10,093') Limestone (boundstone): porous with gastropods, broken ostracods, anhydrite and recrystallizing calcite cements.

NDGS 2820, 5-151N-95W NWSW, Texaco Incorporation, F. P. Keogh #4, McKenzie County, North Dakota.

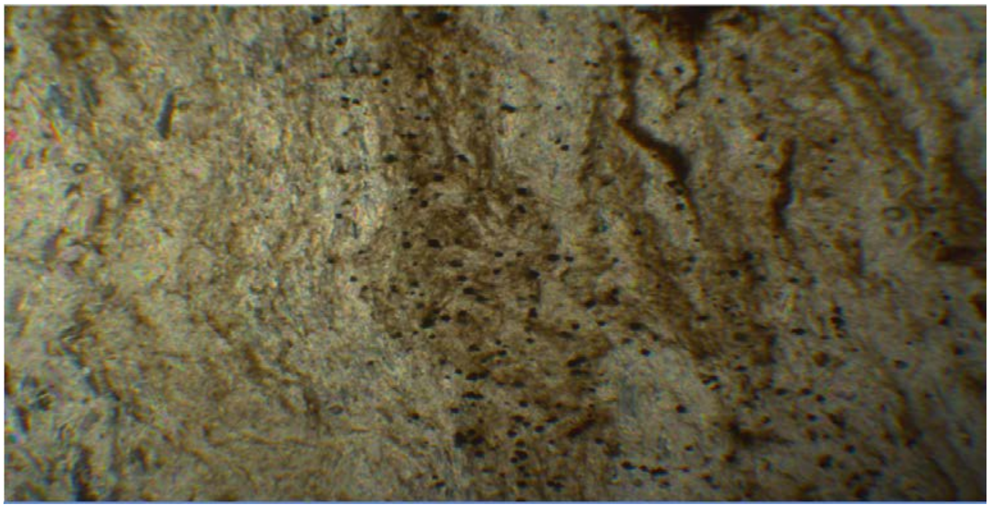
 Mag 4x/0.10

Figure 71. (10,886.7') Dolomite (Boundstone): soft organic sediment laminar, calcite cements.

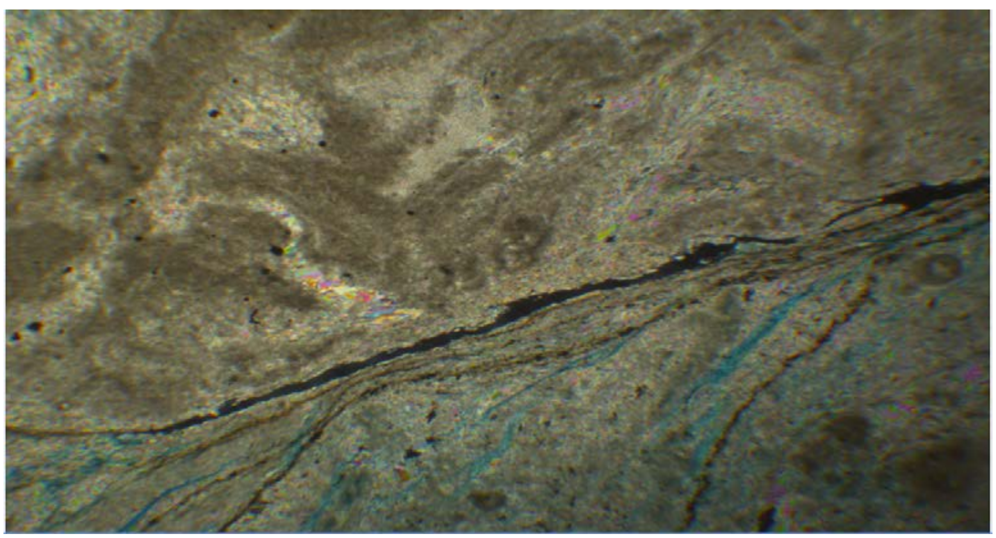
 Mag 4x/0.10

Figure 72. (10,889.10') Dolomite (mudstone): Anhydrite, having calcite cement, fracture with soft organic (algae) infilling and porous.

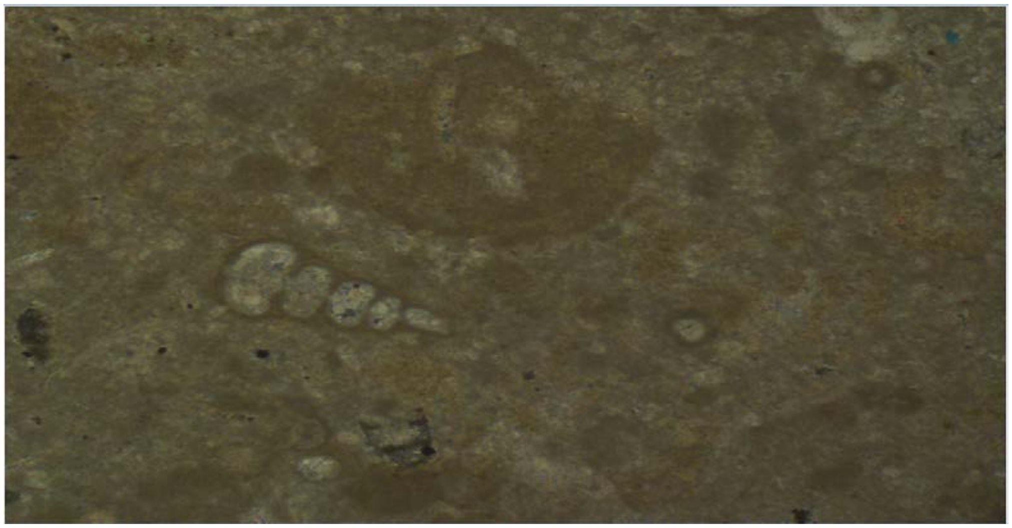

Mag 10x/0.22

Figure 73. (10,893.11') Limestone (packstone): Gastropod, crinoid and bioturbation. Porous matrix cement with grain –grain contact.

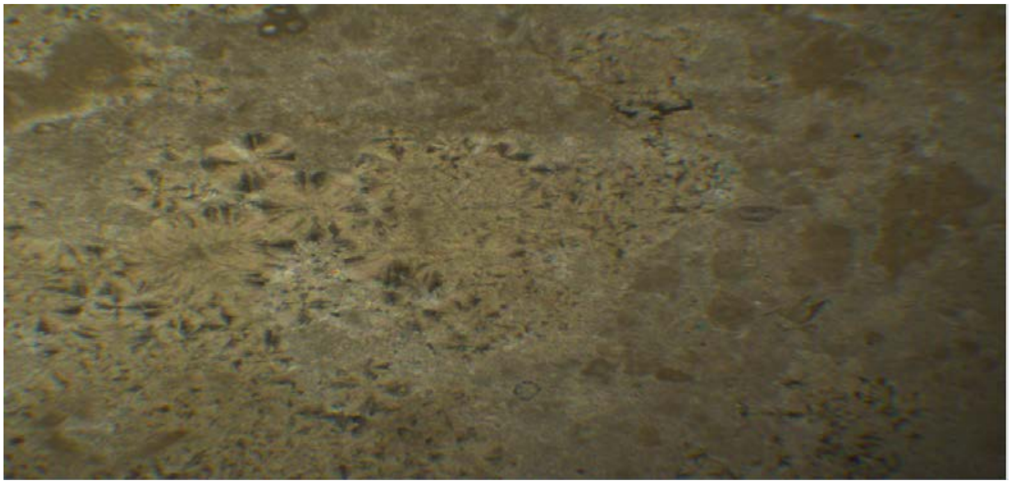

Mag 4x/0.10

Figure 74. (10,893.11') Limestone: Slightly bioturbated, radiaxial chalcedony growth in grains with calcite cements and very porous.

 Mag 10x/0.22

Figure 75. (10,916.4') Limestone (Packstone): brachiopod shell, epoxy stained showing porosity.

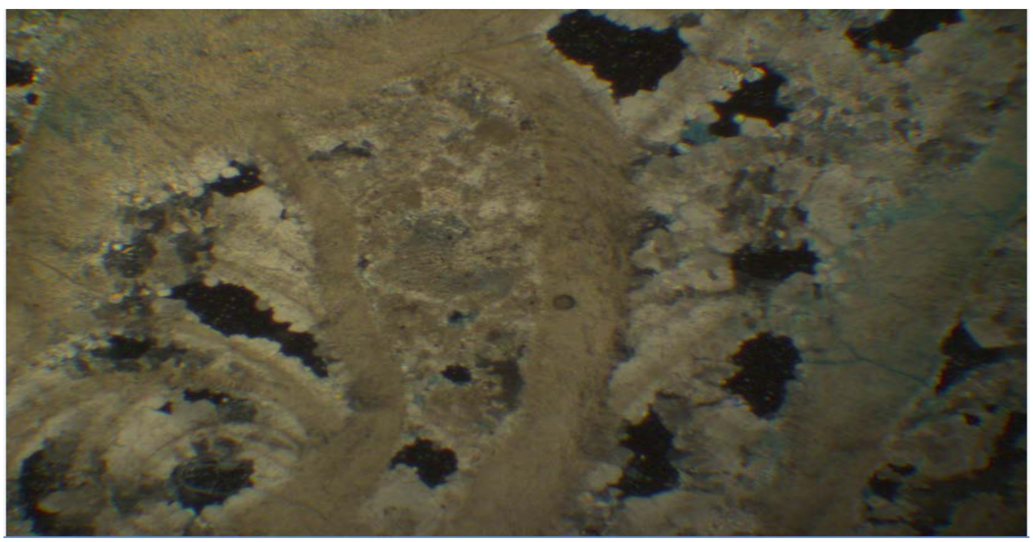
 Mag 4x/0.10

Figure 76. (10,916.8') Limestone (boundstone): spar forming cement been formed by diagenetic processes, dissolving calcite cements giving rise to high intra-granular porosity.

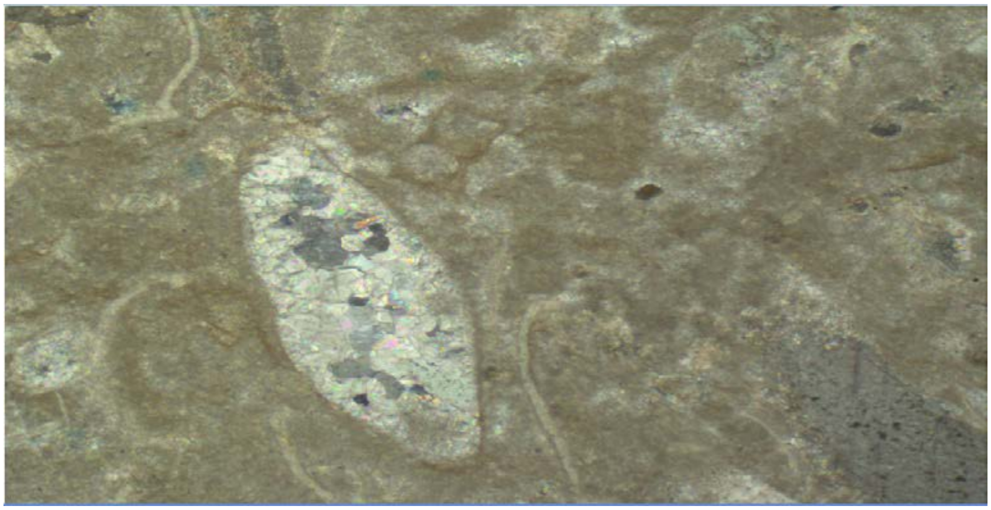

Mag 4x/0.10

Figure 77. (10,919.3') Limestone (mudstone): Amphipora, recrystallizing brachiopod shell, with anhydrite and very porous.

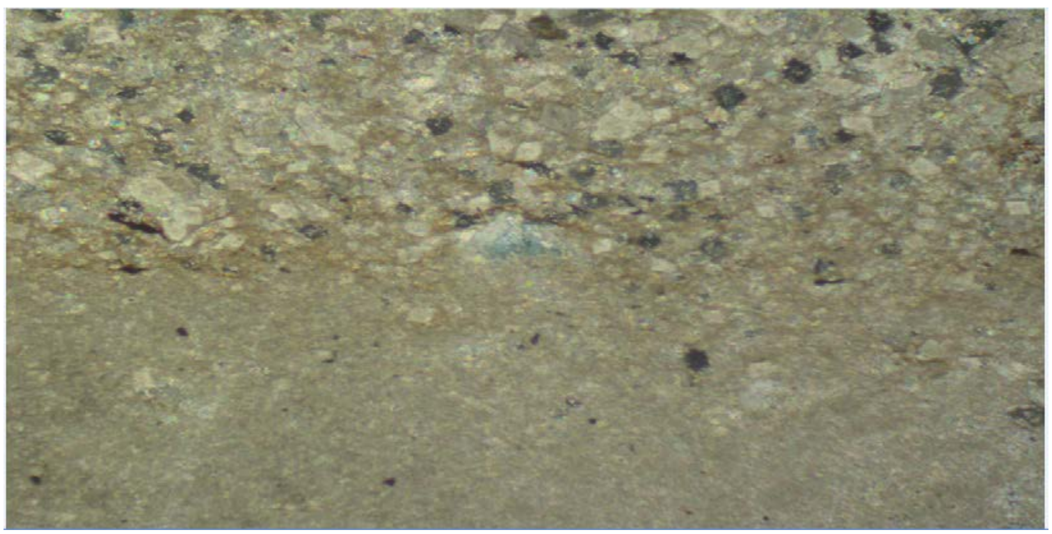

Mag 10x/0.22

Figure 78. (10,920') Limestone (packstone): indicating selective dolomitization of rock grains.

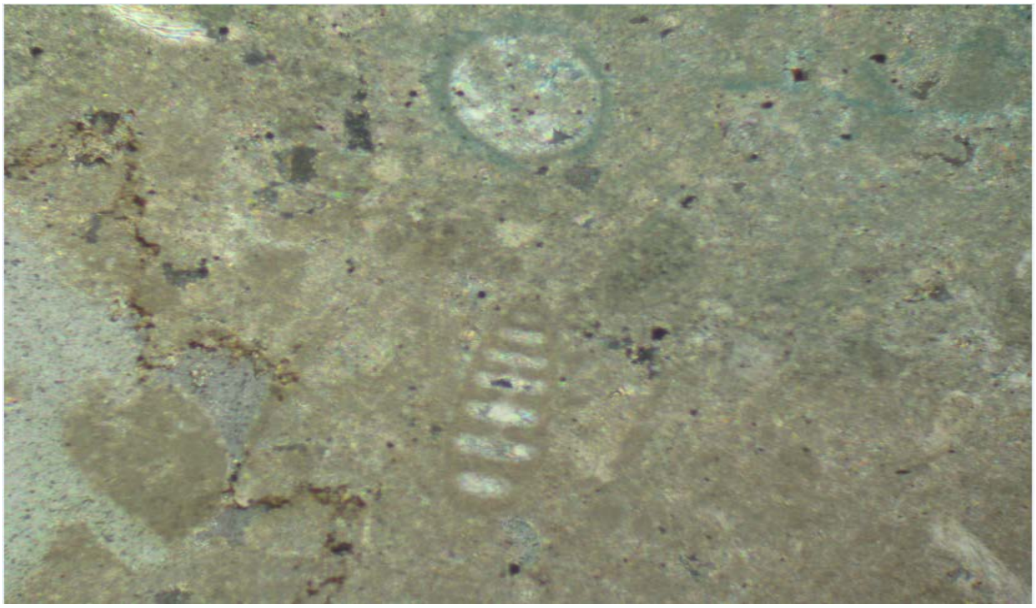
 Mag 10x/0.22

Figure 79. (10,921.10') Limestone (packstone): Stylolite, anhydrite with gastropod and very porous.

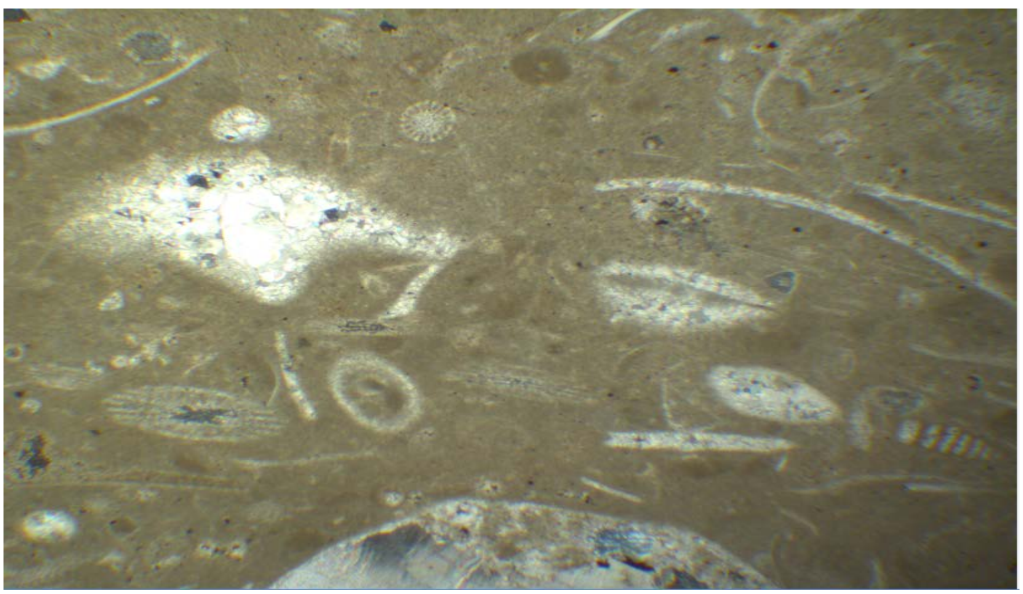
 Mag 4x/.010

Figure 80. (10,927.6') Limestone (wacketone): Crinoids, gastropods, anhydrite with calcite cements.

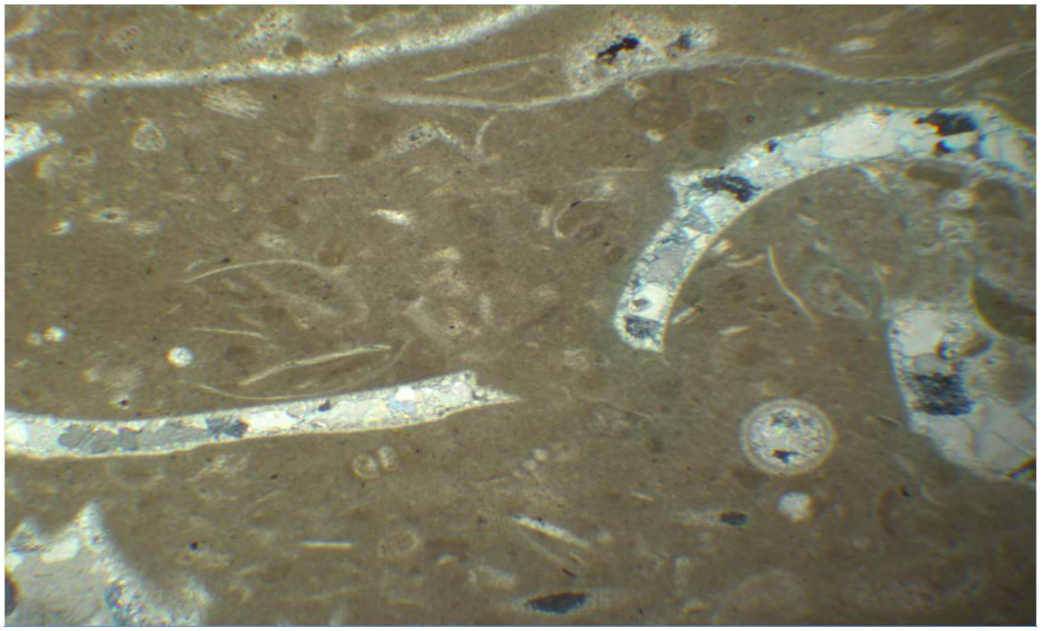

Mag 4x/0.10

Figure 81. (10,927.6') Limestone (packstone): Effect of compaction as ostracod shell breaks, anhydrite and recrystallization that create porosity.

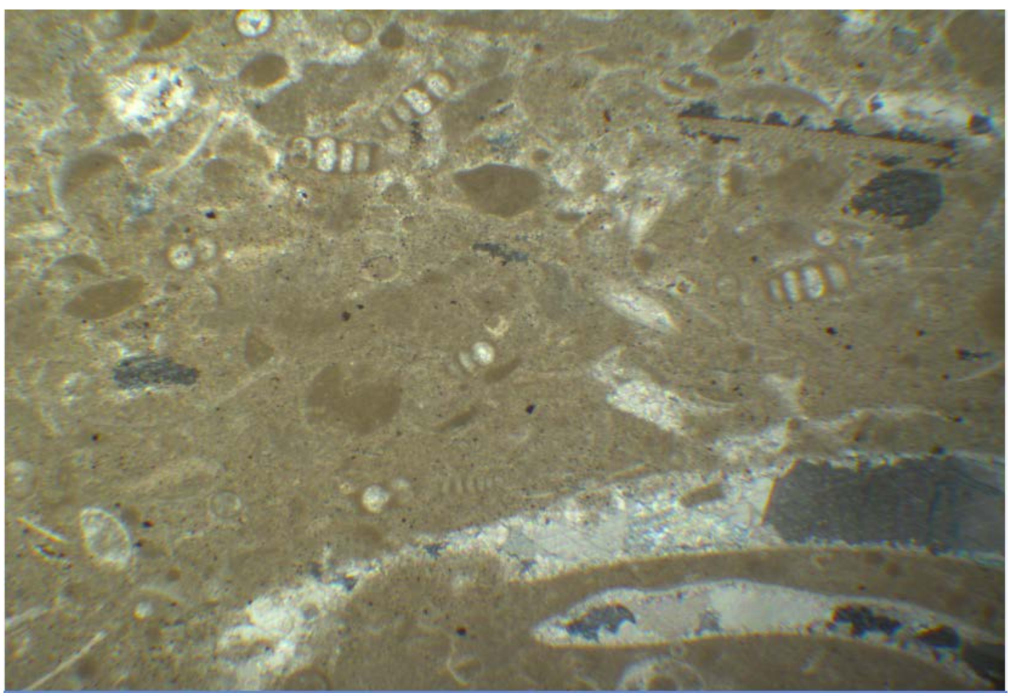

Mag 4x/0.10

Figure 82. (10,927.6') Limestone (mudstone): intra-granular porosity, abundant gastropods, brachiopod, recrystallizing brachiopod carapace, and anhydrite.

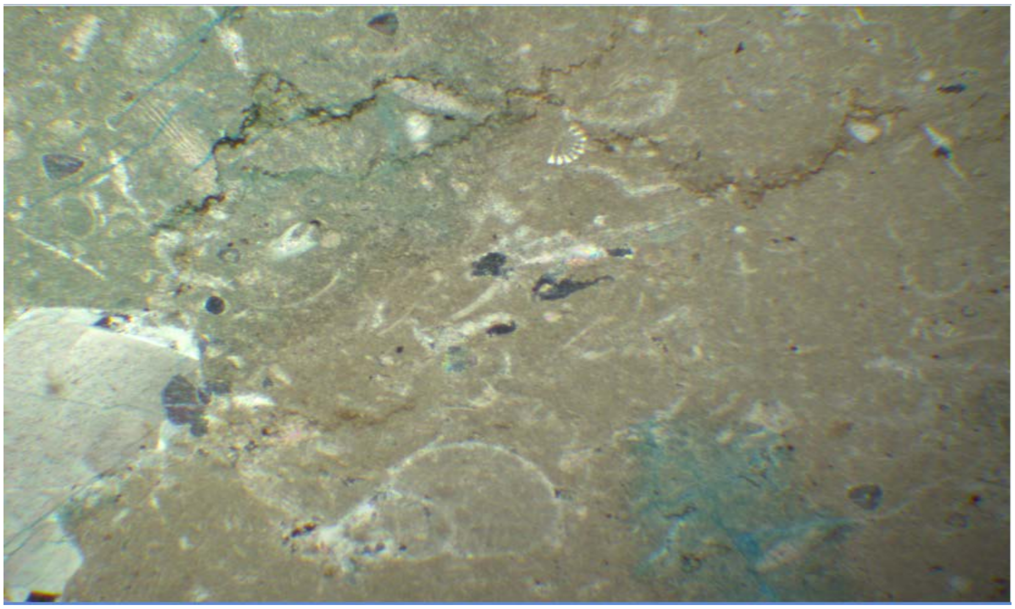

Mag 4x/0.10

Figure 83. (10,930.4') Limestone (mudstone): Gastropod, corals, with calcite cements and stylolite.

NDGS 2967, 3-152N-96W NWSE, Texaco Incorporation, A. S. Wisness #2, McKenzie County, North Dakota.

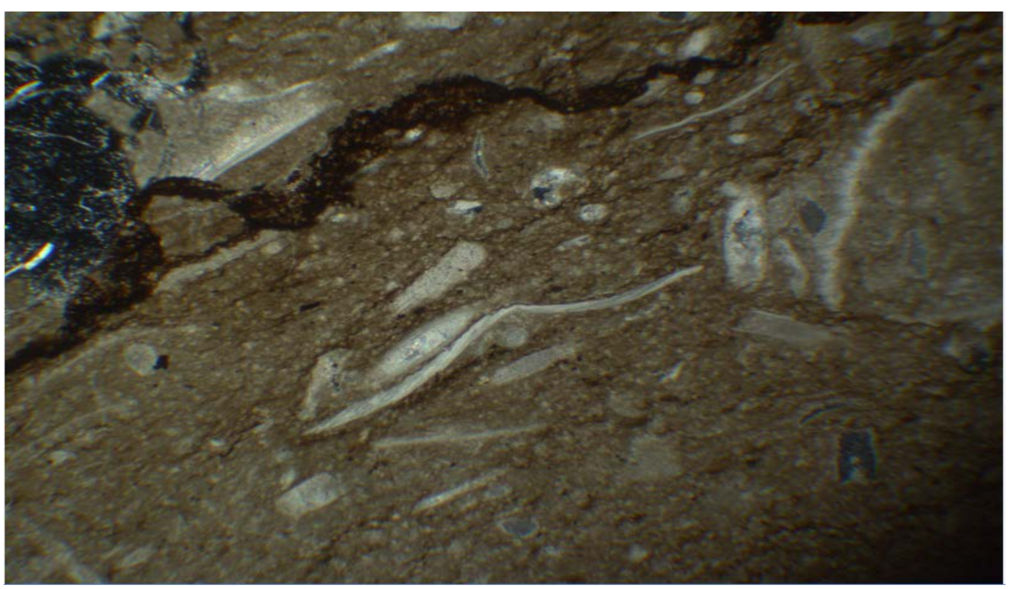

Mag 4x/0.10

Figure 84. (10,586') Limestone (Packstone): Amphipora, solution seam filled with organic matter, anhydrite and very porous.

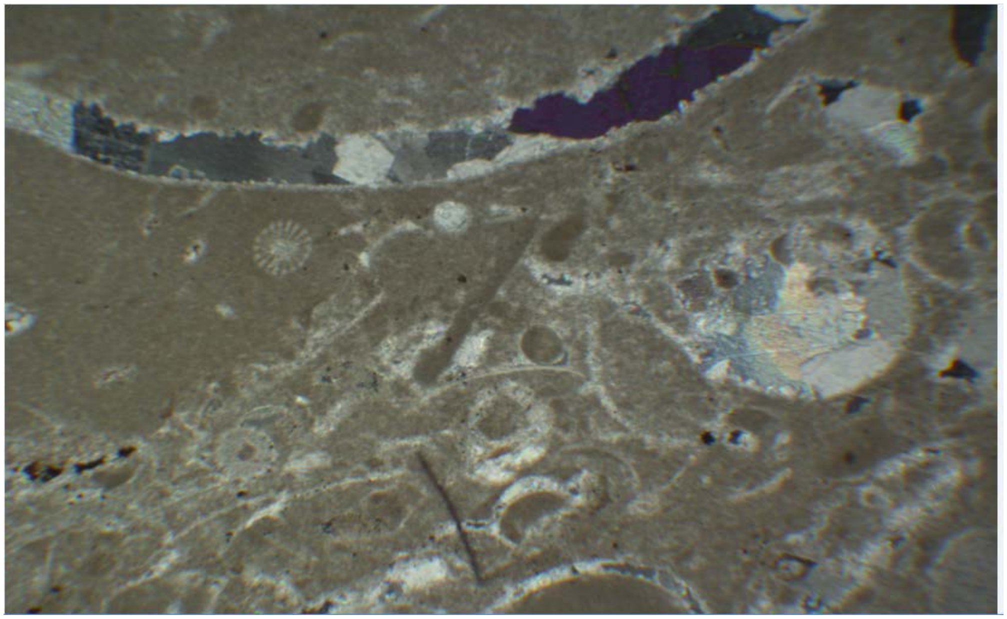

Mag 4x/0.10

Figure 85. (10,586') Limestone (packstone): Rugose coral, recrystallizing ostracods, very porous.

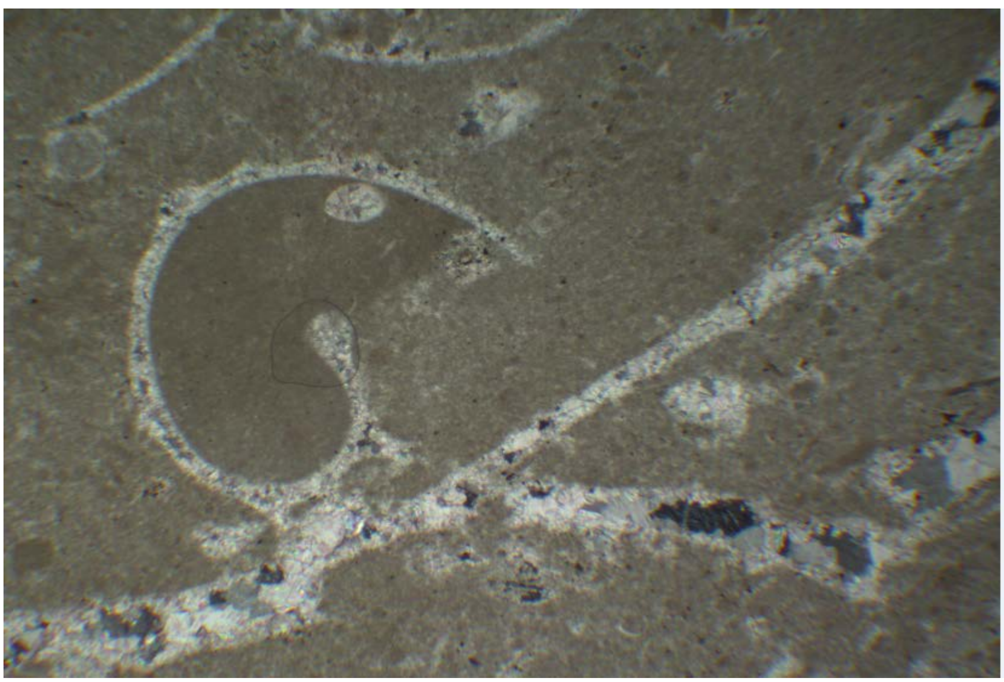
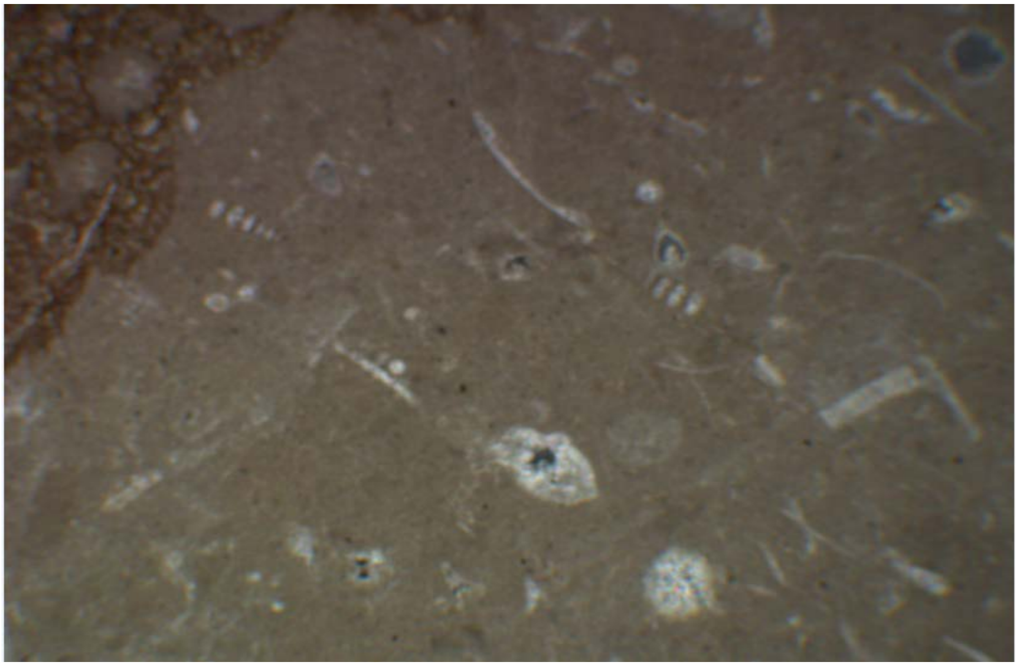
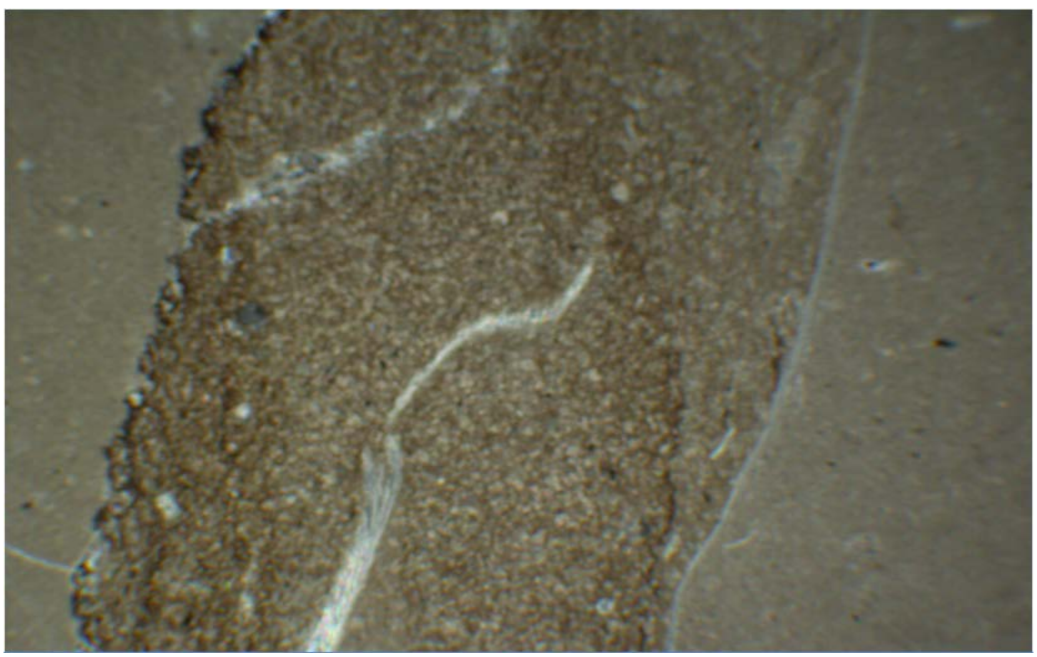

Mag 4x/0.10

Figure 86. (10,586') Limestone (packstone): A geopedal structure, broken recrystallizing ostracod shell in a porous matrix.



Mag 4x/0.10

Figure 87. (10,589') Limestone (Packstone): Anhydrite, broken ostracod shells, gastropods in calcite cement grain.



Mag 4x/0.10

Figure 88. (10,589') Limestone (Packstone): Finer initial sediment deposited, which was later eroded and then medium pebbly organic sediment rich deposited and subsequent finer sediment finally deposited, indicative of a depositional sequence.

NDGS 3086, 1-152N-95W C NW, Amerada Petroleum Corporation, Antelope Unit “B” #1, McKenzie County, North Dakota.

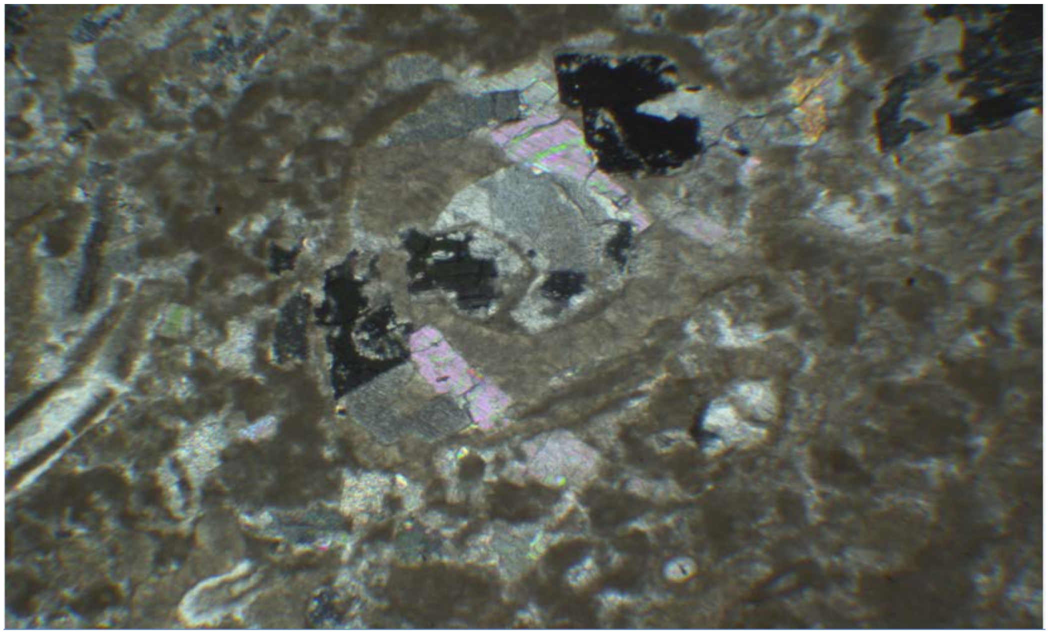
 Mag 4x/0.10

Figure 89. (10,511.8') Limestone (boundstone): Dissolution of calcite cements creating pore spaces, with anhydrite.

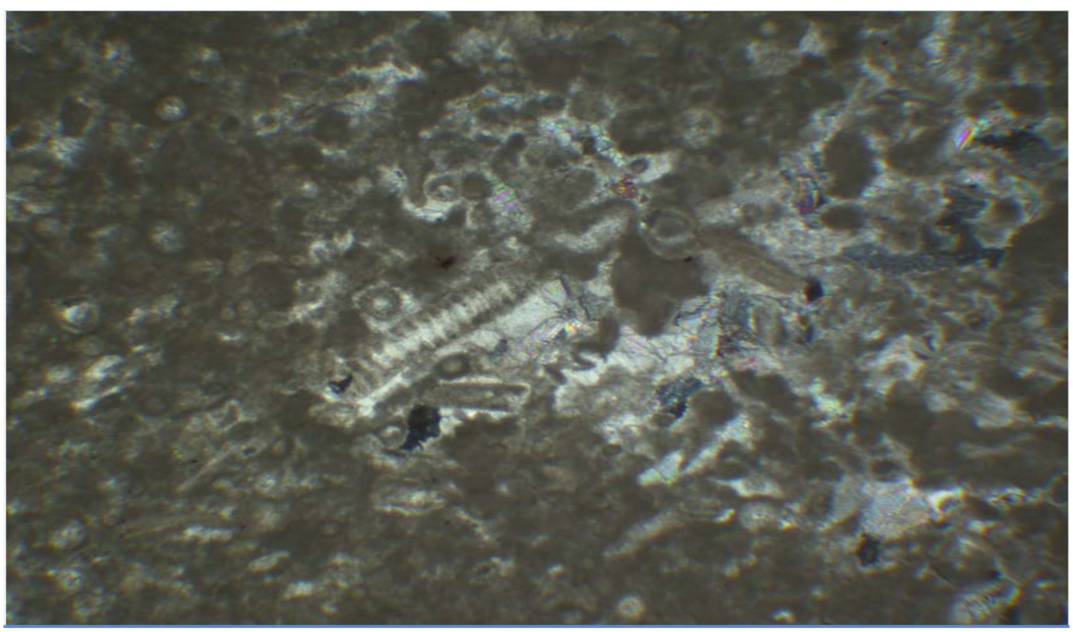
 Mag 4x/0.10

Figure 90. (10,517.7') Limestone (boundstone): Amphipora, crinods with anhydrite and very porous.

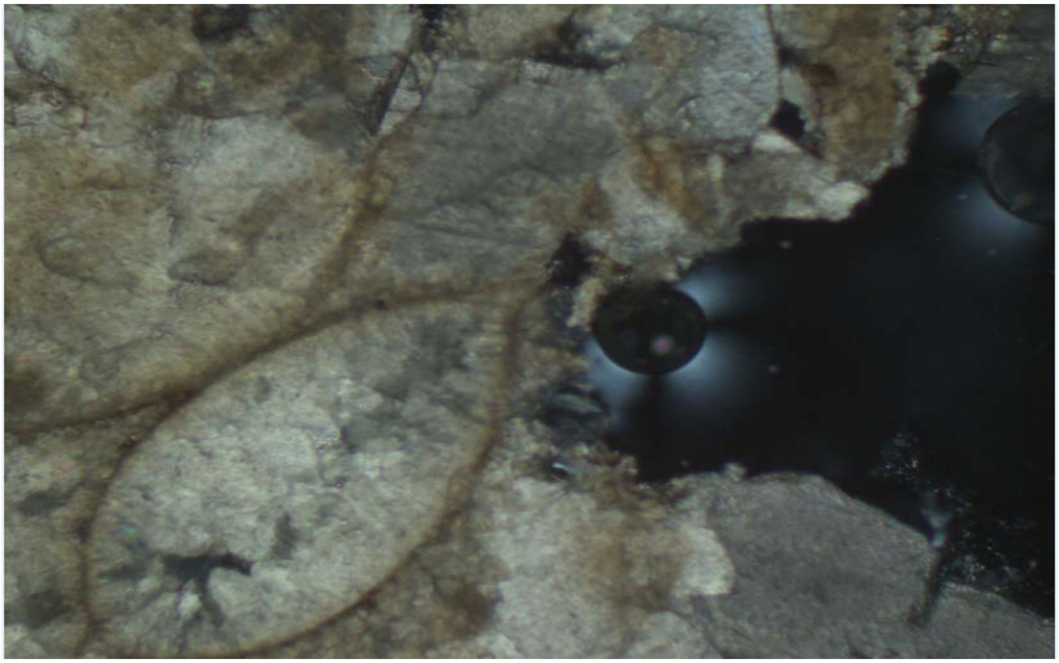

Mag 10x/0.22

Figure 91. (10,521') Limestone (boundstone): Gradual dolomitization of a bivalve remains.

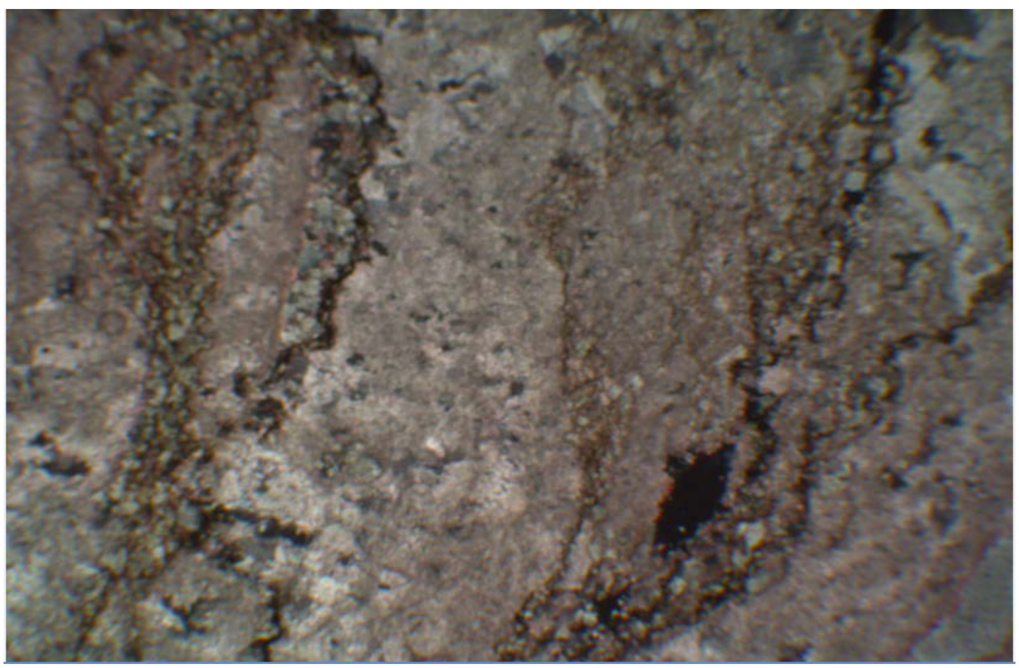
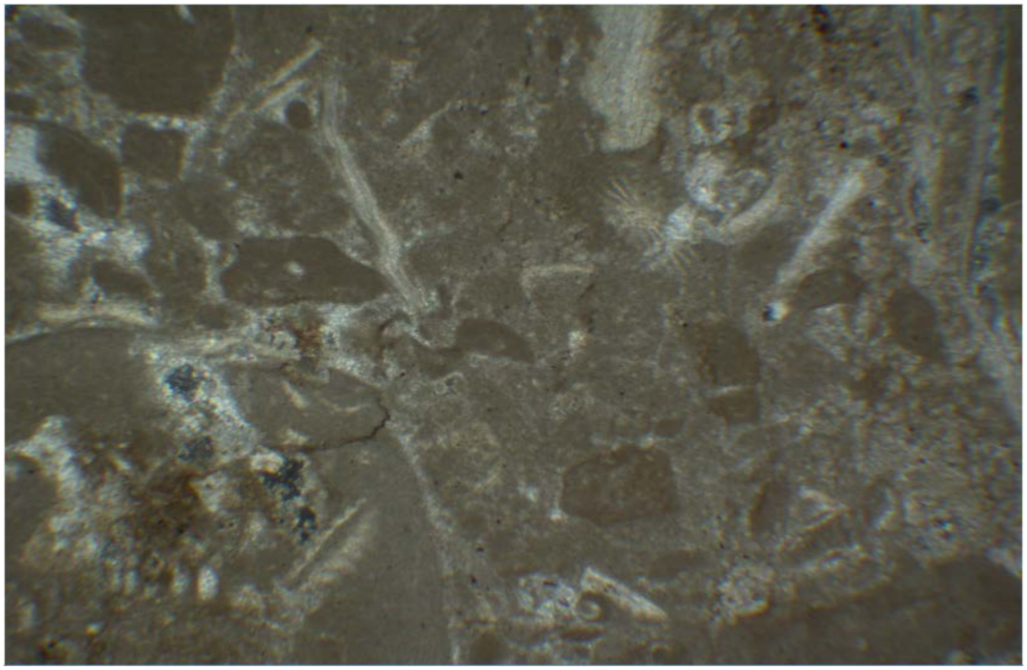
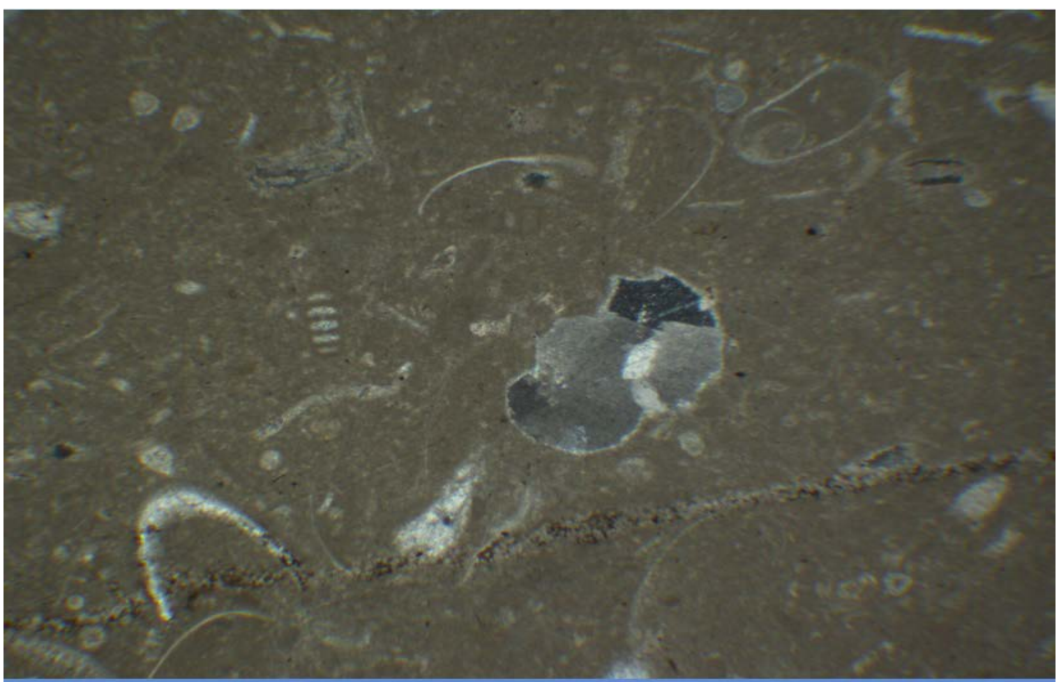

Mag 4x/0.10

Figure 92. (10,545.5'a) Limestone (packstone): Veins of organic soft sediment with calcite cements.



Mag 4x/0.10

Figure 93. (10,548.3') Limestone (boundstone): Dissolution of calcite cements creating porosity with framework, bryozoan, ostracods and anhydrite.



Mag 4x/0.10

Figure 94. (10,551') Limestone (boundstone): Transformation of aragonite to more stable calcite mineral in gastropod shell, ostracods and fracture with slight anhydrite.

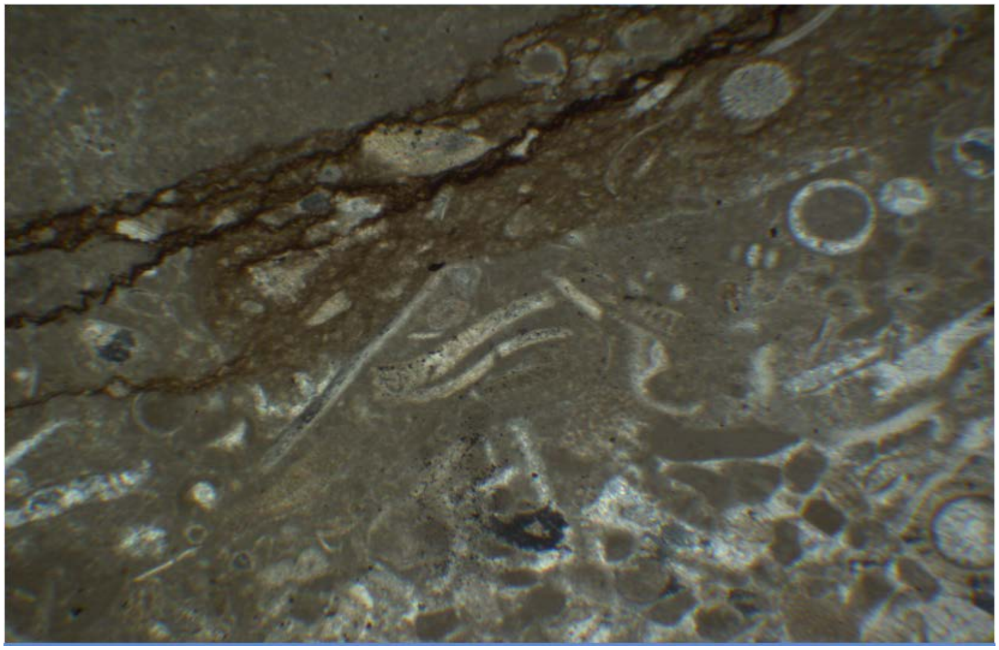
 Mag 4x/0.10

Figure 95. (10,553.5') Limestone (boundstone): amphipora, bryozoan, with broken ostracod shells indicative of deep burial features, anhydrite, soft organic matter infillings and dissolution of calcite cements.

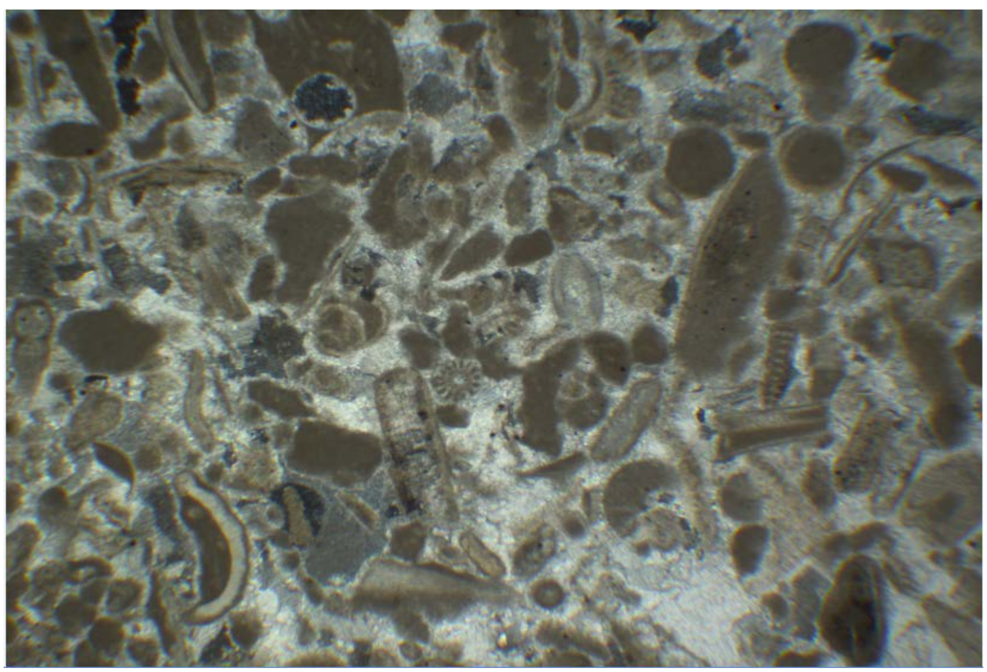
 Mag 4x/0.10

Figure 96. (10,553.5') Limestone (boundstone): Calcite spars, gastropod, ostracods, rugose corals, amphipora and anhydrite with high porosity.

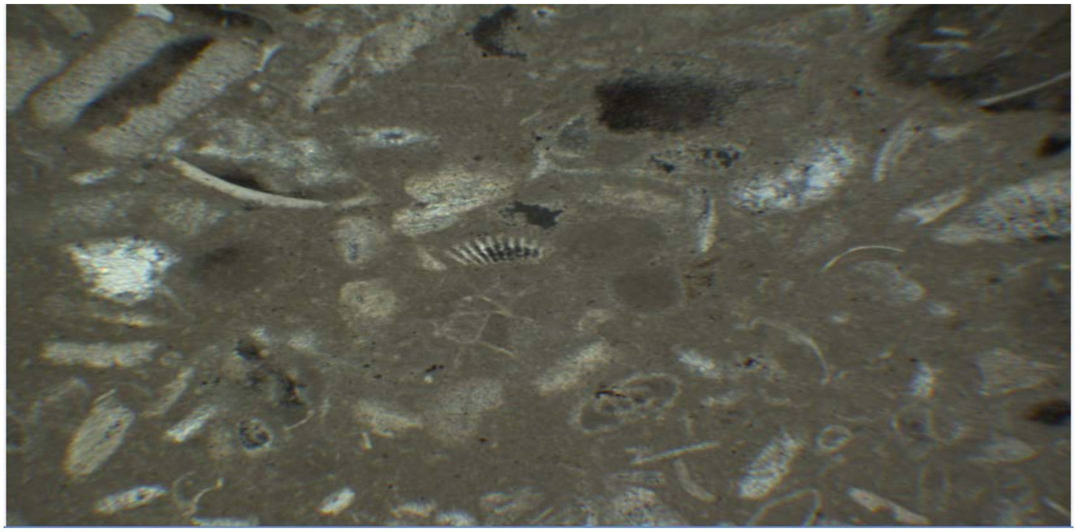

Mag 4x/0.10

Figure 97. (10,562') Limestone (boundstone): Corals, crinoids, gastropods, ostracods, anhydrite within rock sediment and porous matrix.

NDGS 12249, 17-146N-102W NENW, Meridian Oil Incorporated, Moi #21-17, McKenzie County, North Dakota.

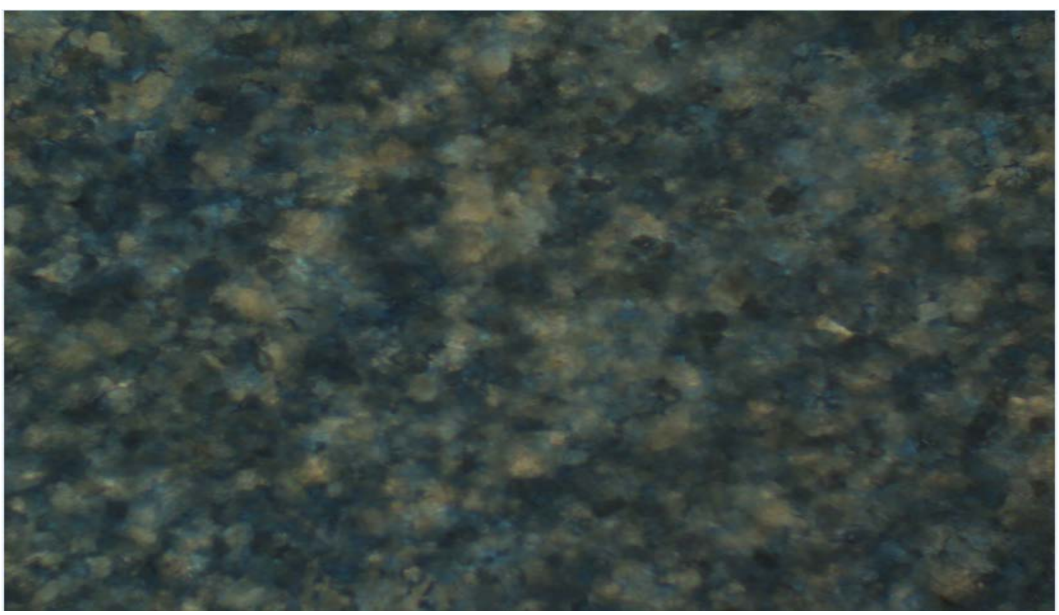

Mag 10x/0.22

Figure 98. (10,970.8'-10,971.1') Dolomite (packstone): Epoxy stained depicting high pore spaces within rock matrix.

NDGS 12962, 35-148N-102W SWSE, Pennzoil Exploration & Production Company, North Branch #35X-34 BN, McKenzie County, North Dakota.

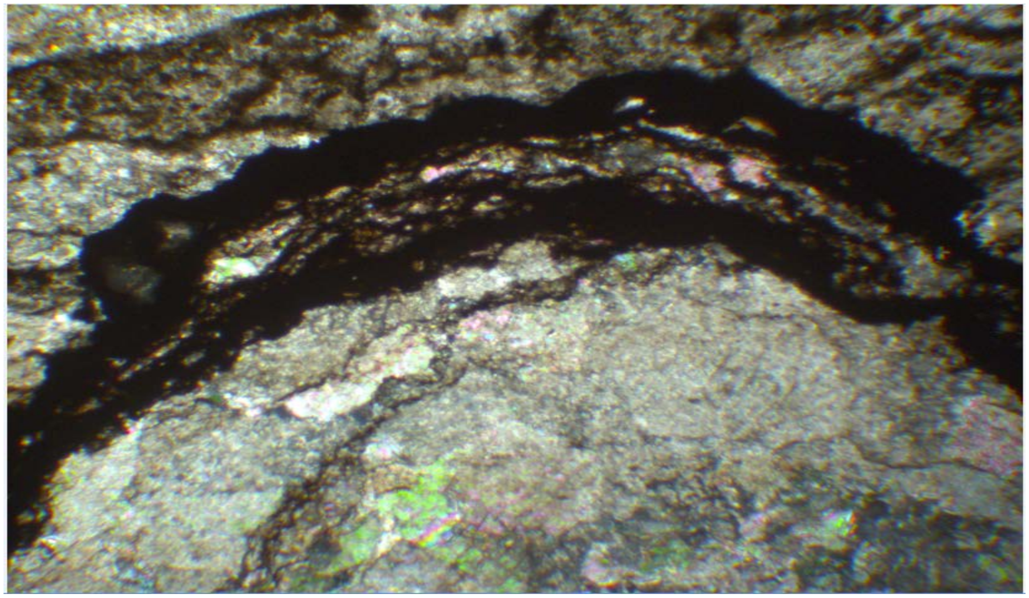

Mag 4x/0.10

Figure 99. (10,969.8') Limestone (packstone): Anhydrite pockets with dark (algae) soft organic sediment infilling with appreciable porosity.

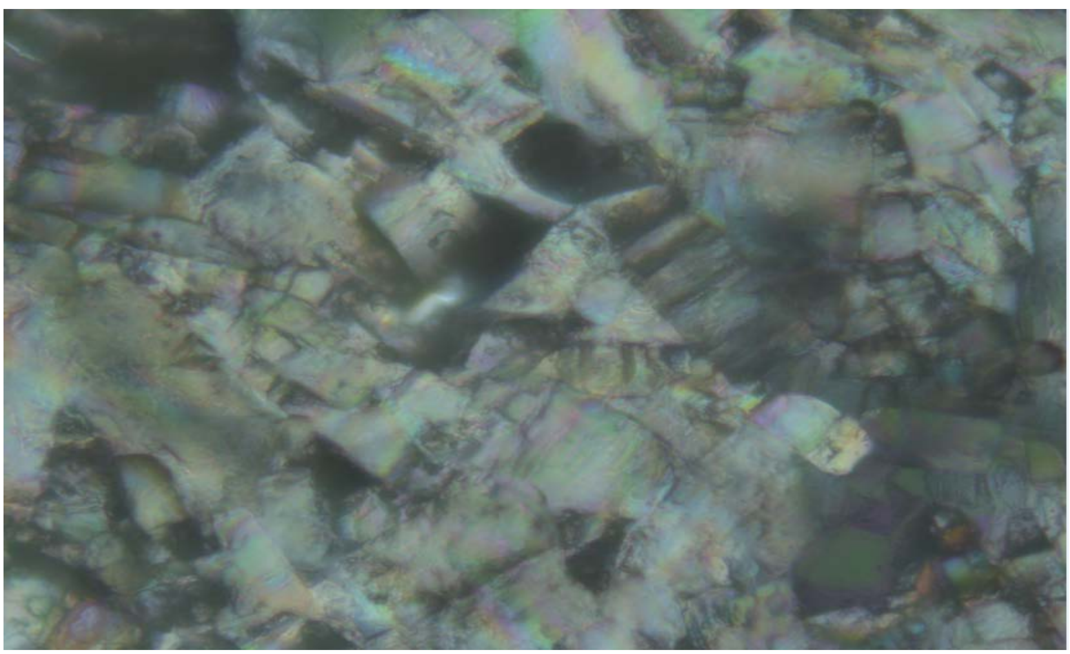
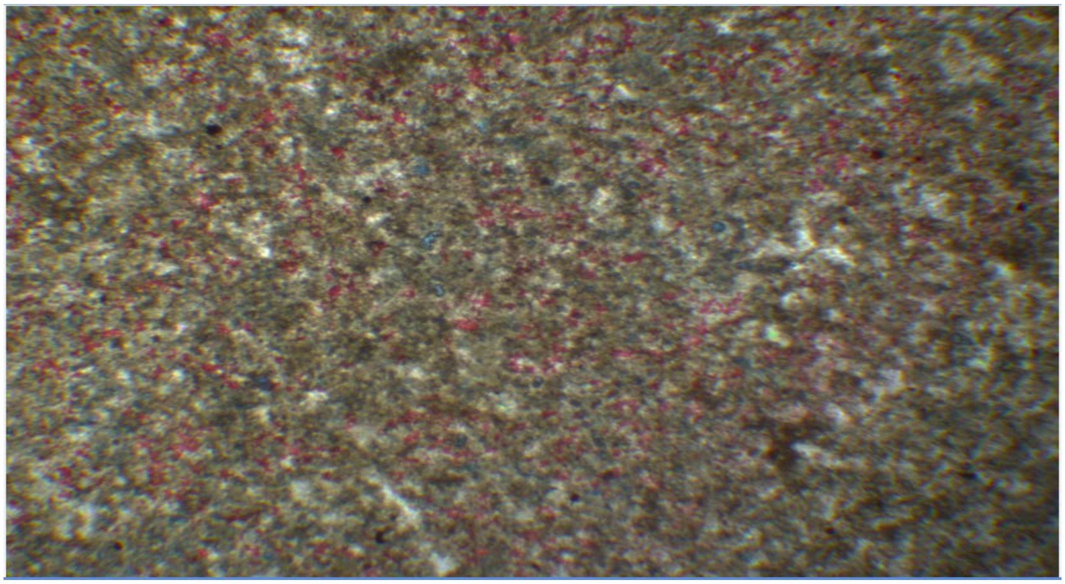
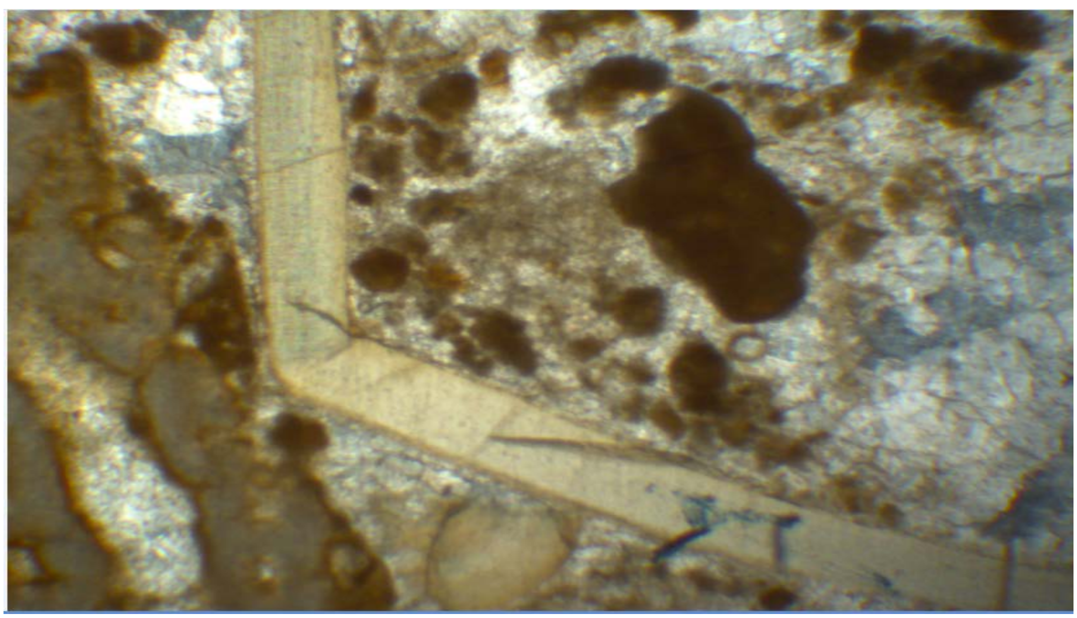

Mag 4x/0.10

Figure 100. (10,969.8') Limestone: Enlarged dolomite rhombohedra crystals in a dolomitizing limestone with calcite cement creating porosity.



Mag 4x/0.10

Figure 101. (10,975') Dolomite (packstone): Epoxy stained showing areas with porosity in rock fabric.



Mag 4x/0.10

Figure 102. (10,991') Limestone (boundstone): Deformed ostracod shell due to over burden pressure, calcite cement with good porosity and anhydrite.

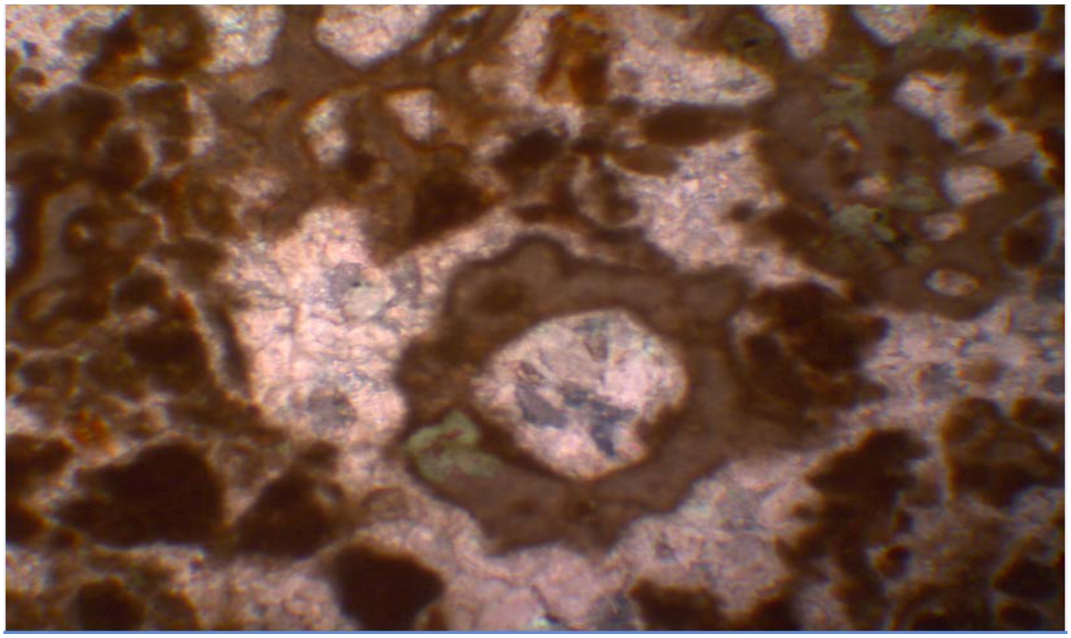
 Mag 4x/0.10

Figure 103. (10,'991) Limestone (boundstone): Ostracod with anhydrite pockets, very porous medium.

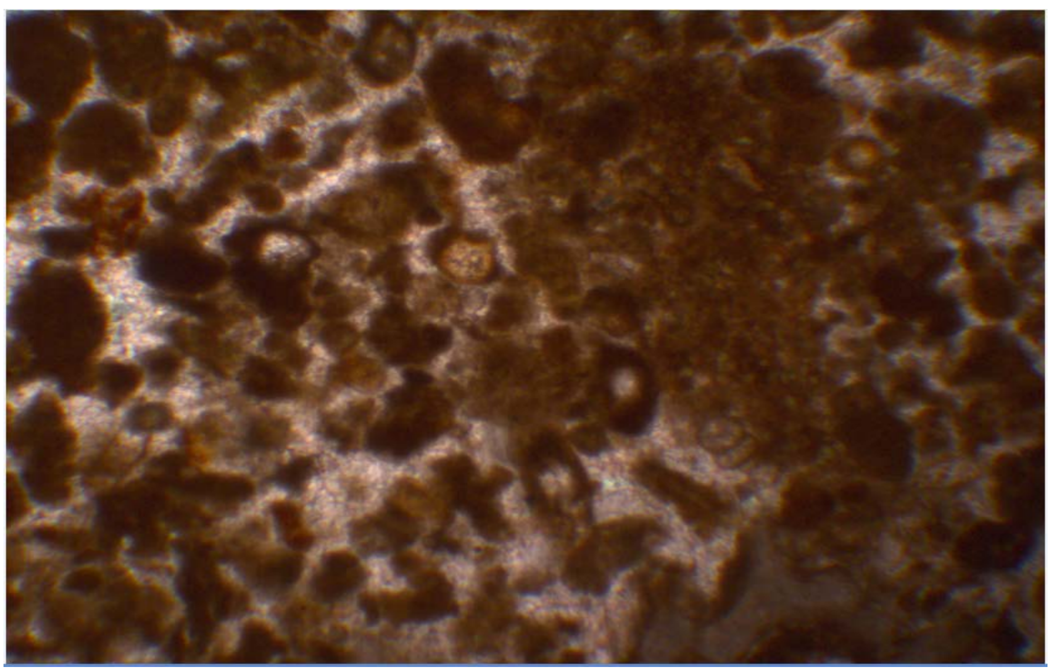
 Mag 4x/0.10

Figure 104. (10,991') Limestone (boundstone): Anhydrite pockets, recrystallization of calcite cements with inter grain porosity.

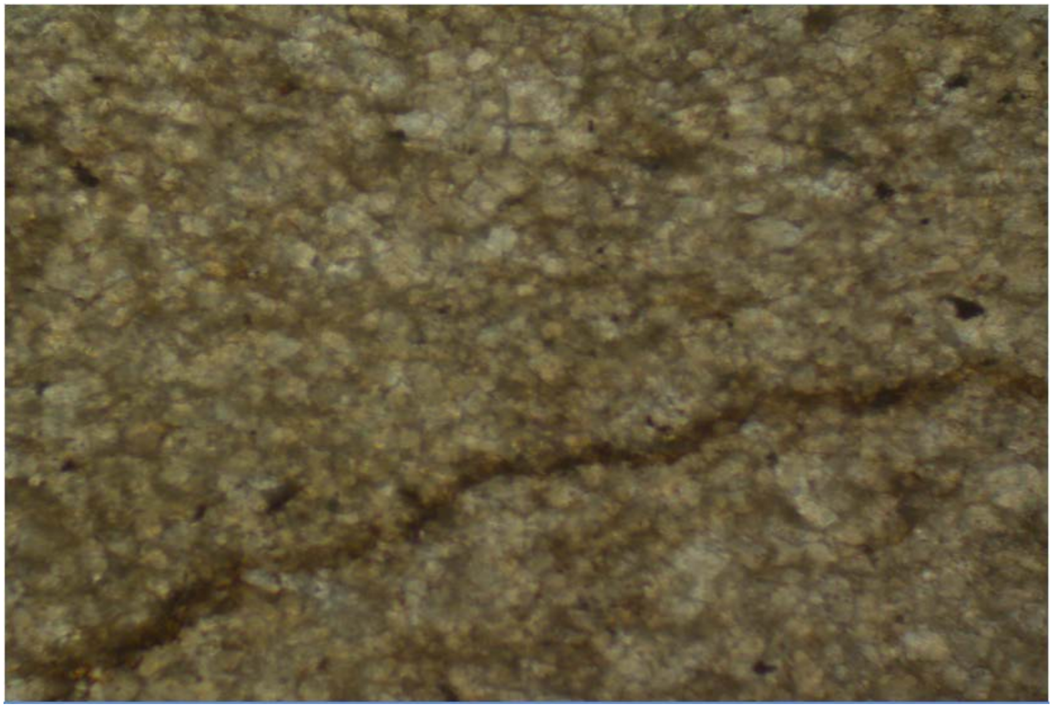
 Mag 10x/0.22

Figure 105. (11,009') Limestone (packstone): Dolomitizing limestone with soft organic sediment filled fracture. High porosity.

APPENDIX E

DATA FROM THE NMR (T_2), TRANSVERSE TIME DISTRIBUTION PLOTS

NUCLEAR MAGNETIC RESONANCE (NMR) SPECTROSCOPY DATA INTERPRETATION

Nuclear magnetic resonance (NMR) spectroscopy is a logging technology that measures hydrogen ion concentrations of pore fluids in hydrocarbon reservoir rocks from free induction decay time that is affected by size of pores in rock matrix due to surface interaction. From laboratory sampling measurements, it was observed that larger pores have long decay times while smaller pores exhibited shorter decay time with both signals combining to produce total relaxation time output for a sample. This technology has been employed in different fields of rock analytical downhole measurements in oil and gas explorations, for the technique was first employed in early 1950's. These measurements provide information on pore size distribution, fluid types, level of saturations, which is free/ bound fluid content of rocks, rock porosity (Washburn, K. E., and J, E. Birdwell, 2013) and the viscosity of fluids and surface interactions of these fluids.

However, nuclear magnetic resonance (NMR) spectroscopy measurements take a look at two units, (T_1) and (T_2) respectively.

The (T_1) unit observes the longitudinal relaxation time that measures how fast a rock sample recovers from magnetization after excitation in an experiment, and has been known to be time consuming to study in the laboratory on rock cores.

The (T_2) unit observes the transverse relaxation time and is the most common studied sampling method of the two parameters in rock core analysis because the relaxation curve is easier and faster to generate in rock sampling.

In this report the study is based on the transverse relaxation time (T_2), and its generated data values interpreted from graphs generated from sample analysis. Based on capillary and bound fluids present pores in the system from thirteen core samples that penetrates the Birdbear

Formation in McKenzie County in west central North Dakota were used for this analysis, which were further distinguished between limestone lithology and dolomite lithology. Measurements of dry core width, dry mass, saturated mass (cores were saturated with ordinary water at room temperature and pressure), and bulk volume samples were analyzed at different relaxation times, ranging from six minutes to twelve hours, as time chosen were dependents on the nature (lithology, mineral composition, and environment of deposition) of rock to produce best fit relaxation curve that generate specific porosity data from rock bound and capillary waters. Although core plugs are best for this analysis, most of the core samples I used were of irregular shape.

From distribution data analysis generated, average porosity values for limestone and dolomite were 1.8% and 7.2% respectively. These results show that both dolomite lithology and limestone lithology of the Birdbear Formation in McKenzie County exhibits good to excellent porosities to have allowed the migration of generated hydrocarbon in McKenzie County, which could be favorable reservoir rocks within the study area.

Generated relaxation graphs from both limestone lithology and dolomite lithology are shown below with interpretations.

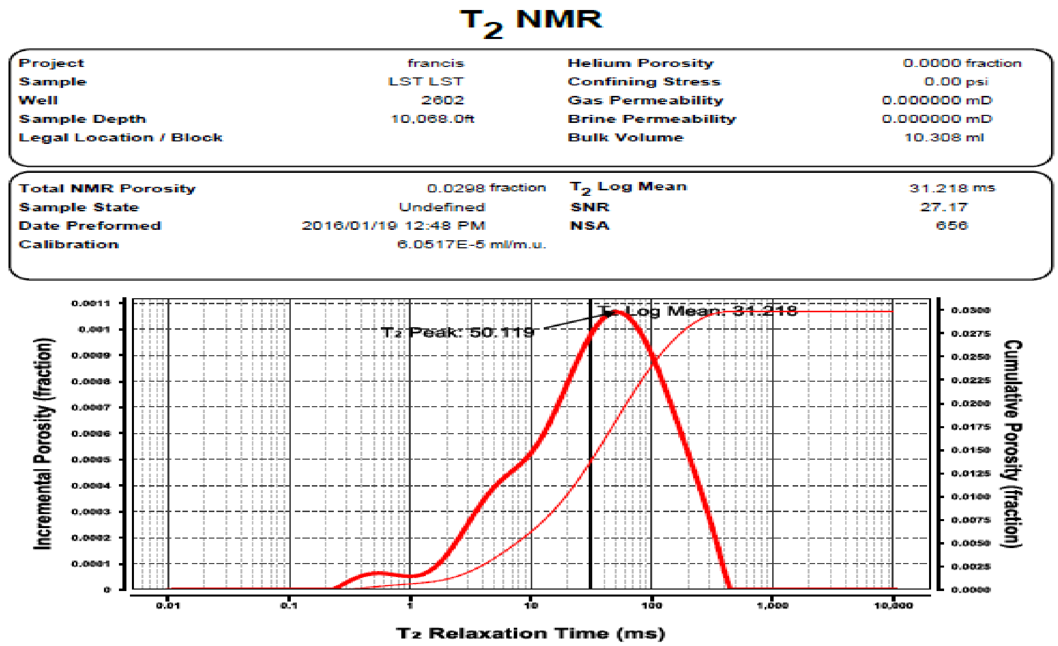


Figure 106. NDGS 2602 limestone lithology generated a uni-modal (T_2) distribution value, with porosity of 2.98%, which is due to the vugs porous nature from inter crystalline connectivity of sediment as observed from both core and thin section which generated high free water in the system during sampling.

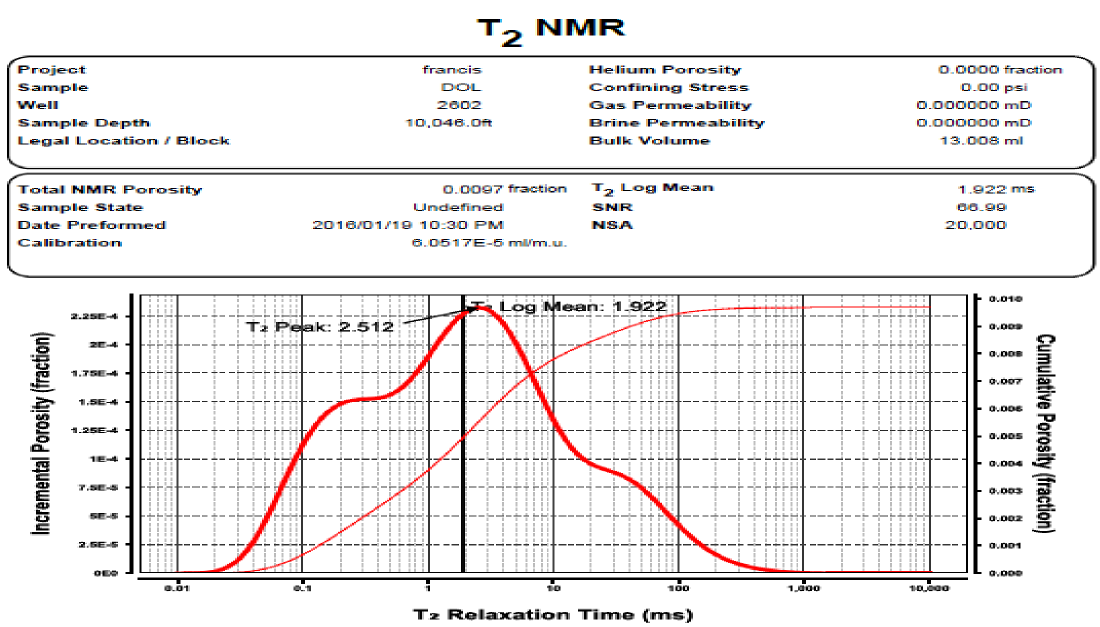


Figure 107. NDGS 2602 dolomite lithology generated a uni-modal (T2) distribution value, with porosity value of 0.97% as sediments were observed to have lost porosity probably by sediment reworking.

NDGS 2820, Texaco Incorporation, F. P. Keogh #4

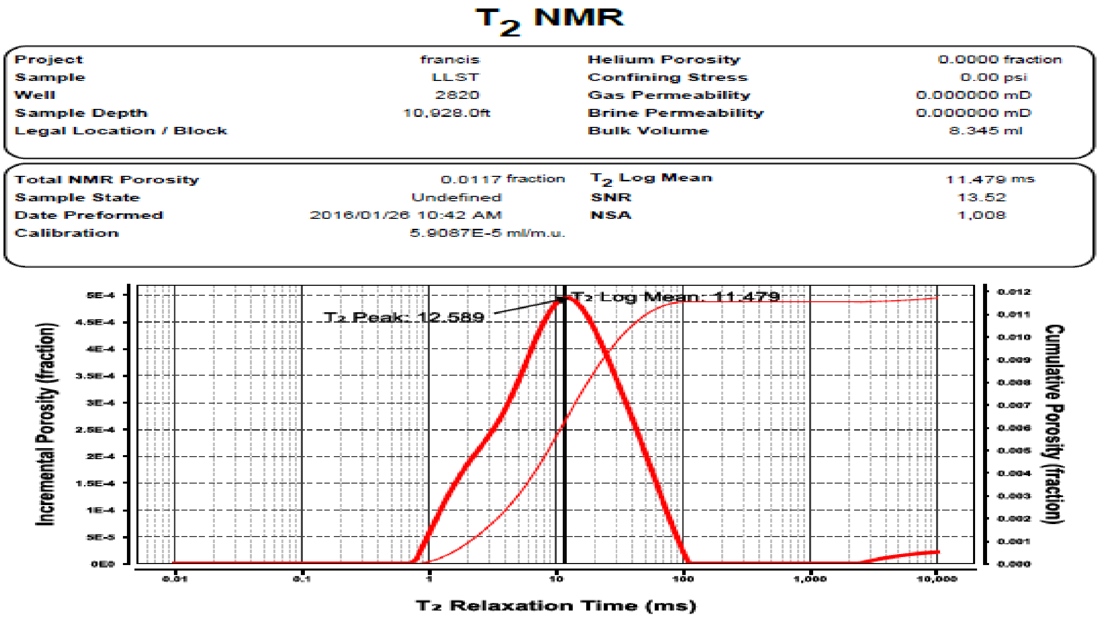


Figure 108. NDGS 2820 limestone lithology generated a uni-modal (T_2) distribution value, with porosity of 1.17% as it indicates an average free water in the system, with intra-particle grain porosity effective at this depth.

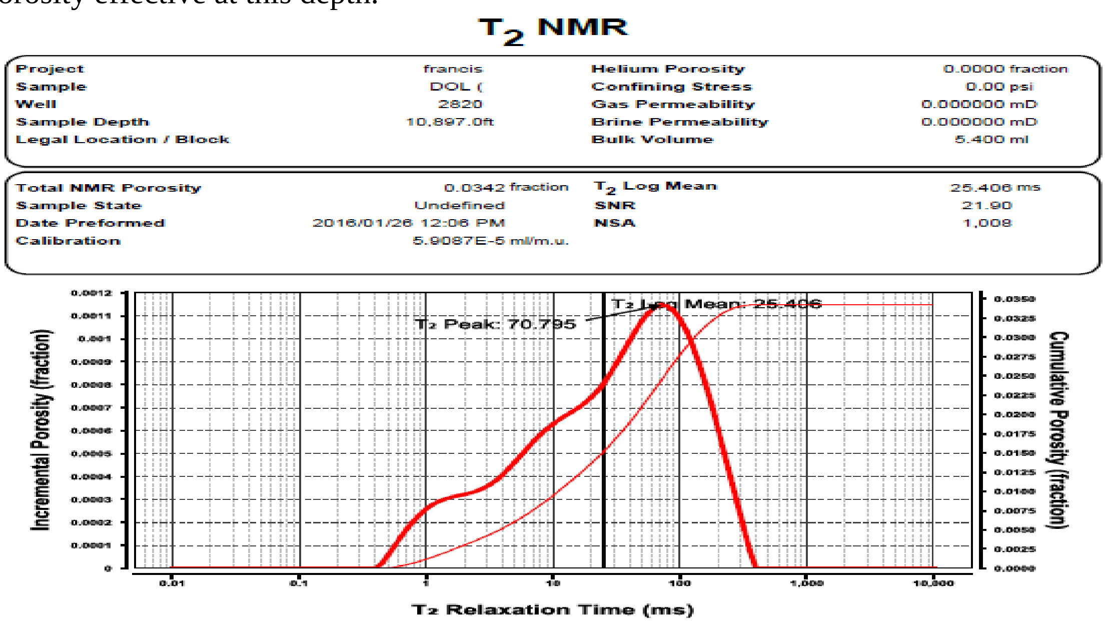


Figure 109. NDGS 2820 dolomite lithology generated a uni-modal (T_2) distribution value, with porosity of 3.42%, indicating an average free water in system that depicts sediments at this depth to be porous.

NDGS 2967, Texaco Incorporation, A. S. Wisness #2

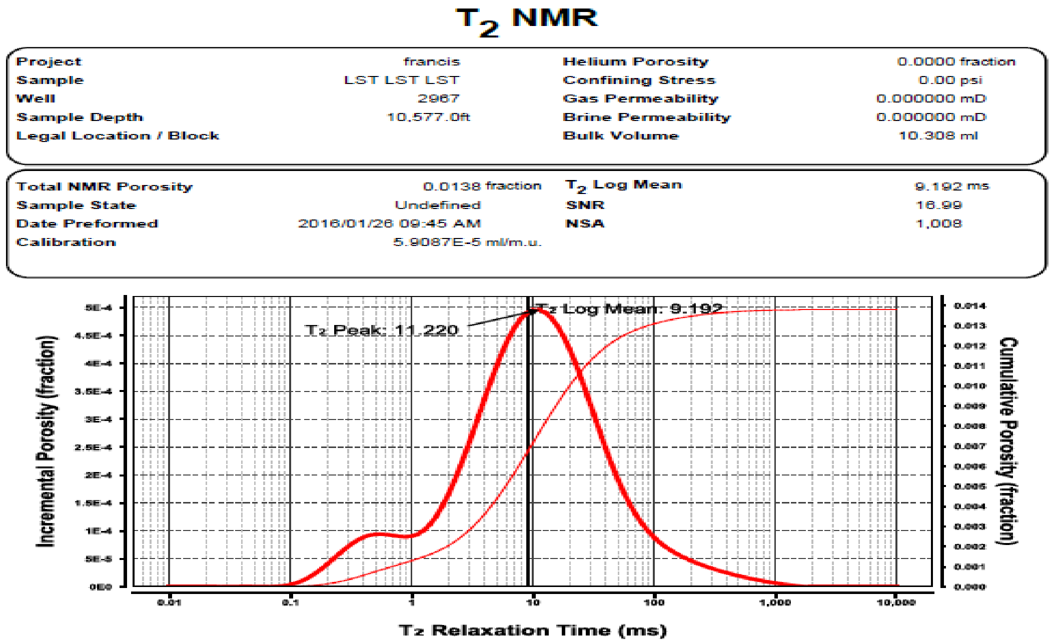


Figure 110. NDGS 2967 Limestone lithology generated a uni-modal (T_2) distribution value, with porosity of 1.38%, indicative of average porous sediments at this depth as free water are less in the system.

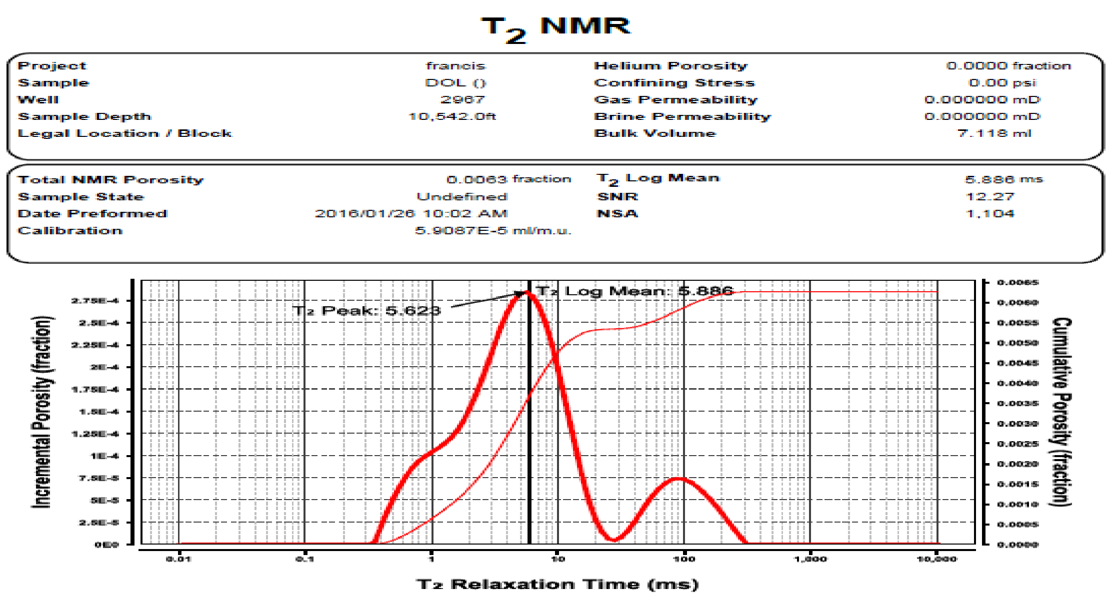


Figure 111. NDGS 2967 dolomite lithology generated a bi-modal (T_2) distribution value, with porosity of 0.63% as sediments here recorded low porosity as observed from core and thin section.

NDGS 3086, Amerada Petroleum Corporation, Antelope Unit "B" #1

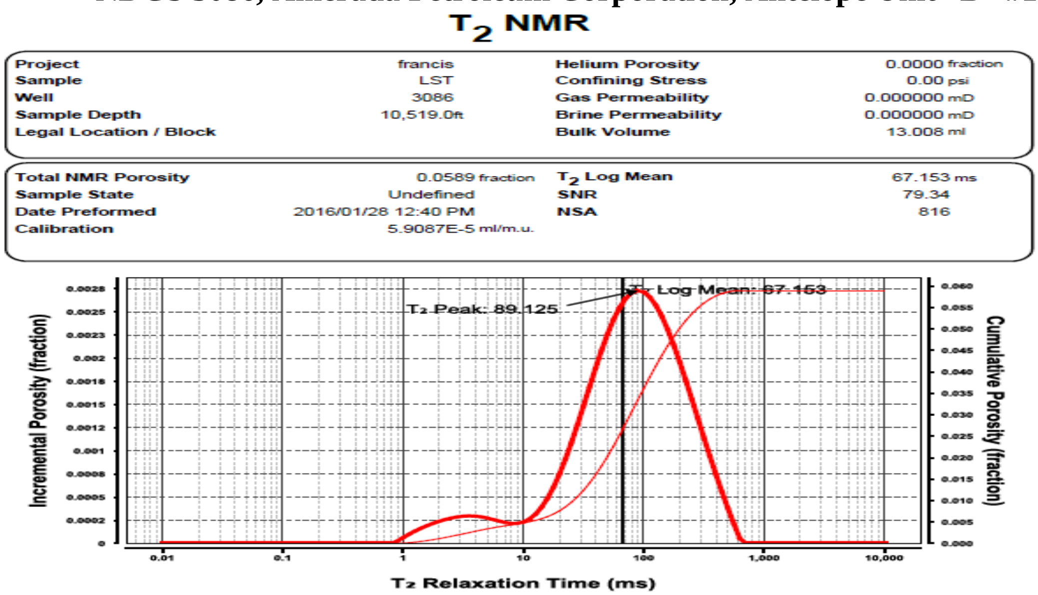


Figure 112. NDGS 3086 limestone lithology generated a uni-modal (T_2) distribution value, with porosity of 5.89% as sediments at this depth were marked with vug porosity that gave average free water in the system.

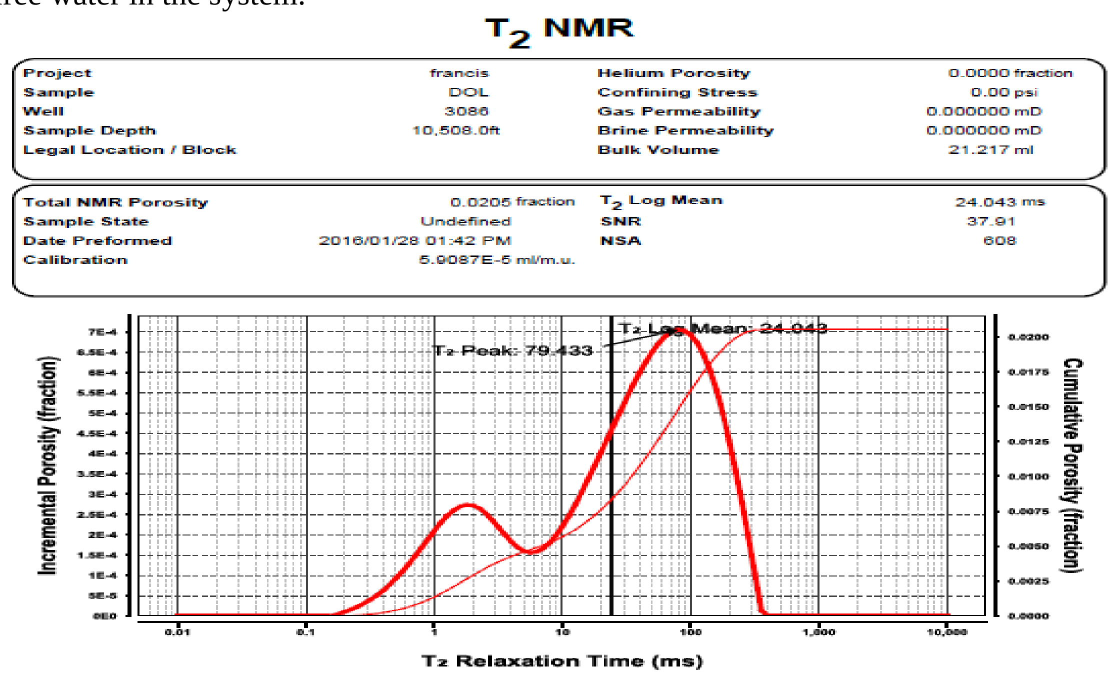


Figure 113. NDGS 3086 dolomite lithology generated a bi-modal (T2) distribution value, with porosity value of 2.05% as sediments at this depth exhibited inter crystalline porosity which generated average free water in the system.

NDGS 3614, Calvert Drilling & Production Corporation, Alfred Brown #1

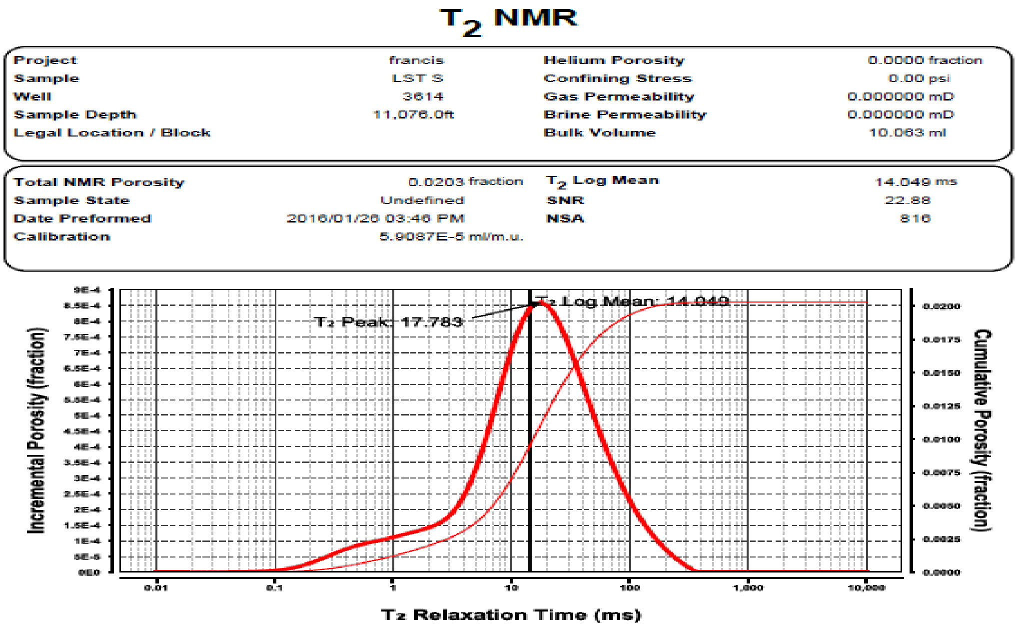


Figure 114. NDGS 3614 limestone lithology generated a uni-modal (T_2) distribution value, with porosity of 2.03% as sediments at this depth exhibits vugs that generated average free water in the system.

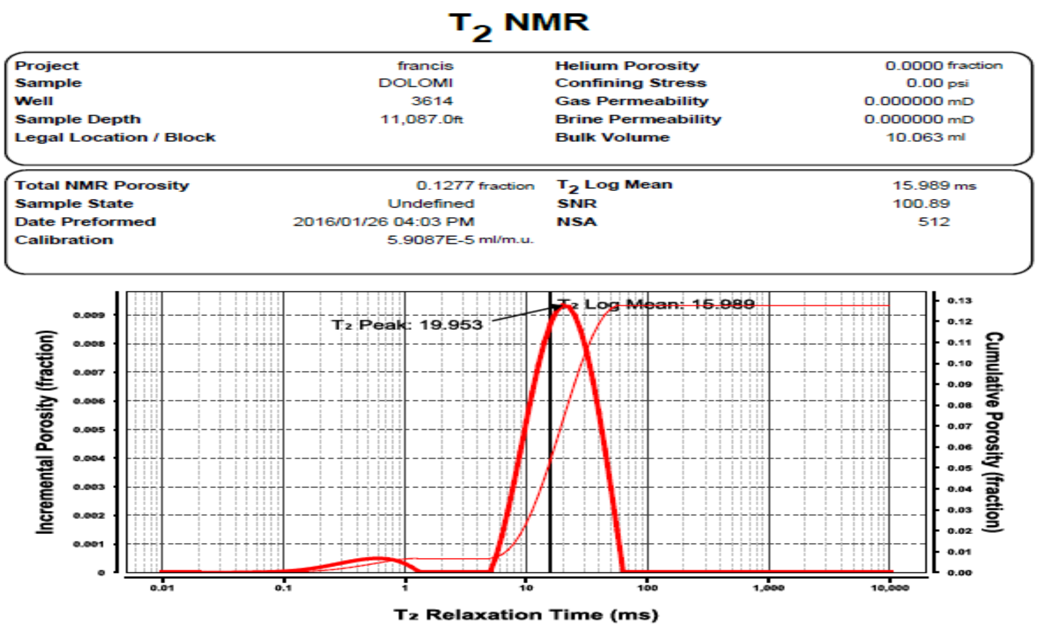


Figure 115. NDGS 3614 dolomite lithology generated a uni-modal (T_2) distribution value, with porosity value of 12.77% from a high free water in the system from sediments at this depth which showed oil stains.

NDGS 5742, Texaco Incorporation, Devonian Unit 2 #1X

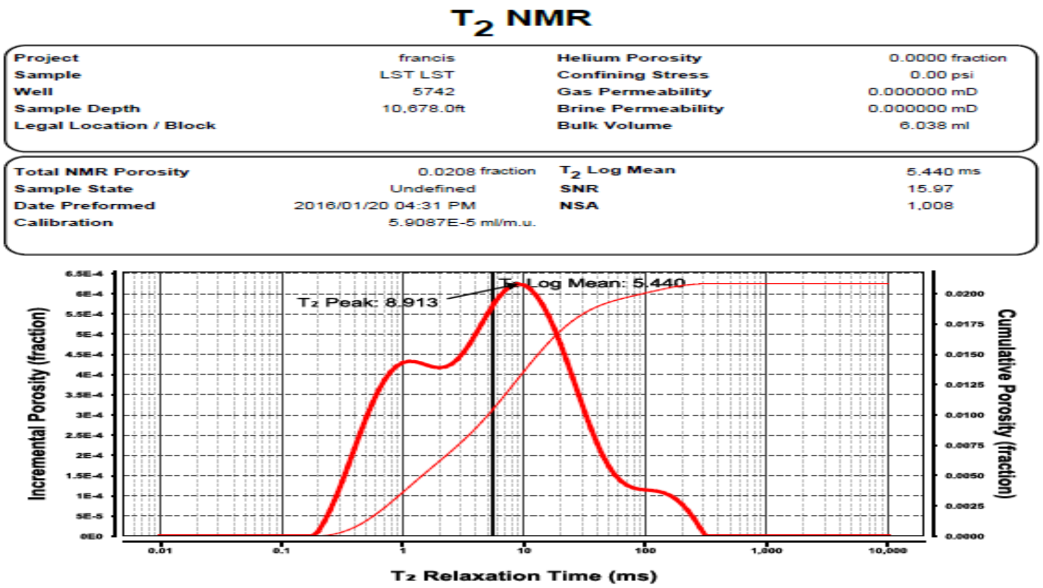


Figure 116. NDGS 5742 limestone lithology generated a bi-modal (T_2) distribution value, with porosity value of 2.08%, indicating an average free water in the system. Sediment porosity here were of fracture and burrows within rock matrix.

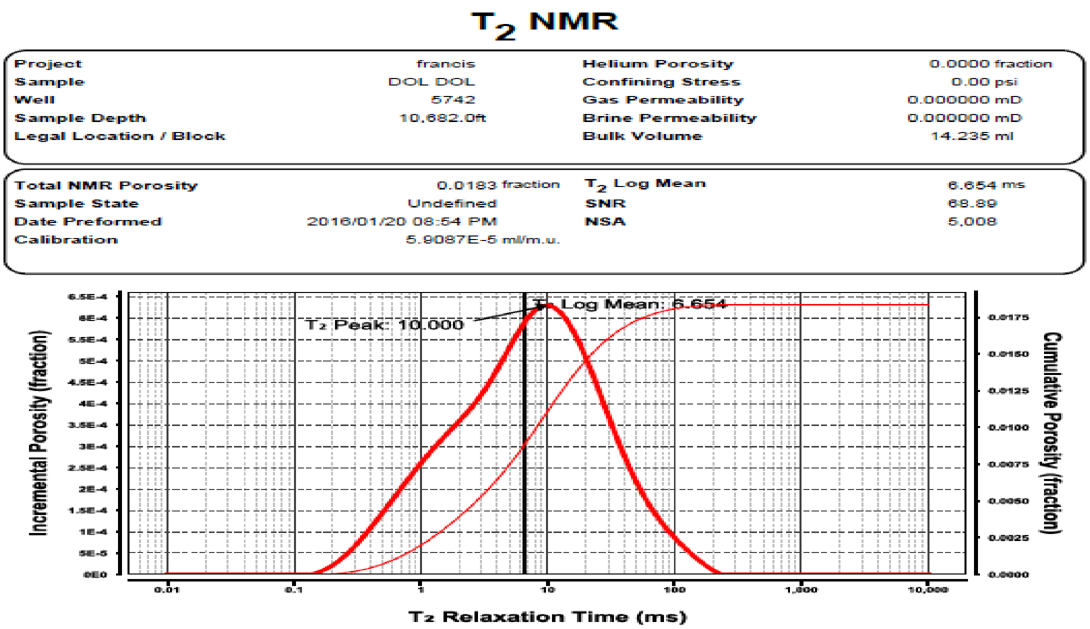


Figure 117. NDGS 5742 dolomite lithology generated a uni-modal (T_2) distribution value, with porosity of 1.83%, as sediment at this depth are not porous enough and generated low free water in the system.

NDGS 12249, Meridian Oil Incorporated, Moi #21-17

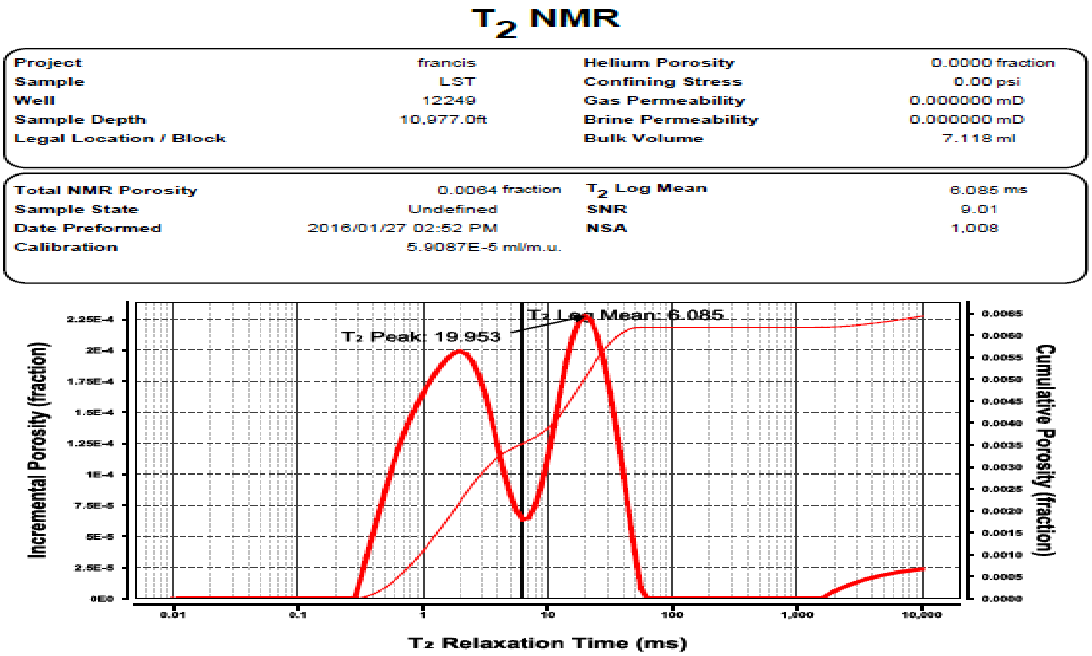


Figure 118. NDGS 12249 limestone lithology generated a bi-modal (T_2) distribution value, with porosity value of 0.64% as sediments here were well compacted with little to no pores present generating low free water in the system.

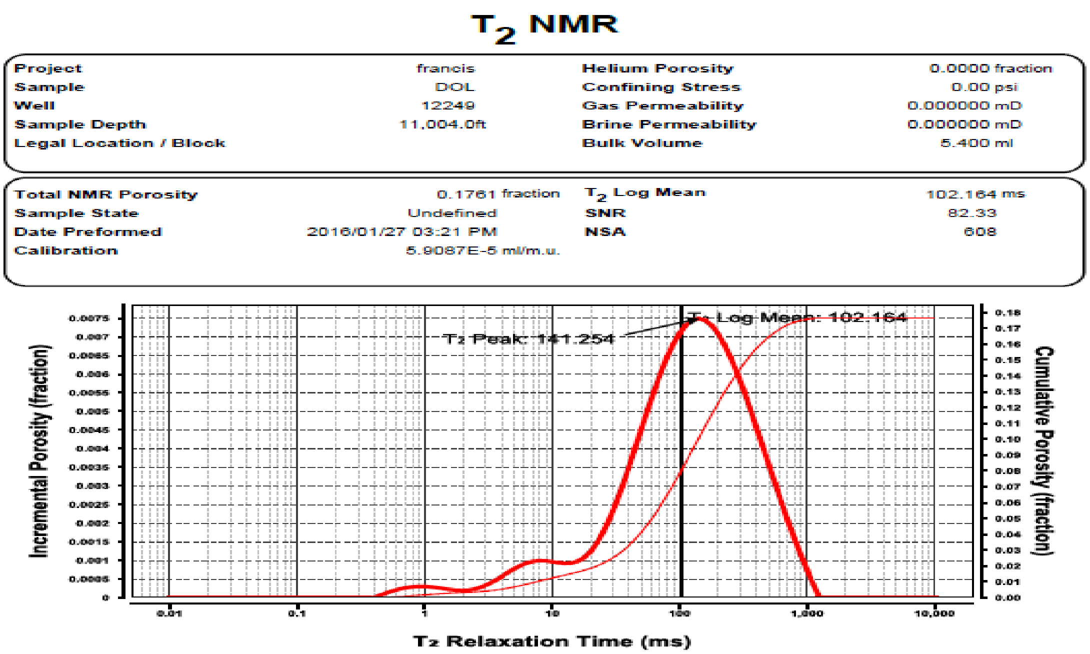


Figure 119. NDGS 12249 dolomite lithology generated a uni-modal (T_2) distribution value, with porosity value of 1.76% due to averagely porous sediments that are found at this depth that generated low free water in the system.

NDGS 12962, Pennzoil Exploration & Production Company, North Branch #35X-34 BN

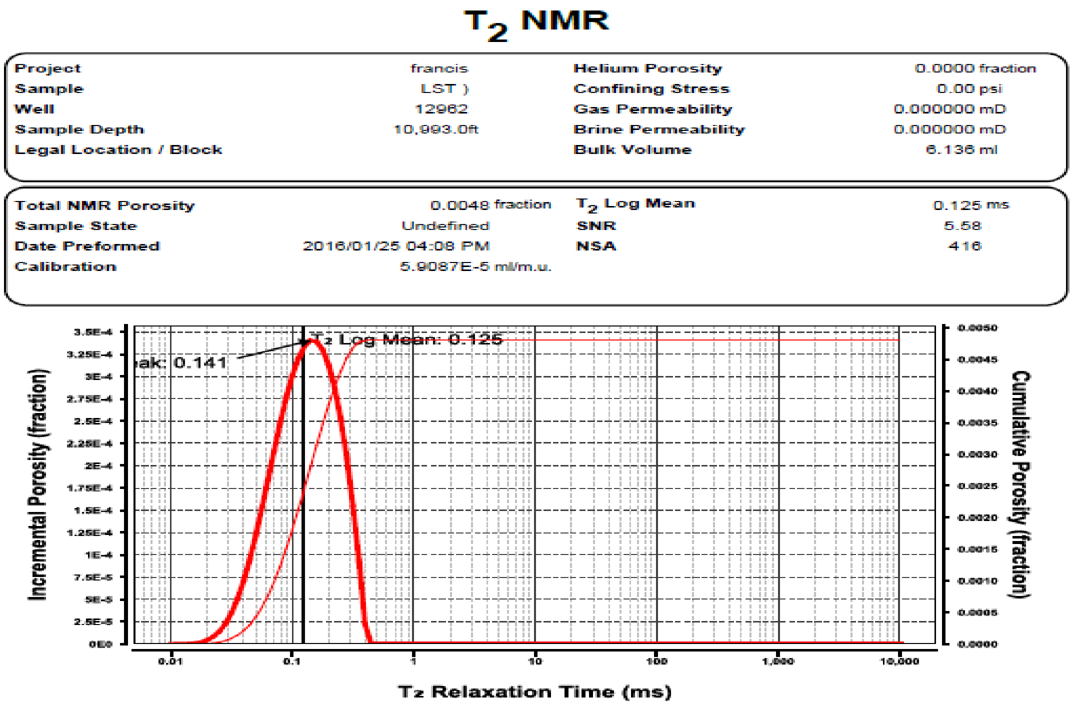


Figure 120. NDGS 12962 limestone lithology generated a uni-modal (T_2) distribution value, with porosity value of 0.48% due to the poor porous nature of sediments at this depth that gave a low free water in the system.

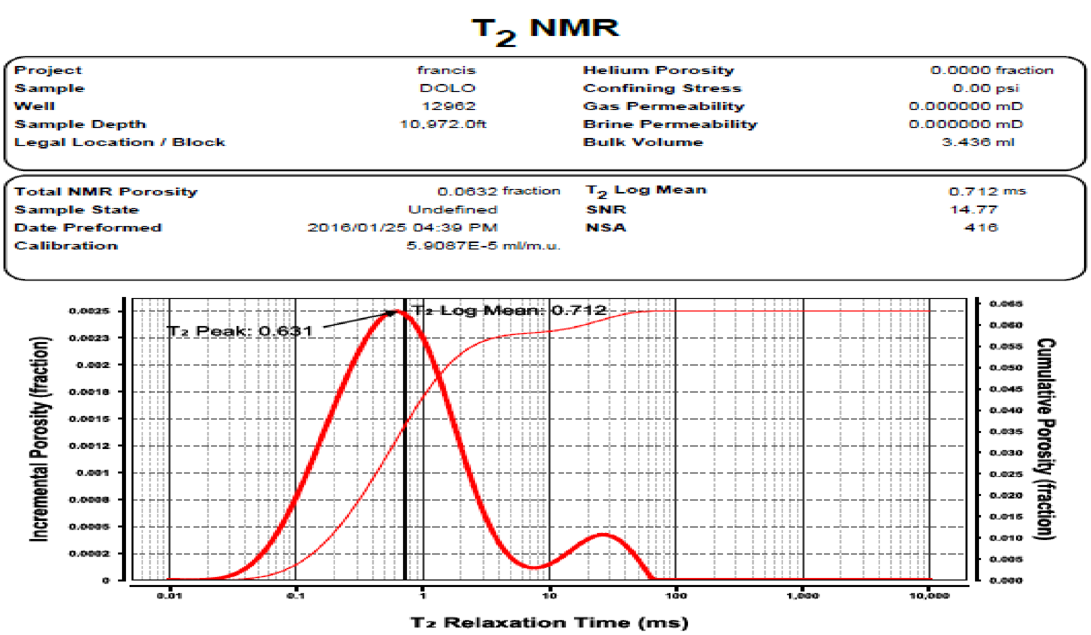


Figure 121. NDGS 12962 dolomite lithology generated a bi-modal (T_2) distribution value, with porosity values of 6.32% due to high selective dolomitization of sediments that increased porosity in the rock matrix, which shows free water in the system.

NDGS 19918, Continental Resources Incorporation, Charlotte 1-22H

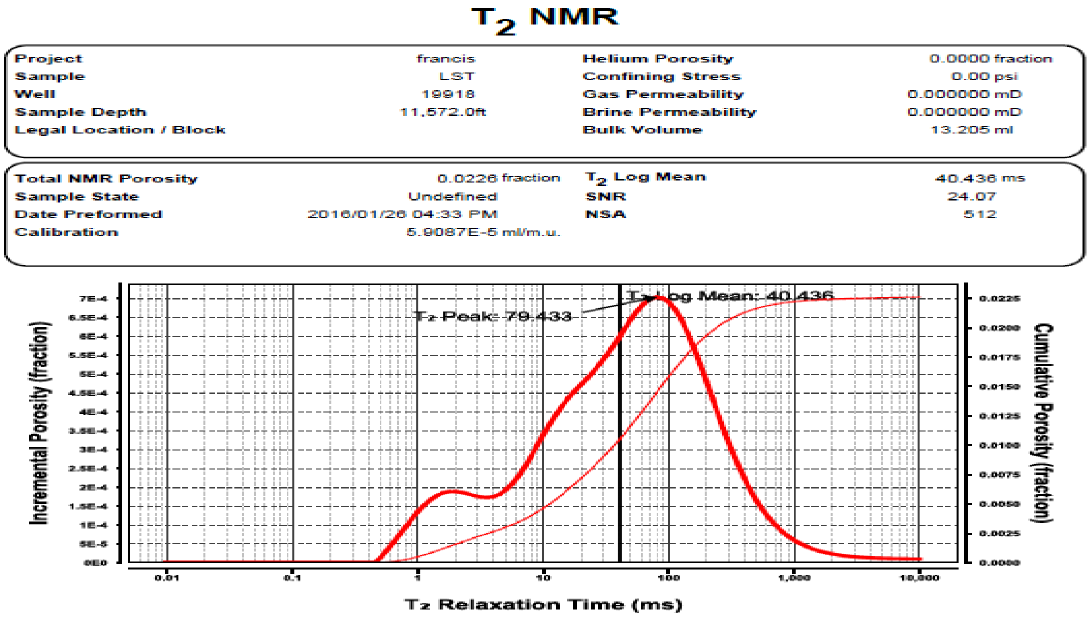


Figure 122. NDGS 19918 limestone lithology generated a bi-modal (T_2) distribution value, with porosity value of2.26%, as sediments here are exhibited fair porosity, generating an average free water in the system.

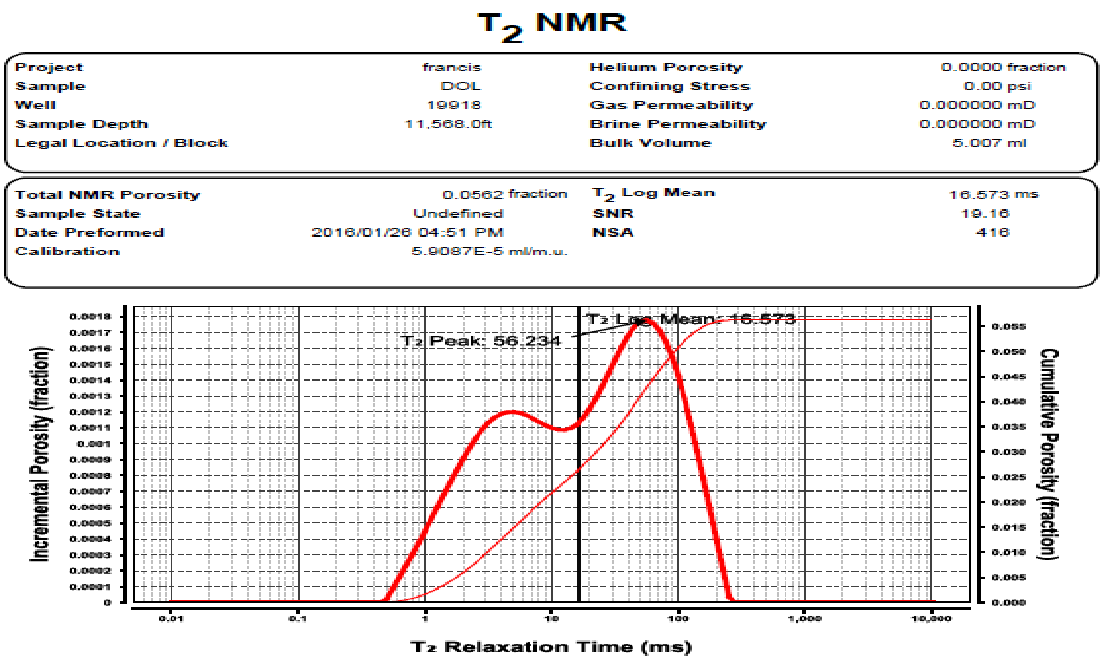


Figure 123. NDGS 19918 dolomite lithology generated a bi-modal (T_2) distribution value, with porosity value of 5.62%, due to the high free water in the system with sediment highly fractured with solution seams.

NDGS 21786, Denbury Onshore LLC, Rink 12-4ESH

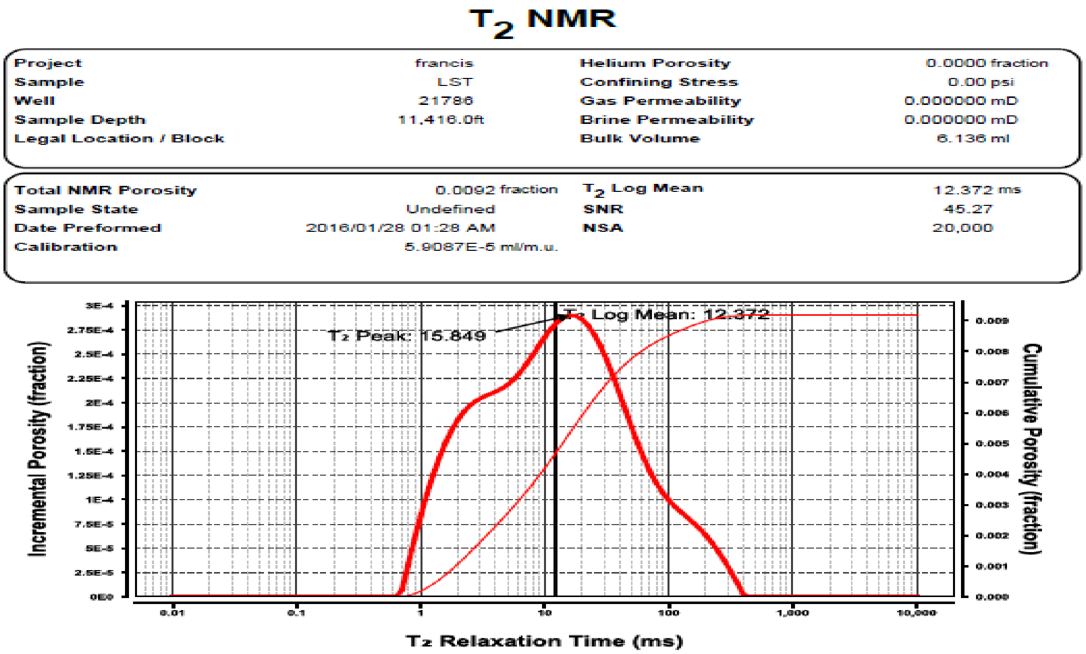


Figure 124. NDGS 21786 limestone lithology generated a uni-modal (T_2) distribution value, with porosity value of 0.92% which indicates that sediments here are lacking porosity generating low free water in the system.

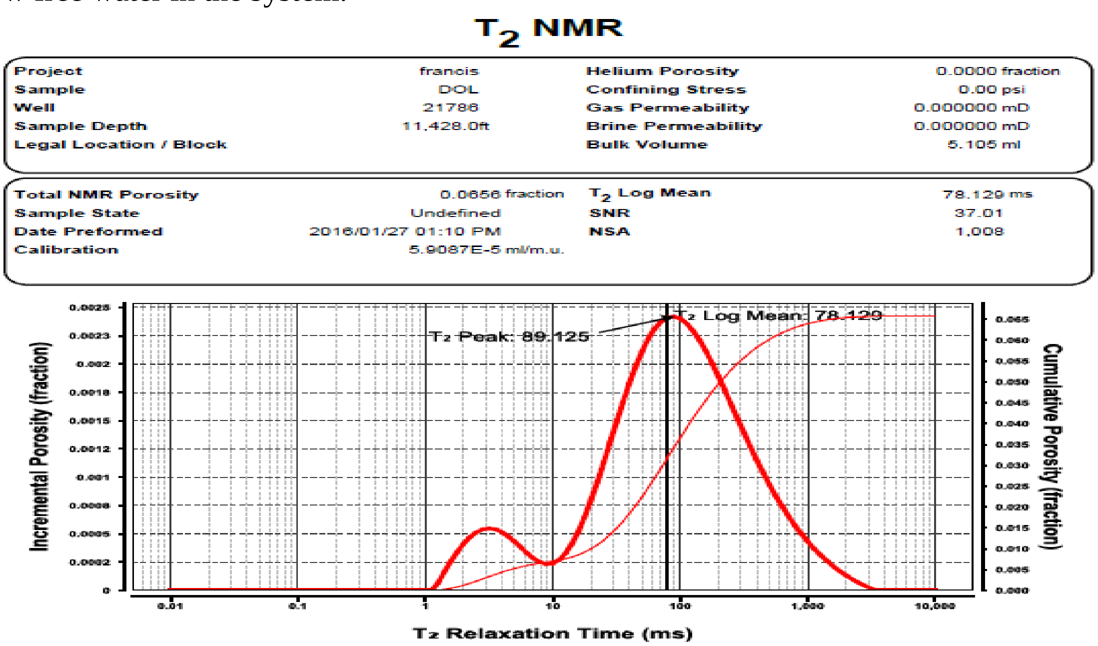


Figure 125. NDGS 21786 dolomite lithology generated a bi-modal (T_2) distribution value, with porosity value of 6.56%, because sediment here exhibited inter crystalline porosity generating high free water in the system.

NDGS 24123, XTO Energy Incorporation, Marina Trust 12X-20G2

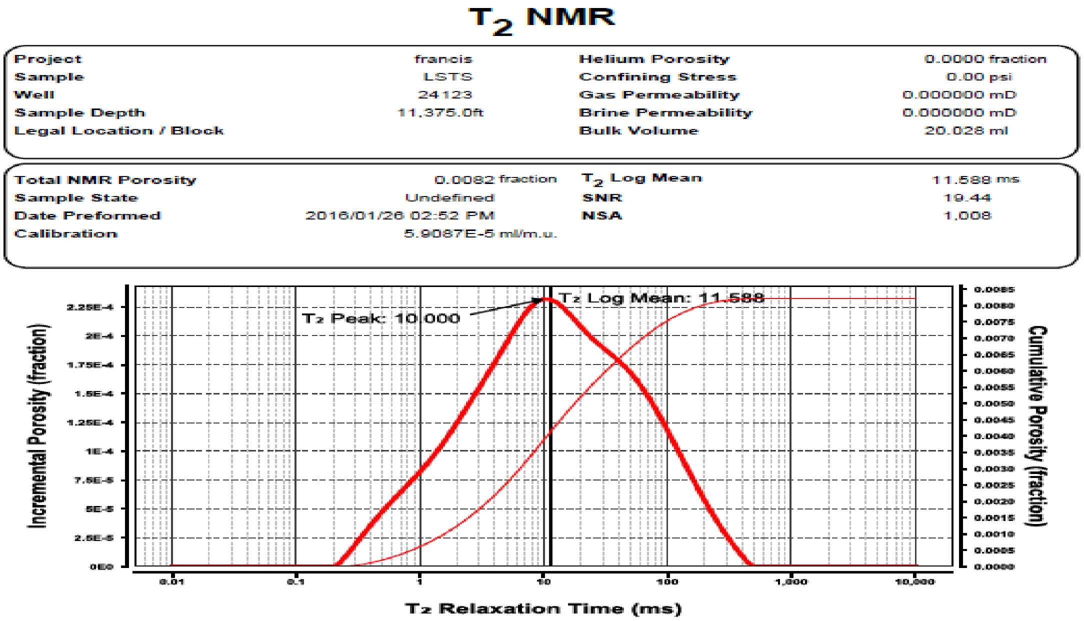


Figure 126. NDGS 24123 limestone lithology generated a uni-modal (T_2) disrtibution value, with porosity of 0.82% as the sediment at this depth are of dense anyhdrite, thus lacking porosity and low free water in the system.

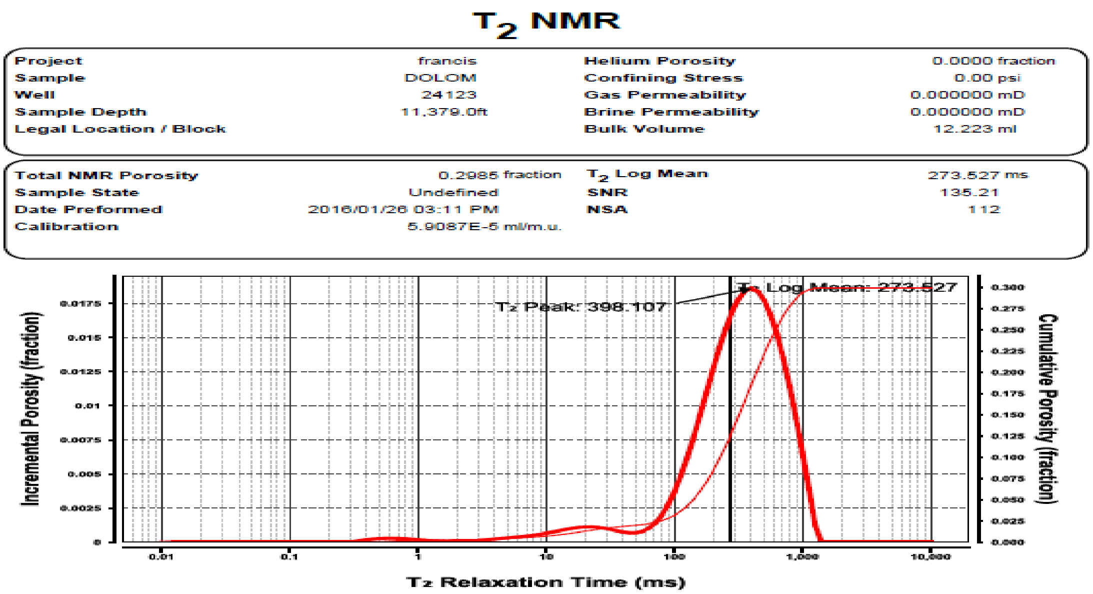


Figure 127. NDGS 24123 dolomite lithology generated a uni-modal (T_2) distribution value, with porosity value of 29.85%. From thin section and core description, samples at this depth exhibited high porosity and high free water in the system.

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