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Petrography and Reservoir Characterization of Cretaceous Sandstones of the Parkin, Fishing Branch, and Cody Creek Formations of the Eagle Plains Sedimentary Basin, Yukon.

By

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The undersigned certify that they have read, and recommend to the department of geosciences for acceptance, a thesis entitled “Petrography and Reservoir Potential of Cretaceous Sandstones of the Parkin, Fishing Branch, and Cody Creek formations of the Eagle Plains Sedimentary Basin, Yukon" submitted by Michael McQuilkin in partial fulfilment of the requirements of the degree of BACHELOR OF SCIENCE (HONOURS).

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Supervisor, Dr. Rudi Meyer, Department of Geoscience

Date

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Abstract

The Eagle Plain Basin is an underexplored region with known hydrocarbon potential located in northern Yukon Territory. The primary objective of this study is to investigate whether the middle to Upper Cretaceous Parkin, Fishing Branch and Cody Creek formations can be distinguished mineralogically and to assess the reservoir quality of each formation through petrographic analysis of fifty-five thin sections from the succession.

The Fishing Branch and Parkin formations are similar in composition but can be differentiated based on mineralogy. The Fishing Branch Formation contains bimodal mineralogical compositions of high modal quartz and high modal chert. Chert rich sandstones of the Fishing Branch delta front sandstones constitute very good reservoir rock, while quartz rich sandstones that dominate the Fishing Branch and Parkin formations constitute very poor to good reservoir rock. Reservoir heterogeneity due to diagenetic cemented zones, clays associated with bioturbation, and compaction plays a major role in the reduction of reservoir quality throughout the Parkin and Fishing Branch formations. Although these features are very apparent in the studied samples, their prevalence will be variable on a basin scale as a result of different depositional and tectonic settings.

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List of Symbols

Symbol	Definition
10-09-05	First number (10) indicates the year the sample was taken, 2010. The second number (09) indicates the assigned outcrop number. The third number (05) represents the sample number from the specified outcrop
I-13-1120.8	Core sample from well I-13, sampled from 1120.8m below KB
PPL	Plane Polarized Light
XPL	Cross Polarized Light

Chapter One: **INTRODUCTION**

The Eagle Plain Sedimentary Basin (EPSB) of the northern Yukon Territory (Fig.1) is an underexplored intermontane basin with potential to contain vast quantities of hydrocarbons (Fig.1). The basin is thermally mature, contains abundant potential reservoir rock, has oil seeps on the surface and has tested gas and oil in five wells in the southern part of the basin despite the limited exploration in the region (*Jackson et al, 2011*). As the demand for fossil fuels increase, there is a need to conduct additional exploration and bring Canada's frontier resources to production to meet rising demand. This undergraduate thesis is a petrographic analysis of middle to upper Cretaceous aged samples collected from outcrops in the Eagle Plain area during 2009 and 2010 field seasons.

This analysis focused on determining reservoir potential and mineralogical composition through petrographic analysis of fifty-five thin section samples from Cretaceous sandstones of the basal and middle Parkin and the Fishing Branch and Cody Creek formations (Fig.4).

Eagle Plain has experienced multiple tectonic episodes during the formation of the Canadian Cordillera; the landscape consists of low rolling hills of the Eagle Plain fold belt, and the basin is bounded by the Ogilvie Mountains to the south and west and the Richardson Mountains to the east.

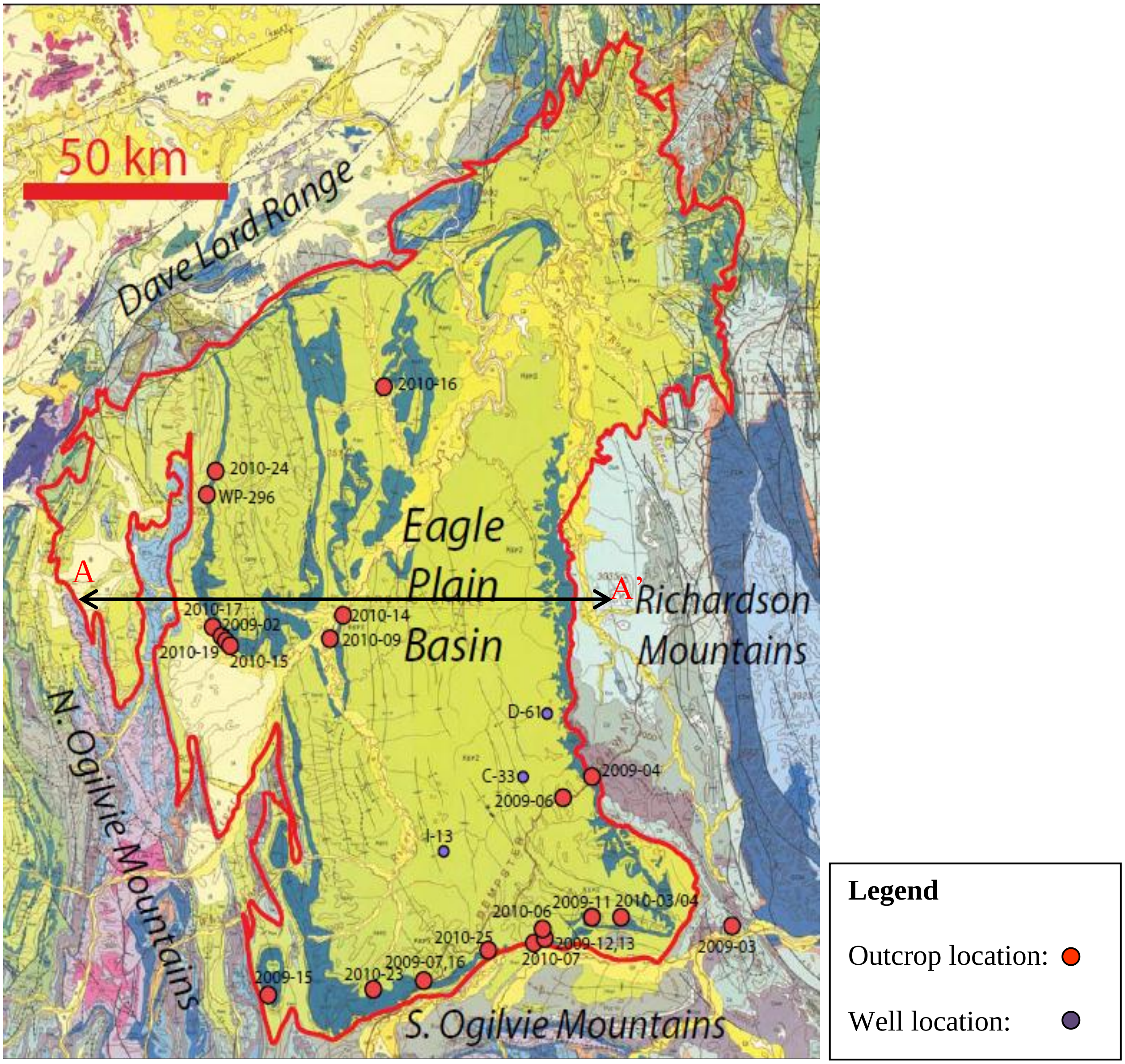

Fig.1. Geologic map of the Eagle Plain Sedimentary Basin showing the northern Yukon study area. ***(Modified from Norris, 1985).*** **Cross section line A-A' shown in Fig.2.**

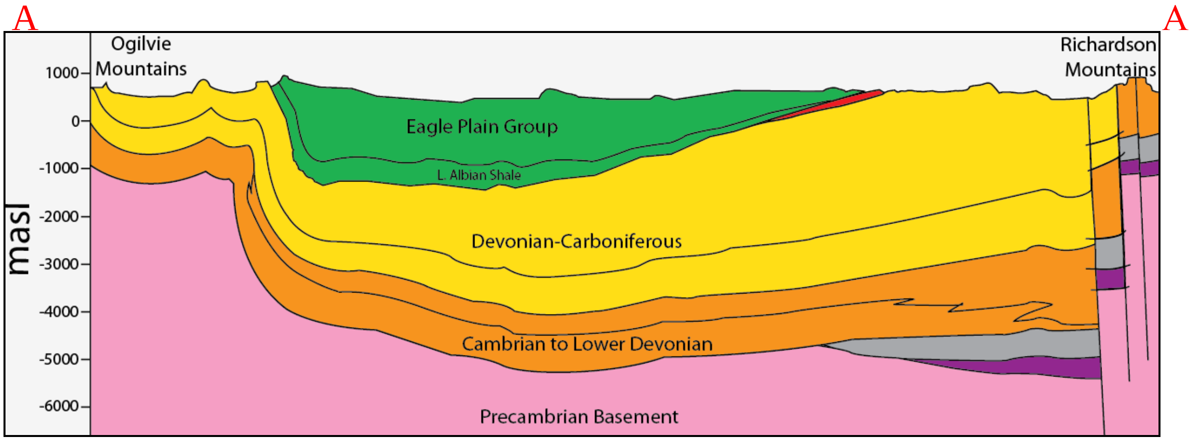

Fig.2. Schematic cross section from west to east (A-A' on Fig.1) across the Eagle Plain Sedimentary Basin showing strata of the basin. ***(Modified from Osadetz et al, 2005 and Jackson pers comm. 2011)***

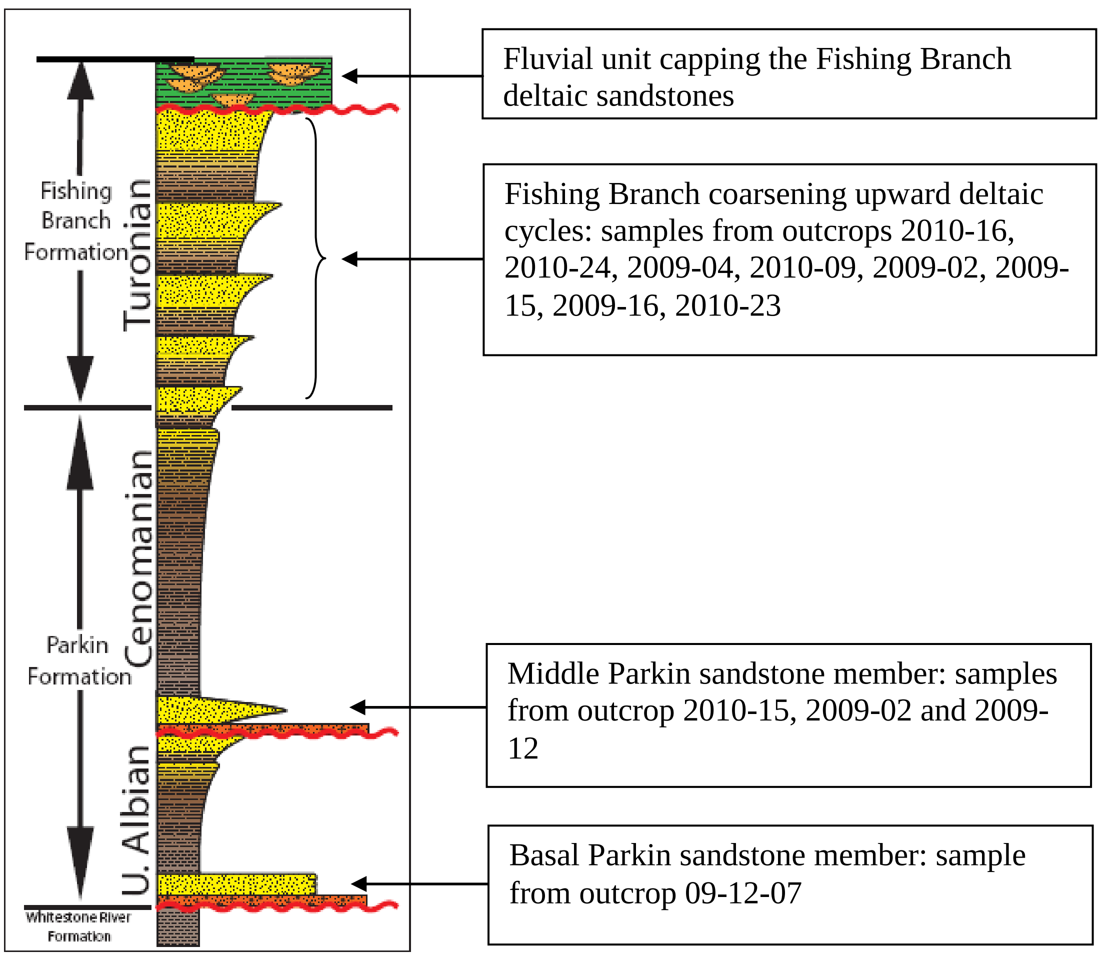

Fig.3. Stratigraphic column of Cretaceous Parkin and Fishing Branch formations of the Eagle Plains Group. ***(Jackson et al. 2011)***

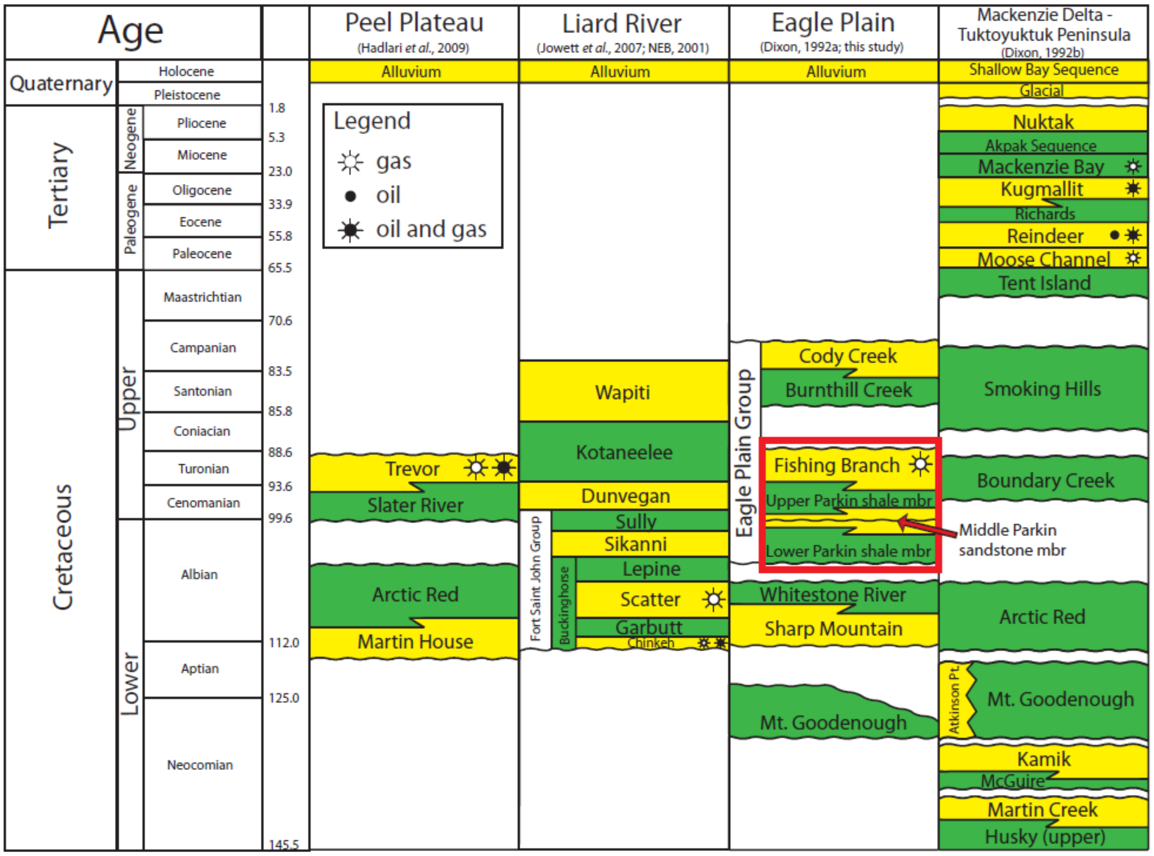

Fig.4. Stratigraphic column highlighting Cretaceous Eagle Plain strata (*Jackson et al, 2011*)

Chapter Two: **PREVIOUS GEOLOGIC WORK**

Work undertaken by Dixon (1992) within the EPSB focused on regional lithostratigraphic mapping and outcrop descriptions of Cretaceous sandstones within the basin. Recent and ongoing work carried out by Jackson et al., (2011) focused on building a high resolution sequence stratigraphic framework for the Parkin and Fishing Branch formations by tying measured outcrop sections to subsurface well data. This undergraduate thesis is intended to complement the studies of Kevin Jackson in his master's thesis by providing petrographic characterization to assist in refining the sequence stratigraphic framework. An absence of detailed petrographic descriptions of the Cretaceous succession and analysis of their reservoir quality are obvious gaps in the understanding of Eagle Plain stratigraphy, and therefore this thesis is an attempt to address these issues.

Chapter Three: **METHODOLOGY**

Samples collected from 21 outcrops of the Parkin, Fishing Branch and Cody Creek formations during summers of 2009 and 2010 were included in this study, in addition to samples from three cored intervals from hydrocarbon exploration wells.

To accomplish the objectives of this study, samples collected from the field study area were slabbed and thin sections were prepared, of which 55 thin sections were selected for detailed analysis. Petrographic analysis focused on determining lithology, depositional features, diagenetic features, and porosity characteristics of each thin section. Samples from cores were also incorporated in to this study. This data was then used to compare the mineralogical composition of units within the Parkin, Fishing Branch and Cody Creek formations and determine their respective reservoir potential. Outcrop, hand sample and thin section samples were classified using a ternary diagram siliciclastic classification schemes (Folk, 1968). A Nikon Eclipse E600 POL petrographic microscope were the main tools in this evaluation.

Chapter Four: **PARKIN FORMATION**

4.1 Introduction

The Parkin Formation is a transgressive - regressive unit that unconformably overlies the lower Albian Whitestone River Formation *(Dixon. 1992a).* Jackson et al. (2011) informally subdivided the Parkin Formation into a basal sandstone member (Fig.5 and 6), which is overlain by the newly defined lower Parkin shale member, the middle Parkin sandstone member (Fig.10) and the upper Parkin shale member *(Jackson et al. 2011)*. The basal Parkin sandstone member is a transgressive unit consisting of inter-fingering coarse-grained fluvial sandstones and fine to medium-grained shoreface sandstones observed in outcrop and core (Figs.5 and 6 respectively) *(Jackson et al. 2011).*

The scope of research is limited to six thin section samples of marine and conglomeratic transgressive lag deposits of the basal Parkin sandstone member and four thin section samples of the middle Parkin slump and pebble lag deposits.

4.2 Basal Parkin sandstone member

Core and outcrop samples of this unit were collected from the eastern and southeastern extents of the EPSB, respectively.

4.2.1 Depositional features

This unit contains moderate to well sorted, sub-angular to sub-rounded, very fine to upper fine grained litharenites. Poorly sorted, sub-rounded to rounded, pebble lag deposits also occur within the unit (sample C-33-692.2). Core samples display no lamination, while outcrop samples have soft sediment deformation and ripple cross-stratified lamina.

Fig.5. Outcrop 2010-04 of fluvial sandstones of the basal Parkin member. Person 6-feet tall for scale.

Fig.6. Outcrop 2009-12 of marine shoreface sandstones of the basal Parkin member.

4.2.2 Lithology

The basal Parkin sandstone member consists mainly of monocrystalline quartz grains with common polycrystalline quartz grains (Fig.9). Feldspars are present in trace amounts throughout the unit, represented by plagioclase and orthoclase when they occur; sample D-61-331.8 contained no feldspars (Fig.7). Rock fragments in this unit consist of common white chert, mudstones, black chert, and sporadic low-grade metamorphic rock fragments, very fine-grained sandstone clasts and siltstone clasts (Fig.9). Accessory grains in this unit include glauconite, organic matter, muscovite, biotite, detrital zircons, isolated calcite grains and isolated shell fragments. Core sample (C-33-692.2) is a lag deposits with framework compositions of mudstone, abundant chert, siltstone clasts, and very fine-grained sandstone clasts (Fig.10). Figure-7 depicts a distinct bimodal mineralogy distribution within this unit, characterized by quartz rich (Fig.9) and lithic rich cluster plots (cluster plots A and B respectively). It is of note that the lithic rich cluster-B consists of predominately chert, while mudstone content is low (Fig.8).

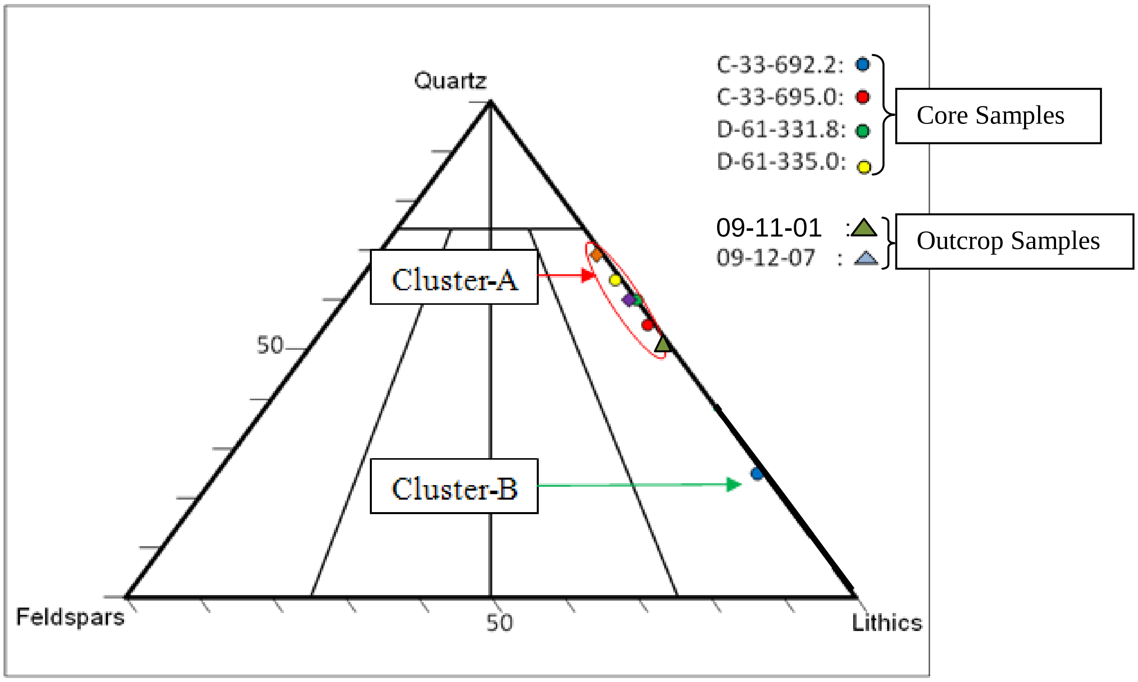

Fig.7. Ternary diagram of basal Parkin sandstones samples. Note the distinct bimodal distribution of mineralogy through the unit forming a quartz rich cluster-A and a chert rich cluster-B.

4.2.3 Diagenetic Features

This unit contains abundant to minor amounts of grain coating and grain lining clay, glauconite is locally abundant throughout the unit, minor quartz overgrowth cement is common and locally pervasive, microcrystalline quartz cement occurs in fractured pebble chert grains, and poikilotopic calcite cement occurs in sample C-33-692.2 (Fig.10). Core samples contain minor deformed mudstone clasts combined with tangential grain contacts indicating that the unit has experienced moderate compaction forces. Outcrop sample 09-12-07 contains sutured contacts, tightly packed grains and grain fractures, indicating that the unit has undergone moderate to high degree of compaction. Outcrop 2010-15 was sampled in the northwest part of the EPSB, while core samples are from wells in the south east of the EPSB and outcrop 2009-12 was sampled in the southern part of the basin (Fig.1). This difference in compaction between the different sample suites can be explain by the difference in their sample location, as samples collected in the south and southeast of the basin have experienced higher degrees of compaction and tectonic stress as a result of the neighbouring Laramide age Richardson Mountains.

Alteration throughout the unit is characterized by precipitation of hematite coating grains, calcite replacement of grains, and minor vacuolization and sericitization of feldspars. Bioturbation (observed in hand sample and thin sections) is common throughout marine sandstones of this unit (Fig.9); only sample D-61-331.8 is non-bioturbated, while the remaining samples exhibit minor to high degrees of bioturbation. Outcrop and core samples contain mainly tangential grain contacts and common to infrequent concavo-convex grain contacts.

4.2.4 Porosity Characterization

The basal Parkin sandstones contain clay, glauconite, quartz and calcite cements that are variably pervasive in different localities and significantly reduce connected macro porosity within the examined samples. Inter-particle, grain dissolution, and intra-particle porosity are the dominant porosity types, with porosity ranging from 0-12% for core and outcrop samples.

Core samples C-33-695 and D-61-331.8 of this unit possess minor inter-particle and intra-particle porosity. Pervasive clay, glauconite, and calcite cementation commonly occupy pore space resulting in a porosity estimate between 0-1%.

Core sample C-33-692.2 (Fig.10) is oil stained which made porosity identification difficult, core analysis reports indicated that this sample contained 14% porosity.

Core sample D-61-335 contains clay associated bioturbated lamina with 0-2% porosity, and unbioturbated lamina containing inter-particle and grain dissolution porosity with 8-10% porosity (Fig.5).

Sample 09-12-07 (Fig.4) contains connected-, macro-, inter-particle, grain fracture and grain dissolution porosity. Unconnected intra-particle micro-porosity in tripolitic chert also occurs. These samples have a total porosity estimate between 10-12% in non-bioturbated areas and between 4-6% in bioturbated areas.

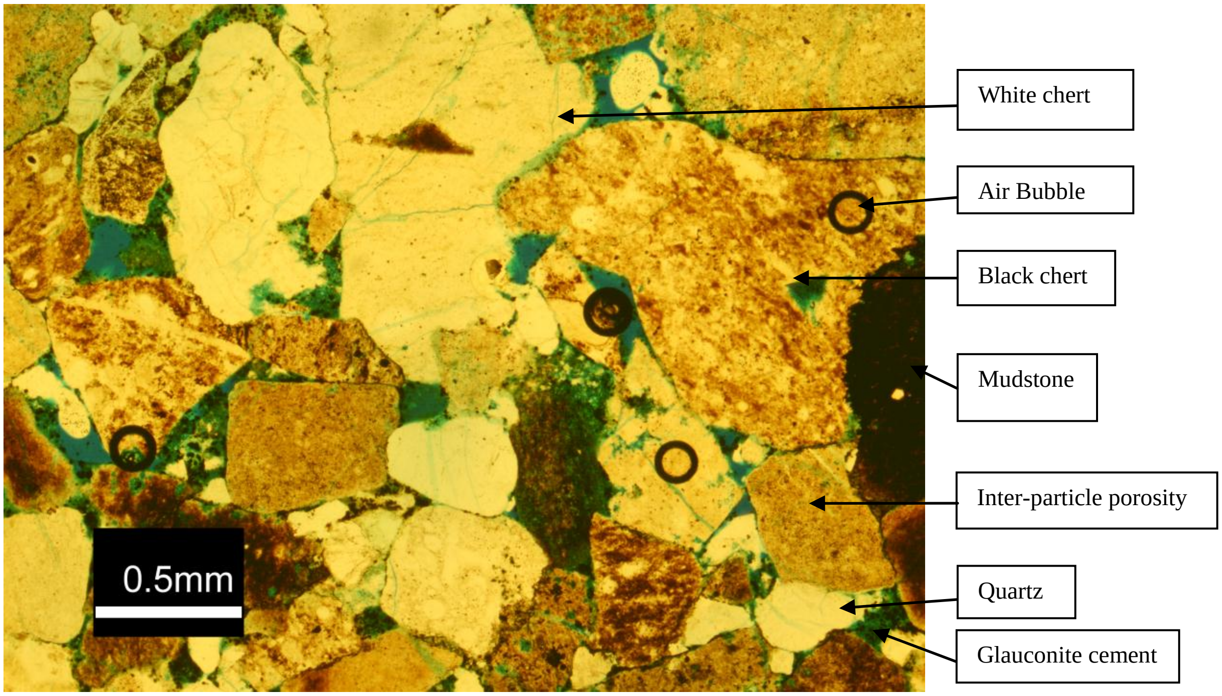

Fig.8a. Sample 09-12-07 in PPL. Upper medium - granule, poorly sorted, sub-angular to sub-rounded granule chert arenite *(Folk 1968)* of the basal Parkin Formation. Note abundant glauconite cement, interparticle porosity and chert rich composition.

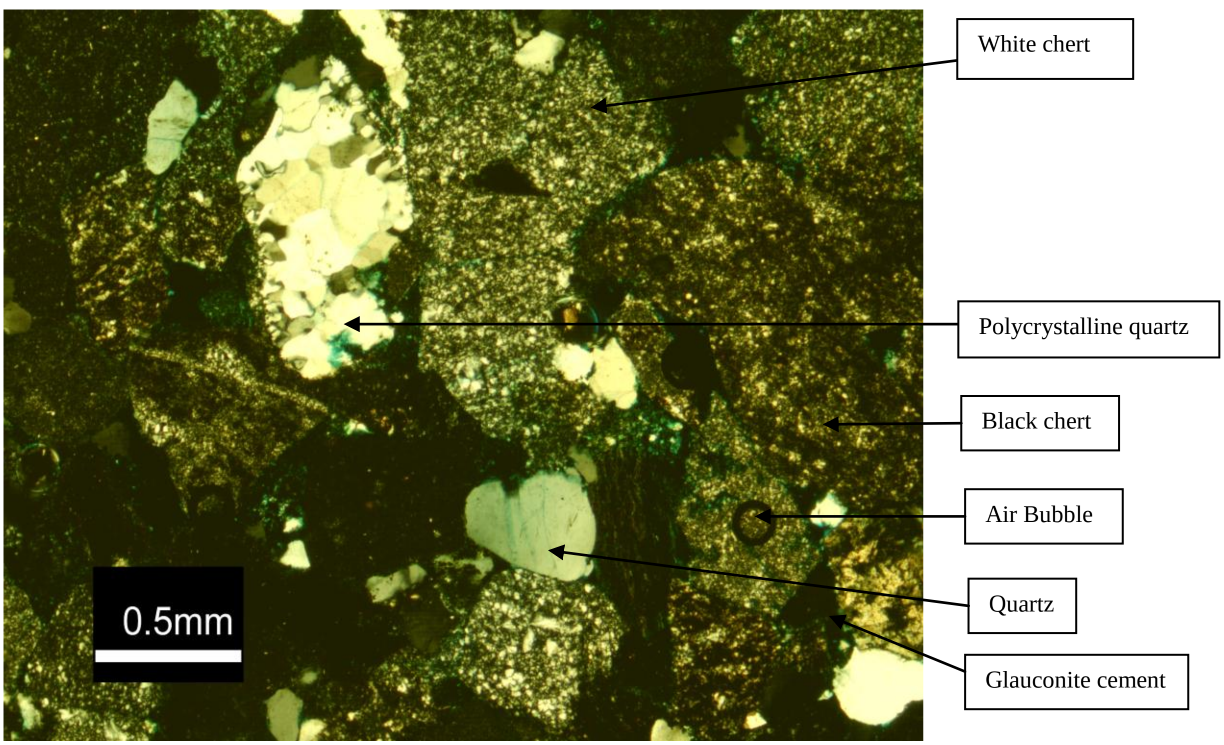

Fig.8b. Sample 09-12-07 in XPL. Note predominate chert composition with minor polycrystalline quartz, monocrystalline quartz and mudstones.

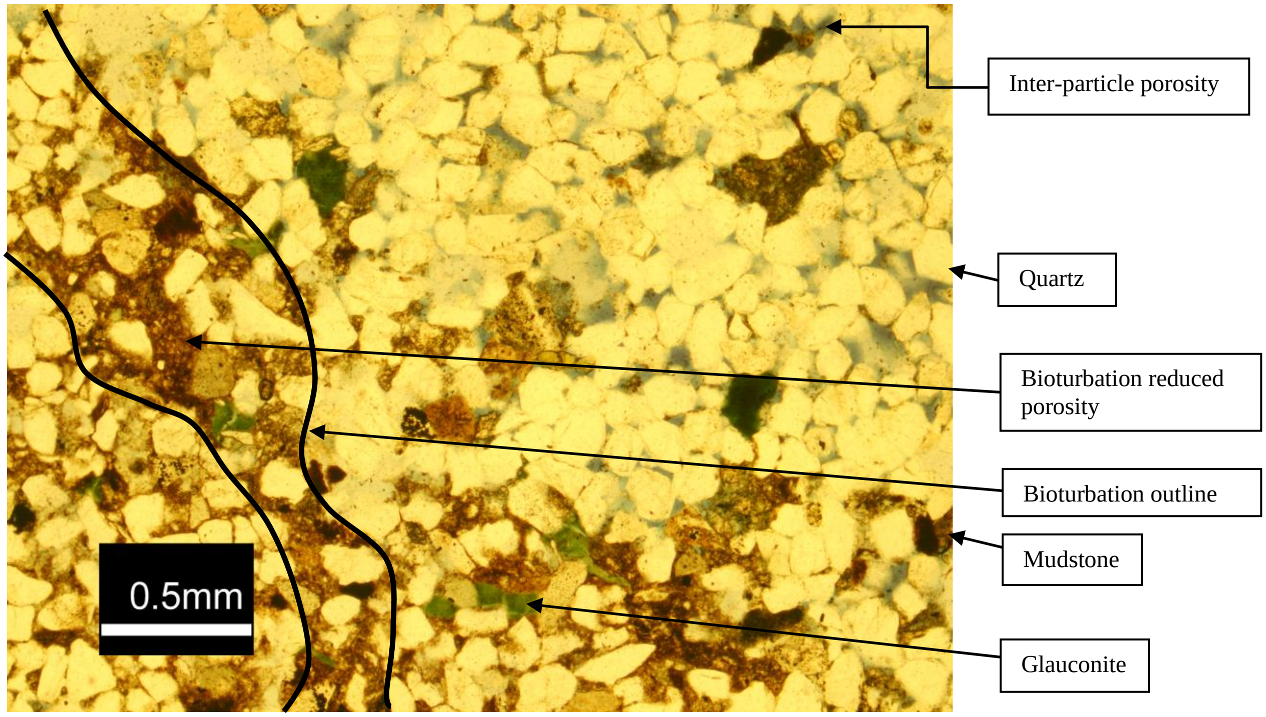

Fig.9a. Sample D-61-335 in PPL. Fine-grained, well-sorted, basal Parkin Formation litharenite (*Folk, 1968*). Note clay associated bioturbation reduces porosity and inter-particle porosity in non-bioturbated zones.

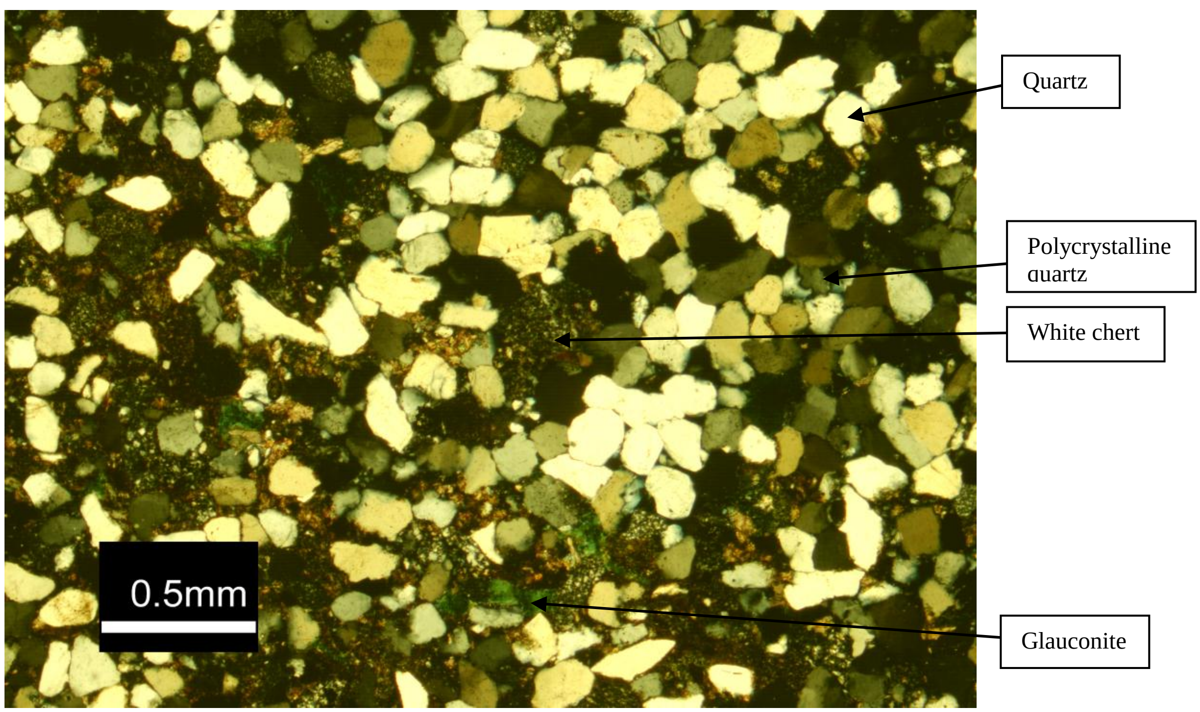

Fig.9b. Sample D-61-335 in XPL.

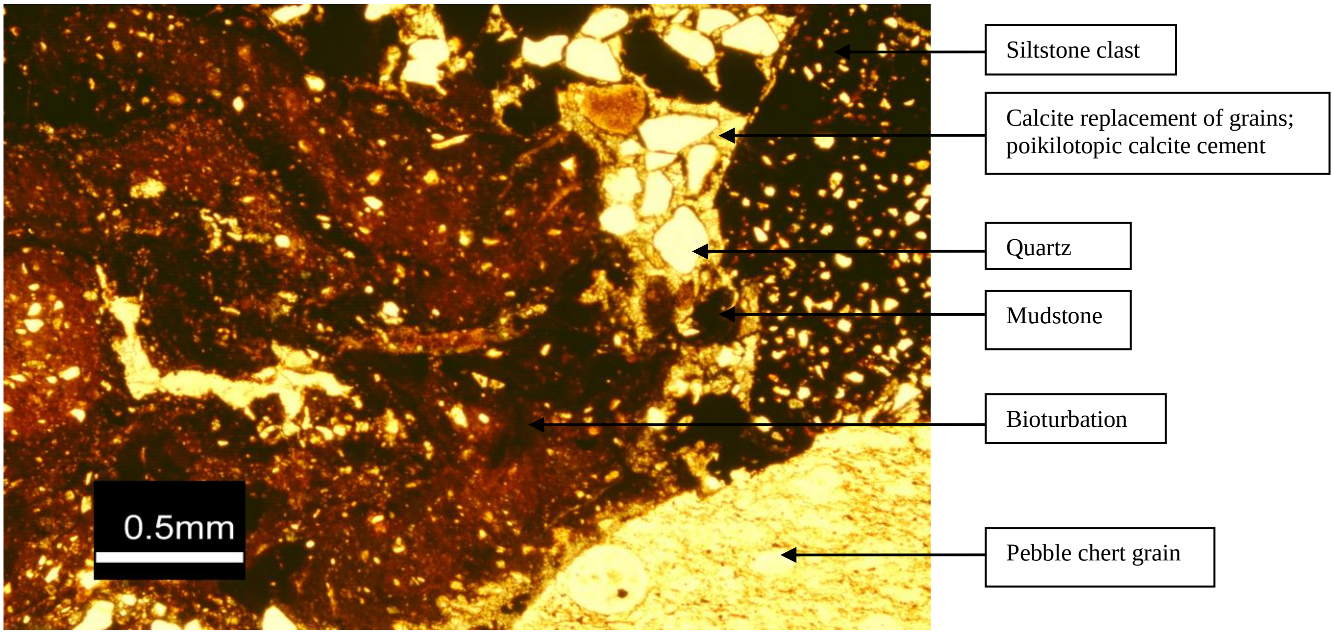

Fig.10a. Core sample C-33-692.2. Poorly sorted, rounded, pebble conglomerate. Note bioturbation, poor sorting, poikilotopic calcite cement, framework and matrix grains.

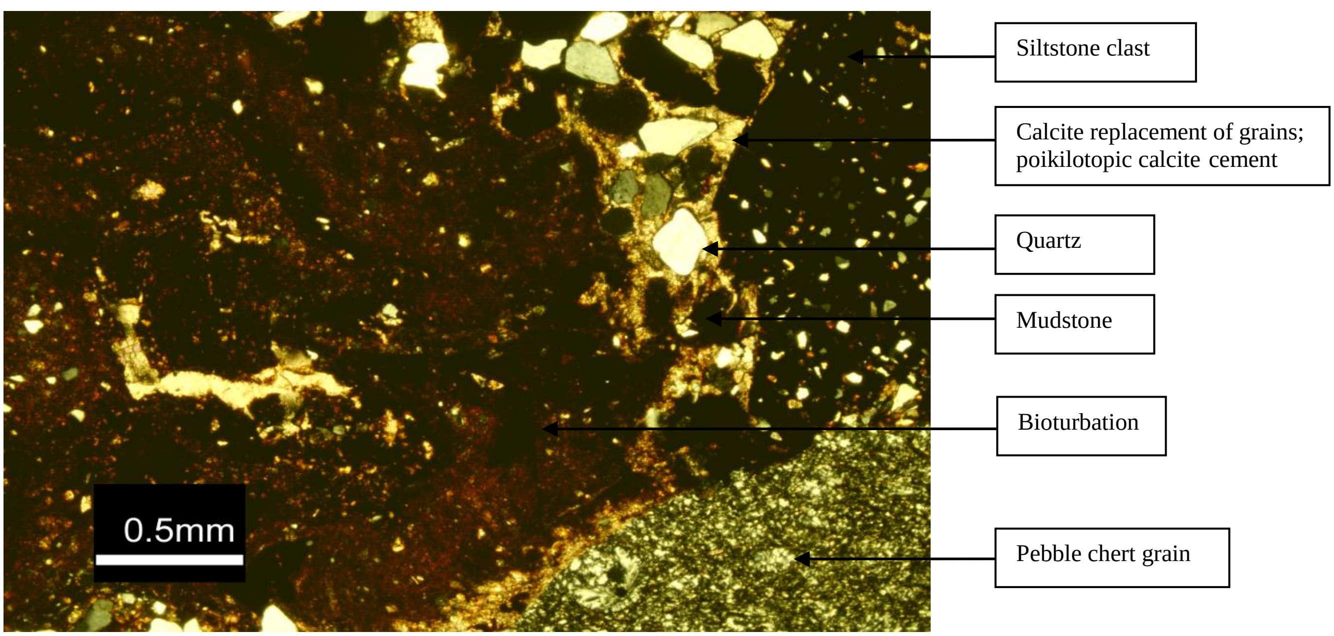

Fig.10b. Core sample C-33-692.2 in XPL.

4.3 Middle Parkin sandstone member

Four thin section samples of the middle Parkin slump and lag deposits (samples 09-02-06, 10-15-01, 10-15-05 and 09-12-19 respectively) were analysed. Samples from outcrop 2010-15, 2009-2 and 2009-12 were collected from the western and southern extents of the basin respectively.

4.3.1 Depositional features

The slump deposits of this unit consist of moderate to well sorted, sub-angular to sub-rounded, very-fine to fine-grained, planar laminated, cross-stratified and soft sediment deformed litharenites (samples 09-02-06, 10-15-01 and 10-15-05; Fig. 11 and 13). Sample 09-12-19 is a poorly sorted, sub-rounded to rounded, massive pebble lag deposit (Fig.12).

Fig.11. Outcrop 2009-12 of middle Parkin member showing soft sediment deformation deposits.

Fig.12. Outcrop 2009-12 hand sample of black chert pebble lag from the middle Parkin member.

Fig.13. Outcrop 2009-02 of middle Parkin member slump deposits. Geological hammer for scale

4.3.2 Lithology

Sandstone slump deposits of the middle Parkin member consist of mainly monocrystalline quartz grains. Feldspars are present in trace amounts and are represented by orthoclase, plagioclase and microcline. Rock fragments consist of predominantly mudstones, black and white chert grains are common, metamorphic rock fragments, and siltstone grain aggregates occur infrequently. Accessory grains in this unit include muscovite, biotite, organic matter, glauconite and clinopyroxene.

The pebble lag deposit has a framework composition of predominately chert. This sample contains no feldspars in the framework or the matrix. Accessory grains include detrital zircons and organic matter.

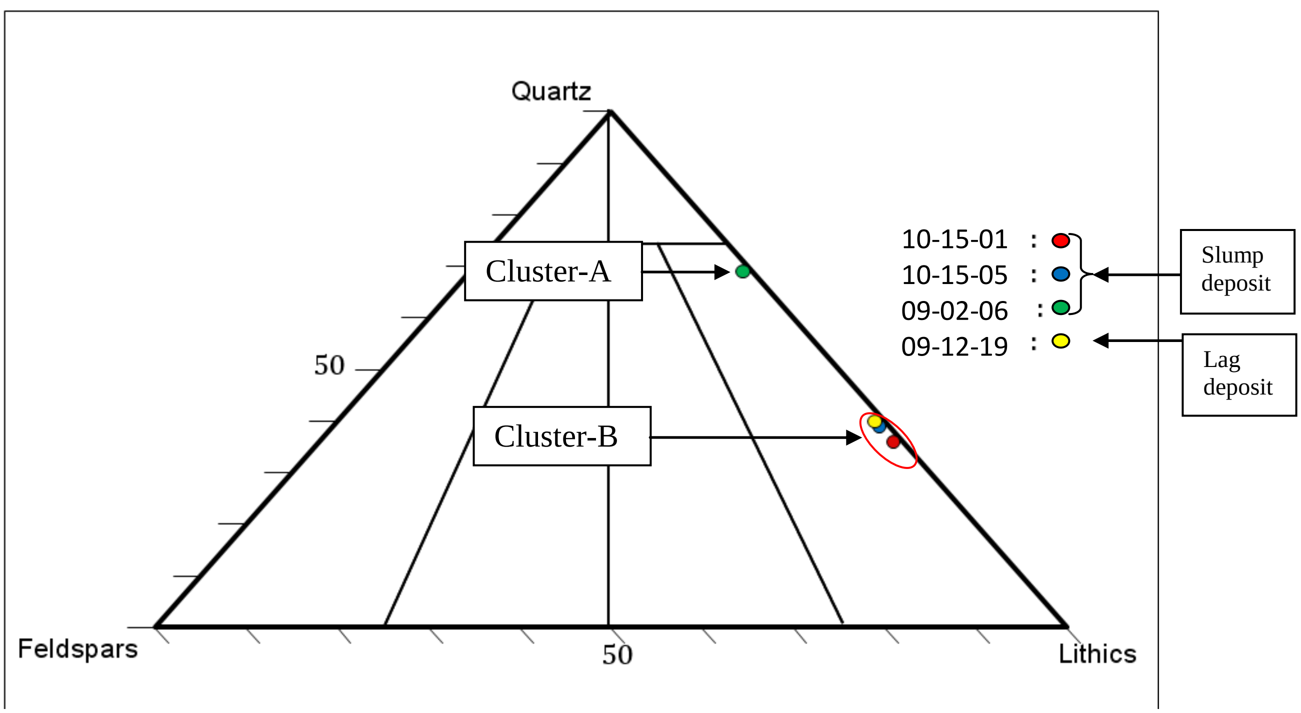

Fig.14. Ternary diagram of middle Parkin member slump and conglomerate lag deposit samples.

4.3.3 Diagenetic Features

This unit contains prevalent quartz grains, common interstitial clay, and subordinate glauconite cement types. Mudstone and mica deformation, pseudomatrix formation and sutured grain contacts indicate that the samples examined of this unit have experience moderate degrees of compaction. The unit is characterised by sericitic alteration and calcite replacement of feldspars and common microlite inclusions in quartz grains. Slump deposit samples are weakly (09-02-06) to intensely bioturbated, (observed in hand sample and thin section). The pebble lag deposit contains grain lining and coating hematite cement over grown by poikilotopic calcite cement. Sutured and concavo-convex grain contains indicate that this unit has experienced high degrees of compaction. Alteration in the pebble lag is characterised by prevalent calcite replacement in framework and matrix grains. No bioturbation is observed within the lag deposit.

Grain contacts within the pebble lag consist of tangential and concavo-convex contacts in matrix, concavo-convex to sutured between matrix and framework grains and sutured between framework clasts. Grain contacts in samples from the slump deposits are characterized by tangential, concavo-convex and sutured contacts.

4.3.4 Porosity characteristics

Samples 10-15-01 and 10-15-05 contain tightly packed grains and prevalent quartz and clay cement that eliminate interparticle porosity. The porosity estimation for these samples is between 0-1%.

Sample 09-02-06 contains prevalent quartz cement that reduces interparticle porosity. Thin seams of interparticle porosity do occur and account for a porosity estimate between 3-5% for this sample.

Sample 09-12-19 contains poikilotopic calcite cement that eliminates all interparticle porosity, grain fracture porosity does exist and accounts for the 0-2% porosity estimation for this sample.

Chapter Five: **FISHING BRANCH FORMATION**

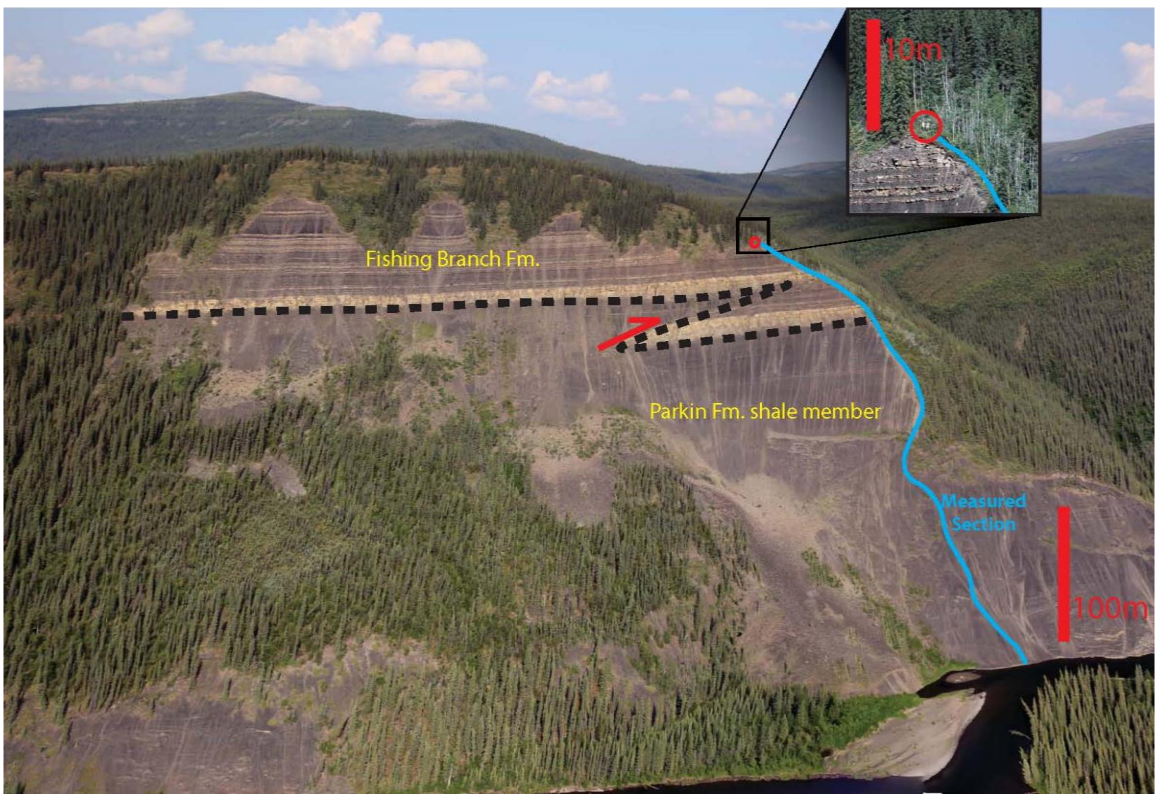

Fig.15a. Eagle Plain type section showing the Fishing Branch and Parkin formations.

5.1 Introduction

The Fishing Branch Formation consists of very fine to medium-grained marine sandstones forming several coarsening upward packages (Fig.15a), individually up to 30m thick. Deposition of the Fishing Branch Formation has been interpreted to have occurred in the delta front to prodelta region of an overall westward and north-westward prograding fluvial-dominated deltaic system *(Jackson et al, 2011).*

The Fishing Branch Formation was sampled from the prodelta, delta front and storm dominated shelf facies at multiple locations across the study area (Fig.1). Petrographic analysis of twenty-seven thin section samples was conducted to determine the lithological characteristics and reservoir properties of the Fishing Branch Formation.

5.2 Prodeltaic Fishing Branch Sandstone

Nine thin section samples of the prodeltaic Fishing Branch sandstone were analyzed (Fig.15). Samples from outcrop 2010-16 (Fig.1 and 16) were collected from the most northern locality in this study. Samples from outcrop 2010-24 (Fig.1 and Fig.16) were collected from the northwestern extent of the basin, while samples 09-02-10, 09-02-11, 09-02-12 and 09-02-14 (outcrop 2009-02, Fig.1 and Fig.15b) were collected from the west-central extent of the basin.

Fig.15b. Outcrop 2009-02 photo of the prodeltaic Fishing Branch sandstone. Individual five foot, ten inches for scale.

5.2.1 Depositional Features

This unit contains moderate to well sorted, sub-angular to sub-rounded, very fine to coarse-grained, cross stratified, planar laminated, soft sediment deformed, litharenites. Elongate, imbricated, coarse-grained sized organic matter is concentrated in high angle lamina of sample 10-16-08. Samples 10, 14, 10-16-09 and 10-16-10 are planar laminated with alternating quartz and lithic rich lamina. Samples 09-02-11, 09-02-12, and 10-16-08 are mud poor and contain high angle cross-stratified lamina. Sample 10-24-02 contains convoluted, soft sediment deformed lamina, and is very muddy in appearance.

5.2.2 Lithology

The prodeltaic Fishing Branch sandstone contains mainly mono-crystalline quartz, common polycrystalline quartz, and isolated chalcedony grains. Two distinct mineralogical clusters (A and B) occur within the prodeltaic Fishing Branch, cluster-A being quartz rich and cluster-B being lithic rich (Fig.16). Cluster-A samples occur as very fine to fine-grained planar to cross-stratified litharenites and sub-litharenites while cluster-B samples occur as very fine to fine-grained, soft sediment deformed to planar laminated litharenites. Feldspars are present in trace amounts throughout the unit, represented by plagioclase, microcline and orthoclase. Rock fragments are represented by predominately mudstones, minor white and trace black chert. Accessory grains within this unit include sericite, detrital zircons, glauconite, muscovite, biotite, clinopyroxene and organic matter.

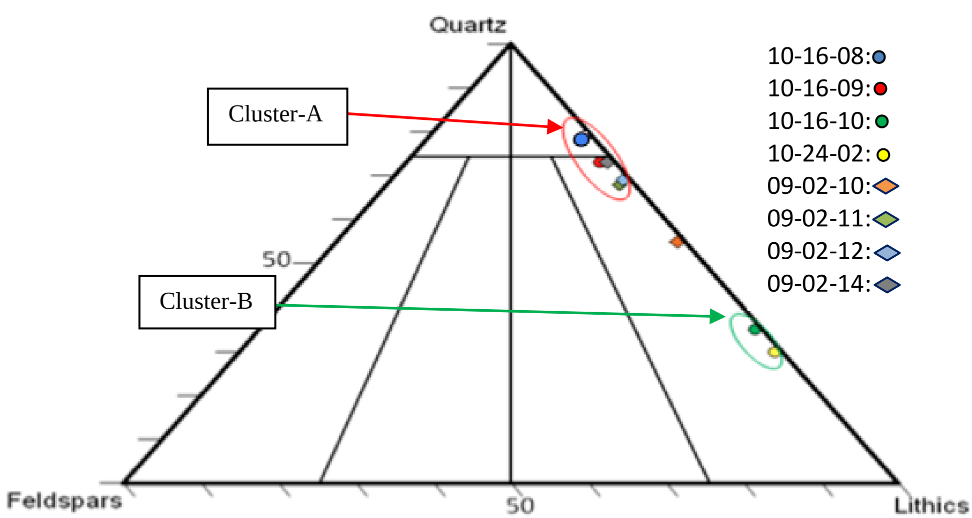

Fig.16. Ternary diagram of Fishing Branch prodeltaic sandstones from outcrop showing two distinct quartz and lithic rich mineralogical compositions forming clusters A and B.

5.2.3 Diagenetic Features

This unit is dominated by prevalent quartz and minor clay cementation. Glauconite is locally pervasive and the main type of cement in sample 10-16-08 (Fig.18a and 18b); minor clay, very minor chert and isolated fibrous micro-quartz cement in grain fractures is also present. Samples 10-24-02 and 09-02-10 contain prevalent quartz cement with abundant clay cement and pseudo-matrix (Fig.19).

Minor amounts of dissolution at grain boundaries, minor grain deformation and the tightly packed grains indicate that the samples examined of this unit have experienced moderate compaction (Fig.17). Alteration throughout the unit is minimal, with minor calcite and sericitic replacement of grains, vacuolization of feldspars, muscovite altering to kaolinite, calcite microlite inclusions in quartz, and biotite alteration to chlorite occurs. Samples throughout the unit are non-bioturbated (09-02-10, 09-02-14, 10-16-08 and 10-16-09) to weakly bioturbated (09-02-11, 09-02-12, 10-16-10 and 10-24-02). Grain contacts throughout the samples are mainly tangential and concavo-convex with infrequent sutured contacts.

5.2.4 Porosity Classification

The prodeltaic Fishing Branch in western Eagle Plain has undergone moderate compaction resulting in tightly packed grains within the selected thin sections (Fig.17). This, combined with the occurrence of pervasive quartz cement and minor to locally abundant clay cementation, significantly reduces the porosity in this unit resulting in a porosity range of 0-6% within the prodeltaic Fishing Branch Formation.

In sample 09-02-11, 09-02-12, 09-02-14 and 10-16-09 grains are tightly packed and well cemented; they contain no inter-particle macro-porosity, and trace amounts of grain dissolution porosity from tripolitic chert resulting in a porosity estimate of 0-2%.

Sample 10-16-08 contains thin streaks of connected inter-particle macro-porosity, intra-particle porosity within tripolitic chert and grain dissolution macro-porosity. Porosity estimations range from 4-6% in less cemented lamina, to 0-1% in well cemented, tightly packed lamina (Fig.18a and 18b).

Samples 09-02-10, 10-24-02 and 10-16-10 contain no connected inter-particle macro-porosity as a result of pervasive quartz and abundant clay cement between tightly packed grains. No type of porosity is visible within these samples (Fig.19).

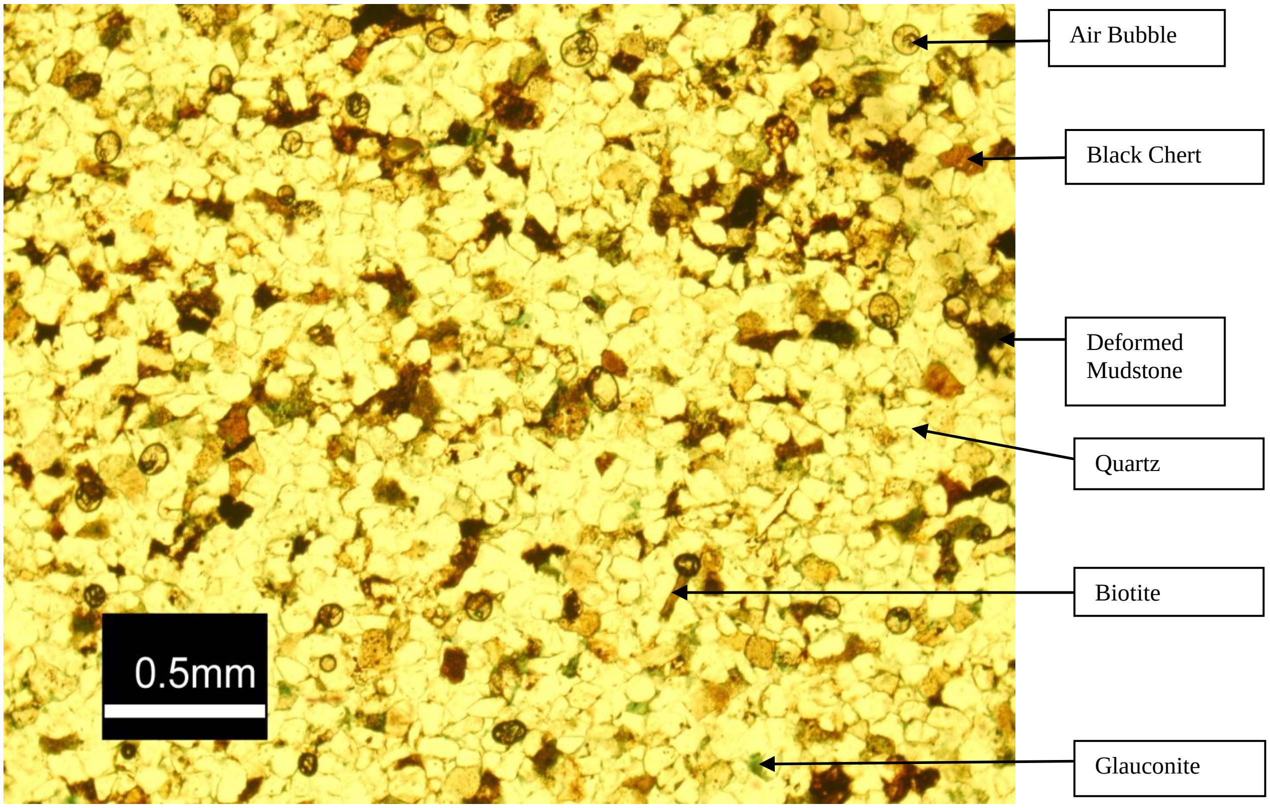

Fig.17a. Sample 09-02-06 in PPL. Fine-grained, well-sorted, prodeltaic Fishing Branch sub-litharenite sandstone (*Folk 1968*). Note accessory glauconite, trace black chert, minor grain deformation, tightly packed grains and no visible porosity.

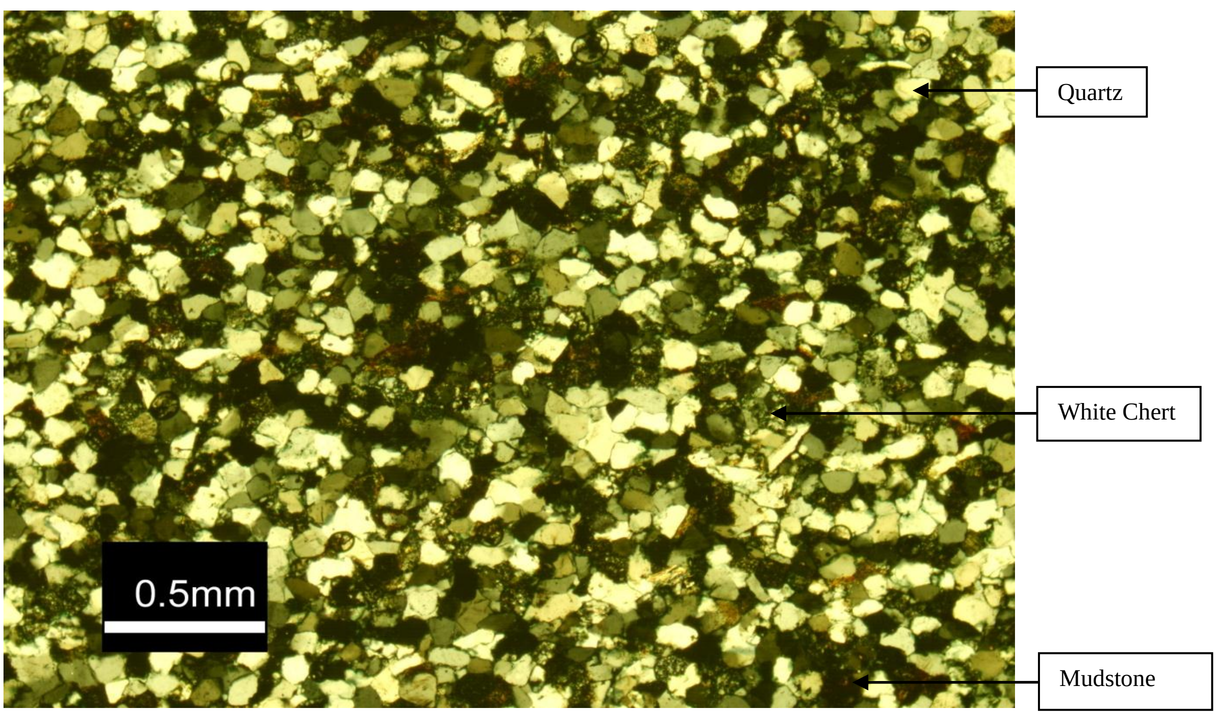

Fig.17b. Sample 09-02-06 in XPL. Note abundance of quartz and minor rock fragments.

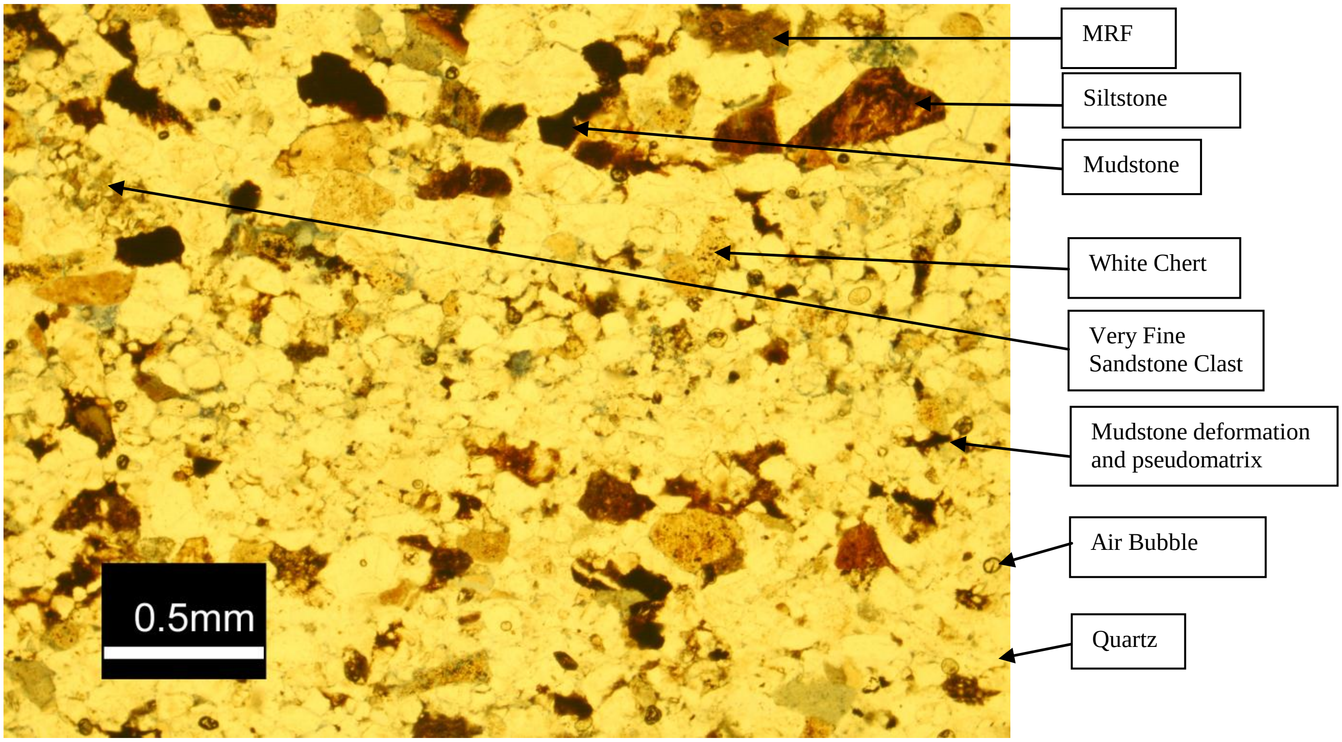

Fig.18a. Sample 10-16-08 in PPL. Fine-grained, poorly sorted prodeltaic Fishing Branch litharenite sandstone (*Folk 1968*). Note tightly packed grains, mudstone deformation, pseudomatrix formation and no visible porosity.

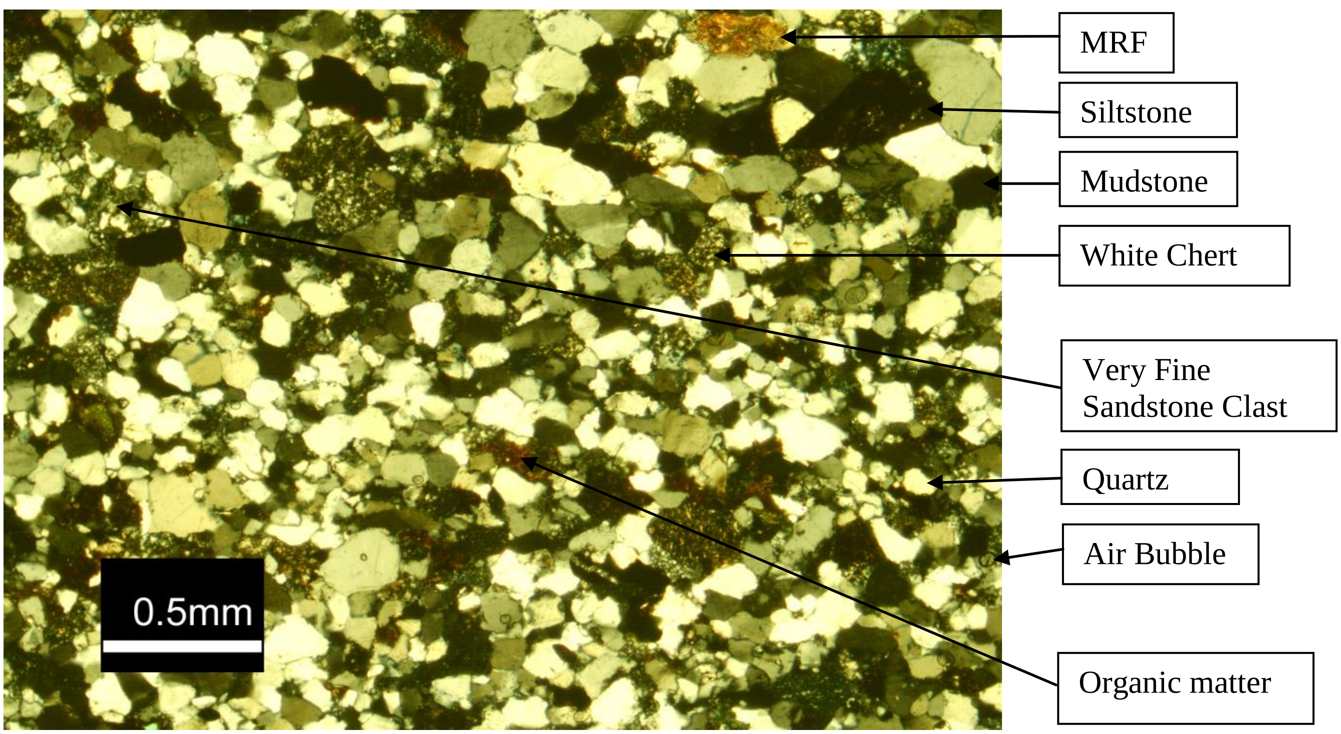

Fig.18b. Sample 10-16-08 in XPL. Note common chert grains and isolated MRFs.

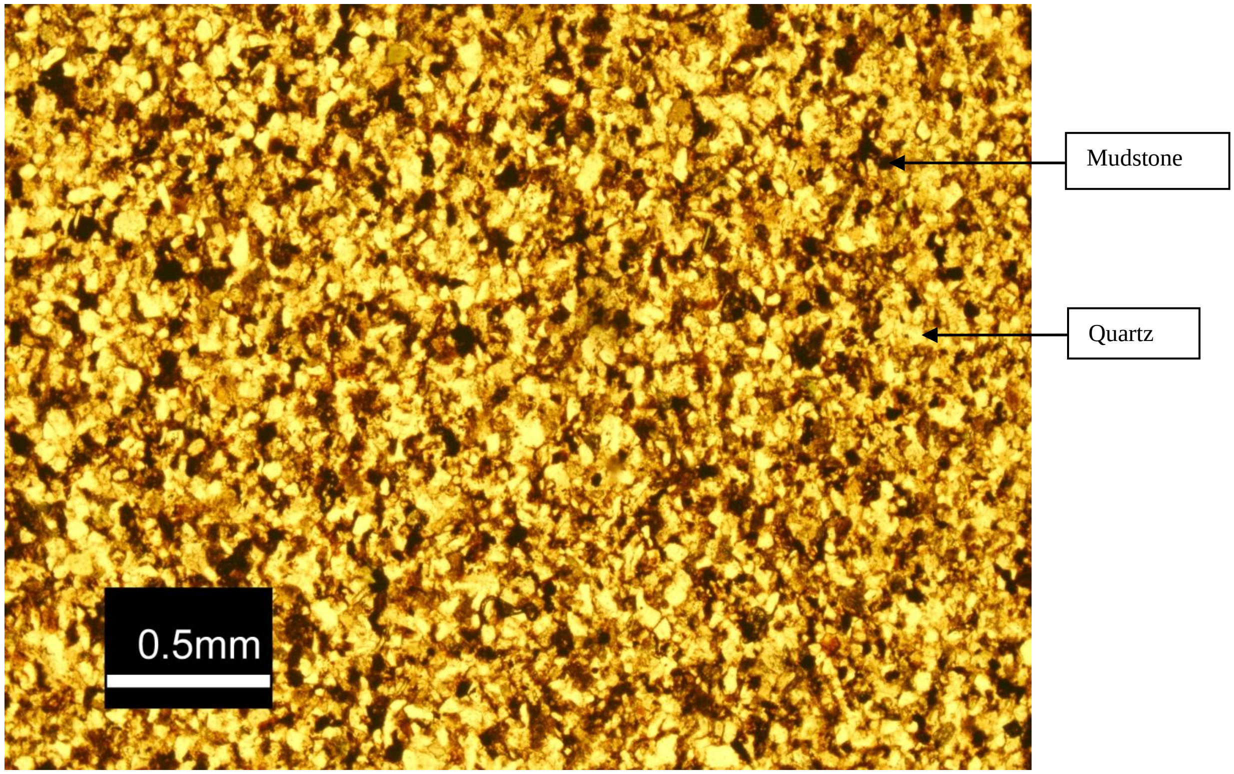

Fig.19a. Sample 10-24-02 in PPL. Very fine-grained, well-sorted prodeltaic Fishing Branch slump litharenite sandstone (*Folk 1968*). Note abundant mudstone grains, tightly packed grains, and no visible porosity present.

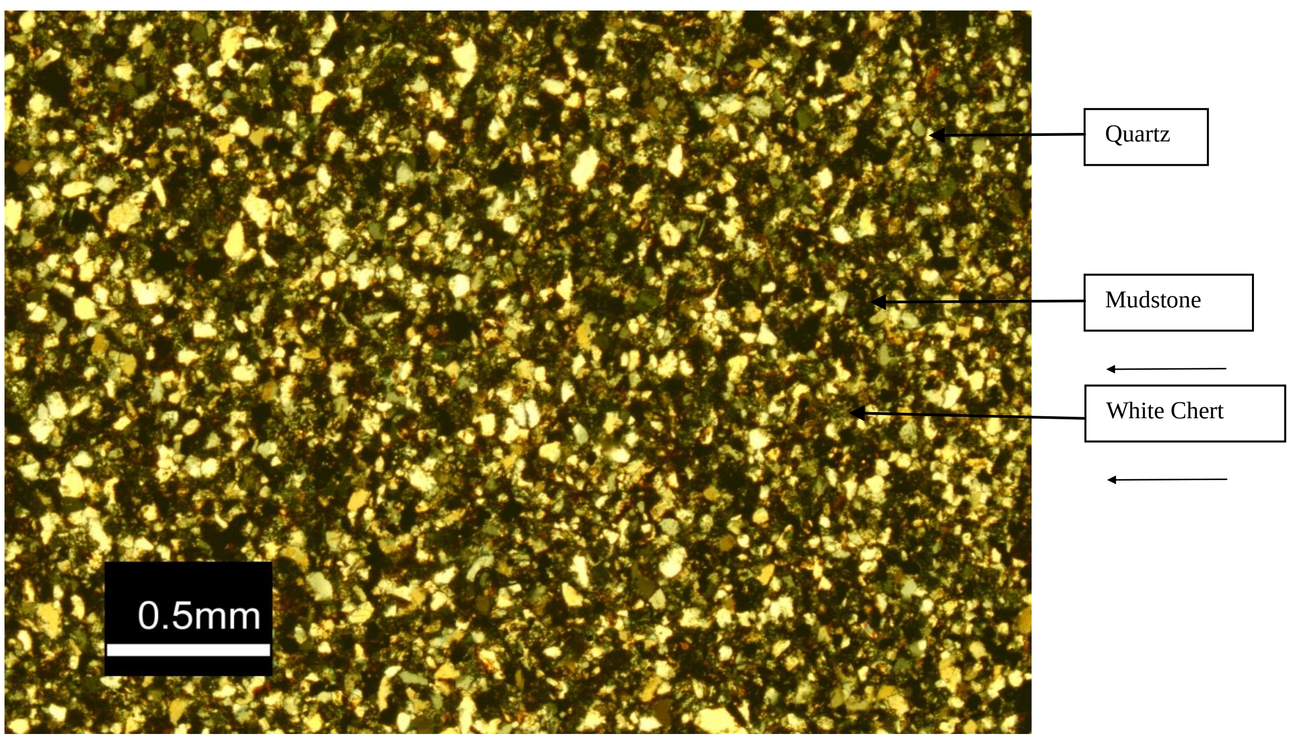

Fig.19b. Sample 10-24-02 in XPL. Note abundance of white chert grains.

5.3 Delta Front Fishing Branch Sandstone

Samples I-13-1116.9, I-13-1120.8, I-13-1124.4 were taken from core of the Fishing Branch delta front sandstone retrieved from well location I-13 (Fig.1). Samples from outcrops 2009-04 and 2010-09 of the Fishing Branch delta front sandstone were collected from the southeastern and west-central parts of the basin respectively (Fig.1). 11 samples from this unit were analyzed.

5.3.1 Depositional Features

Grain size within this unit ranges from lower very fine grained in massive clay rich samples (10-09-01), upper fine grained in chert rich samples (10-09-03, 10-09-06 and 10-09-07) (Figs.21 and 22 respectively) and massive pebble lags in core sample I-13-1124.4. This unit contains angular to sub-rounded grains that are well sorted in clay rich samples to moderately sorted in chert rich samples (Figs.21 and 22 respectively).

Core samples I-13-1116.9 and I-13-1120.8 are well sorted with planar to low-angle inclined lamina composed of upper very fine to lower fine grains; while sample I-13-1124.4 is a poorly sorted massive pebble lag that contains coarse sand to pebble size framework grains within a moderately sorted lower fine matrix.

Outcrop samples 09-04-02, 09-04-04, and 09-04-05 are poorly sorted, angular to sub-rounded, granule to pebble size, chert conglomeratic-sandstones and conglomerates (Fig.24). They display no obvious lamination but have alternating tightly and loosely packed lamina and imbricated grains. Their grain contacts are characterized by common concavo-convex and tangential contacts in compacted lamina while point and tangential contacts occur in loosely packed lamina. Bioturbation preferentially concentrates finer-grained material and associated clay that packs together more tightly which reduces porosity significantly.

5.3.2 Lithology

The Fishing Branch delta front samples mainly contain monocrystalline quartz, with infrequent polycrystalline quartz grains. Plagioclase, microcline and orthoclase are representative of the feldspars assemblage, found in trace amounts throughout the unit. Rock fragments consist of predominately mudstones, common white chert, and minor black chert. Accessory grains include glauconite, muscovite, organic matter, calcite, sericite and detrital zircons. Core sample I-13-1120.8 is a lag deposit consisting of mudstone and chert framework grains; however its matrix composition is similar to the fine-grained sandstone composition of the Fishing Branch delta front sandstone.

Outcrop samples 10-09-01, 10-09-03, 10-09-05, 10-09-06 and 10-09-07, currently interpreted to be from the Fishing Branch delta front sandstone (*Jackson et al.2011*) are anomalous because they contain very abundant modal lithic grains (Fig.20). These samples can be further differentiated by their lithic grain composition as samples 10-09-03, 10-09-06 and 10-09-07 consist of predominately chert (Fig.20; cluster-D and Fig.24), while lithic grains from samples 10-09-05 and 10-09-01 consist predominately of mudstones with common chert (Fig.10; cluster-C and Fig.21). The latter is similar to muddier intervals in the prodeltaic Fishing Branch sandstone. Accessory grains in cluster-C include biotite, muscovite, calcite, gluaconite, clinopyroxene, organic matter, isolated coral fragments and detrital zircons.

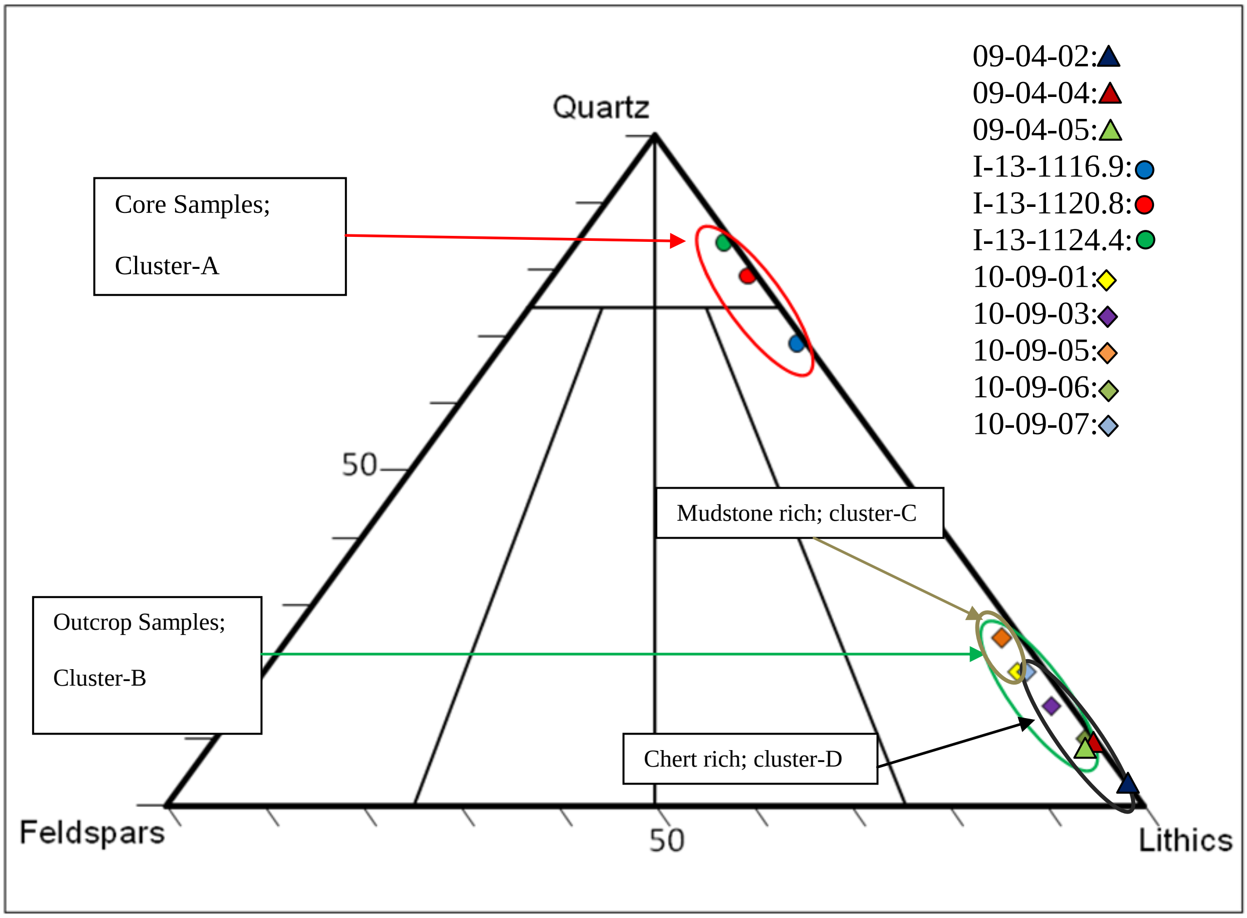

Fig.20. Ternary diagram of the Fishing Branch delta front sandstone samples from outcrop and core showing two distinct mineralogical assemblages.

5.3.3 Diagenetic Features

Core samples contain abundant quartz and minor clay cementation, while sample I-13-1120.8 contains common inter-particle calcite cement. Outcrop samples contain more common clay and glauconite cement, with quartz overgrowth cement occurring frequently.

Cementation in outcrop sample 10-09-01 contains pervasive clays, minor quartz overgrowth cement, and isolated zones of minor glauconite cement. Sample 10-09-05 has less abundant clay (due to lower degrees of bioturbation) with areas of minor clay cement present, quartz overgrowth cement also occurs pervasively throughout the section.

Outcrop samples 10-09-03, 10-09-06 and 10-09-07 from the west-central part of the basin, contain pervasive, fibrous, grain lining glauconite cement, with samples 10-09-03 and 10-09-06 containing bioturbation associated clays (Fig.22); sample 10-09-07 is non-bioturbated and contains minor clay cement. Minor dissolution at grain boundaries, minor grain deformation, mainly tangential and some concavo-convex contacts indicate that the unit has experienced moderate degrees of compaction.

Outcrop samples 09-04-02, 09-04-04 and 09-04-05 from the southeast part of the basin bordering the Richardson Mountains differ diagenetically as they contain minor kaolinite (and other clay types) cement in dissolved grain pore spaces. Fibrous quartz micro cement occurs in quartz grain fractures. There is minimal alteration within these samples as only minor sericitic replacement of feldspars and minor calcite replacement in chert grains occur. Grain dissolution, sutured contacts, grain fractures and grain deformation indicate these samples have experienced high degrees of compaction. These observations are consistent with sample proximity to the Laramide-aged Richardson orogeny.

Samples 09-04-04 and 09-04-05 are minor to moderately bioturbated while sample 09-04-02 is non-bioturbated (based on thin section and hand sample interpretations).

This unit (core and outcrop samples) has undergone minor calcite replacement of grains, minor sericitic alteration and vacuolization of feldspars, muscovite altering to kaolinite and biotite altering to chlorite occurs in minor amounts locally within sections 10-09-05 and 10-09-07 respectively. Alteration throughout the samples is minimal.

Sample 10-09-01 is strongly bioturbated (Fig.21), samples 10-09-03 and 10-09-05 are moderately bioturbated, sample 10-09-06 is weakly bioturbated and sample 10-09-07 is non-bioturbated (based on hand sample and thin section interpretations). No thin sections from core exhibit bioturbation.

5.3.4 Porosity Classification

The Fishing Branch delta front outcrop samples have undergone moderate (10-09 sample suite) to strong degrees of compaction and stresses from Laramide tectonic events (09-04 sample suite). Tightly packed grains, minor grain fracture porosity and abundant inter-particle porosity dominate 09-04 samples examined from the unit (Fig.21). Grain dissolution is common, resulting in abundant intra-particle porosity in tripolitic chert grains.

Common pervasive quartz overgrowth cement, local clay associated bioturbation and pervasive glauconite cement contribute to porosity reduction in samples from outcrop 10-09 and I-13 core samples resulting in a visual porosity estimates ranging from 0-2% (Figs.21, 22 and 23).

Samples 09-04 from outcrop exhibit abundant inter-particle macro porosity (10-25%) despite possessing features of strong compaction (stylolites and sutured grain contacts) (Fig.24).

Samples 10-09-01 and 10-09-05 contain no inter-particle macro-porosity, and trace amounts of fracture porosity, resulting in a porosity estimate between 0-1% (Fig.21).

Samples 10-09-03, 10-09-06 and 10-09-07 contain no inter-particle macro-porosity, and trace amounts of isolated, unconnected grain dissolution macro-porosity, resulting in porosity estimates of 0-2%.

Samples 09-04-02, 09-04-04, and 09-04-05 contain abundant inter-particle porosity, abundant grain dissolution porosity, grain fracture porosity, and intra-particle porosity in tripolitic chert. Bioturbation causes a reduction of porosity due to high clay contents within bioturbated lamina. This results in a porosity estimate of 10% in bioturbated, compacted lamina, and 18-20% in uncompacted lamina (09-04-02); samples 09-04-04 and 09-04-05 contain 20-25% porosity in non-bioturbated lamina (Fig.24).

Samples I-13-1116.9 and I-13-1120.8 have no visible inter-particle porosity due to pervasive quartz and calcite cementation. Grain fracture porosity is present in I-13-1120.8, resulting in a porosity estimate between 0-1%.

Sample I-13-1124.4 has isolated unconnected pockets of inter-particle porosity amongst pervasive quartz cement. Unconnected intra-particle porosity is common in tripolitic cherts, resulting in a porosity estimate of 1-2% (Fig. 23).

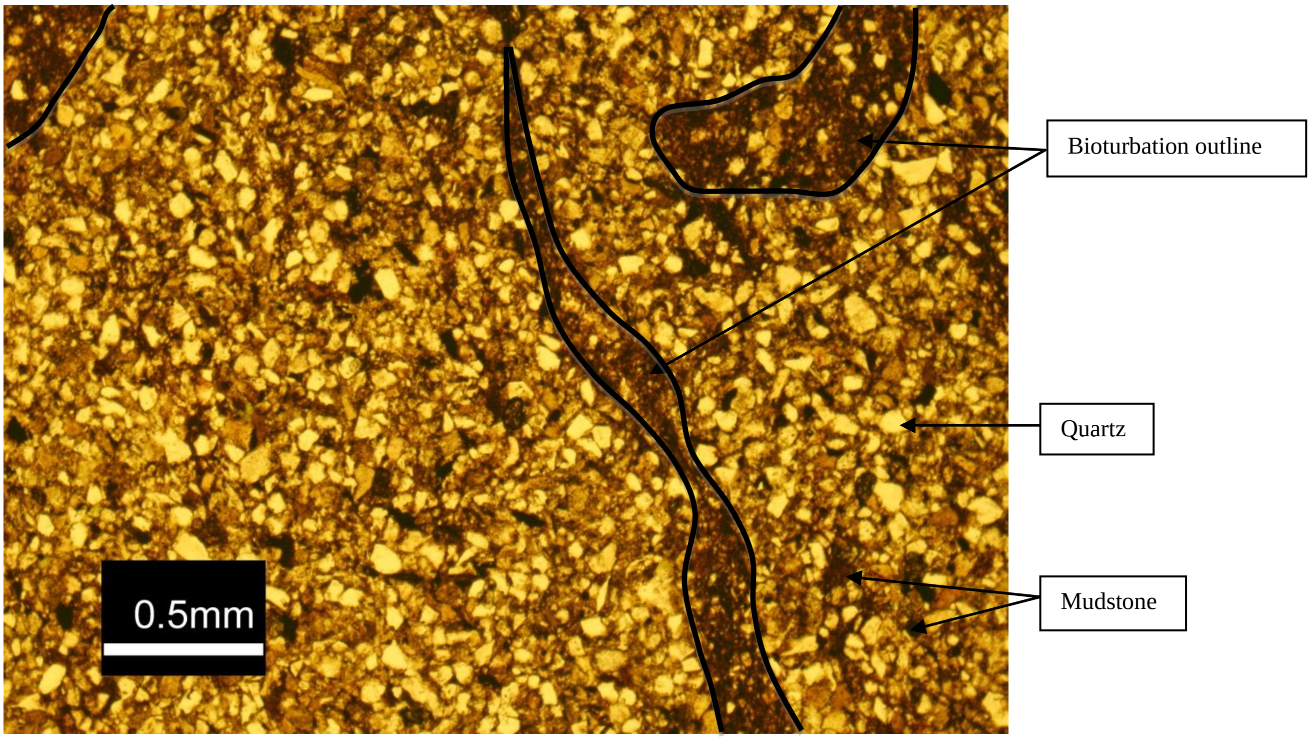

Fig.21a. Sample 10-09-01 in PPL. Very fine-grained, well sorted, strongly bioturbated litharenite (*Folk 1968*) of the Fishing Branch delta front sandstone. Note clay associated bioturbation.

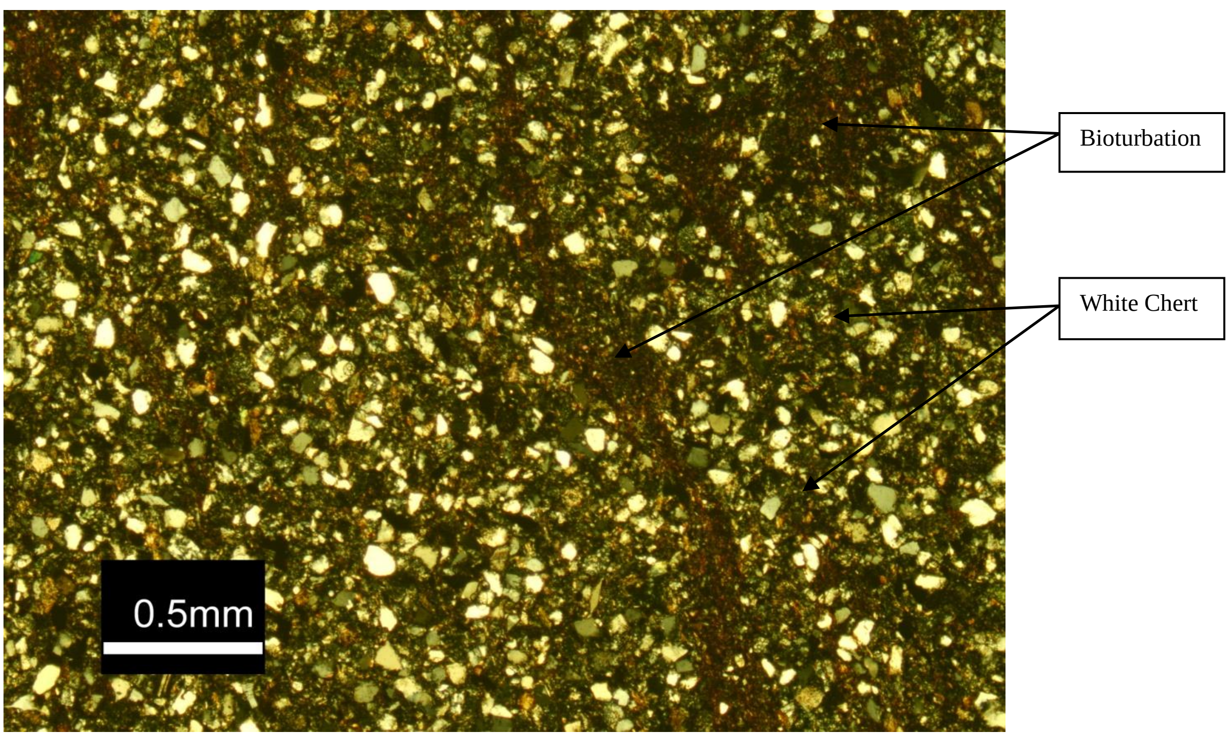

Fig.21b. Sample 10-09-01 in XPL. Note abundance of white chert and no type of porosity present.

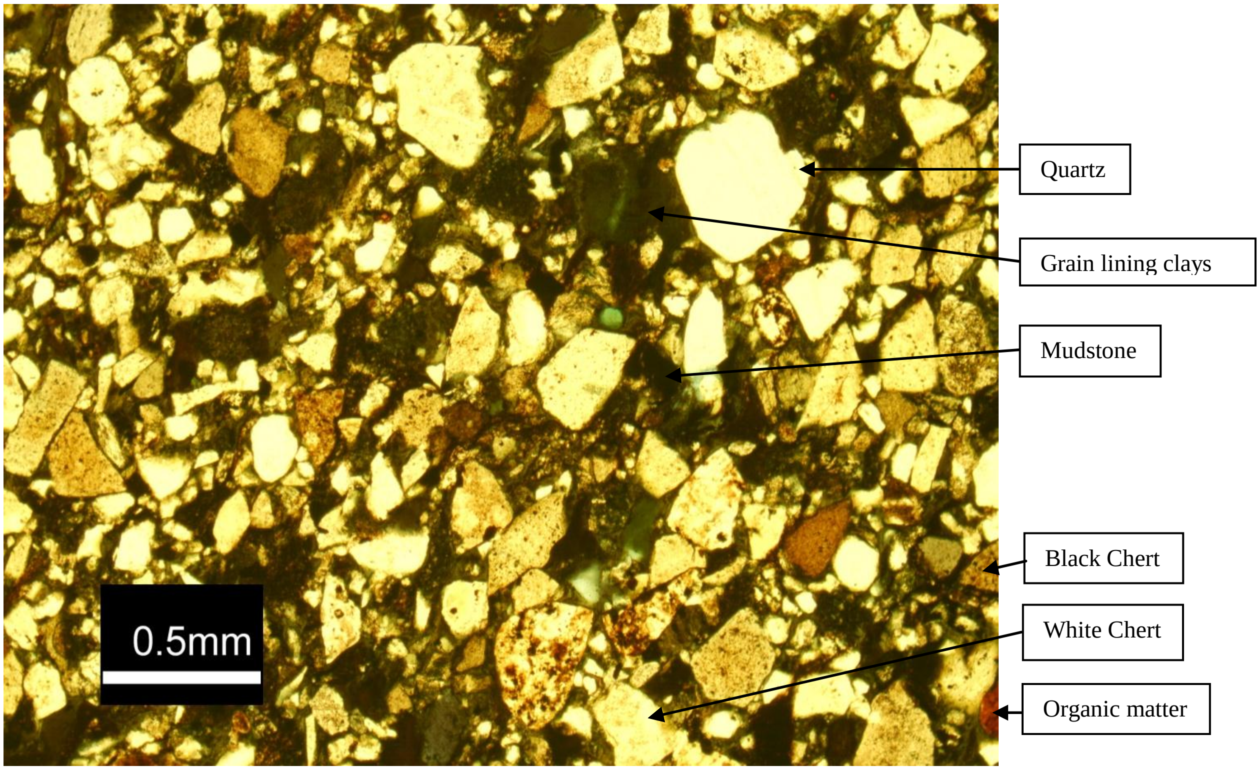

Fig.22a. Sample 10-09-06 in PPL. Moderately sorted, very fine to fine-grained Fishing Branch delta front chert arenite sandstone (*Folk 1968*). Note common grain lining clays, and no visible porosity present.

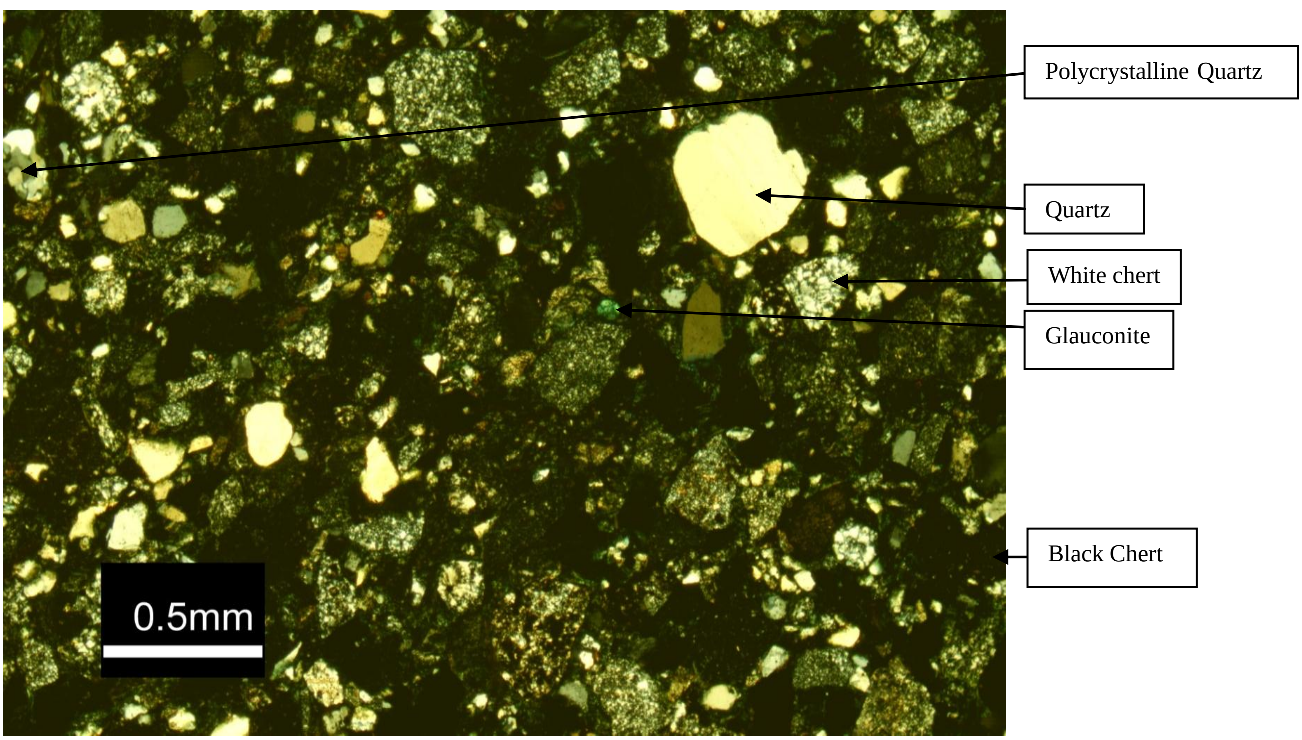

Fig.22b. Sample 10-09-06 in XPL. Note the abundance of chert and minor quartz concentration.

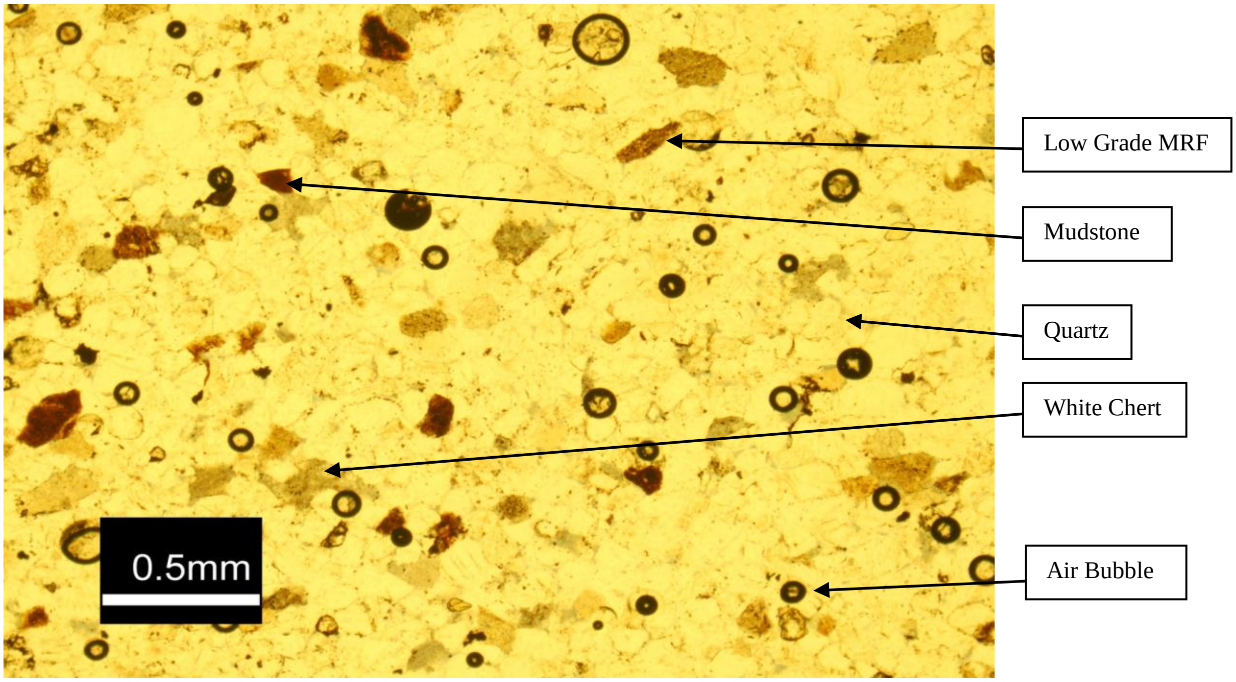

Fig.23a. Core sample I-13-1124.4 in PPL. Well sorted, fine-grained, Fishing Branch delta front sub-litharenite sandstone (*Folk 1968*). Note no visible porosity present, minor lithic and clay content.

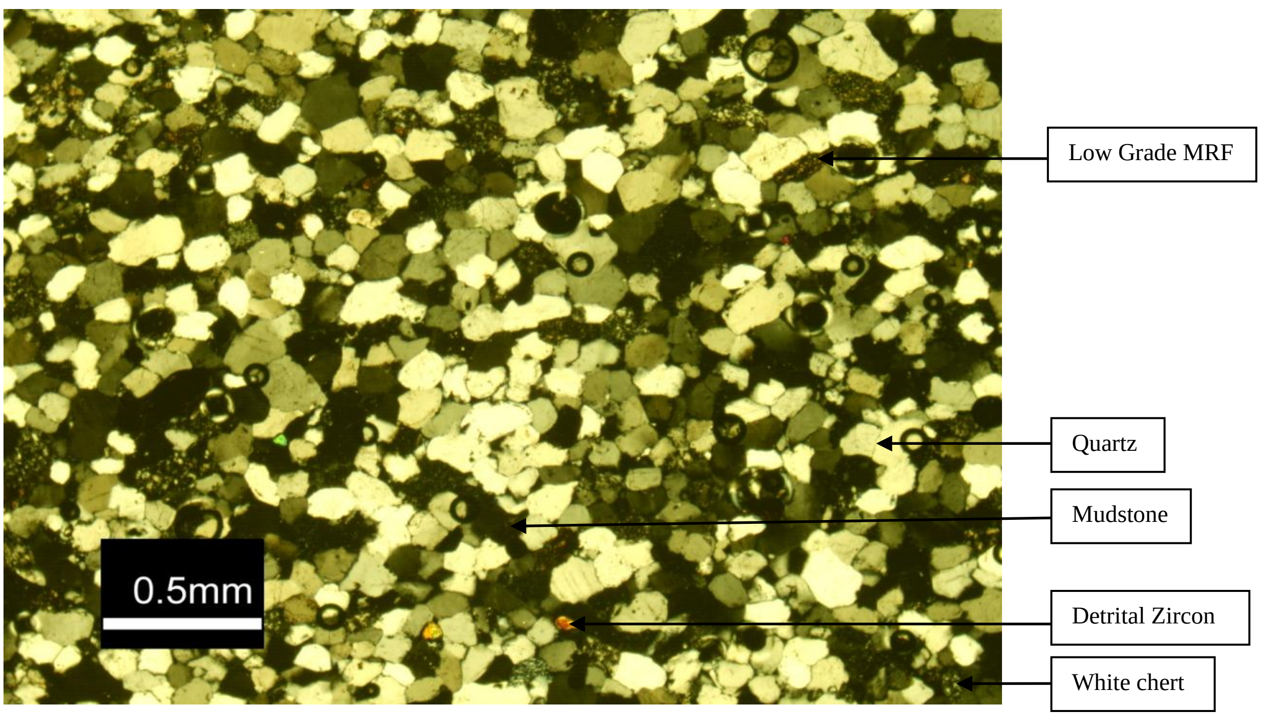

Fig.23b. Core sample I-13-1124.4 in XPL. Note white chert is the main lithic fragment and common detrital zircons.

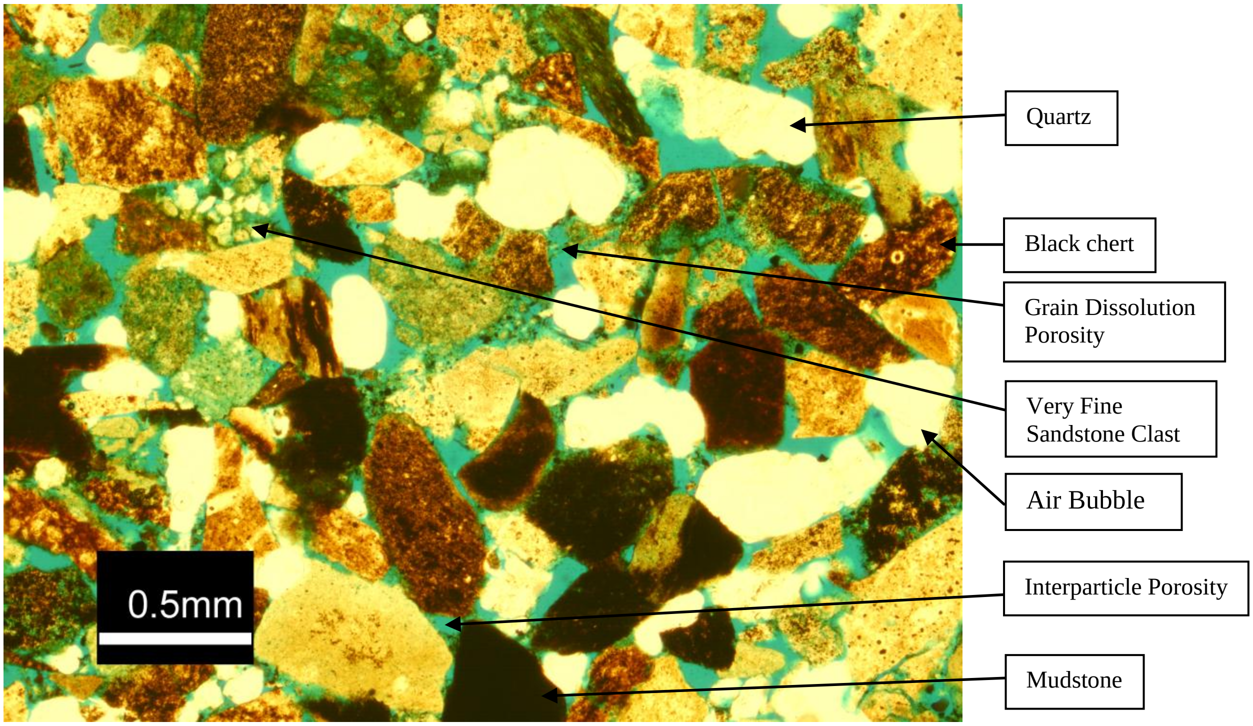

Fig.24a.Sample 09-04-02 in PPL. Medium-grained, poorly sorted Fishing Branch delta front chert arenite sandstone (*Folk 1968*). Note high interparticle and grain dissolution porosity in chert rich samples.

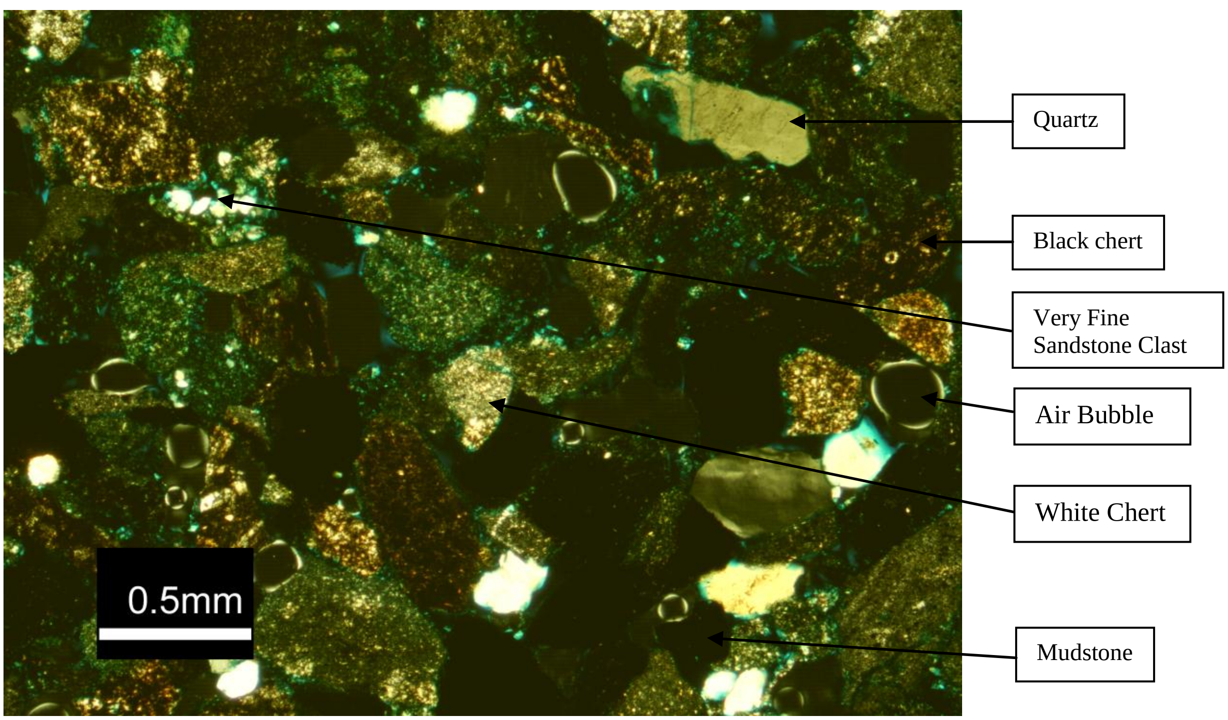

Fig.24b. Sample 09-04-02 in XPL. Note very high modal chert abundance.

5.4 Upper Fishing Branch Marine Sandstone

Samples of the upper Fishing Branch marine sandstone were collected from outcrops 2009-15, 2009-16 and 2010-23 located in the southwestern part of the basin. Of the samples collected, seven thin sections were analysed.

Upper Fishing Branch marine sandstone strata are dominated by storm-generated bedforms including large hummocks (Fig.25). Deposition of this unit has been interpreted to occur in a storm dominated offshore to distal onshore shelf environment (*Jackson et al, 2011*).

Fig.25. Outcrop 2009-07 photo of the upper Fishing Branch marine hummocky cross stratified sandstones. Individual six feet tall for scale.

5.4.1 Depositional Features

This unit contains moderate to well-sorted, angular to sub-rounded, lower to upper very fine-grained, alternating quartzose-lithic planar laminated (09-15-04, 09-16-03 and 09-16-02) to massive samples (09-15-01). Lag deposits consist of poorly sorted, sub-rounded to rounded, massive pebble conglomerate with a moderately sorted, sub-angular to sub-rounded, upper fine matrix (09-16-06); and an imbricated, planar laminated, poorly sorted, sub-rounded to rounded, granule conglomeratic-sandstone with a moderately sorted, sub-angular to sub-rounded, upper fine grained matrix (09-15-03).

5.4.2 Lithology

The upper Fishing Branch marine sandstones contain mainly monocrystalline quartz, less abundant polycrystalline quartz and isolated chalcedony grains. Feldspars are present in trace amounts, represented by orthoclase, plagioclase and microcline. Rock fragments are represented by mudstones, abundant white chert, minor black chert, minor medium to low grade metamorphic rock fragments and very fine sandstone clasts; however sample 09-16-03 contains isolated cherts. Accessory grains in outcrop 2009-15 (Fig.1) samples include detrital zircons, organic matter, and muscovite. Accessory grains in 2009-16 (Fig.1) samples include organic matter, glauconite, detrital zircons, muscovite and biotite. Samples 09-15-03 and 09-16-06 are of pebble lags whose framework grains consist of chert and mudstone clasts. The matrix composition of these lags is similar to the composition of the fine-grained sandstones sampled from this unit (Fig.11) as the lag matrix and sandstone framework plot in the same litharenite to sub-litharenite cluster (Fig.15).

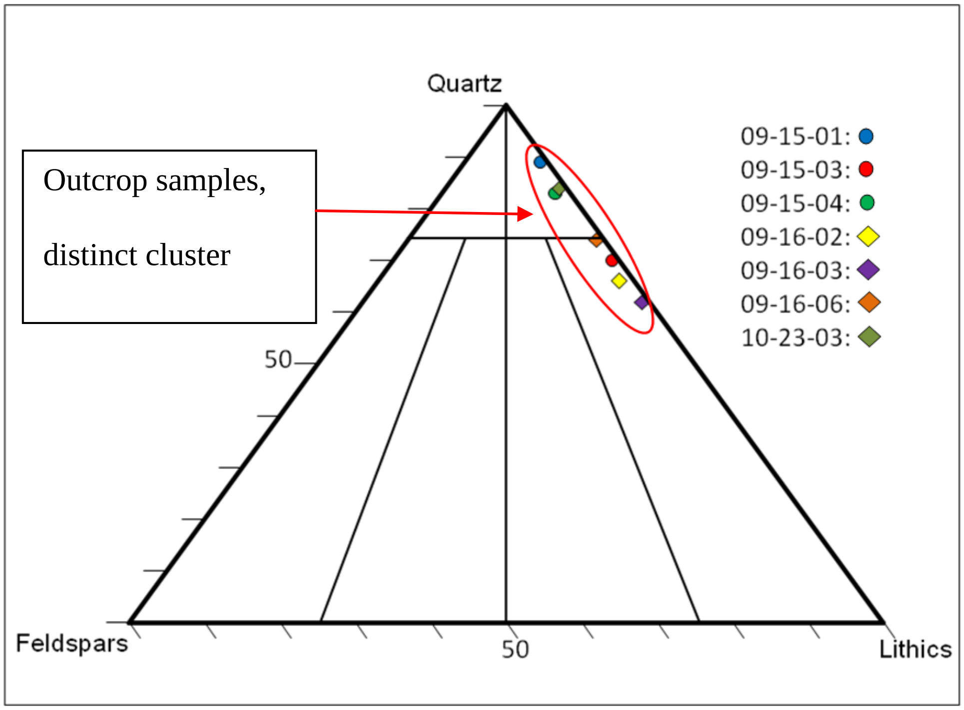

Fig.26. Ternary diagram of the upper Fishing Branch marine sandstones samples from outcrop. Note the formation of one distinct cluster in same position as Fishing Branch delta front sandstone samples in Fig. 10.

5.4.3 Diagenetic Features

The upper Fishing Branch marine sandstones generally contain pervasive quartz cement, minor to abundant clay cement, micro quartz cement in grain fractures and locally abundant glauconite cement.

Sample 09-15-01 contains pervasive quartz cement (Fig.27). Sample 09-15-03 contains pervasive quartz cement and minor clay cement. Sample 09-15-04 contains pervasive quartz cement, micro quartz cement in grain fractures and minor clay cement. Sample 09-16-02 contains pervasive quartz cement and abundant clay cement. Sample 09-16-03 contains prevalent quartz cement, abundant glauconite cementation and pervasive mud cementation (Fig.28). Sample 09-16-06 contains prevalent quartz cement in the matrix, micro quartz cement in pebble chert fractures and abundant clay cementation.

Grains in samples from outcrop 09-15 and 09-16 are tightly packed with minor grain dissolution, deformed mudstone and muscovite clasts, minor pseudomatrix formation, and stylolites (09-15-03 and 09-15-04) occur throughout the unit. This indicates that the examined samples have experience moderate to heavy degrees of compaction.

Alteration throughout the unit is minimal, with minor sericitic alteration of feldspars and cherts occurring frequently throughout the unit.

Grain contacts in this unit are characterized by common concavo-convex and tangential contacts between matrix grains, with sutured contacts occurring between matrix and framework grains in the lag deposits.

Samples from outcrop 09-15 are non-bioturbated while samples from outcrop 09-16 are low to moderately bioturbated.

5.4.4 Porosity Classification

This unit contains streaks of inter-particle porosity, grain dissolution porosity, grain fracture porosity and intra-particle porosity. Pervasive cementation, tightly packed grains and bioturbation are major controls that reduce connected macro porosity. This results in a porosity range between 0-12% for the upper Fishing Branch marine sandstones.

Samples from outcrop 2009-15 display thin streaks of connected inter-particle macro-porosity, grain dissolution macro-porosity from tripolitic cherts, connected grain fracture macro-porosity and unconnected intra-particle micro-porosity also in tripolitic cherts. This results in a porosity range between 2-6% for outcrop 2009-15 samples (Fig.27).

Specifically, 3-5% for sample 09-15-01, 2-4% for sample 09-15-03 and 4-6% for sample 09-15-04.

Samples from outcrop 2009-16 display more variable porosity abundances. Sample 09-16-02 contains inter-particle porosity, grain dissolution, grain fracture and intra-particle porosity from tripolitic cherts resulting in an average porosity estimate of 8%, with 0% in compacted lamina and 10-12% in less compacted lamina (Fig.28 and 29).

Sample 09-16-03 contains minor inter-particle macro-porosity and intra-particle porosity in tripolitic cherts resulting in a porosity estimate between 0-1% (Fig.28).

In sample 09-16-06, grain dissolution macro-porosity is the main form of porosity, minor macro inter-particle porosity, micro-porosity in tripolitic chert and grain fracture porosity is also present (Fig.29). This results in a porosity estimate between 6-8% in areas with high degrees of dissolution, and 2-4% in areas with less dissolution. Areas with bioturbation generally have less dissolution, fine grain size and higher clay content within burrows result in reduced porosity.

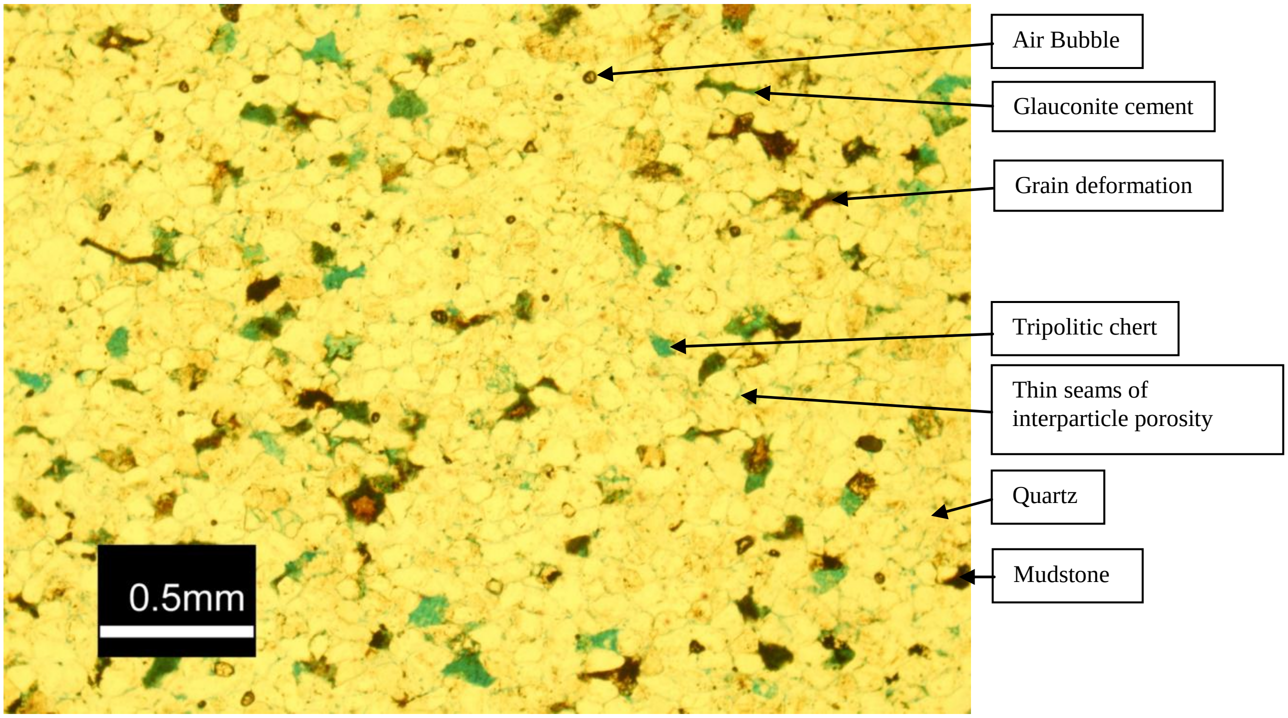

Fig.27a. Sample 09-15-01 in PPL. Fine-grained, well sorted upper Fishing Branch marine quartz arenite sandstone (*Folk 1968*). Note grain dissolution porosity in tripolitic chert, minor glauconite cement, and deformation of mudstone clasts.

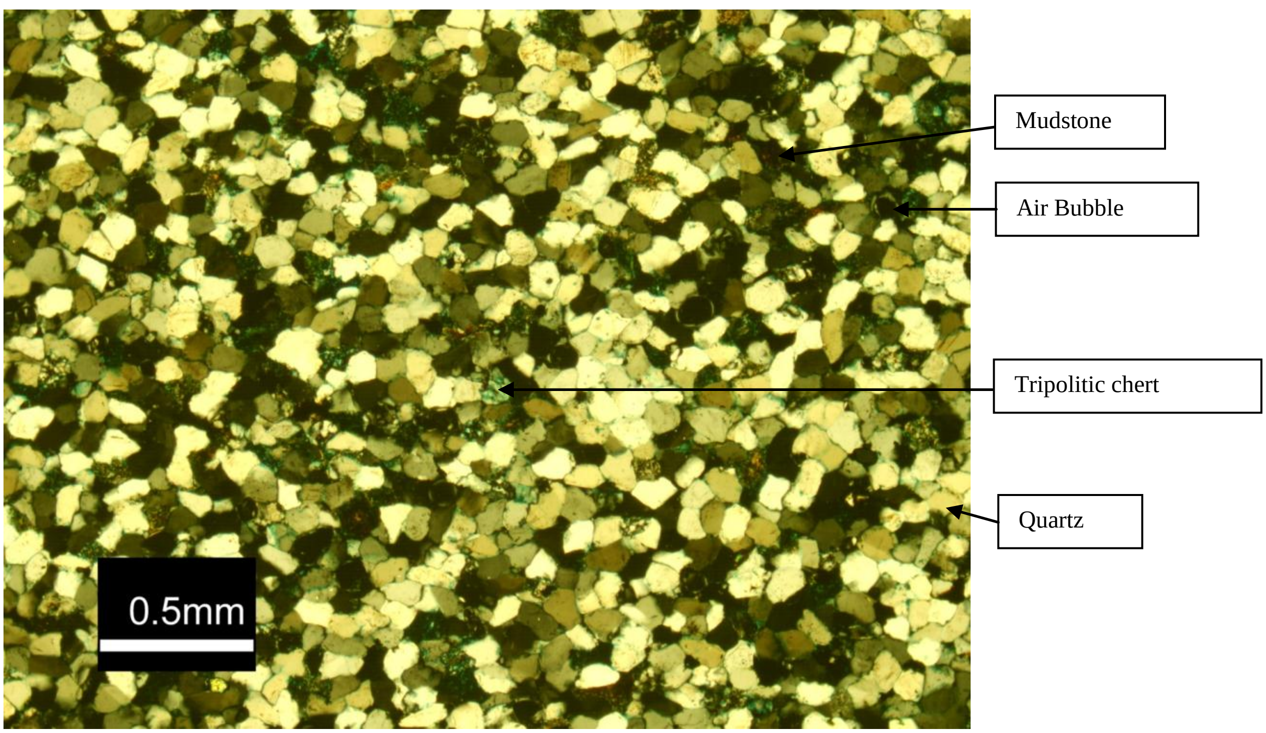

Fig.27b. Sample 09-15-01 in XPL. Note grain dissolution porosity in tripolitic chert.

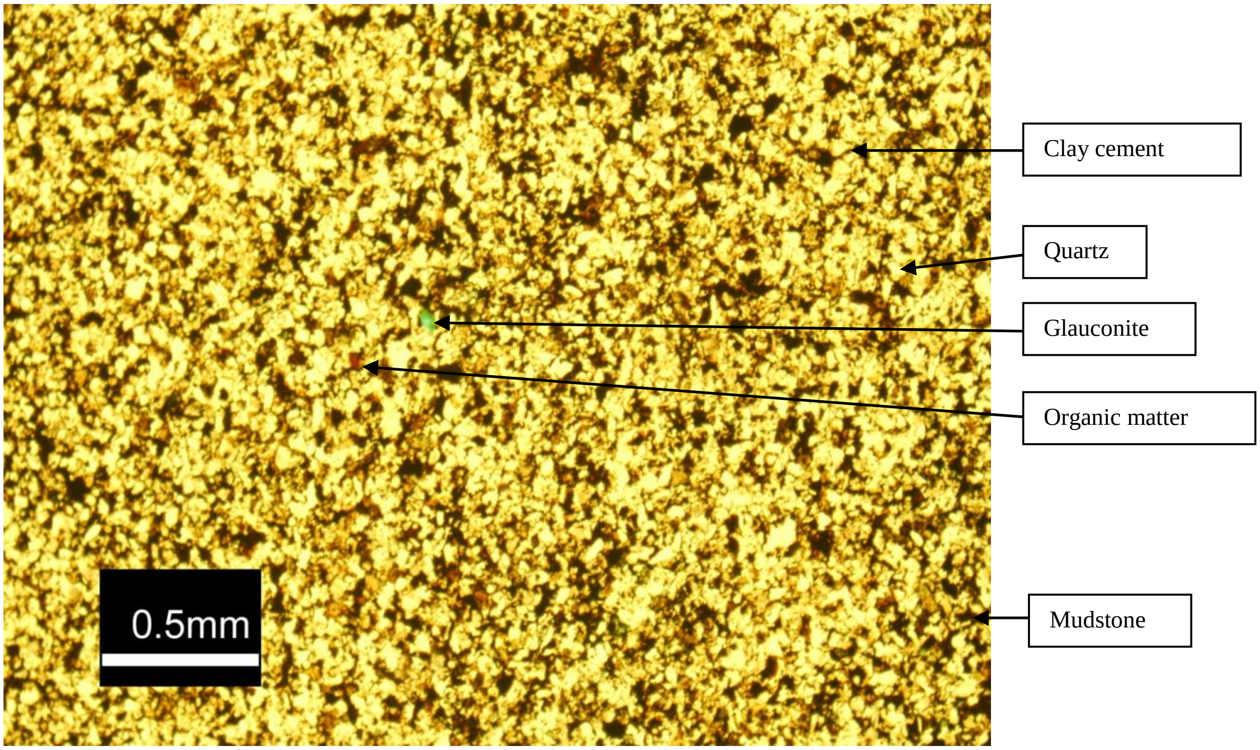

Fig.28a. Sample 09-16-03 in PPL. Very fine-grained, well-sorted upper Fishing Branch marine litharenite (*Folk 1968*). Note abundant lithic fragments and no visible porosity present.

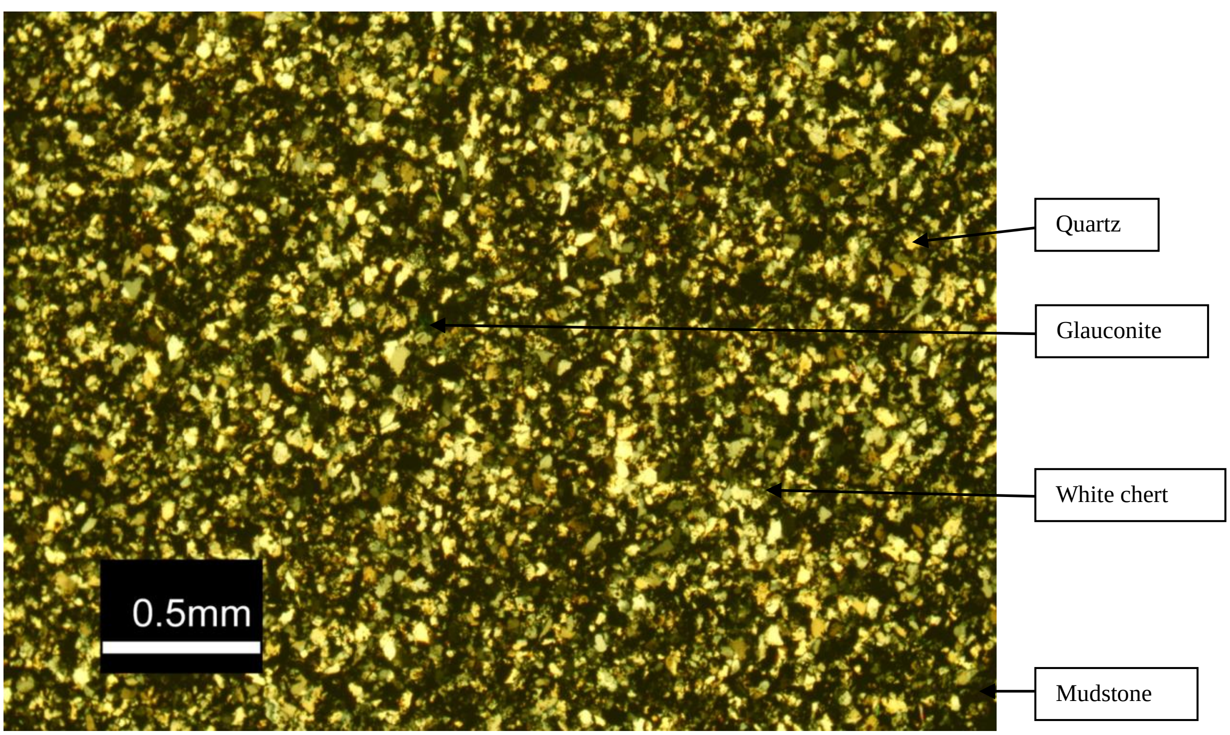

Fig.28b. Sample 09-16-03 in XPL.

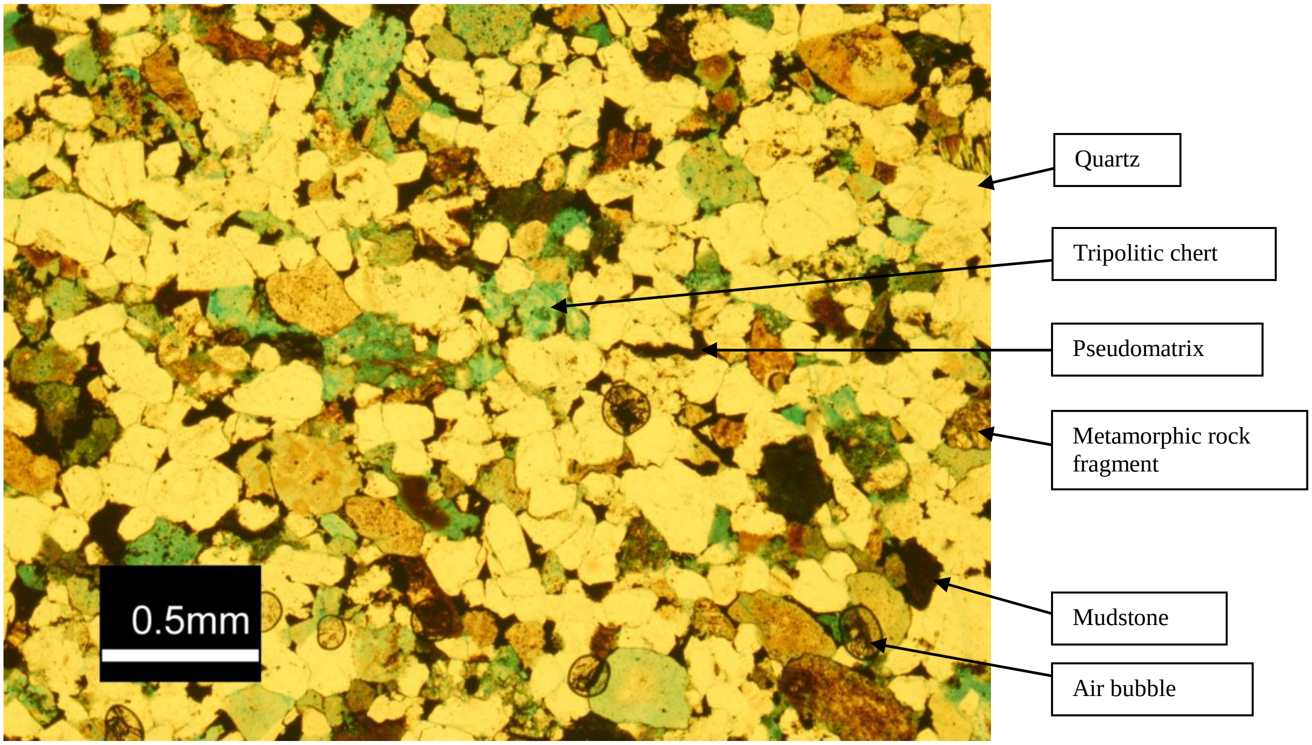

Fig.29a. Sample 09-16-06 in PPL. Moderately sorted, upper fine-grained sandstone matrix of a pebble lag. Note intra-particle porosity in tripolitic chert, common pseudomatrix formation, and common rock fragments.

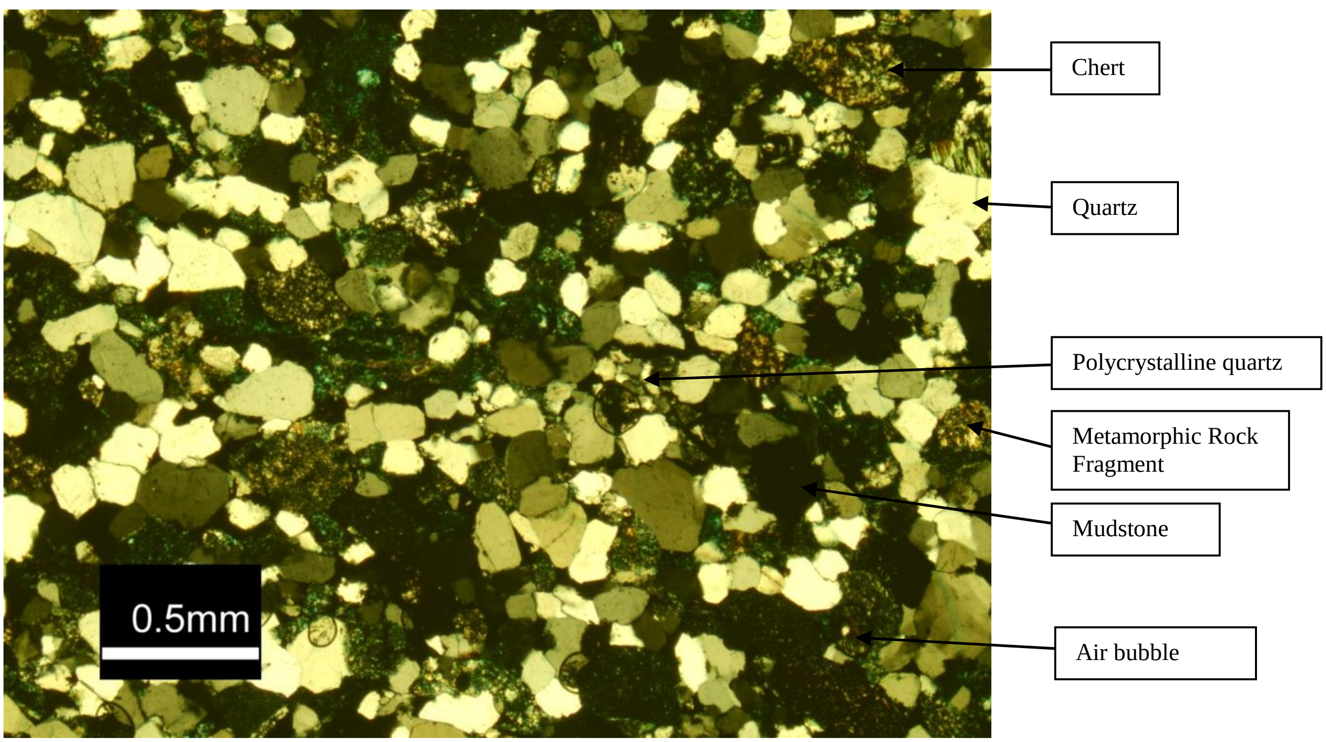

Fig.29b. Sample 09-16-06 in XPL.

Chapter Six: **Cody Creek**

6.1 Introduction

The Cody Creek Formation is a fluvial unit consisting of intercalated sandstone and mudstone, where sandstone is the dominant facies (Fig.30). Sandstone beds are fine to coarse grained and locally granular to pebbly. They occur as cross bedded or planar laminated fining-upward sequences (Fig.30). Non-marine strata predominate in southern Eagle Plain and transitions northwest into marine shelf deposits *(Dixon. 1992).*

The Cody Creek Formation is not the primary focus of this study, thus only one sample was analysed in order to form a basis for mineralogical comparison with the Parkin and Fishing Branch formations.

6.2 Depositional Features

Sample 09-06-02 was collected from the south eastern extent of the basin (Fig.1). This sample is a massive, moderately sorted, medium grained, sub-angular to sub-rounded chert arenite (Fig.32).

Fig.30. Outcrop 2010-06 photo of the Cody Creek cross bedded sandstones.

6.3 Lithology

This sample consists of predominately chert and common mudstone, monocrystalline and polycrystalline quartz. Metamorphic rock fragments, siltstone and very fine grained sandstone clasts also make up the lithic assemblage in this sample. Feldspars are present in trace amounts and are represented by plagioclase. No accessory grains were identified in this sample.

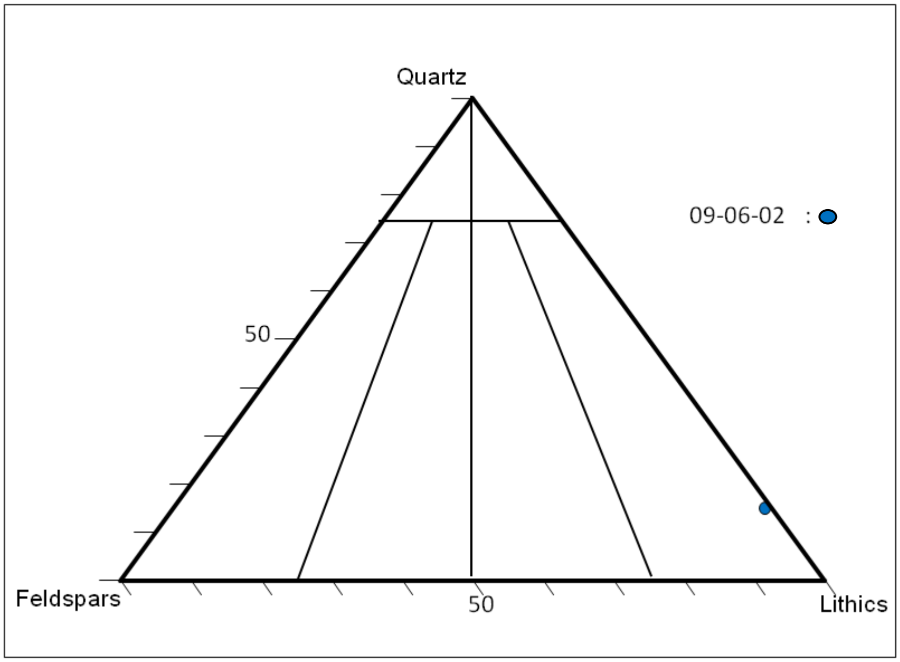

Fig.31. Ternary diagram of chert rich Cody Creek sample.

6.4 Diagenetic Features

This sample contains minimal cement in the form of kaolinite coating grains. Grain dissolution, mudstone deformation, sutured and concavo-convex grain contacts indicate that this unit has experience moderate to strong degrees of compaction (Fig.32). This sample has undergone minimal alteration and is non bioturbated.

6.5 Porosity Characteristics

Sample 09-06-02 contains abundant interparticle and grain dissolution macro porosity, micro porosity is also present in tripolitic chert. This results in a porosity estimate between 20-25% for this sample (Fig.32).

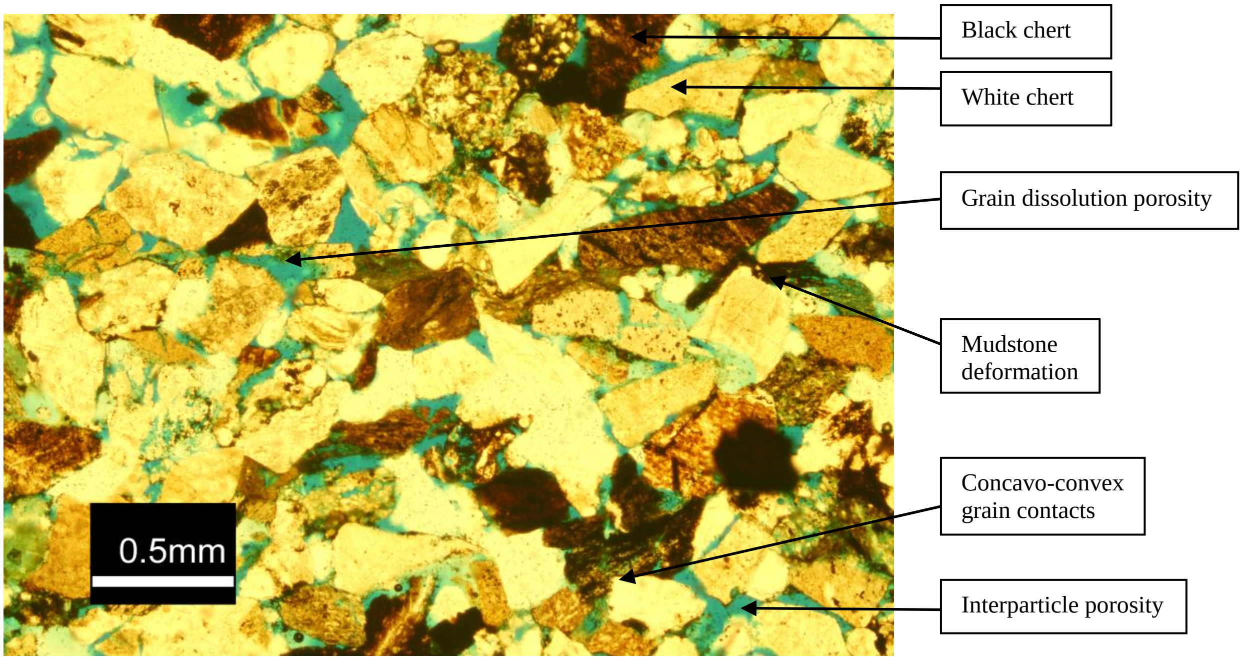

Fig.32a. Sample 09-06-02 in PPL. Medium grained, moderately sorted, Cody Creek chert arenite (Folk, 1968). Note abundant interpartcle and grain dissolution porosity, deformation of grains and concavo-convex grain contacts.

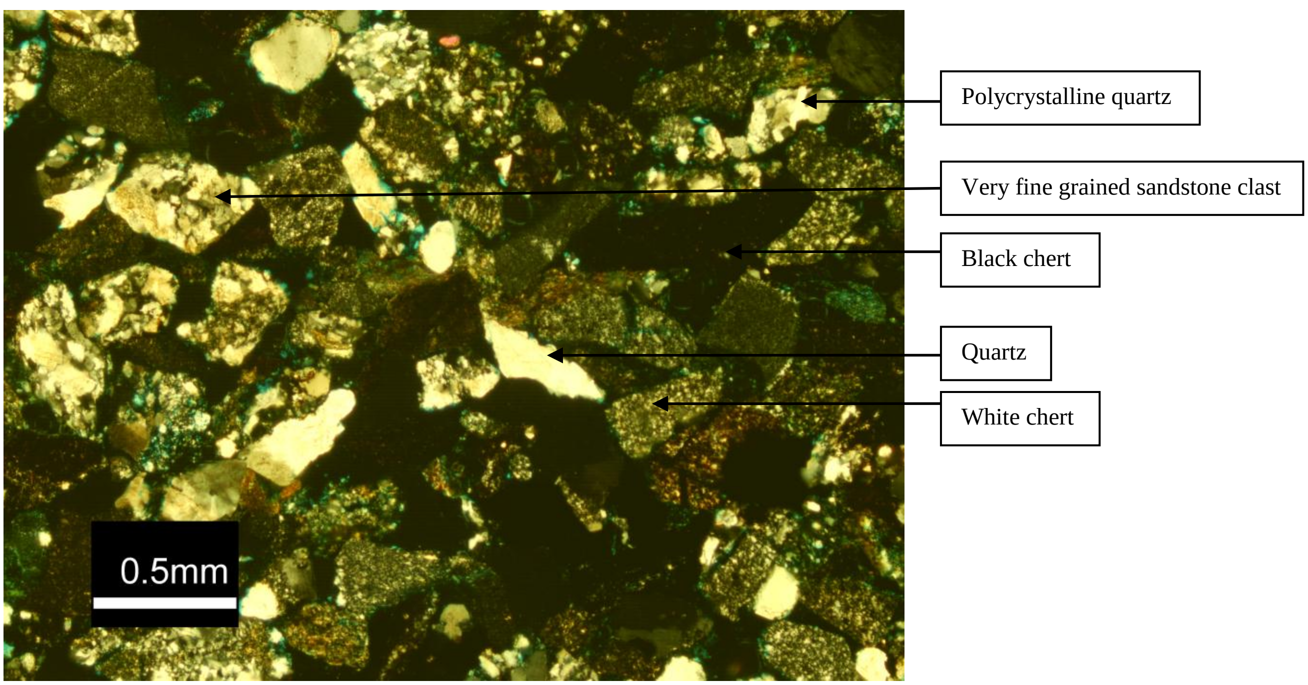

Fig.32b. Sample 09-06-02 in XPL. Note lithic rich composition.

Chapter Seven: **DISCUSSION**

7.1 Basal Parkin Formation

Samples collected from the basal Parkin Formation display one distinct, moderately high, modal quartz mineralogical cluster-A, and a lithic rich outlier mineralogical cluster-B (Fig.7). Cluster-A (Fig.7) reflects a similar but not as quartz rich composition to the Fishing Branch sandstones. The similarity of the quartz rich lithofacies of the Parkin and Fishing Branch formations are interpreted to be the result of similar southern sediment sources during the time of deposition. Cluster-B of Fig.7 is distinct because it reflects a high abundance of modal lithic fragments. Sample C-33-692.2 (cluster-B) is a lithic rich transgressive lag deposit consisting of predominately coarse to pebble size chert grains; this mineralogy is not considered to be characteristic of the Parkin Formation. This anomalous mineralogy is likely a result of the large clast size associated with this lag deposit.

The reservoir quality of the basal Parkin sandstone varies from very poor to good (0-10%) porosity values within the unit. Inter-particle porosity, grain dissolution porosity and intra-particle porosity are the main porosity types in this unit. Locally pervasive clay, glauconite, quartz and calcite cementation types are the main controls on reservoir quality that significantly reduces connected macro porosity within the basal Parkin sandstone.

7.2 Middle Parkin sandstone member

Samples from the middle Parkin sandstone member consist of slump and transgressive lag deposits that occur in the form of two lithofacies (represented by cluster-A and B; Fig. 14). Lithofacies-A is quartz rich, while lithofacies-B is lithic rich. Both the basal and the middle Parkin members display similar lithofacies compositions, however they do not display the sample lithofacies abundance. Middle Parkin slump deposits located in the west and south west of the basin represented by lithofacies-B are more lithic rich and interpreted to be the result of changing depositional process and reduction in depositional energy as sediment is transported basinward.

The pebble lag deposits in the basal and middle Parkin members are compositionally similar in their high modal chert abundance.

7.3 Prodeltaic Fishing Branch Sandstone

Samples collected from the prodeltaic Fishing Branch sandstones display a bimodal mineralogical distribution as cluster-A contains quartz rich samples while cluster-B contains lithic rich samples consisting of mudstone clasts in particular. Lithofacies-B (represented by Fig. 19) was likely deposited in more distal sections of the upward shallowing prodeltaic cycles (Fig. 2). Lithofacies-A (represented by Fig. 17 and 18) are mud poor, fine-grained sandstones; deposition likely occurred in a more proximal, higher energy, prodeltaic location within upward shallowing deltaic cycles. Lithofacies A and B can be consistently found at different outcrops within the basin indicating the similarity in the prodeltaic Fishing Branch sediments basinwide. Therefore lithofacies A and B and considered to be characteristic of the prodeltaic Fishing Branch unit.

The reservoir quality of the prodeltaic Fishing Branch sandstone is poor due to locally abundant clay and glauconite cement followed by pervasive quartz cementation throughout the well-sorted fine-grained sandstones. This combined with the moderate compressional forces within the sample suite results in poor porosity values (0-6%) within the prodeltaic Fishing Branch sandstone.

7.4 Delta Front Fishing Branch Sandstone

Samples collected from the Fishing Branch delta front sandstones display two distinct mineralogical trends as cluster-A samples (Fig. 20) display the characteristic high modal quartz concentration while cluster-B samples display a high modal lithic concentration. Cluster-B is further sub-divided into cluster-C and cluster-D, which represent mudstone and chert rich contents respectively. Cluster-C displays compositions similar to that of cluster-B in the prodeltaic Fishing Branch sandstone (Fig. 7); however cluster-D (Fig. 20) of the Fishing Branch delta front sandstone contains anomalously high white chert compositions. Cluster-D is therefore interpreted to be the result of a period of higher depositional energy within the upward shallowing deltaic cycles, combined with a change in sediment source during the time of deposition. Samples of the chert rich lithofacies-B were collected in the southeast of the basin, in the most proximal location to the sediment source at the time of deposition. Core samples I-13 collected in the south-central part of the basin are represented by lithofacies-A; this may be the result of deposition lithofacies-A occurring in a lower depositional energy portion of the delta lobe. Mud rich Lithofacies-C occurs in the northern extent of the basin, at the most distal delta front location.

The reservoir quality of the Fishing Branch delta front sandstones are very poor (0-2% porosity) due to locally abundant clay cement followed by pervasive quartz and locally pervasive glauconite cement within the unit.

7.5 Upper Fishing Branch Marine Sandstone

Samples collected from the upper Fishing Branch marine sandstone display a distinct quartz rich mineralogical composition cluster (Fig. 26) containing litharenites to sub-litharenites. This high modal quartz composition reoccurs within each unit of the Fishing Branch Formation, further supporting that this composition is a characteristic of the Fishing Branch Formation. This lithofacies is likely the result of storms concentrating quartz rich sediment into hummocky sandstone deposits.

The reservoir quality of the upper Fishing Branch marine sandstone varies from very poor to good (0-12%) porosity values within the unit. This is due to the thin streaks of inter-particle porosity, grain dissolution porosity and grain fracture porosity. Locally pervasive quartz, clay and glauconite cementation, tightly packed well-sorted grains, and clay-associated bioturbation reduce the porosity within this unit.

7.6 Cody Creek

The Cody Creek is mineralogically similar to chert rich lithofacies and lag deposits contained in the Parkin and Fishing Branch formations. However the Cody Creek can be differentiated from the latter based on its lithic composition, anomalous abundance of polycrystalline quartz, metamorphic rock fragments, siltstone, shale and fine grained sandstone clasts. This observation is consistent with the fluvial depositional environment of the Cody Creek and its proximity to the sediment source.

7.7 Trends

Outcrop and core samples differ in the amount of alteration and cementation seen in thin section samples; that is, outcrop samples display more altered and mud rich compositions, while the samples from core have a lower mud content and less altered compositions.

This indicates that weathering has played a role in altering the sandstone composition of the samples, thus outcrop samples are not a good indication of subsurface reservoir potential of these samples.

Fluvial samples are coarser grained, poor to moderately sorted, are predominately chert rich, and display a diverse rock fragment assemblage. This is consistent with the depositional processes and close proximity to the sediment source associated with fluvial deposits in this basin.

Marine samples are typically finer grained, moderate to well sorted, and quartz rich in proximal locations while very fine grained, well sorted mudstone rich sandstones occur in distal depositional parts in the basin. These observations are likely the result of lower depositional energy in basinward locations compared to proximal locations.

Pebble lag deposits in the Cretaceous strata of this basin are very similar as they typically occur as pebble chert conglomerates to conglomeratic-coarse grained sandstones.

7.8 Summary and Exploration Strategy

The Fishing Branch Formation samples are characterized by mud poor and mud rich deltaic sandstones. The Parkin Formation displays a similar but lower modal quartz compositions to the Fishing Branch Formation. Transgressive pebble lag deposits are common in the basal Parkin sandstone but are not considered representative of the composition of the formation.

Both the Parkin and the Fishing Branch formations have variable reservoir qualities as a result of local variability in porosity within the formations. Diagenetic features, grain size, sorting and compaction are major controls on porosity within these formations. The variability of the examined samples highlights the reservoir heterogeneity on a thin section scale. This could result in many unexpected flow barriers and locally pervasive clay content could threaten reservoir performance. Therefore care and due diligence should be applied when undertaking exploration projects within these formations. The results suggest advanced drilling methods such as horizontal multi-frac technology could be implemented to enhance the economic viability of hydrocarbon production from these relatively low porosity sandstones.

Samples containing high modal chert abundances contain excellent (18-25%) porosity values and represent the best reservoir rock within the studied formations. These high porosity chert arenites are localized in the Fishing Branch delta front sandstone. Additionally, an increasing chert concentration within the upper part of the Cretaceous strata has been observed and is likely the result of a change in sediment source during the deposition of the Fishing Branch deltaic cycles.

Chapter Eight: **CONCLUSIONS**

1. The basal Parkin Member can be distinguished mineralogically from the Fishing Branch Formation due to its lower modal quartz concentrations.
2. Core samples contain less clay and diagenetic features than outcrop samples.
3. Sandstone samples collected in proximal marine locations are slightly coarser grained and mud poor, while samples collected in distal marine locations are very fine grained and mud rich.
4. Mineralogically it is difficult to distinguish between the different units of the Fishing Branch deltaic cycles as they all contain similar high and low modal quartz lithofacies, with the exception of the Fishing Branch delta front sandstone which contains high modal chert lithofacies.
5. The basal Parkin member and Fishing Branch Formation contain highly variable, negligible to good porosity values that result from heterogeneities occurring across the basin.
6. Lithofacies mapping and a detailed understanding of the local diagenetic features will be needed to predict reservoir quality of Cretaceous strata within the Eagle Plain Sedimentary Basin.
7. Chert arenite samples of the Fishing Branch delta front and Cody Creek fluvial sandstones form the best reservoirs.

Chapter Nine: **REFERENCES**

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