IMPACT OF DIAGENETIC OVERPRINTS ON RESERVOIR QUALITY AND HETEROGENEITY, UPPER MORROW SANDSTONE, MORTON COUNTY, KANSAS.

By

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UPPER MORROW SANDSTONE, MORTON

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Chapter I

Introduction

1.1. General statement

The economic importance of hydrocarbons and their crucial role in the 20^{th} century has resulted in unending studies of the processes leading to its formation, accumulation and production. With increasing demand, geologists are being challenged to improve the methods for locating and recovering oil and natural gas. Large volumes of oil and natural gas have been discovered worldwide and in the Mid-continent region of North America where this study is located. The Mid-continent contains the Anadarko basin, which is one of the largest in North America with an area of 35,000 square miles (Al-Shaieb and Walker, 1986).

Hydrocarbon accumulations in the Anadarko basin were initially discovered in Pennsylvanian rocks (Rascoe and Adler, 1983) that host the majority of the oil and gas producing reservoirs (Van Evera, 2004). One of the principal hydrocarbon producing intervals in the Anadarko Basin is the Pennsylvanian upper Morrow (Krystinik and Blakeney, 1990). On the northern shelf of this basin, upper Morrowan sandstones occur at shallow depths of less than 6000 ft and form excellent traps because of their encasement by shale and mudstone (Wheeler et al., 1990).

The Morrowan, which is informally called Morrow by the petroleum industry, is informally divided into upper and lower subunits (Swanson, 1979). Cores used for this study are from the upper Morrow whose sandstone is a primary target of exploration and production in the Anadarko basin. Sandstone reservoirs in the upper Morrow have documented production of over 280 million barrels of oil and 3.3 trillion cubic feet of gas on the northwestern shelf of the basin and Hugoton Embayment in Oklahoma and Texas (Al-Shaieb and Puckette, 2001).

The paloedrainage system and sediment dispersal systems for the upper Morrow are extensively studied (Kystinik and Blakeny, 1990, Wheeler et al., 1990, Swanson, 1979), though little work has been published regarding the effect of sedimentary features such as cements and pseudomatrix in channel lag deposits, early carbonate cements in clean coarse - grained sandstones, detrital silt and clay in low energy sandstone such as channel fill and burrowing in estuarine and marginal marine facies that homogenizes the sandstones and destroy porosity and permeability. Further diagenetic processes of interest include detrital and authigenic clays that preserve primary porosity and occlude porosity.

Therefore, understanding the impact of sedimentary features and subsequent diagenetic overprints on reservoir properties and reservoir heterogeneity is a major concern for this research**.** This work investigates the influence of sedimentary features at a centimeter to decimeter scale on the evolution of porosity, generation of intrareservoir seals and reservoir heterogeneity. This study addresses problems of reservoir heterogeneity induced by sedimentary features and ties these features to specific depositional environments. As a result, problems of reservoir heterogeneity at hand specimen scale will be considered during exploration and development therefore, increasing reservoir output and deliverability during primary and secondary recovery processes.

1.2. Objectives

The primary objective of this work is to examine the relationship between depositional environments and diagenetic processes, and analyze the evolution of porous zones and intrareservoir seals in the upper Morrow sandstones. Other objectives include:

i. Determine the petrophysical properties of the cores (porosity and permeability).
ii. Determine detrital and authigenic constituents.
iii. Determine the diagenetic history of the upper Morrow sandstone.
iv. Establish predictive tools for locating boundary conditions in reservoir that could contribute to reservoir heterogeneity.

1.3. Location

The study area is the Mustang East field in Morton County, southwest Kansas (Figure 1). The cores studied are from the upper Morrowan sandstone, early Pennsylvanian. Tectonically, the field is located in the southwestern corner of the Hugoton Embayment and northwestern part of the Anadarko basin. The basin is bounded to the northwest by the Las Animas Arch, the southwest by the Sierra Grande Uplift, the south by the Amarillo-Wichita Uplift, and the Nemaha Ridge and Central Kansas Uplift to the northeast.

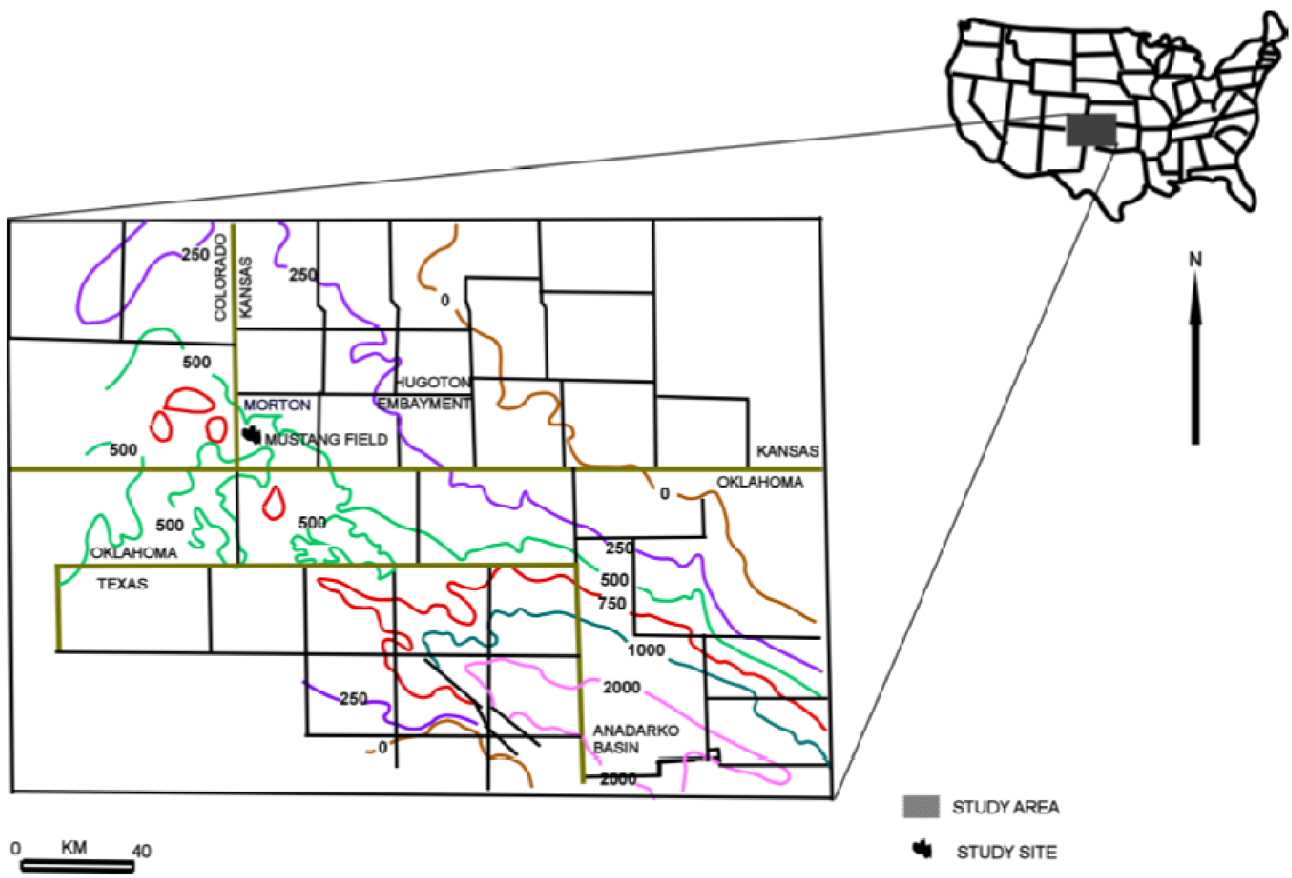


Figure 1: Location of the study area, in the Hugoton Embayment of the Anadarko Basin. Contours show thickness of the total Morrowan Stage (modified from Buatois et al., 2002).

Chapter II

Literature review

Previous studies on the Pennsylvanian Morrow sandstone focused primarily on depositional processes, structural setting, tectonics, facies analysis and hydrocarbon production (Adler et al., 1971, Swanson, 1979, Rascoe and Adler, 1983, Johnson, 1990, Krystinik and Blakeney, 1990, Wheeler et al., 1990, Buatois et al., 2002). These studies contributed to the understanding of reservoir genesis and petroleum trapping and they provide a platform for present and future studies. Particularly, this area is of interest to the oil and gas industry because of its location in the highly petroliferous Anadarko basin, one of the largest volume-hydrocarbon-producing basins in North America. (Al-Shaieb and Walker, 1986, Al-Shaieb and Puckette, 2001). As a result, a detailed study of the impact of sedimentary features on reservoir quality of the Morrow sandstone will enable the application of ideas and knowledge gained from this study to other formations with similar characteristics.

Most of the productive sandstone reservoirs of the upper Morrow are believed to be incised valley deposits, whose heterogeneity complicates exploration and development (Van Evera, 2004 and Krystinik and Blakeney, 1997). Porosity is dominantly secondary

(Puckette et al., 2008) that results from the dissolution of feldspars, rock fragments and carbonate materials by organic acids produced during burial (Al-Shaieb and Puckette, 2001). Primary porosity is reduced by the presence of clay and carbonates and the dissolution of detrital grains results in increase permeability values (Puckette et al., 2008). The Morrow, which is considered as a transgressive sequence that overlies the post Mississippian unconformably (Sonnenberg, 1990), is divided informally into the upper and lower Morrow (Swanson, 1979). The lower Morrow consists of fluvial and marine sandstones together with shale, all of which were deposited during the transgression across the eroded Mississippian surface (Johnson, 1990). The upper Morrow is mainly siliciclastics (Krystinik and Blakeney, 1990) that consist of incised valleys, heterogeneous valley fills and shelf muds. Due to the coarse nature of these Morrow valley-fill sandstones, the drainage system is thought to have been subjected to flashy discharge of substantial velocity of 3 – 6 ft/sec (Krystinik and Blakeney, 1990).

Potter and Olsen (1954) used cross-bedding to assess environment of deposition and found cross-bedding facilitates stratigraphic correlation and could be used to infer direction of sediment sources. Potter and Olsen (1954) observed cross-bedding to be consistent and unidirectional in sandstones of fluvial channel origin. Van Evera (2004) and Puckette et al. (2001) identified fluvial facies in the upper Morrowan channel fills of Oklahoma. Potter (1962) observed that a number of depositional features affect reservoir quality and that bioturbation was particularly destructive due to homogenization of the sediment. Bandel (1967) used fossil tracts, trails, and burrows to interpret the source of sediments in which they are formed. In the Morrow sandstones, brachiopods and burrows were found in sections of the cores interpreted to be of marine or estuarine origin.

Wilson and Pittman (1977) observed that the presence of authigenic clays strongly influence reservoir quality and explained that water saturation and permeability are very sensitive to relative clay abundance. Puckette et al. (2008) identified authigenic clays in the upper Morrow sandstone that could affect the production of oil and gas.

Wheeler et al. (1990) observed that the Morrow sandstone reservoirs occur at shallow depths and form excellent traps due to their encasement by shales. Wheeler et al. (1990) also observed that these sandstones have a high deliverability due to their high porosity and permeability and that valley-fills are heterogeneous and variable depending on the incisement depth, the amount of available sediment and number of primary and secondary drainage systems available. In addition, they suggested that valley-fills reflect climatic changes, paleotectonics and sea-level fluctuation magnitude and duration. To conclude, Wheeler et al. (1990) proposed that a complete depositional sequence in a valley-fill goes from unconformity (sequence boundary) to another unconformity (sequence boundary) overlain by marine shale (Figure 2)

Archer and Greb (1995) noted that conglomeratic sandstones represent changes in base level because they formed during eustatic lowstand or major tectonic uplift. The upper most parts of the Pennsylvanian sandstone sequence indicate shallow water estuarine deposition and the coarse-grained nature of the sandstones indicates they were deposited as part of a lowstand system tract (Archer and Greb, 1995).

Puckette et al. (2008) observed three major lithofacies; fluvial, estuarine, and marine in the upper Morrowan interval. They found that these lithofacies are controlled by their sequence stratigraphy; lowstand system tract deposits are mainly clay-clast conglomerates, transgressive system tract deposits are fluvial sandstones, estuarine sandstone and shale while high system tracts deposits are mostly marine shale.

A number of these studies by Van Evera (2004), DeVries (2005) and Puckette et al. (2008) examined the upper Morrow sandstone and qualitatively linked porosity and permeability to lithofacies. Puckette et al. (2008) provided porosity and permeability data for the upper Morrow in Oklahoma and DeVries (2005) provided average porosity and permeability data for the upper Morrow sandstone in East Mustang Field. In this study, specific depositional and diagenetic features such as cemented zones are targeted for analysis to determine how changes in lithofacies affect flow barrier (seal) generation and reservoir heterogeneity.

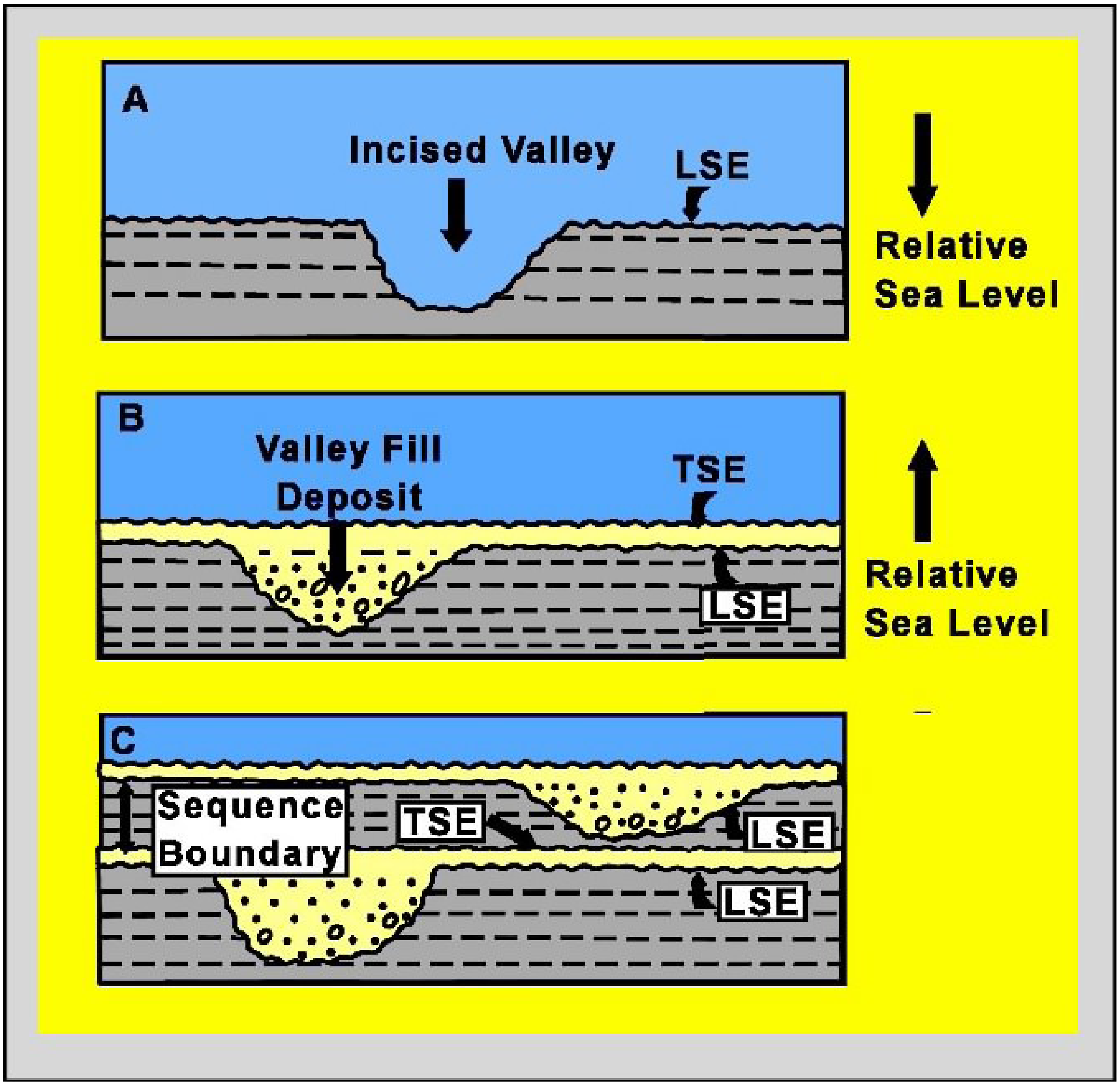


Figure 2: An illustration of incised valley- fill deposit (from Sonnenberg, 1990). Lowstand surface of erosion (LSE) and Transgressive surface of erosion (TSE). (A) initial stage of valley incisement during Lowstand system tract. (B) Deposition of sediments during transgressive system tract. (C) Continuation of the cycle with a sequence boundary and new valley incision.

Chapter III

Geologic Setting

3.1. Pennsylvanian Tectonics

The study area is located on the northwestern shelf of the Anadarko basin (Figure 3) which formed during the Pennsylvanian orogeny that began in late Morrowan time (Adler et al., 1971), as the result of the collision between the North American plate (Laurentia) and South American plate (Gondwana) (Rascoe and Adler, 1983). The collision generated major tectonic features including the Ouachita fold belt, Arkoma basin, Amarillo-Wichita Uplift, Arbuckle Uplift and Las Animas Arch (Rascoe and Adler, 1983). The upper Morrow deposition occurred simultaneously with the structural growth and erosion of the Amarillo-Wichita Uplift (Johnson, 1990) and as a result it is wedge shaped and thickens close to the Wichita Uplift and thin towards the shelf on the northern side of the basin (Al-Shaieb and Walker, 1986)

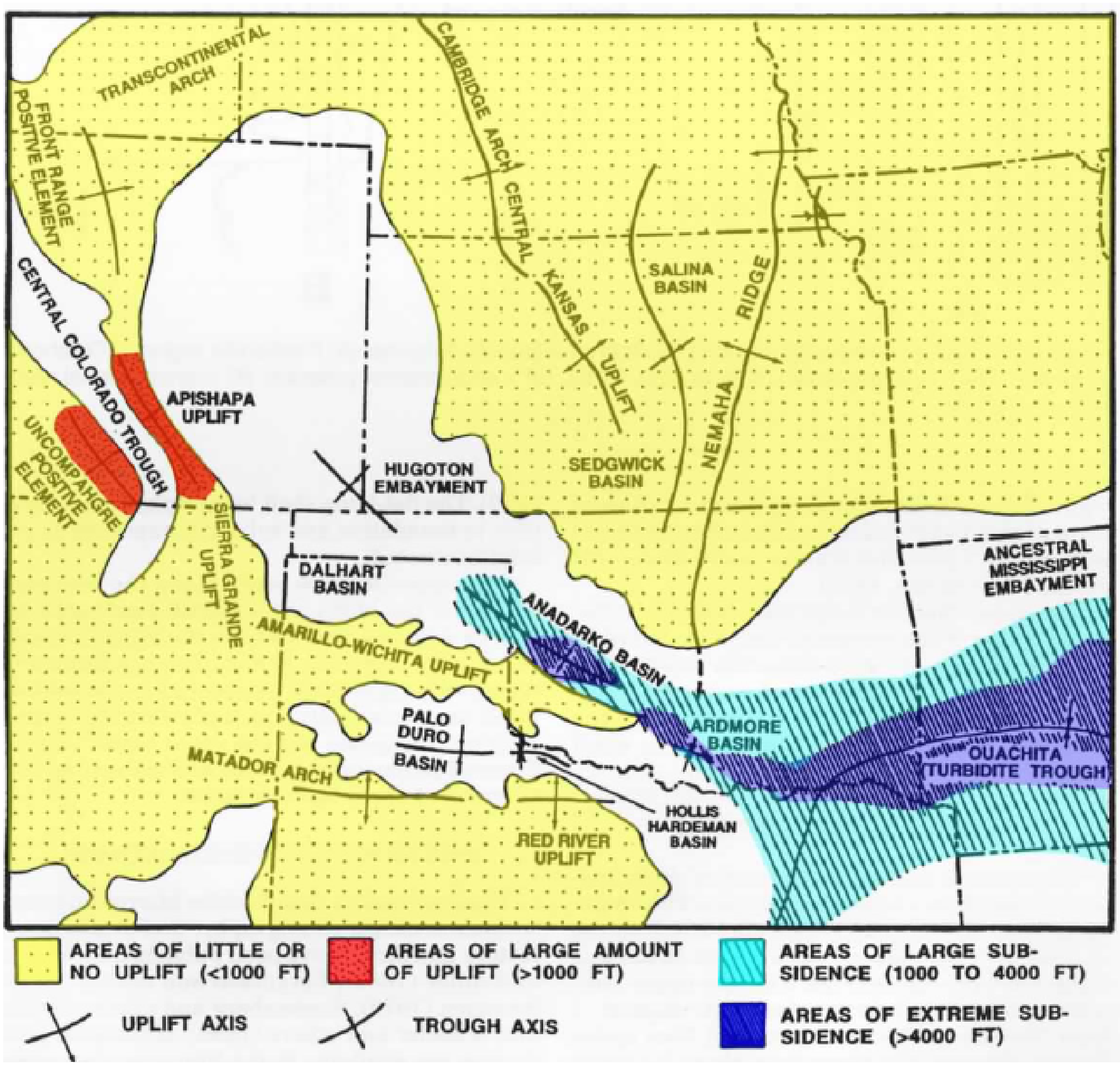


Figure 3: Map showing geological setting of the study area with major structural features shown. Uplifts and basins highlighted (Sonnenberg, 1990)

3.2. Regional Stratigraphy

The Morrow formation informally is divided into the upper and lower Morrow (Figure 4) and studied cores are upper Morrowan. The upper Morrowan interval is found above the “Sqaw belly” limestone, an informal marker that separates the upper Morrowan interval from the lower Morrowan. The Morrow is stratigraphically located above the Mississippian Chester limestone and below the Atokan Thirteen Finger Limestone. Williams et al. (1995) and Bowen and Weimer (2004) observed that the Morrowan series is separated from adjacent formations by two angular unconformities, one above the Mississippian Chester limestone and one below the Atokan limestone. Other authors have proposed that the unconformities above and below the Morrow are disconformities (Rascoe and Adler, 1983, and Wheeler et al., 1990).

The upper Morrowan is dominated by shale that contains thin sandstones. These sandstones commonly are cross bedded with parallel bedsets that form fining upward sequences. They are poorly to fairly sorted and have angular to rounded grains. The shales are dark in color and can be rich in fossils, while others are bioturbated. Wheeler et al. (1990) described the Morrow as a southward thickening wedge of siliciclastics and carbonate sediments.

The lower Morrow varies greatly in thickness over relatively short distances (Swanson, 1979). Sonnenberg (1985) attributed the variability in thickness to onlap and different rates of sedimentation. Krystinik and Blakeney (1990) suggested that the lower Morrowan in Colorado is dominantly limestone that ranges from wackestone to grainstone with abundant fossils at exposed surfaces or unconformities.

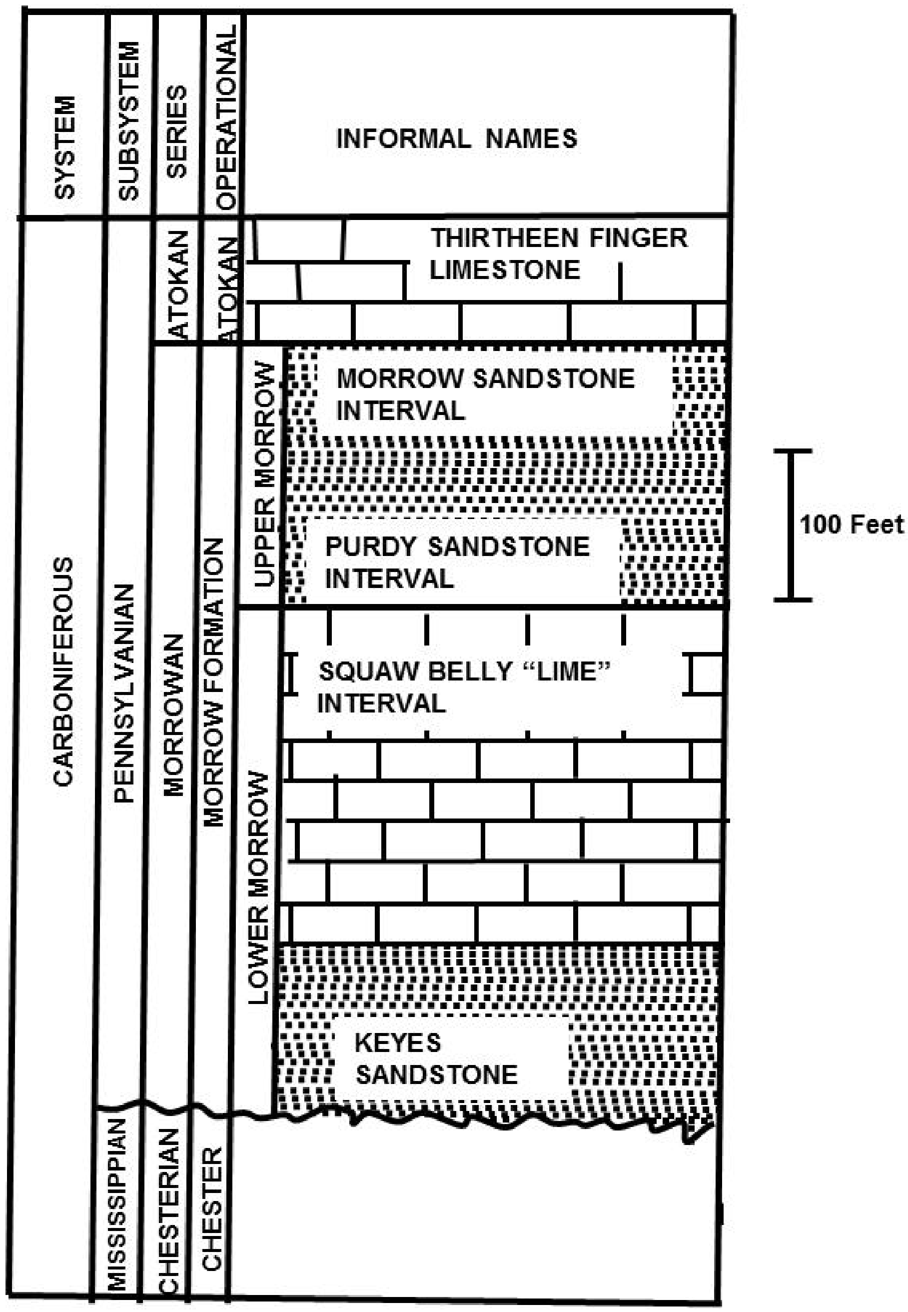


Figure 4: Stratigraphic nomenclature for the Pennsylvanian Subsystem (modified from Puckette et al., 2008)

3.3. Sequence Stratigraphy

In the early Morrowan time, the Mississippian carbonate was transgressed by seas that eroded and deposited a series of sediments. Throughout the Morrowan, the shoreline shifted as a result of glacio-eustasy and tectonics (Figure 5), creating an incised drainage system in the upper Morrow. This system was fed by a broad drainage network that covered western Kansas and Colorado (Krystinik and Blakenley, 1994).

Relative fall in sea-level, due to subsidence or glacio-eustasy caused the shoreline to move basinward and river systems to advance across the shelf. These rivers eroded the shelf creating incised valleys (Figure 6), whose filling began as lowstand paraconglomerate. Most filling occurred when seas transgressed due to relative rise in sea-level. Early transgression resulted in deposition of sandy facies as rising sea level reduced stream energy (Figure 6). As transgression continued, distal sections of the valley were flooded first and estuarine deposits accumulated over the older fluvial deposits. As the transgression continued, the valleys became flooded and were covered with marine mud during the highstand systems tract (Figure 7).

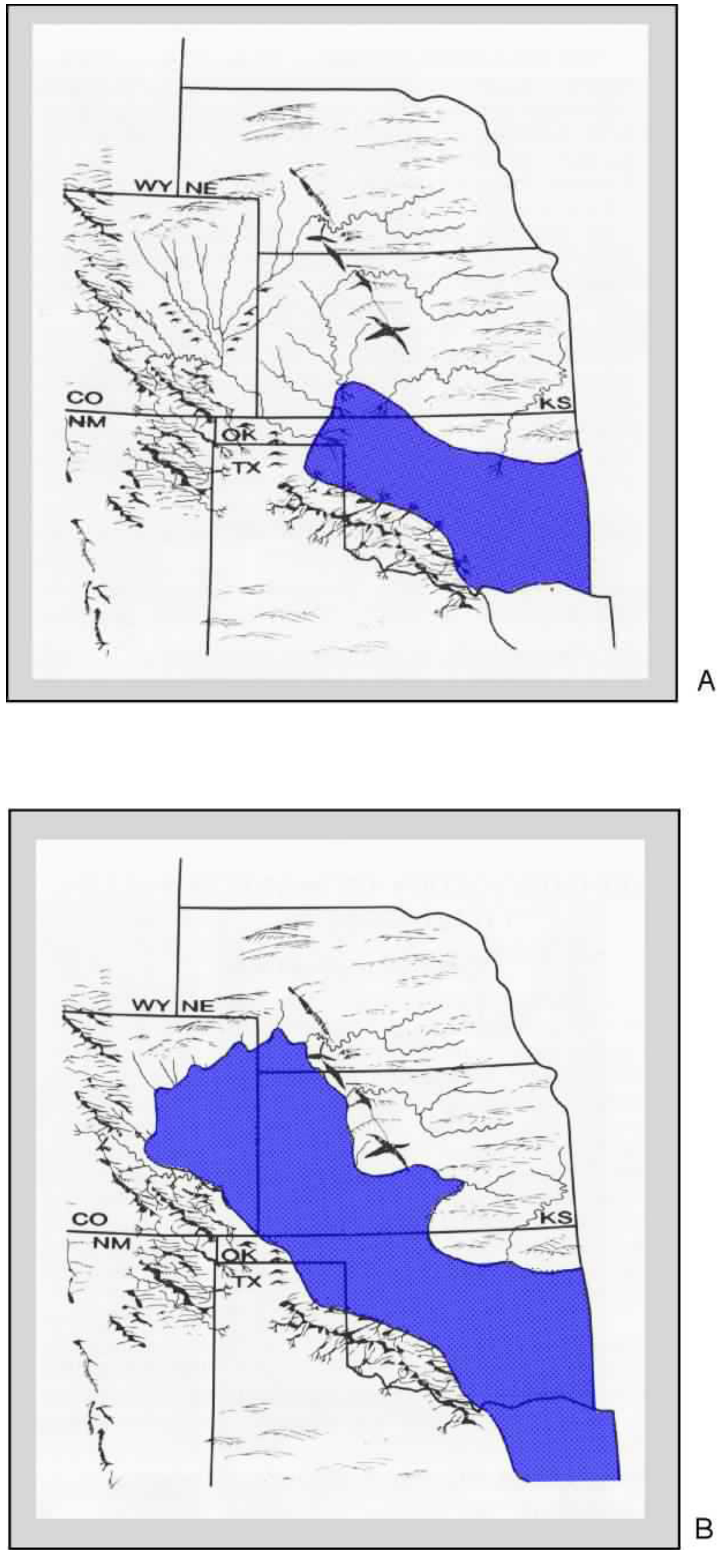


Figure 5: Regional paleogeography for the Morrow. (A) During lowstand (B) During highstand (from Krystinik and Blakeney, 1990)

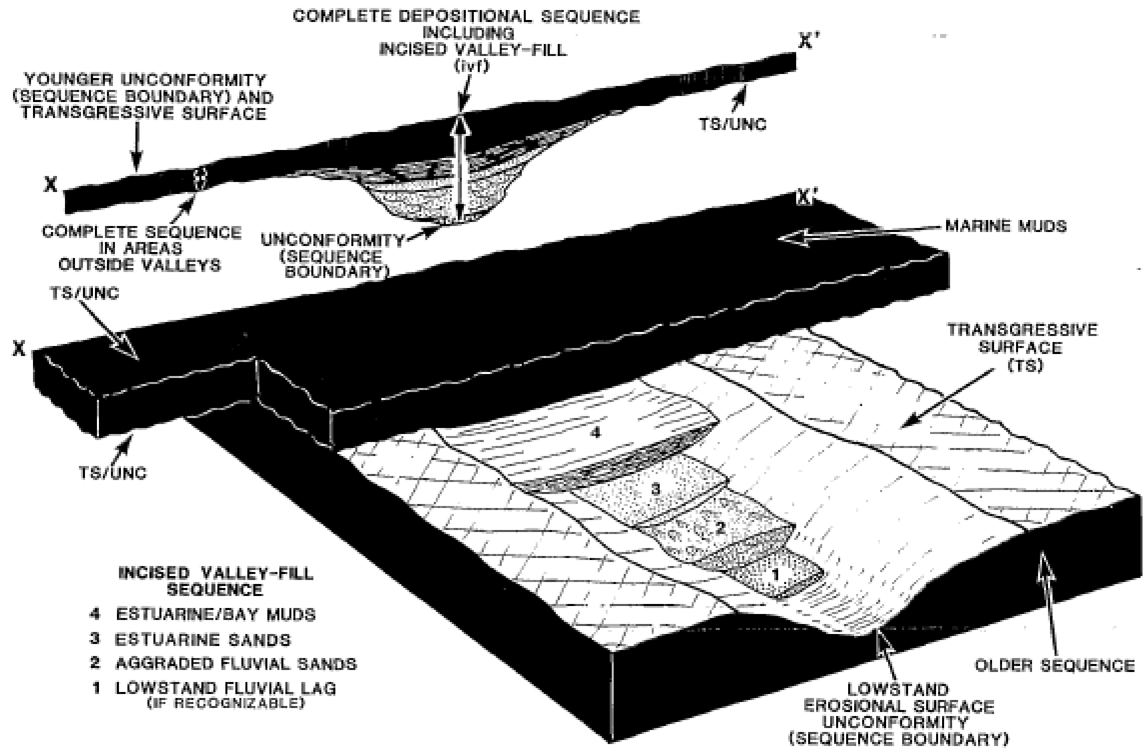


Figure 6: Diagram showing complete depositional sequence in a valley-fill (from Wheeler et al., 1990)

3.4. Depositional Setting

Several depositional settings have been proposed for the upper Morrowan on the northern shelf of the Anadarko basin (Swanson, 1979, Krystinik and Blakeney, 1990, Puckette et al., 2008, Fischbein et al., 2009). Most authors proposed similar settings such as shallow water, fluvial-estuarine-delta and marine (Figure 8). Published work of the past decade overwhelmingly supports a shallow shelf setting that was profoundly influenced by changes in sea level (Puckette et al., 2008). Archer and Greb (1995) and Krystinik and Blakeney (1990) used several lines of evidence including paleosols to indicate aridity and proposed that the coarse nature of basal upper Morrow sandstones supports deposition by flashy discharge.

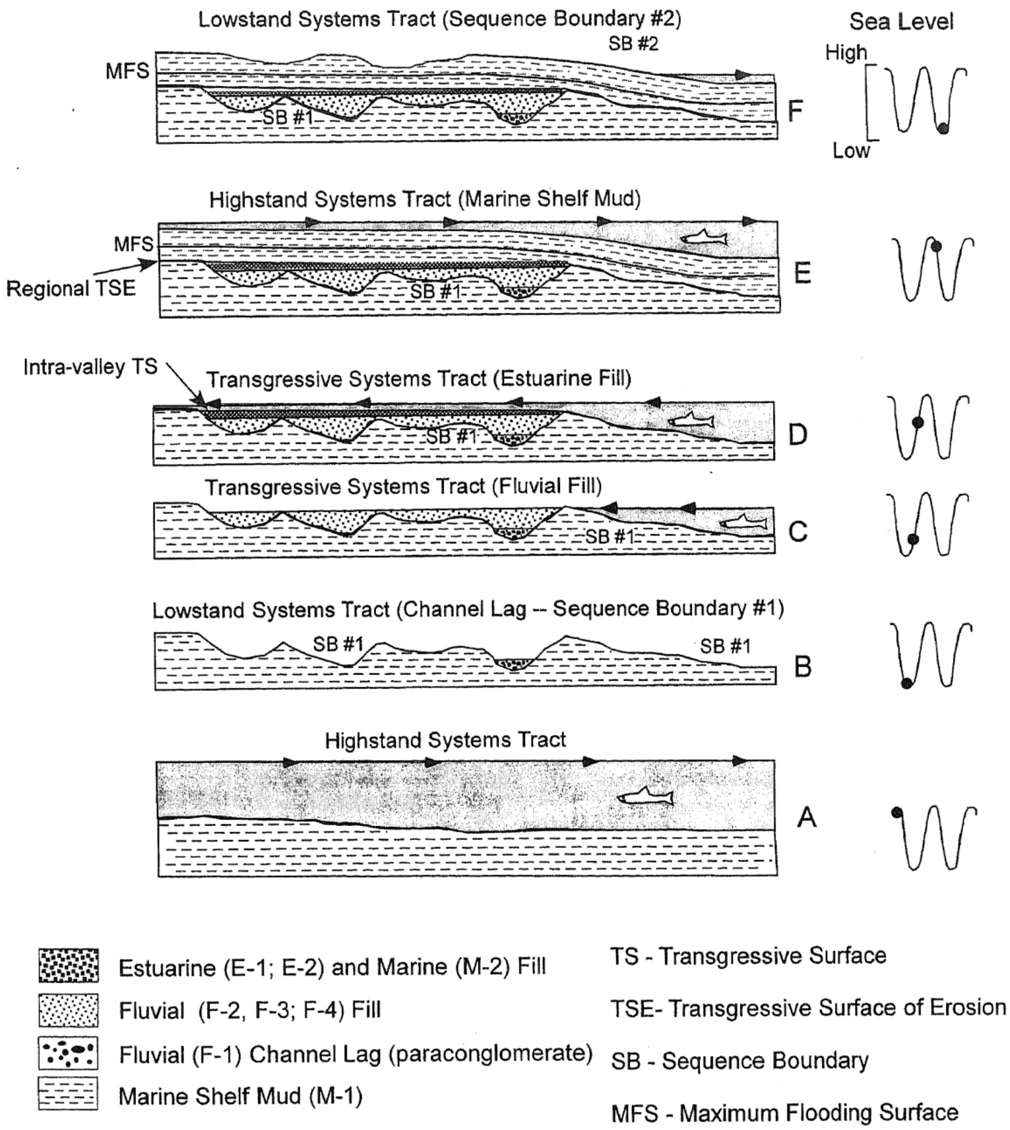


Figure 7: Diagram of the depositional process of the upper Morrow in response to eustasy (after Lutchtel, 1999; Puckette et al., 2008)

3.5. Depositional Models

Depositional models proposed for the upper Morrow, vary from fluvial (Forgotson, 1969) through deltaic (Curtis and Oestergard, 1979, Swanson, 1979) to marine. Krystinik and Blakeney (1990), supported the interpretation that sediments of the upper Morrow were fluvial and estuarine to marine deposits. They specified these interpretations were for the shelf margin of the Anadarko basin and that the absence of aerially vast flood plains outside the incised valley supports confinement to a valley system. Krystinik and Blakeney (1990) described the Morrow in Sorrento/Mt. Pearl/Siaana trend (SMS) and State line in Kansas to be predominantly fluvial deposit in the sandy sections of the valley fills. Incised valley fill depositional models have been supported by Mark (1998), Luchtel (1999), and Puckette et al. (2008). Analysis of cores from Morton County, Kansas, supported three environments of deposition: fluvial and estuarine valley fill and marine shelf mud that covered the channel filled systems (DeVries, 2005).

3.6. Paleogeography and Sediment Supply

The late Morrowan fluvial drainage basin was located on mud and carbonate rich sedimentary rocks, which limited the supply of siliciclastic sediments in the basin (Puckette et al., 2008). This resulted in sediment starved rivers that remained trapped in their channels during base flow and flood events. During lowstand, suspended sediments was transported by rivers beyond the shoreline into the Anadarko Basin . During the subsequent rise in sea level, the valleys were partly filled by coarse-grained braided river deposits, followed by lower gradient, meandering rivers that deposited from coarse to fine sands as transgression continued. Fluvial deposits were succeeded by estuarine sand and mud. In some cores, marine processes dominated and the valley fill sandstone and mudrock contain normal marine invertebrates.

CHAPTER IV

Methods

4.1. Core Sampling

Cores from three wells in Mustang East Field, Morton County, Kansas were selected for analysis. These were the Dominion Exploration Blout 7-5, 6-5 and 3-5 (Figure 8). Specific intervals of interest were selected, marked and drilled to obtain plugs of about 1 inch by 2.5 inches. Zones of interest were selected based on sedimentary structure, textural properties such as lamination and grading, oil saturation, degree of cementation, color (regions stained with oil), grain shapes and grain type.

4.2. Core Analysis

The total volume of each plug was measured using calipers. Grain volume was determined using a helium pycnometer (PORG-200^{TM}) and the grain density was calculated from the mass of the plug measured using an electric balance and the volume. Porosity for each plug was calculated by subtracting the grain volume and total volume of each plug. Permeability was measured using the nitrogen gas permeameter (PERG-200^{TM}) with a Fancher core holder and a digital pressure transducer flow rate meter.

4.3. Data Analysis

Data such as grain density, grain volume, porosity and permeability obtained from core plugs was analyzed and compared to texture, lithofacies and environments of deposition. In addition, previously prepared thin sections were used along with wireline logs to compare porosity and permeability values obtained from plugs. Thin section microscopy was used to establish detrital and authigenic constituents and the diagenetic history of the sandstones. 20 thin sections were analyzed for detrital constituents, authigenic constituents and porosity. The detrital composition of the sandstone were plotted on a ternary QRF (quartz, rock fragments and feldspars) diagram to determine rock classification.

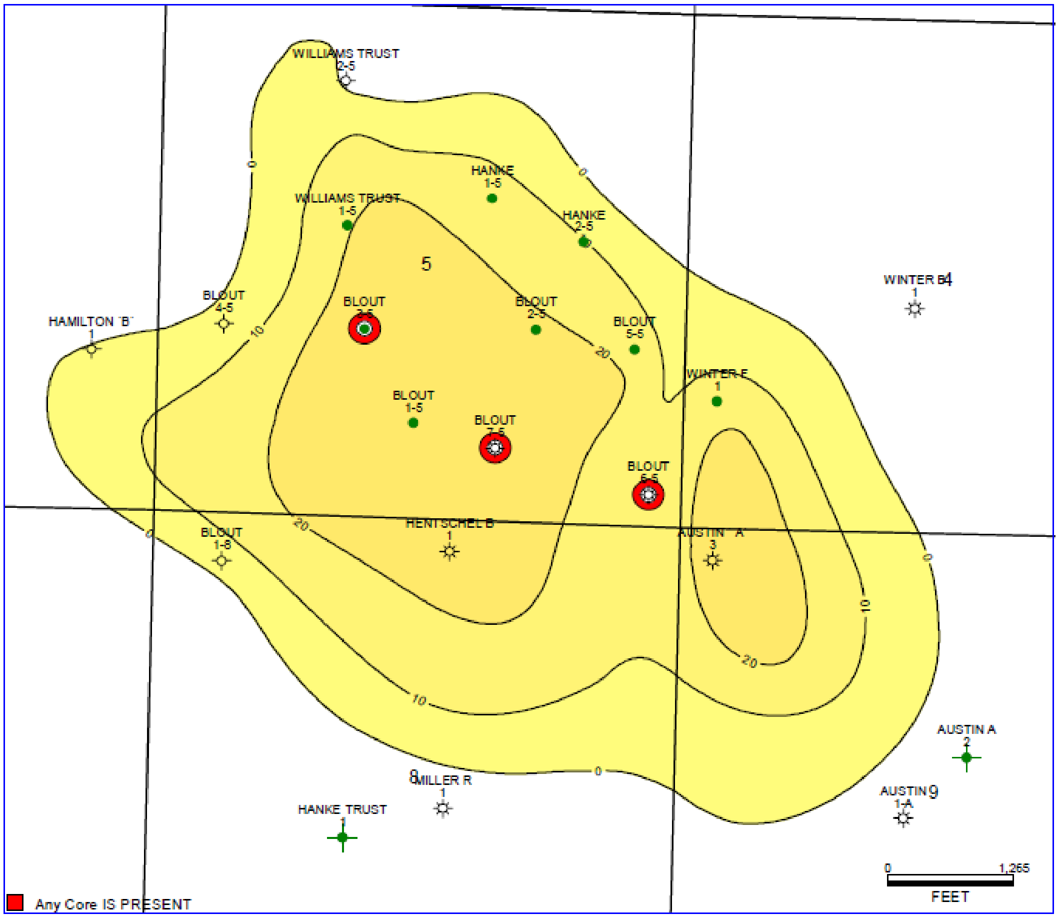


Figure 8: Isopach map of Mustang East field. Analyzed cores highlighted in red (Gagliardi, 2002)

Chapter V

Results

A. Facies Descriptions and Characterization

Lithofacies recognized in the upper Morrowan sandstones have been described in detail by Luchtel (1999). The common lithofacies are fluvial, estuarine and marine. These facies are described and their reservoir properties characterized in Figure 9.

5.1. Fluvial Lithofacies

Fluvial facies are deposited by rivers and fluvial lithofacies models depict the variable stages or processes in the life of a river. Cant (1982) categorized the types of river processes into straight, anastomosing, meandering, and braided, with the latter two being the most common. Fluvial lithofacies are the dominant facies observed in the upper Morrow sandstones and were subdivided into four micro-lithofacies (F-1, F-2, F-3, and F-4), based on grain size, texture, structure, clay content, and cement (Figure 9). These four fluvial micro- lithofacies were distinguished based on a classification developed by Luchtel (1999). Conglomeratic F-1facies is interpreted as deposition in a high current energy stream, F-2 lithofacies represents deposition in a high energy braided stream. F-3 lithofacies formed in lower energy meandering streams, whereas F-4 lithofacies are interpreted deposition during channel abandonment.

Lithofacies	Sedimentary Structures and Depositional Facies	Reservoir Characteristics
Fluvial (F)		
F-1	Matrix-supported paraconglomerate. High current-energy stream	Generally poor quality, low porosity and permeability due to cement and pseudomatrix.
F-2	Coarse-grained sandstone to conglomerate. Characterized by trough and planar cross- bedding and contains stacked fining-upward sequences. High- energy braided stream of middle to lower channel sequence.	Generally fair to good quality. Primary and enlarged intergranular porosity common.
F-3	Ripple to low-angle planar crossed-bedded, fine- to coarse-grained sandstone with scattered clay clasts and carbonaceous material. Meandering stream of upper channel sequence.	Generally fair to good quality. Porosity reduction caused by clay matrix, carbonate cement, and/or pore-filling authigenic kaolinite.
F-4	Fine-grained sandstone sporadically interbedded/interlaminated with silty, shaly and coaly intervals. Plant fossils scarce to common Channel abandonment	Generally poor to fair quality. Significant amount of pore space filled with clay matrix.
Estuarine (E)		
E-1	Interbedded fine- to medium-grained sandstone and shale containing abundant trace fossils. Mid estuary with minimal fluvial and marine influence: low energy	Generally poor quality. Low porosity and permeability are results of carbonate cement and pseudomatrix.

Figure 9: Lithofacies classification, depositional facies, sedimentary structures and reservoir characteristic for the upper Morrow. (modified from Luchtel, 1999)

Continuation of lithofacies description chart.

Lithofacies	Sedimentary Structures and Depositional Facies	Reservoir Characteristics
Estuarine (E)		
E-2	**Fine- to medium-grained, burrowed sandstone and dark shale that is interbedded with thin, coarse grained sandstone.** **Upper estuary: tidally influenced with variable energy and possible fluvial input.**	**Generally fair quality. Primary and enlarged intergranular porosity types are common.**
Marine (M)		
M-1	**Dark shale and/or claystone. Calcareous intervals contain abundant marine invertebrate fossils** **Marine low-energy environment. Disaerobic offshore shelf setting**	**Seal-forming lithofacies**
M-2	**Fine-to coarse-grained, calcite-cemented, and fossiliferous sandstone.** **Shallow-marine high-energy environment**	**Poor-quality reservoir as a result of extensive calcite cement.**

Figure 9: Lithofacies classification, depositional facies, sedimentary structures and reservoir characteristic for the upper Morrow. (modified from Luchtel, 1999)

Fluvial lithofacies have a number of textural features and sedimentary structures such as horizontal beds and clast-supported gravel. Sandstones are fine-grained and clay rich to coarse-grained to conglomeratic with trough and planar cross beds. In general, sandstones fine upward from channel lag conglomeratic sandstone to very fine-grained sandstone and shale. Zones of laminated finer-grained sandstones occur within zones dominated by coarser-grained sandstone. Ripple structures and mud drapes are common in the fine-grained sandstones. The dominant matrix is clay and silt, which typically increase upward and accompanies deposition of increased volumes of carbonaceous debris along bedding planes. The presence of small scale cross-bedding with clay or carbonaceous drapes and wavy irregular ripples are interpreted as indicators of point bar deposits. Each facies identified in the study cores is described in the following section.

5.1.1. F-1 Lithofacies: Matrix-Supported Paraconglomerate

F-1 conglomeratic lithofacies was found in the Dominion Blout 6-5 and 7-5 cores but was absent in the Blout 3-5. Thicknesses varied from 0.4m to 0.9m, and the conglomeratic sandstone was gray to brown in color. The F-1 framework consists of large clay clasts supported in a coarse sand- to granule-size matrix. The matrix grains and clasts were subangular to subrounded, and tightly cemented with carbonate (Figure 10). F-1 lithofacies was deposited in a high current energy environment.

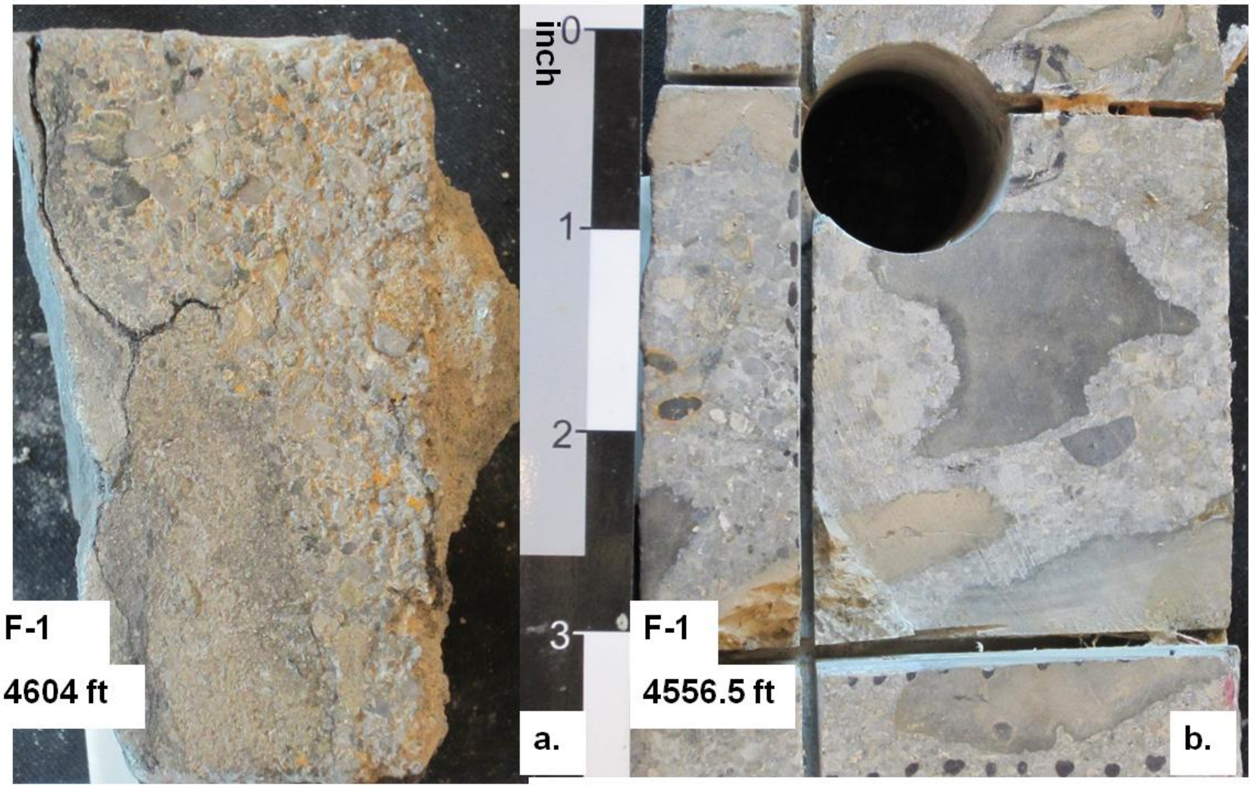


Figure 10: Core photomicrograph (a) matrix supported paraconglomerate with natural fractures filled with carbonaceous material. (b)Tightly carbonate cemented clay-clast pebble conglomerate.

5.1.2. F-2 Lithofacies; Coarse-Grained Sandstone to Granule Conglomerate

F-2 lithofacies consists of very coarse-to granule-grained sandstones. They are trough cross-bedded with color ranging from dark brown to brown due to oil staining in sone intervals and gray in others. Carbonaceous material is present, but not common. Beds in F-2 lithofacies are normally graded (fine upward). Sandstone grains are moderately to poorly sorted and angular to subangular. Some intervals are friable and crumbled during drilling of core plugs (Figure 11). These loosely cemented zones lack matrix implying deposition in a high energy braided stream.

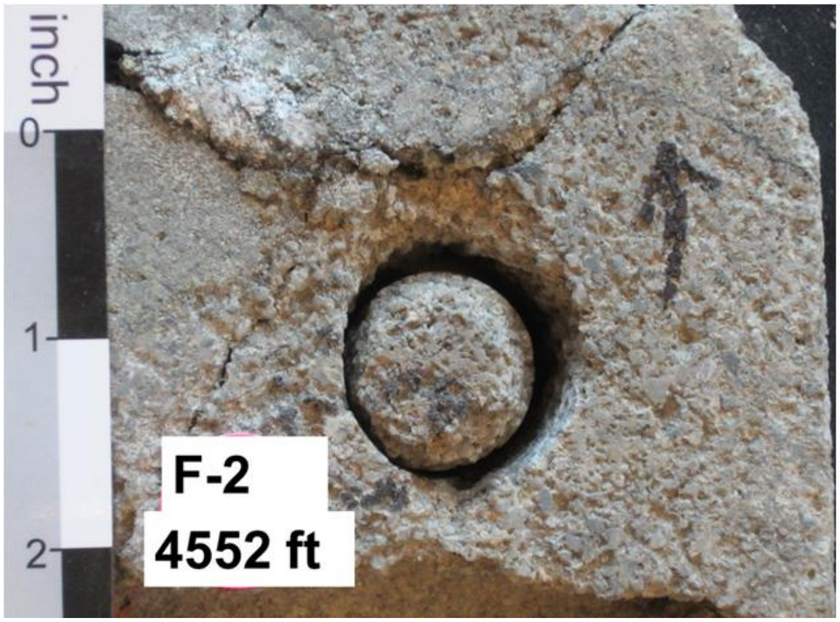


Figure 11: Very coarse-grained sandstone to granular conglomerate, loosely cemented and fractured.

5.1.3. F-3 Lithofacies: Coarse- to Fine-Grained Sandstone with Ripple- and Low-Angle Cross Bedding

F-3 lithofacies is rich in interbedded clay and consists of coarse- to fine-grained sandstone. Thin laminae of dark shale alternate with sandy intervals. These sandstones are brown to gray and often oil stained. Thin zones of carbonaceous material occur in the transition zones between sandstone and mudstones. The carbonaceous material is accompanied by abundant pyrite. Fine-grained sandstone intervals are current rippled. Sharp contrasts between shale and overlying coarse -grained sandstone are common. A fluvial sandstone interval contains a larger gray silty clay clast that is approximately 8 cm long. (Figure 12). The lithofacies has low angle cross-bedding with shale lenses and is naturally fractured. F-3 lithofacies is interpreted as being deposited in a lower energy meandering stream based on the finer grain sizes and sedimentary structures (Puckette et al., 2008).

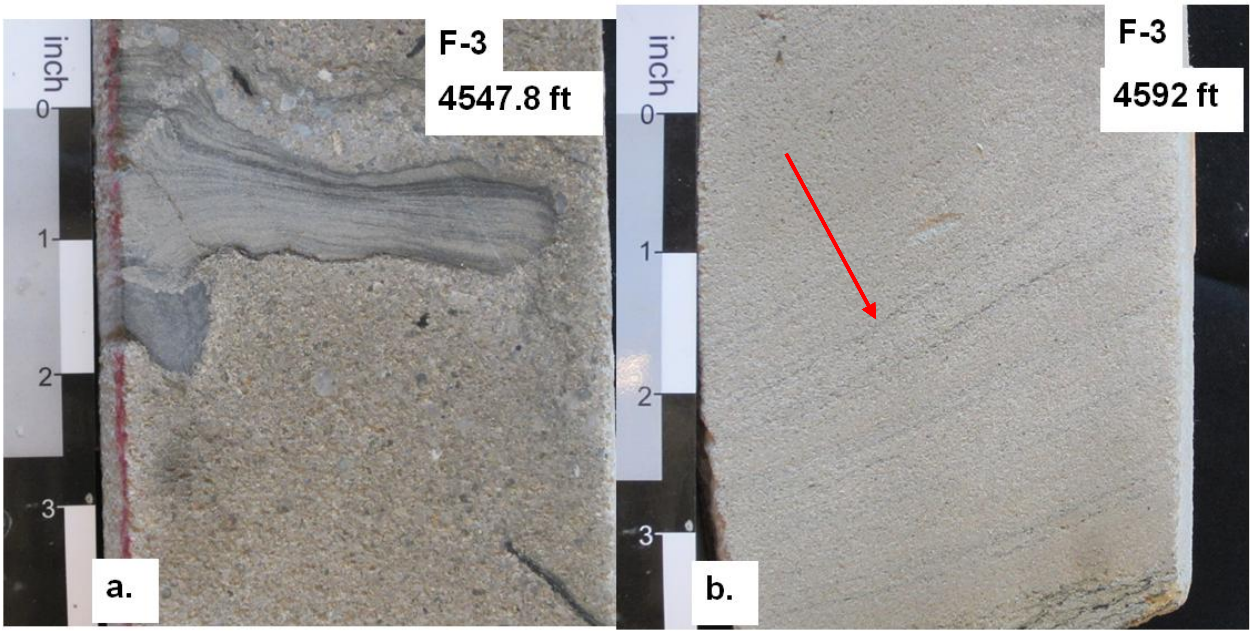


Figure 12: (a) F-3 lithofacies with oil stain, scattered carbonaceous material and clay-clast. (b) Fine-grained sandstone displaying low angle trough cross bedding (arrow).

5.1.4. F-4 Lithofacies: Fine- Grained Sandstone, Siltstone, Shale and Coaly Material.

F-4 lithofacies consist of fine-grained sandstone that alternates with dark gray shale. This lithofacies contains pyrite lenses and accumulation of (coaly) carbonaceous materials along bedding surfaces. (Figure 13). Puckette et al. (2008) suggested that the abundance of plant material is an indication of channel abandonment.

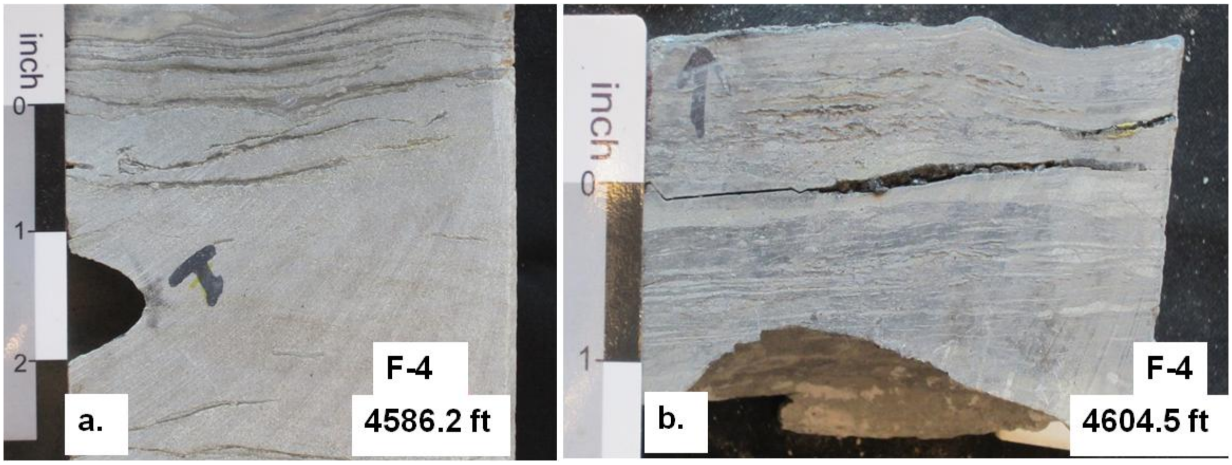


Figure 13a &b: F-4 lithofacies displaying coaly, and pyrite along bedding surfaces. The sandstone is typically very fine to fine grained and cemented with calcite

5.2. Estuarine Lithofacies

Estuaries formed as the upper Morrowan valleys flooded during transgression. Sediments in estuaries are influenced by complex mixture of tides, currents, oceanic waves, river discharges and precipitation (Clifton, 1982) and the upper Morrow estuarine deposits reflect these influences.

Two estuarine lithofacies were identified, E-1 and E-2. Some estuarine sandstones and mudstones were interlayered in discrete beds, but others were mixed and homogenized by bioturbation (Figure 14). Estuarine sediments typically fine upward and sandstones grade vertically into estuarine mud. Estuarine muds are succeeded by marine shelf muds that eventually fills the remaining topography of the Morrow valley-fill (Krystinik and Blakeney, 1990).

5.2.1. E-1 Lithofacies: Fine- to Medium- Grained Burrowed Sandstone

E-1 lithofacies is highly burrowed, fine- to medium- grained sandstone interbedded with laminated shale (Figure 14). The sandstone is typically low porosity as the result of matrix and calcite cement. Burrowing and bioturbation make E-1 lithofacies low-quality reservoirs as clay and sandy sediments were reworked into a poorly sorted mixture. These sediments were deposited in low energy mid-estuarine environment.

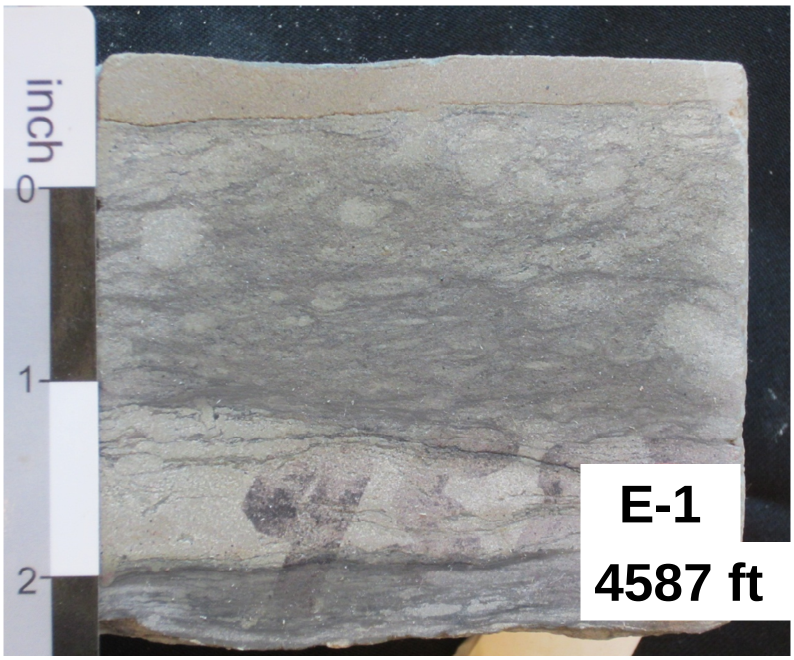


Figure 14: Highly burrowed sandstone of low energy mid-estuarine environment.

5.2.2. E-2 Lithofacies: Thinly Bedded Fine- to Medium- Grained Burrowed Sandstones, Shale and Coarse- Grained Sandstone.

E-2 lithofacies is composed of burrowed fine- grained sandstone that is interbedded with shale and coarse- grained sandstone (Figure 15). This lithofacies grades upward to clayey silt with ripple laminations. Pyrite occurs within lenses and the smell of sulfur is common. The shales were gritty with laminations (0.2mm) of coarse silt or fine sand. E-2 intervals are burrowed and gray to yellow green in color.

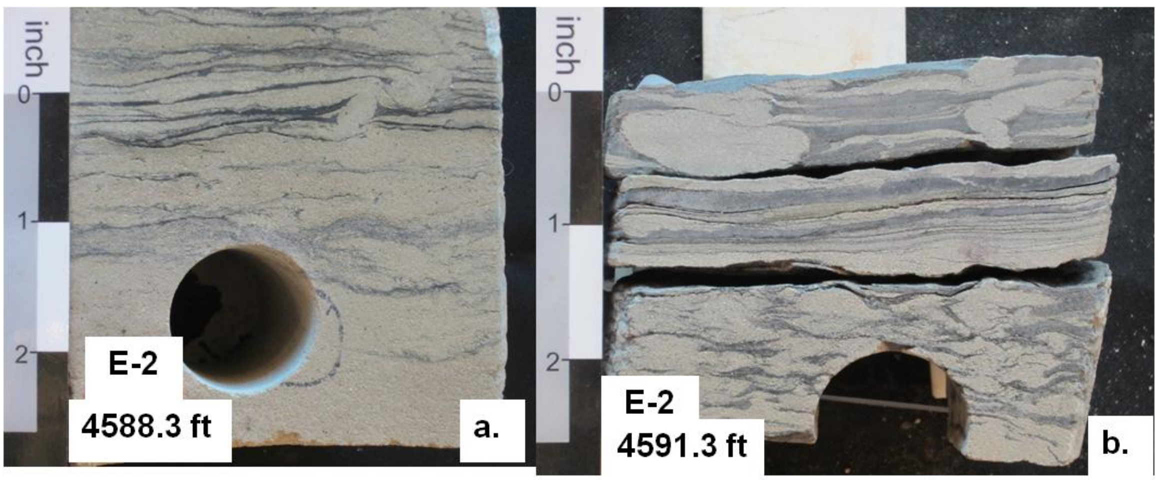


Figure 15a & b: E-2 lithofacies showing ripple lamination and burrowed andstone intervals.

5.3. Marine Lithofacies

Marine lithofacies in the upper Morrow are the result of the flooding of fluvial valleys and the widespread flooding of the interfluves areas to form marine shelf mud. Shelf muds are typically separated from estuarine deposits by a transgressive surface of erosion represented by a lag deposit (Al-shaieb and Puckette, 2001)

5.3.1. M-1 Lithofacies: Fossiliferous Dark Shale or Claystone

Marine facies identified in cores include dark-gray fossiliferous mudrock (shale/claystone). Complete preserved brachiopods are indicative of a low energy deposition setting. Crinoids fragments occur in shallow water burrowed high energy setting. (Figure 16a &b).

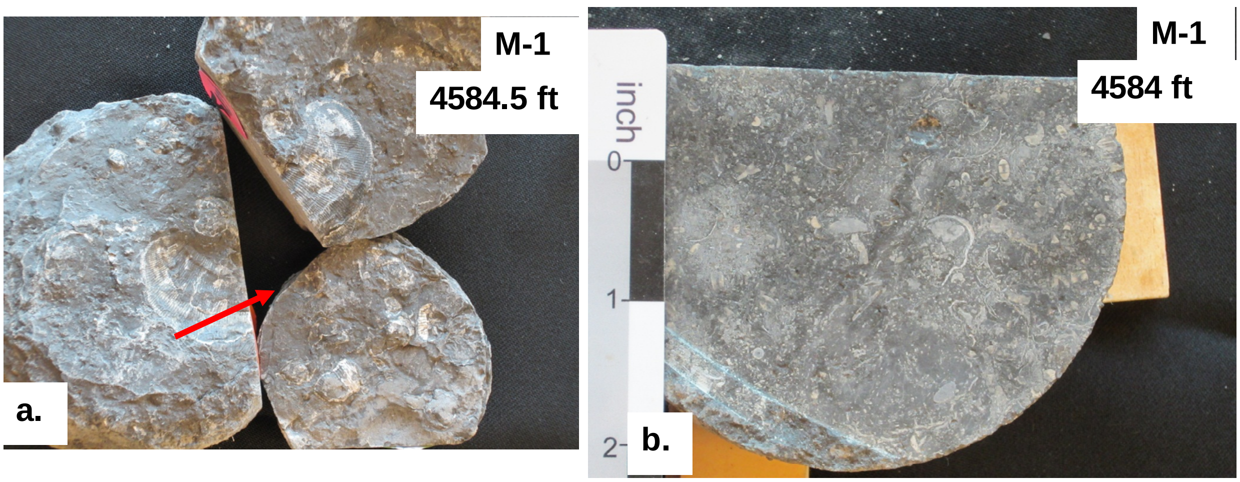


Figure 16: Dark gray marine shale with abundant fossils. (a) Wholly preserved brachiopods (arrow). (b) Showing crinoids in a highly burrowed bed.

5.3.2. M-2 Lithofacies: Fine- to Coarse- Grained Calcite Cemented and Fossiliferous Sandstones

M-2 lithofacies is characterized by fine- to coarse-grained tightly cemented sandstones that contain marine invertebrates. (Figure 17). Reservoir quality is greatly reduced by calcite cement. This lithofacies is characteristic of sediments deposited in a shallow marine, high-energy environment such as a drowned estuary.

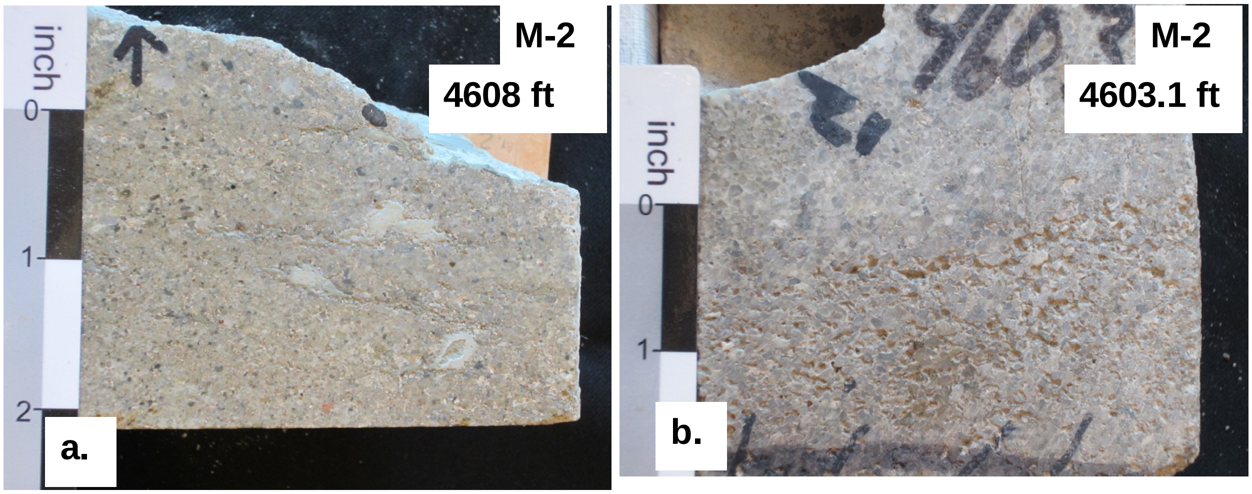


Figure 17: Calcite cemented sandstone (a). Calcite filling fractures (b) Very coarse -grained **sandstone.**

B. Petrography and Diagenesis

5.4. Detrital constituents

Monocrystalline quartz is the dominant detrital constituent in the upper Morrow sandstone as it makes up 60% of the rock. Quartz grain size varies from fine to coarse grained to granule with extinction that varies from straight to undulose. Polycrystalline quartz and chert are present, but a smaller portion (4-17%) of the framework grains. Chert and polycrystalline quartz appear highly weathered and are replaced by carbonate cement.

Plagioclase is the second most dominant detrital mineral and makes up about 10% of the grains in the upper Morrowan sandstone. Some of the feldspar grains are altered to clay minerals, while some were partially or completely replaced by carbonate cement. Those not altered still displayed albite twinning (Figure 18). The grain size ranged from fine to coarse. Granitic rock fragments make up about 15% of the sandstone (Figure 18).

These grains are commonly replaced by dolomite and other clay minerals such as kaolinite Other detrital grains including zircon, biotite and muscovite were observed in minor quantities. These grains make up about 2% of the detrital framework.

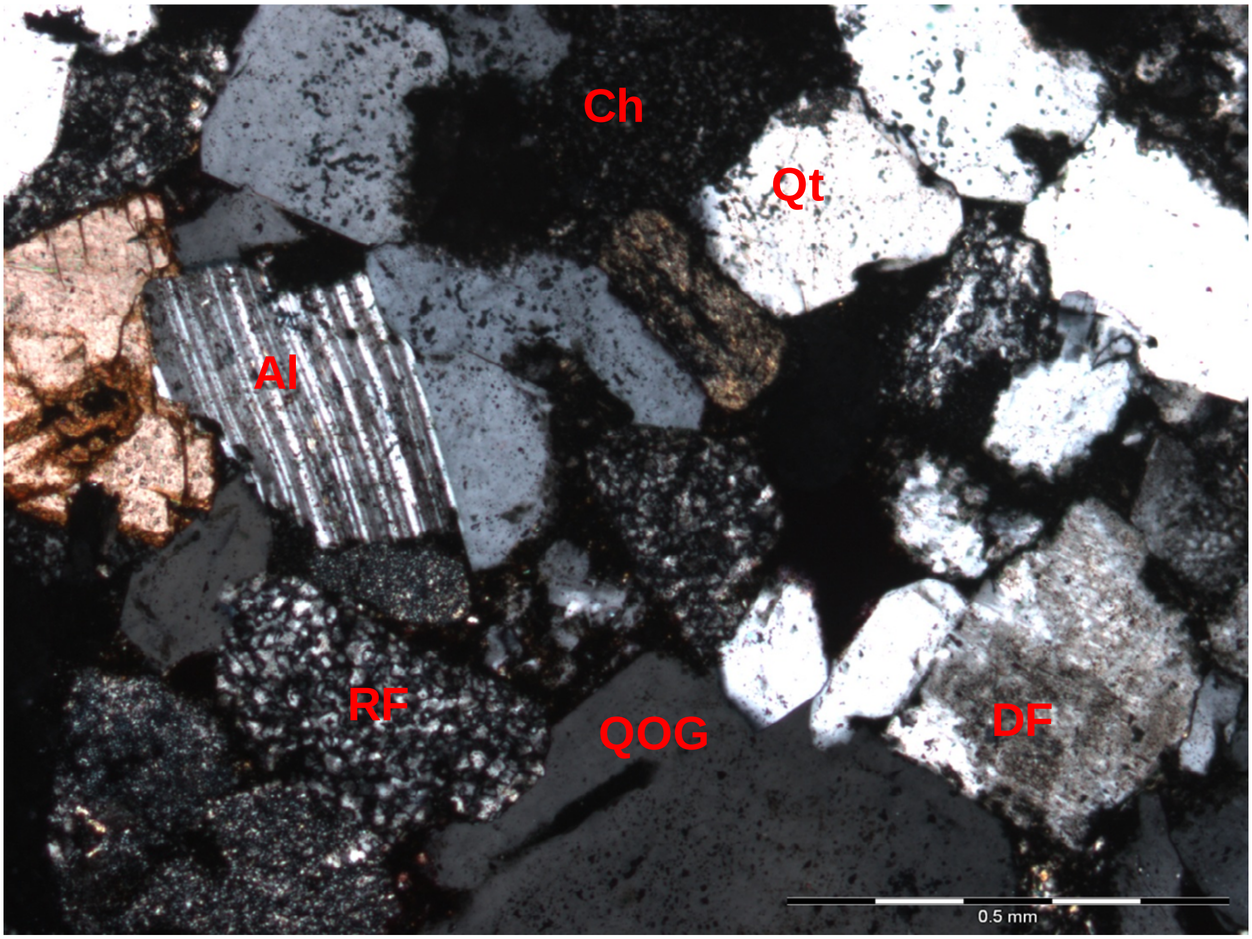


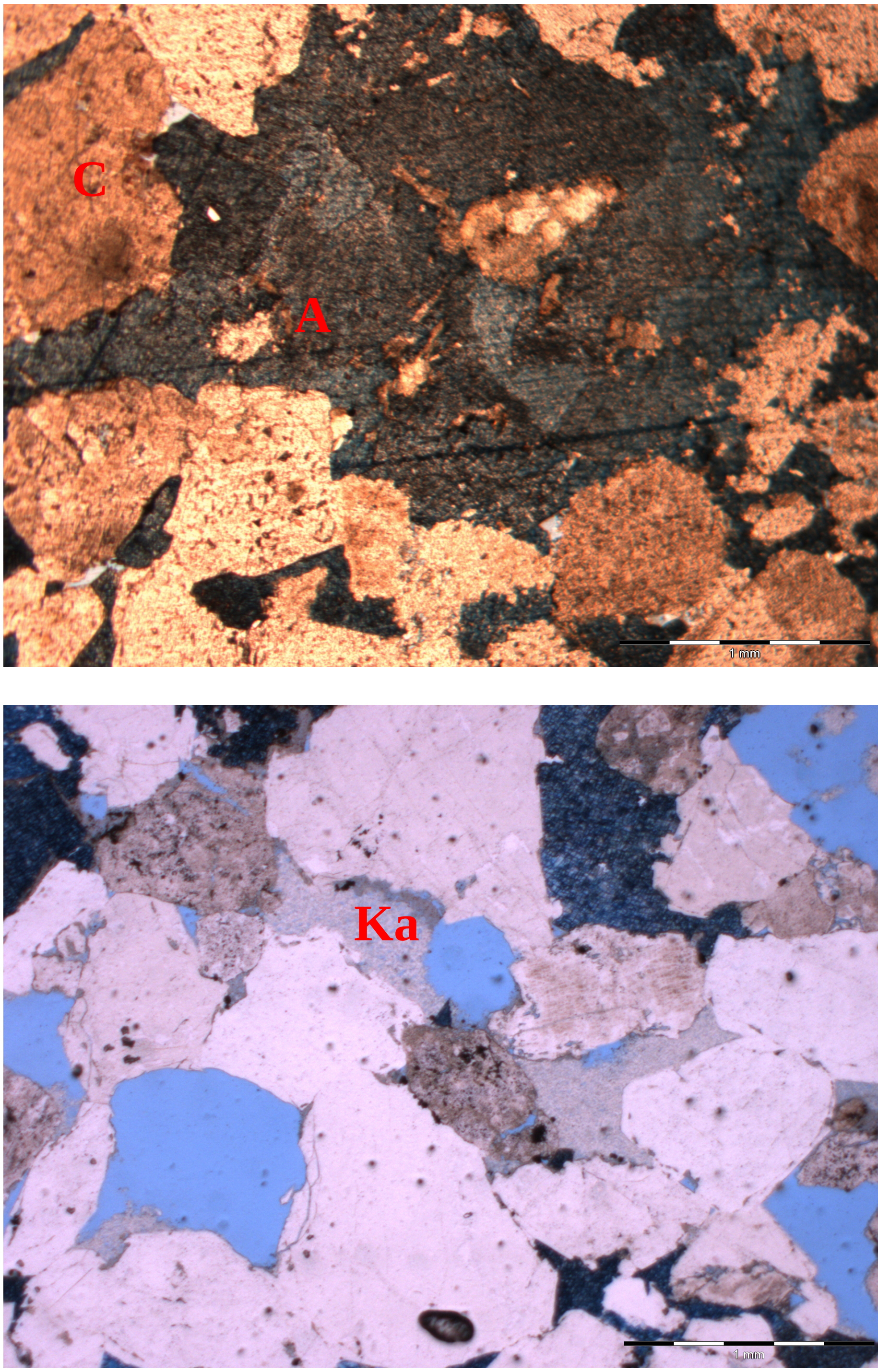
Figure 18: Photomicrograph of F3 lithofacies; sample depth 4637 ft. Dominion Blout 3-5 Al= albite, Ch= chert, RF= rock fragments, QOG= quartz overgrowth, DF= dissolved feldspar, Qt= quartz (CPL)

5.5. Diagenetic Constituents

Carbonate cement and kaolinite are the dominant diagenetic constituents in the upper Morrow sandstone. Calcite ($CaCO_3$), dolomite ($CaMg(CO_3)_2$ and ankerite ($FeMg\ (CO_3)_2$) were observed in thin section. (Figure 19a). These cements enclose quartz grains and contributed to the occlusion of primary porosity. Cements in some regions completely or partially replace feldspar grains or other detrital grains such as chert, granitic rock fragments and polycrystalline quartz

Primary porosity in the upper Morrow sandstones is somewhat reduced by quartz overgrowths. Calcite is common in the lower energy environment and was prominent in the estuarine E-1 lithofacies and fluvial F-4 and F-3 lithofacies.

Kaolinite is abundant and reduces porosity significantly in some areas. (Figure 19b). Other clay minerals such as chlorite may be present but could not be identified by thin section microscopy.



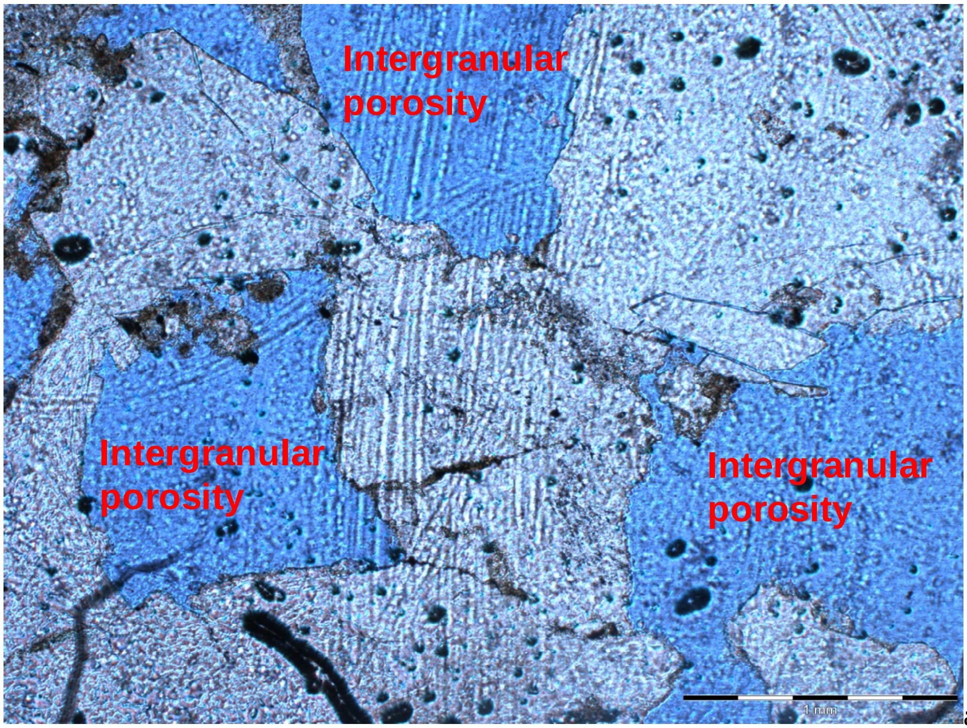
A

B

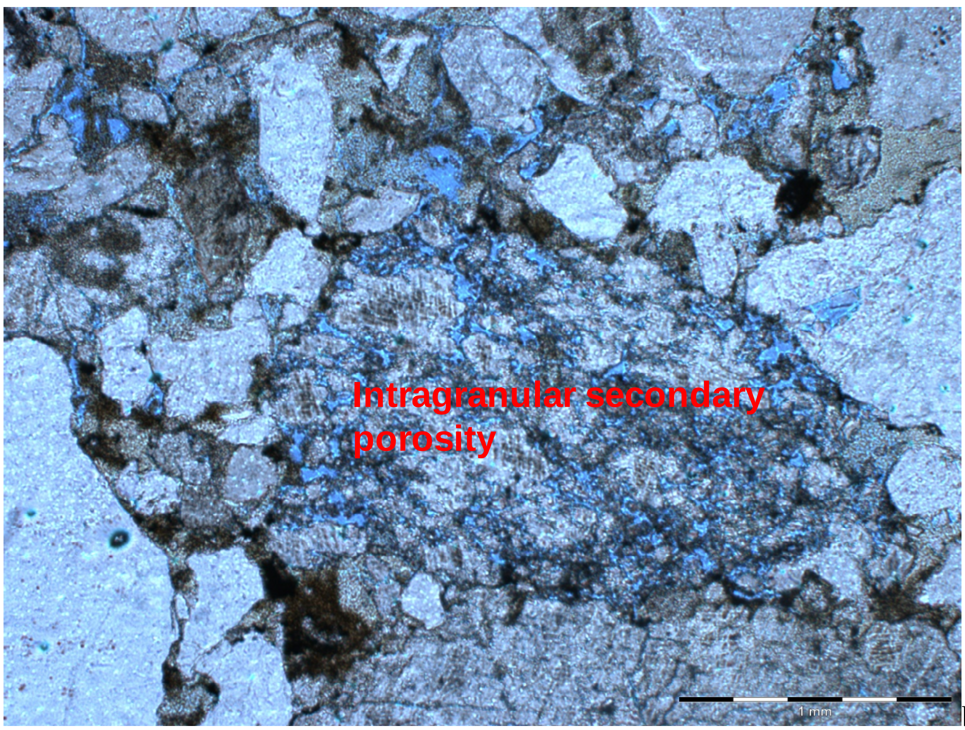
Figure 19: Thin section photomicrographs. A. Cross polarized light (CPL). Depth 4626ft Dominion Blout 3-5. (B). PPL Depth 4623.4ft. Dominion Blout 3-5.Sample depth 4625 ft and (B) Diagenetic constituents of E2 lithofacies. C= Calcite, A= Ankerite, Ka= Kaolinite

5.6. Porosity

Primary and secondary porosity are evident in the upper Morrow sandstone. Primary porosity is mainly intergranular and identified by the straight euhedral crystal faces that border the pores. Many of these intergranular pores are filled by carbonate cement and kaolinite. This is especially common for E-1, F-3 and F-4 lithofacies. This is equally reflected in the neutron density log, thin sections and core plug porosity measurements. Secondary porosity is the dominant type of porosity in upper Morrowan sandstones (Figure 20a & 20b). Most secondary pores are irregular or oversized intergranular void that form from the dissolution of metastable grains such as feldspar and granitic rock fragments. Carbonate cement in some facies prevented early quartz overgrowths, reduced primary porosity and subsequently secondary porosity. Other types of secondary porosity include fractures and intragranular dissolution of the feldspar and granitic rock fragments (Figure 20b). In general, 90% of porosity in the upper Morrow sandstone is secondary and resulting from the dissolution of metastable grains.



a



b

Figure 20: Photomicrograph showing (A) secondary intergranular porosity and (B) secondary intragranular porosity in dissolved feldspar grain. Plain polarized light (PPL). Depth 4652 ft Dominion Blout 3-5

5.7. Petrology

The sandstones analyzed from the upper Morrowan interval in Morton County, Kansas are part of channel fill deposit of estuarine (Figure 21) and fluvial origin (Figure 22). Based on thin section microscopy, the sandstones were classified using into five categories (Folk, 1962). These are in decreasing abundance: litharenite (50%), sublitharenites, (35%) and feldspathic litharenite (15%) (Figure 23). The sandstones have grain sizes that range from fine to coarse granules, with occasional pebble channel lag conglomerate. The grain shapes range from angular to subrounded. Sorting is poor to fair and majority of the sandstones are submature. Wireline log (neutron/density) porosity ranges from 5% to about 28% (2.71g/cc). Porosity measurements from core plugs deviate from log values, but follow similar trends.

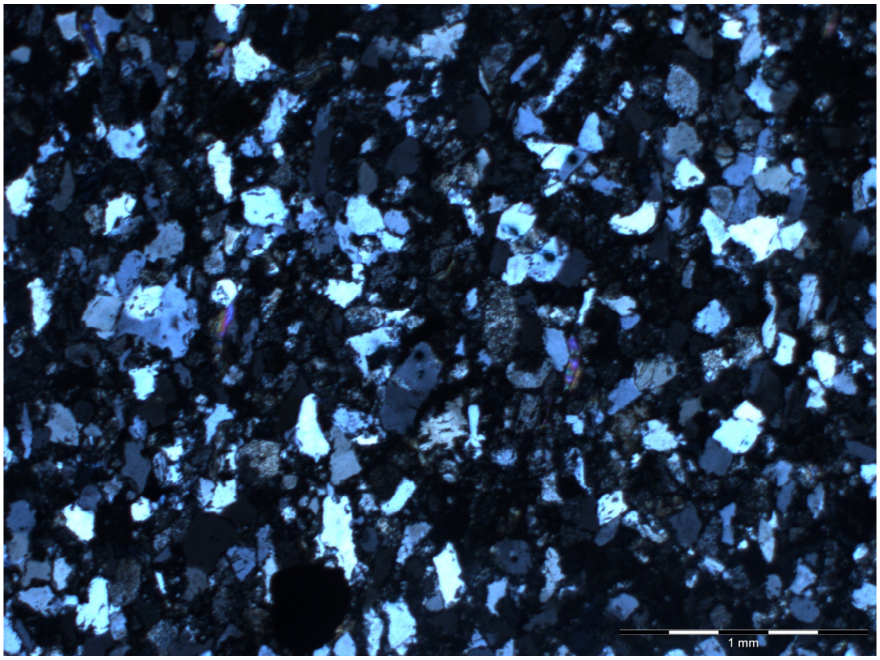


Figure 21: Photomicrograph of fine-grained estuarine sandstone E-2 lithofacies CPL. Depth 4626.5ft. Dominion Blout 3-5

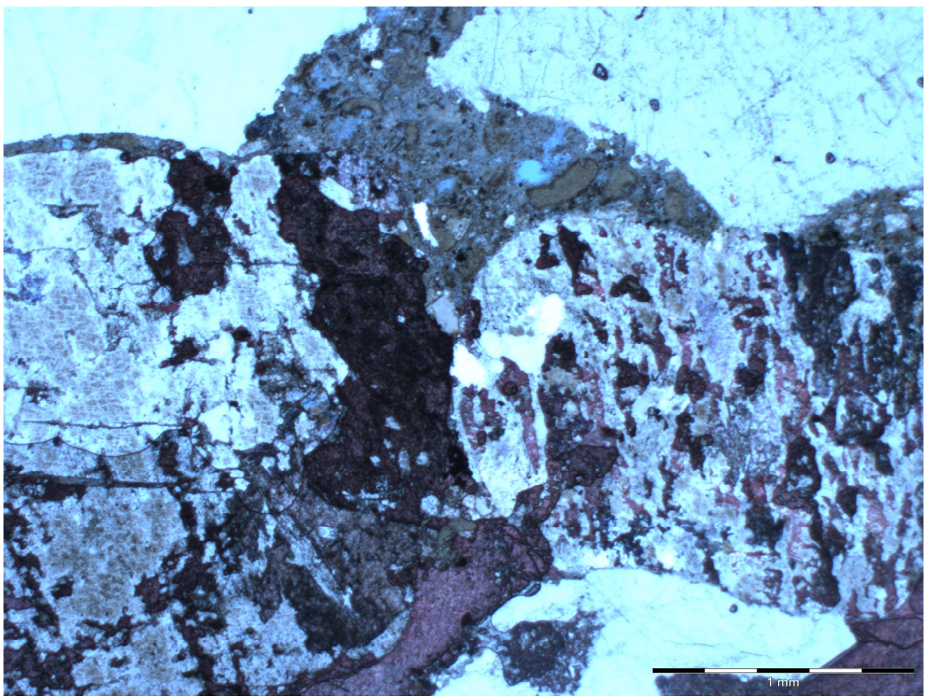


Figure 22: Photomicrograph of fluvial F-3 facies with highly weathered feldspar grains. Dominion Blout 3-5

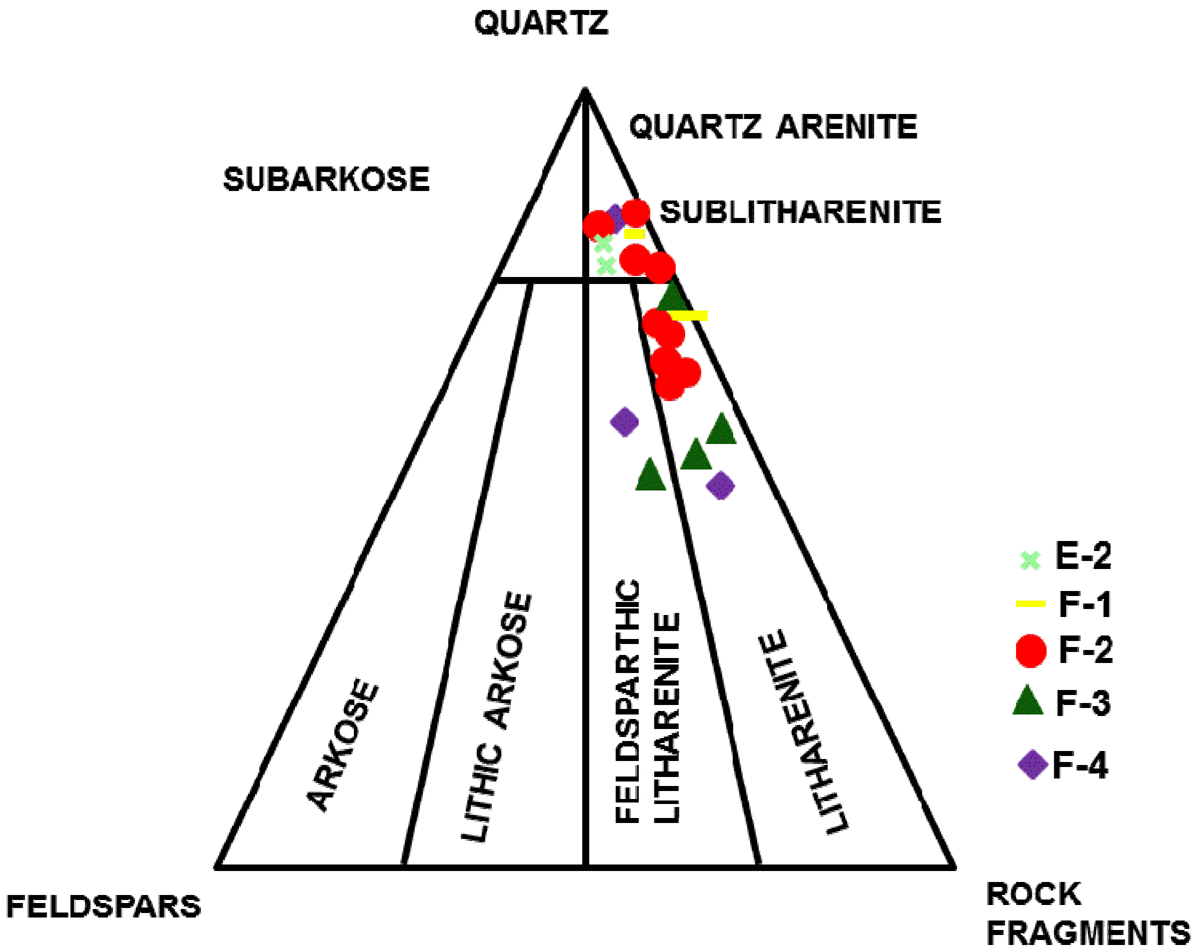


Figure 23: Classification of the upper Morrow sandstone facies using Folk (1962) classification. F-1, F-2, F-3 and F-4 represent fluvial facies. E-2 represents estuarine facies

Chapter VI

Reservoir Characterization

6.1. Reservoir Quality

Grain dissolution accounts for the high permeability and porosity values measured in some F-2 and F-3 lithofacies. Secondary porosity is common in F-3 and F-4 lithofacies as intragranular microporosity.

Porosity and permeability determined from core plugs were compared to lithofacies (Figure 24a, b & c) to analyze the relationship between these parameters. When porosity and permeability measurement (Table 1, 2 & 3) for the different lithofacies were graphically compared (Figure 25), it became apparent that they could be grouped into four zones of similar porosity- permeability values. These are:

Zone I: High porosity (13.4 % - 28.3 %) and high permeability (32.3 md- 54.2 md). Rich in F-2 and F-3 facies

Zone II: High porosity (16.8% - 26.8 %) and medium permeability and (14.4 md – 27.1 md). This zone is dominantly F-2 and F-3 facies.

Zone III: High porosity (11.8 % - 21.5 %) and low permeability (0.9 md – 11.3 md). This zone is made up of E-2, F-2 and F-3 facies.

Zone IV: Low porosity and low permeability (3.1 % - 6.8 % and 0.3 md – 8.2 md). This zone is made up of E-2, E-1, M-2, F-4 and F-1 facies.

			Blout 6-5		
Facies	Depth (ft)	Porosity (%)	Permeabilty (md)	Grain Vol. (cm^3)	Grain density (g/cm^3)
F2	4547	22.2	33.6	10.3	2.61
F2	4548	25.6	32.8	9.1	2.65
F2	4549.6	28.3	38.5	10.3	2.7
F2	4549.8	23.1	54.9	14.7	2.65
F2	4550.3	25.5	44.2	12.2	2.66
F2	4551.8	21.3	54.5	14.9	2.63
F1	4556.4	3.5	0.9	16.5	2.74
F1	4556.9	11	3.6	13.3	2.71

Table 1: Porosity, permeability, grain volume and grain density measurements of plugs from Blout 6-5.

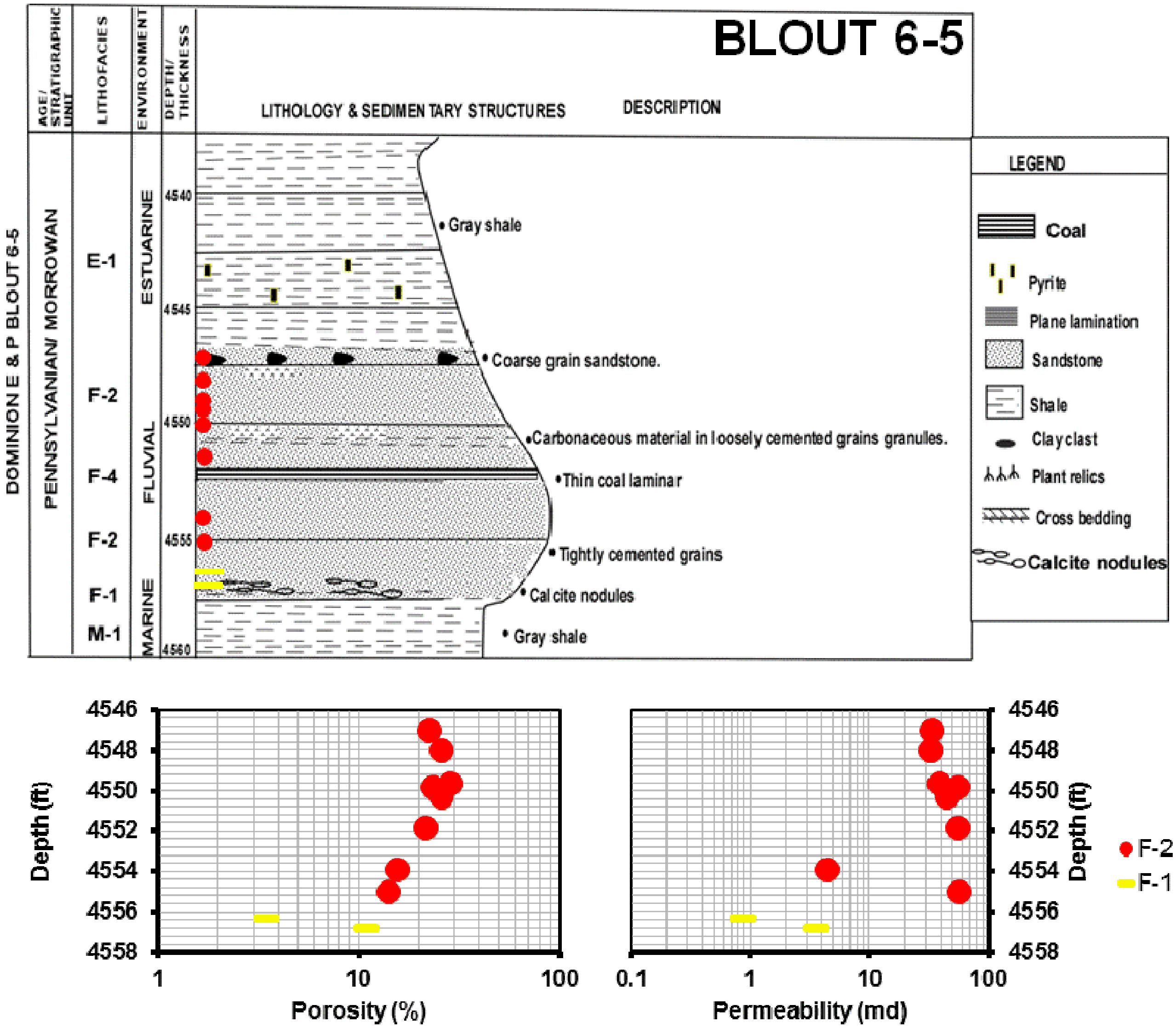


Figure 24a: Schematic diagram of the upper Morrow sandstone in the Blout 6-5 showing the distribution of facies and variation of porosity and permeability with depth.

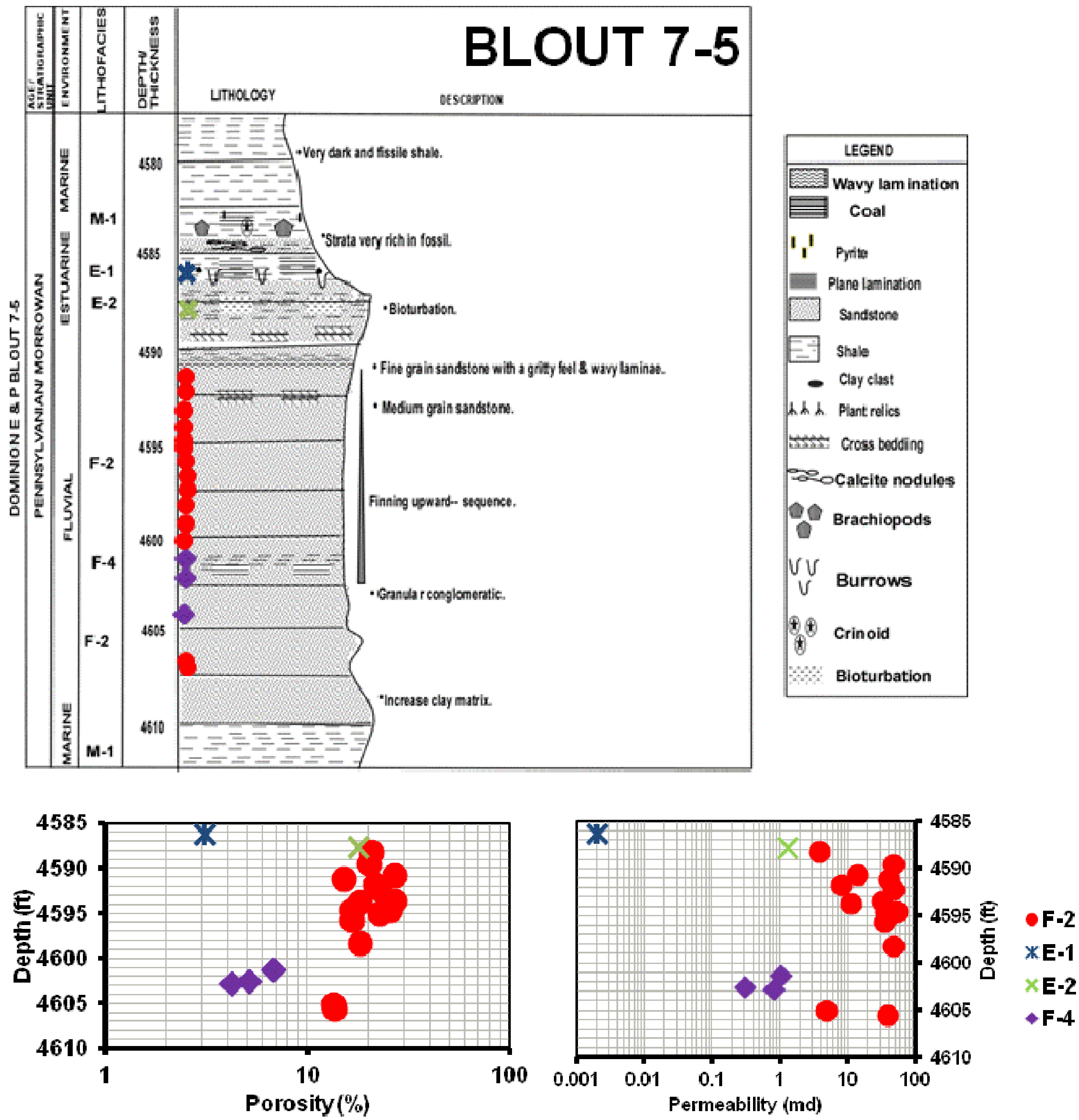


Figure 24b: Schematic diagram of the upper Morrow sandstone in the Blout 7-5 showing the distribution of facies and variation of porosity and permeability with depth.

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			Blout 7-5		
Facies	**Depth (ft)**	**Porosity (%)**	**Permeabilty (md)**	**Grain Vol. (cm^3)**	**Grain density (g/cm^3)**
E1	4586.4	3.1	0.002	13.753	2.68
E2	4587.8	17.8	1.3	13.937	2.67
F2	4588.3	20.8	3.8	12.857	2.41
F2	4589.6	20.2	48.3	13.132	2.65
F2	4590.8	26.8	14.3	10.486	2.6
F2	4591.2	15	41.3	12.06	2.65
F2	4591.8	21.5	8.1	10.157	2.65
F2	4592.3	22.8	47.3	12.686	2.21
F2	4593.6	26.8	32.3	11.531	2.74
F2	4593.8	18.1	11.3	14.711	2.52
F2	4594.6	25.4	54.2	13.937	2.81
F2	4594.7	16.5	36	11.755	2.6
F2	4595	22.6	41.9	11.131	2.61
F2	4595.8	16.5	35.6	11.756	2.57
F2	4598.3	18.1	47	12.965	2.64
F4	4601.3	6.8	1	16.404	2.4
F4	4602.6	5.1	0.3	16.634	2.72
F4	4602.8	4.2	0.8	16.404	2.37
F2	4605.1	13.4	5	14.557	2.64
F2	4605.6	13.6	39.3	11.755	2.73
M2	4607	6	8.2	11.755	2.6
M2	4607.9	3.1	0.4	13.799	2.65

Table 2: Porosity, permeability, grain volume and grain density measurements of plugs from Blout 7-5.

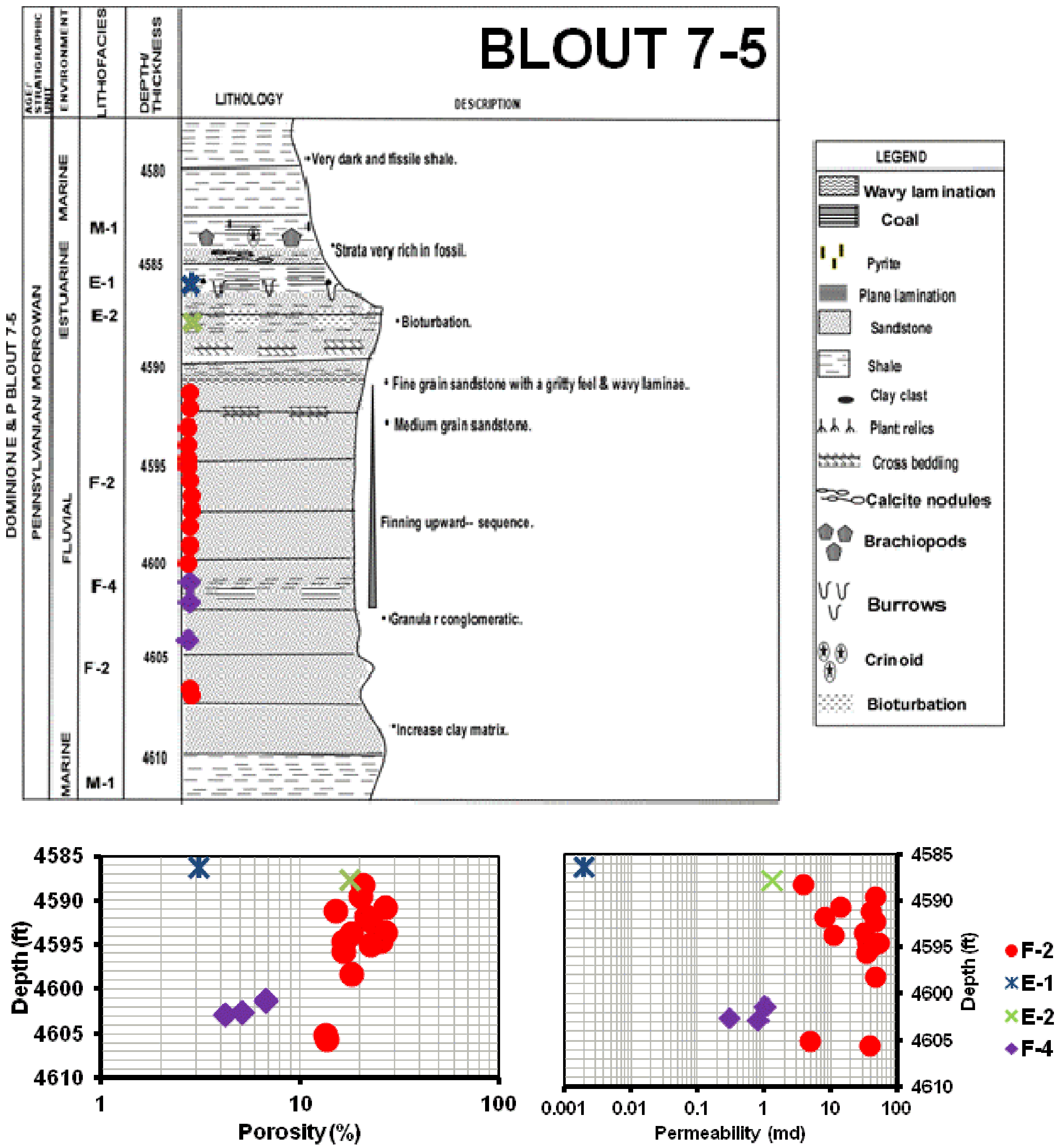


Figure 24c: Schematic diagram of the upper Morrow sandstone in the Blout 3-5 showing the distribution of facies and variation of porosity and permeability with depth

			Blout 3-5		
Facies	Depth (ft)	Porosity (%)	Permeabilty (md)	Grain Vol. (cm^3)	Grain density (g/cm^3)
E2	4625.3	11.8	0.9	12.193	2.67
E2	4525.8	6.9	0.6	13.68	2.7
F3	4626.4	18.5	36	10.264	2.62
F3	4628.2	18.2	17.4	11.883	2.68
F3	4628.5	13.3	4.6	10.597	2.65
F3	4629	11.4	4.4	12.244	2.69
F3	4629.3	12.1	2.5	10.65	2.71
F3	4631.2	13.8	6.4	9.98	2.64
F3	4631.8	12.6	18.4	11.934	2.67
F2	4632.6	20.1	34.8	9.637	2.56
F2	4633.2	22.4	38.9	10.317	2.61
F2	4633.9	20.1	38.2	9.98	2.58
F2	4634.7	22.1	40.8	10.978	2.61
F2	4635.2	13.4	5.1	11.934	2.58
F2	4635.7	18.3	31.1	10.978	2.6
F4	4635.9	9.8	0.88	10.89	2.71
F2	4636.3	17.5	27.1	11.62	2.62
F2	4637.5	21.7	43.1	11.62	2.57
F2	4639.3	20.8	44.5	12.244	2.58
F2	4640.5	18.2	44	12.549	2.6
F2	4640.8	19.7	44.1	12.295	2.58
F2	4641.9	20.7	43	11.986	2.64
F2	4642.2	19	39.2	11.031	2.58
F2	4642.6	16	25	11.627	2.65
F2	4642.9	19.6	36.1	10.032	2.6
F2	4643.4	20.1	43.1	11.986	2.64
F4	4643.6	7.1	0.17	10.97	2.7
F3	4646.3	17	1.4	12.6	2.69
F3	4646.6	14	10.6	13.197	2.68
F3	4647.1	23.9	42.2	11.354	2.89

Table 3: Porosity, permeability, grain volume and grain density measurements of plugs from Blout 3-5.

These results show that fluvial sandstones of F-2 and F-3 lithofacies have better reservoir properties. F-1, F-4, M-2, E-1 and E-2 lithofacies have fair to poor reservoir qualities as they often are cemented with carbonate or contain pore-occluding kaolinite.

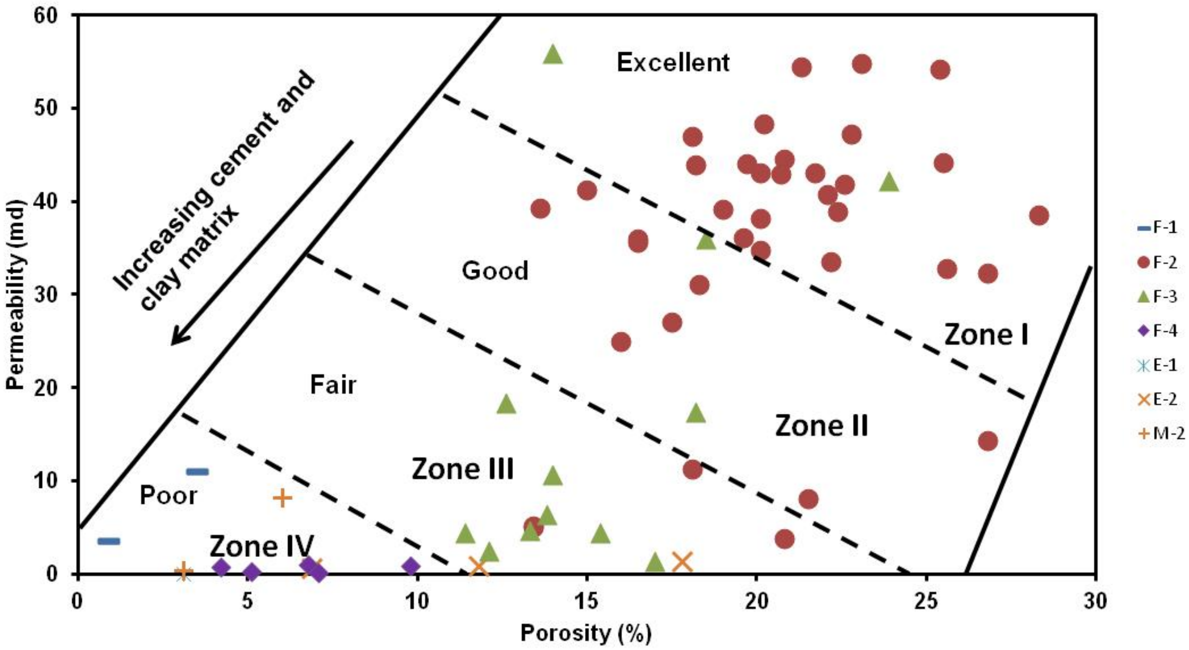


Figure 25: Porosity and permeability cross-plot showing changes in reservoir quality in different lithofacies. F-1, F-2, F-3 and F-4 represent fluvial facies. E-1 and E-2 represent estuarine facies and M-2 represents marine facies. (F-4 facies were obtained from Devries, 2005)

6.1.1. Grain volume control on reservoir quality

a. Grain volume and porosity

The control of grain volume on reservoir quality is a function of the relationship between grain, sorting, packing and shape, as well as pore throat size and surface area to volume ratio (Bloch et al., 2002). The depositional environment controls the grain type deposited in each lithofacies. Grain volume varies with lithofacies as each facies has specific features prevailing at the time of deposition. For the fluvial environment in the braided stage, high energy causes the deposition of coarser sediments whereas when energy reduces in the meandering stage, fine-grained sands are deposited. Tides and current energy as well as biotic activity control estuarine lithofacies. Variation in grain sizes, sorting, cementation and burrowing all affect sediment properties and ultimately reservoir quality.

The mean grain volume (MGV) of the measured plugs was 13.4cm^3 (Figure 26). No clear linear correlation between grain volume and porosity was observed but a general trend exists. The majority of the samples below mean grain volume have high porosities. Very coarse-grained conglomeratic sandstones have low porosity due to increase in carbonate cement and clay/silty matrix. Most samples of sandstones from M-2 and F-1 lithofacies plot above the mean grain volume and exhibit low porosity (Figure 26). All sandstone samples of F-3 lithofacies origin plot beneath the mean grain volume and generally have high porosity values. E-2 lithofacies samples have grain volumes that are lower than mean grain volume, but lower porosity values as a result of poor sorting, mixing of grains from bioturbation and clay matrix. The majority samples of F-2 lithofacies have porosity values above the mean porosity value (17 %) plotted beneath the mean grain volume (Figure 26).

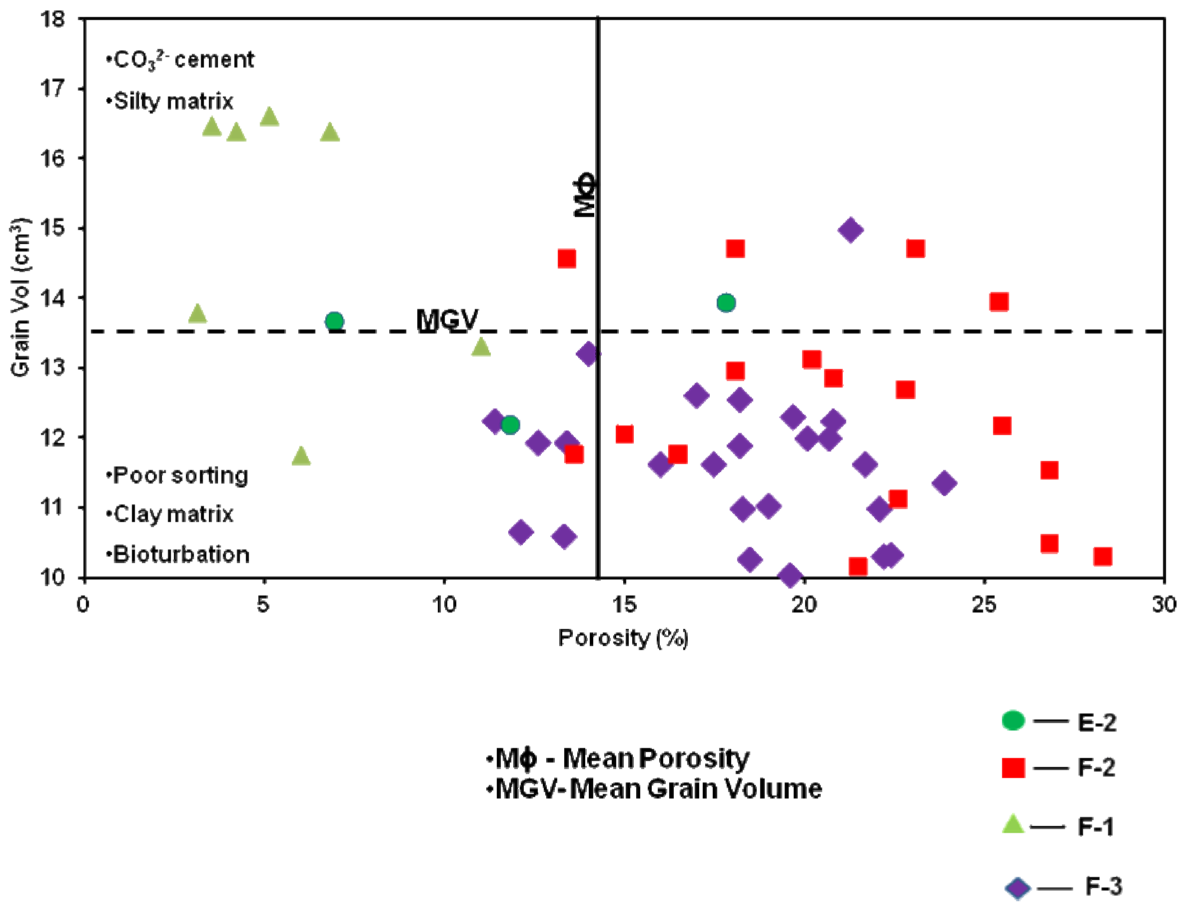


Figure 26: Porosity and grain volume cross-plot showing distribution of different lithofacies. F-1, F-2 and F-3 represent fluvial facies. E-2 represents estuarine facies.

b. Grain volume and permeability

Grain volume also influences permeability values in sandstone as the same processes creating or reducing porosity also affect permeability. In most cases, permeability increases with decreasing grain volume. Exceptions are evident for the F-3 lithofacies which have low grain volume and high porosity but low permeability. One of the F-2 samples have grain volume above the mean, but high permeability. These samples contain high permeability sandstones as well as cemented areas. Permeability varies more than porosity and 50% of the samples are below the mean permeability (mk) value of 27md and 50% above (Figure 27).

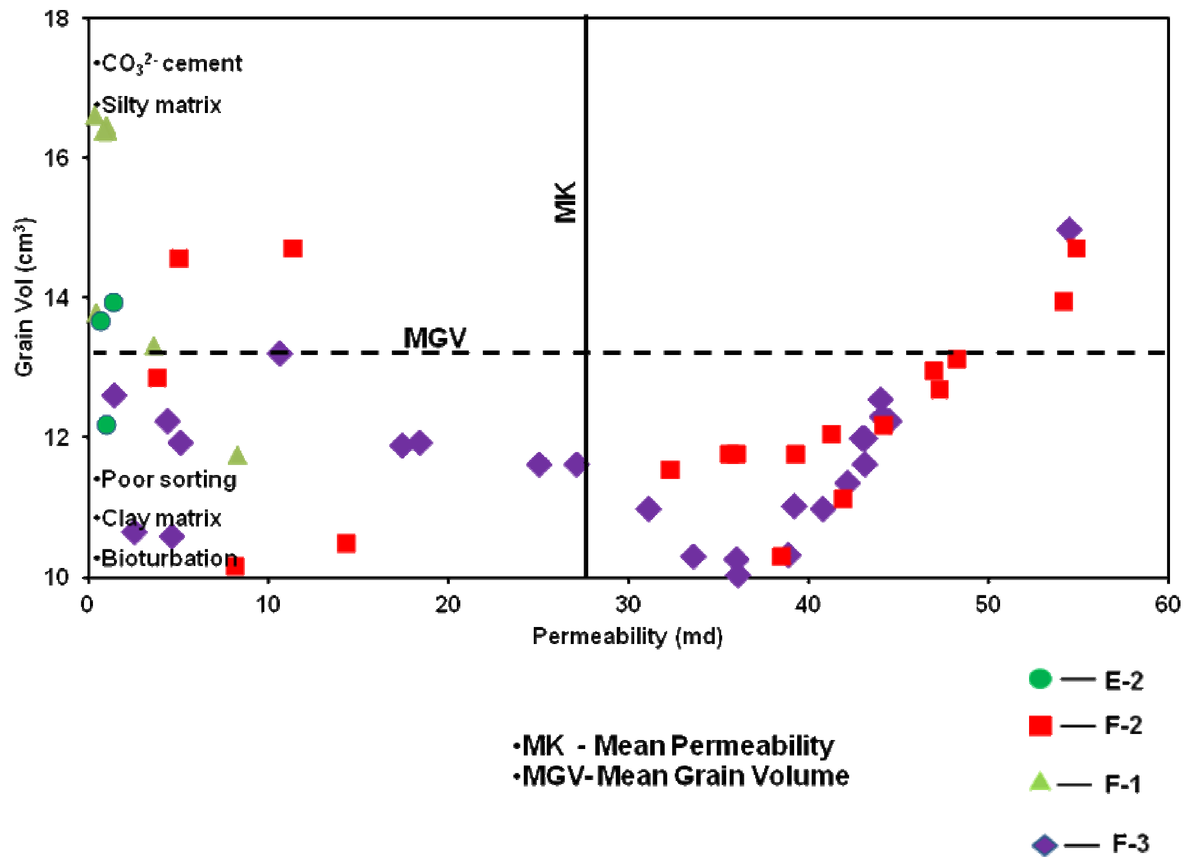


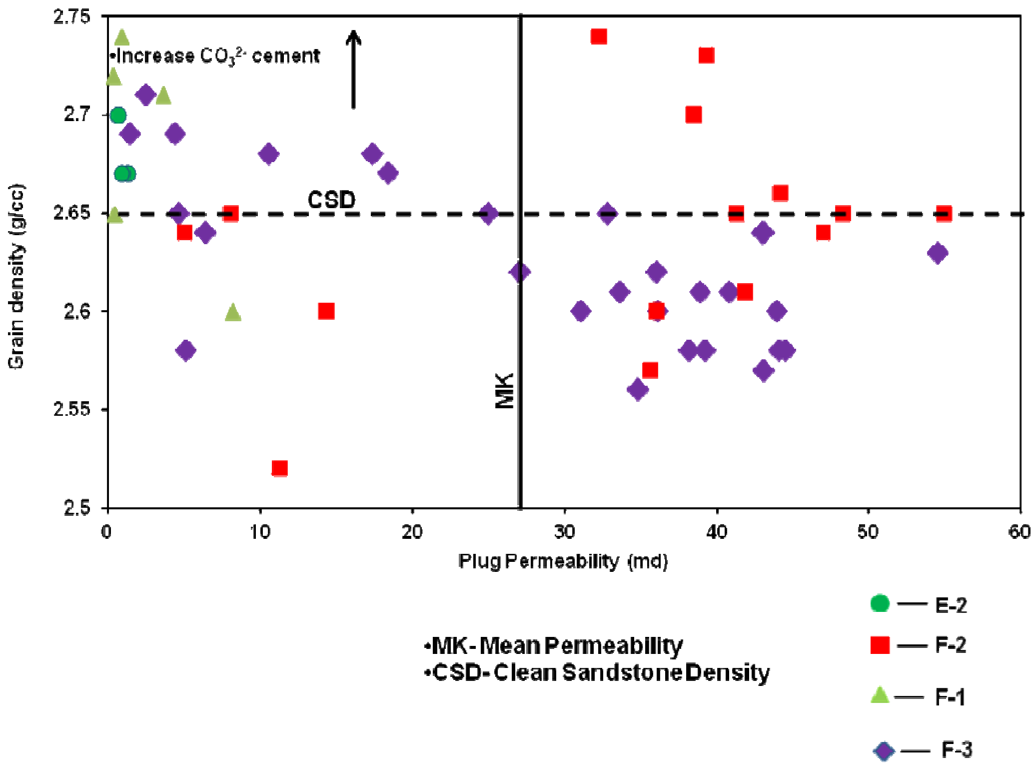
Figure 27: Permeability and grain volume cross-plot showing distribution of different lithofacies. F-1, F-2, F-3 and F-4 represent fluvial facies. E-1 and E-2 represent estuarine facies and M-2 represents marine facies

6.1.2 Grain density control on reservoir quality

A linear correlation exists between grain density and porosity for some facies (Figure 28a). Cross plots of grain density and porosity show that F-1 lithofacies have higher grain density and very low porosity. This is the result of carbonate cement that influences grain density measurement and consequently porosity values. F-2 and F-3 lithofacies have lower grain densities and higher porosities because they have lowest volume of cement.

Grain density strongly influences reservoir quality especially permeability (Figure 28b). Sandstones cemented or replaced by carbonate exhibit low permeability measurements. In contrast, sandstones not cemented by carbonates exhibit lower grain density values, higher permeability and porosity (Figure 27a & b). E-2 sandstones with matrix have higher grain density values and lower porosity and permeability.

a.



b.

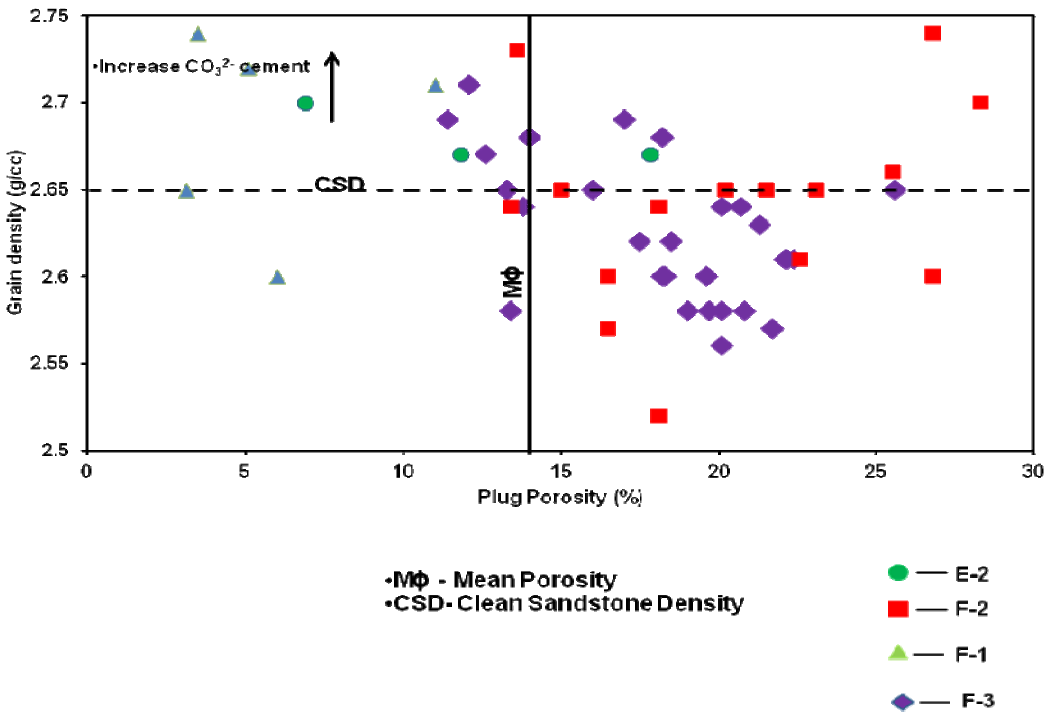


Figure 28 (a): Permeability and grain density cross-plot for upper Morrowan sandstone lithofacies (b): Porosity and grain density cross-plot for the sandstone. F-1, F-2 and F-3 represent fluvial facies. E-2 represents estuarine.

6.2. Heterogeneity and effects on reservoir quality

Most heterogeneity in the upper Morrow sandstone interval is the result of shale interbeds and calcite concretions. However, grain size distribution and sorting within individual beds affect porosity distribution within these sandstones, which further controls heterogeneity as observed in the different lithofacies. Vertical heterogeneity was obvious in all cores, but the lateral reservoir continuity could not be assessed due to a lack of data. As evidenced from the porosity and permeability data, lithofacies changes affect porosity and permeability and introduce vertical heterogeneity.

Chapter VII

Discussion and conclusions

The graphical comparison of lithofacies with porosity and permeability reveals that fluvial lithofacies F-2 and F-3 are the better reservoirs in the upper Morrow sandstone. In the Dominion Blout 6-5, F-2 and F-3 facies have core plug porosity value of 21 to 28 %,that compare to log density value of 17.5 to 30% (Figure 29). In the Blout number 3-5 core, F-2 lithofacies porosity values ranged from 15-28%. Permeability values varied widely for F-2 and ranged from 1.3 md to 54.2md. This variability is attributed to the presence of carbonate cement and kaolinite, which locally reduce permeability by pore occlusion. Calcite serves to reduce both porosity and permeability, whereas kaolinite reduces permeability much more than porosity.

F-1 facies has low porosity and permeability. In Blout 6-5, F-1 porosity values were 3.5 to 11 % from core plugs and 7 to 20% from density log. Permeability values for F-1 facies ranged from 0.9 to 3.6md. These values are attributed to carbonate cement, clay matrix and pseudomatrix formed by the deformation of the clay clasts in the channel lag conglomerate. In the Blout 3-5, F-1 permeability measurements ranged from 0.3 to 9.2md.

F-3 facies in the Blout 7-5 has high porosity 12.5 to 23.5% (Figure 28) and lower permeability values of 1.3 to 17.4md. However, one permeability value of greater that 44md was obtained for F-3 facies in this well. The lower permeability values were from the intervals with carbonate cement.

Estuarine lithofacies were not intensively sampled due to difficulty in securing intact core plugs in these laminated rocks. In the Blout 7-5, E-2 lithofacies has measured porosity values of 6-11% and permeability values of 0.6 to 0.9md. The low porosity and permeability values are attributed to burrowing that reduces porosity and permeability. A permeability measurement for the E-2 lithofacies in the Blout 3-5 was 1.3md.

These results indicate that vertical changes in reservoir quality in the upper Morrowan sandstone interval occur over short distances. Furthermore, the differences in the cored lithofacies in these closely spaced wells (Figure 30) are evidence that lateral changes are equally common. With this in mind, it is evident that careful mapping of facies distribution is critical to determining flow units in the reservoir.

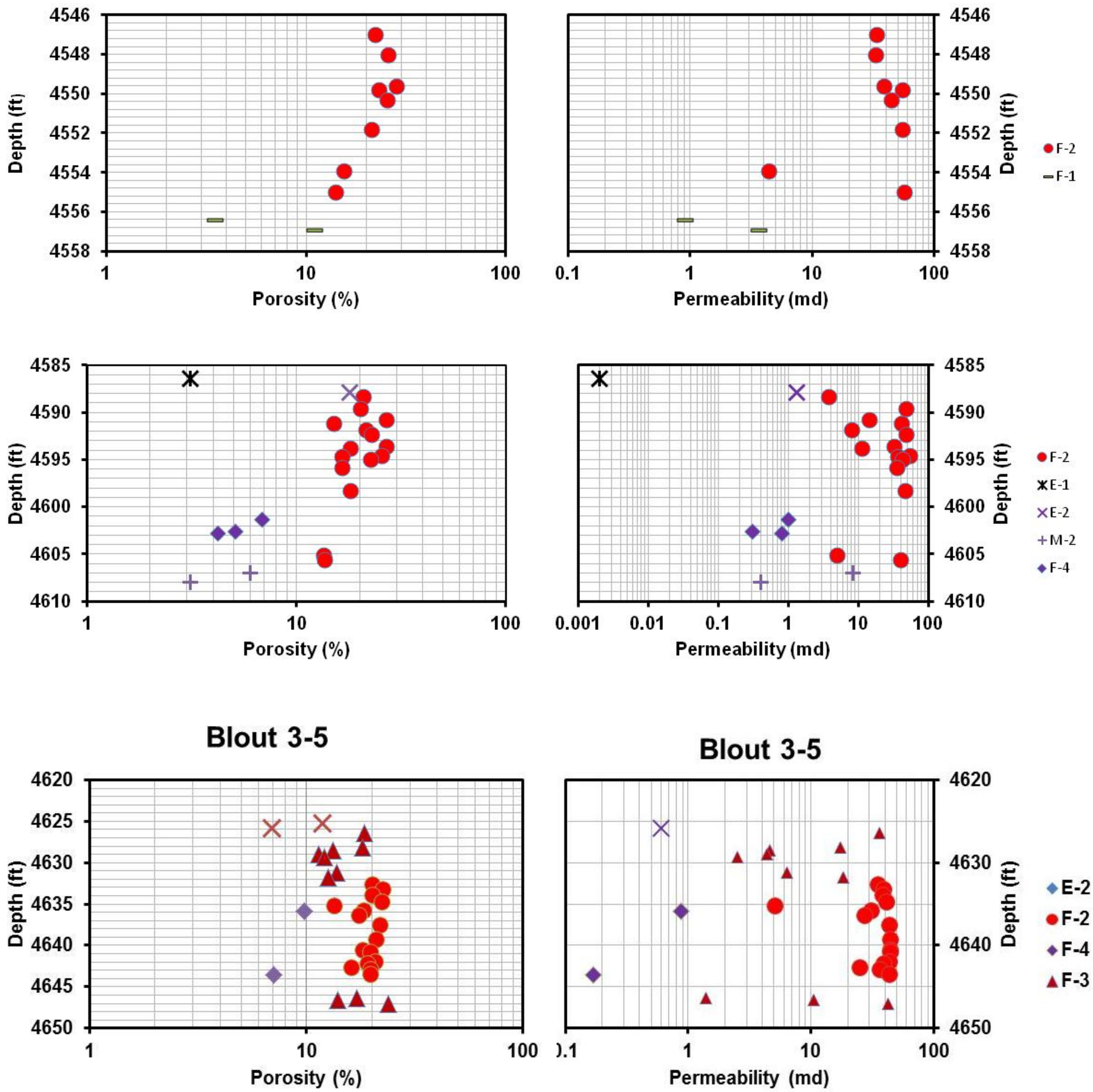


Figure 29: Graphical representation of facies changes with depth along with porosity and permeability variation with lithofacies. F-1, F-2 and F-3 represent fluvial facies. E-2 and E-1 represent estuarine. M-2 represents marine facies.

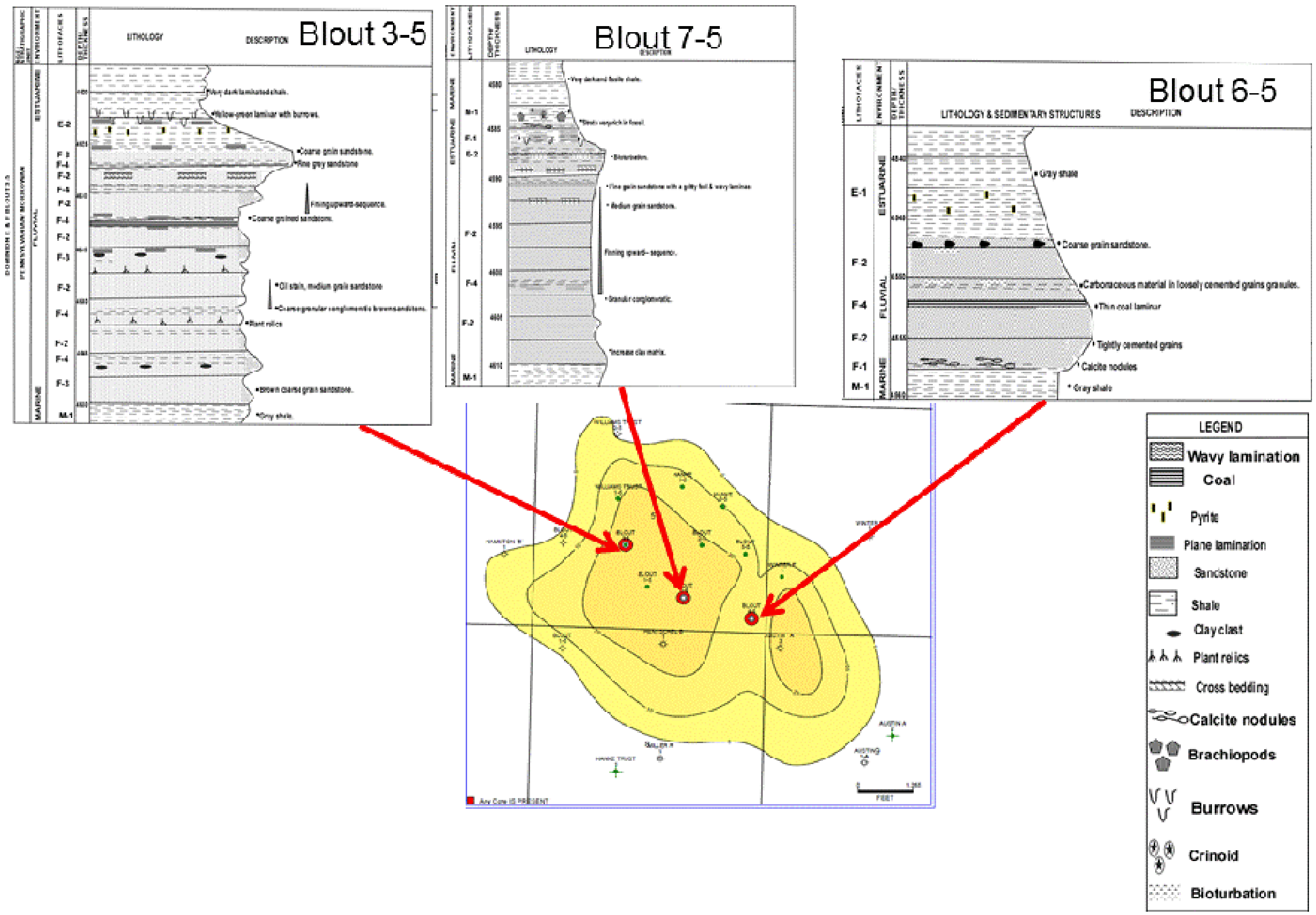


Figure 30: Evidence of lateral variation in facies.

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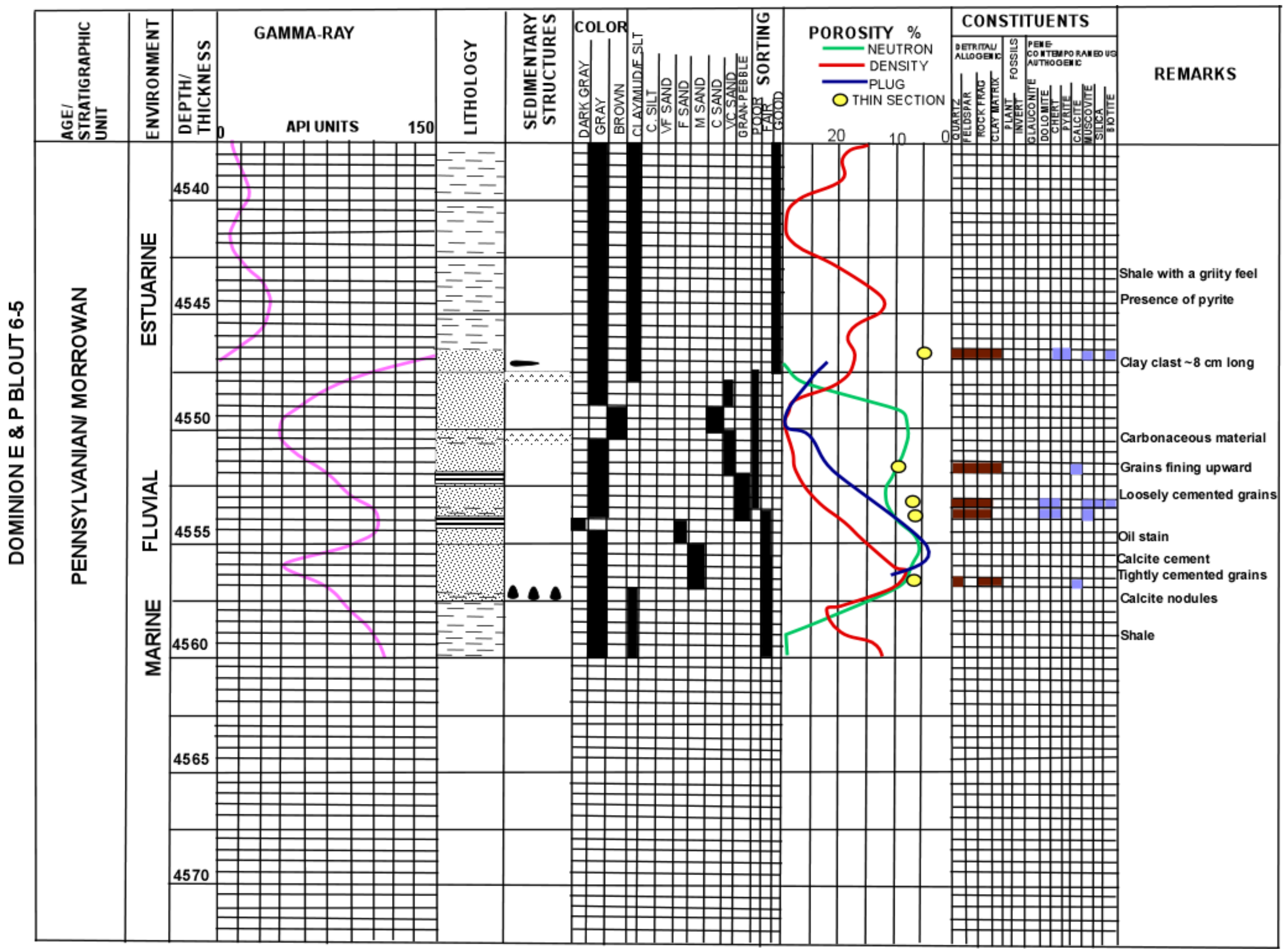
Appendices

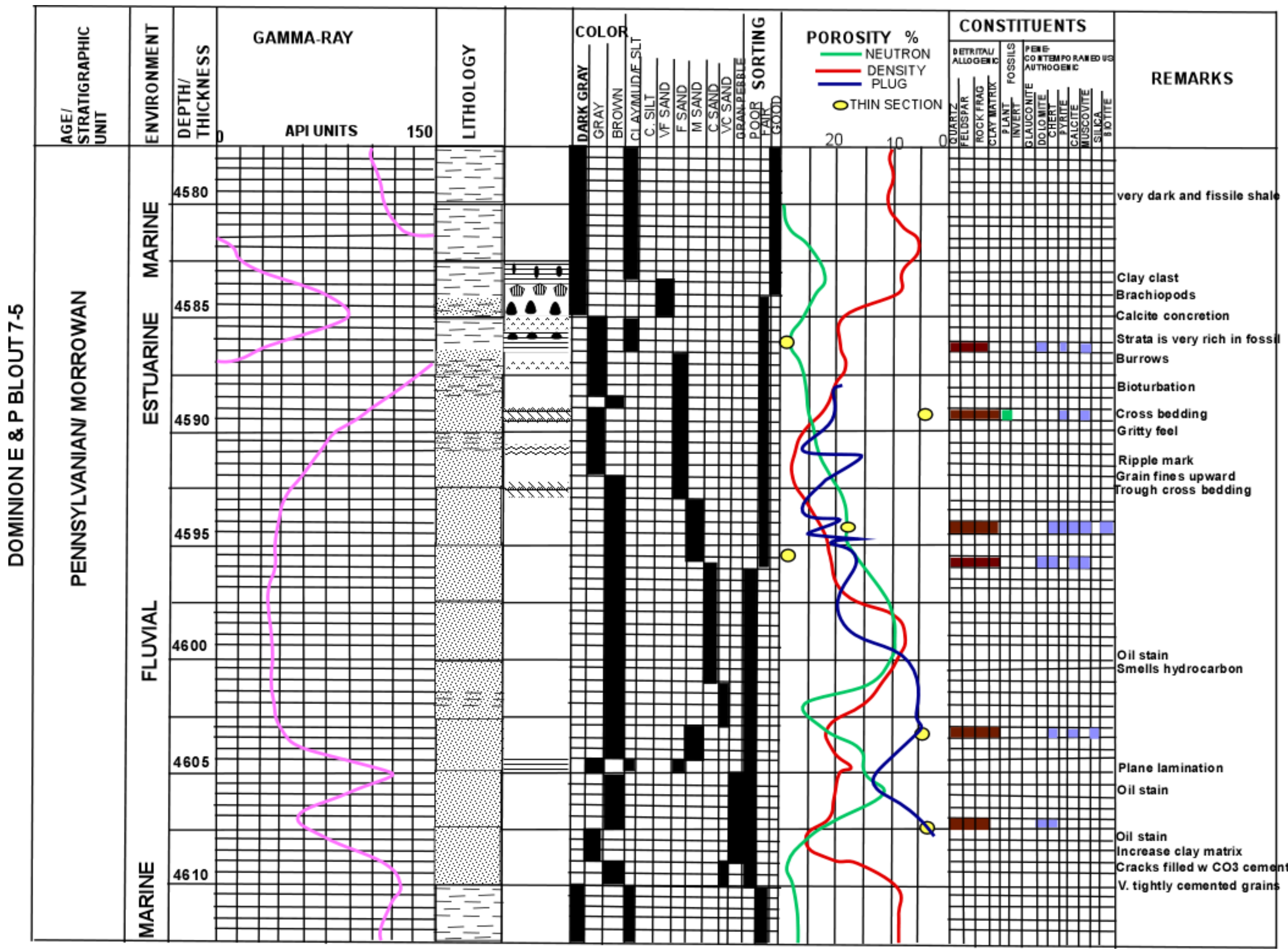
Appendix A. Petrologs

Appendix B. Classification of upper Morrow sandstones

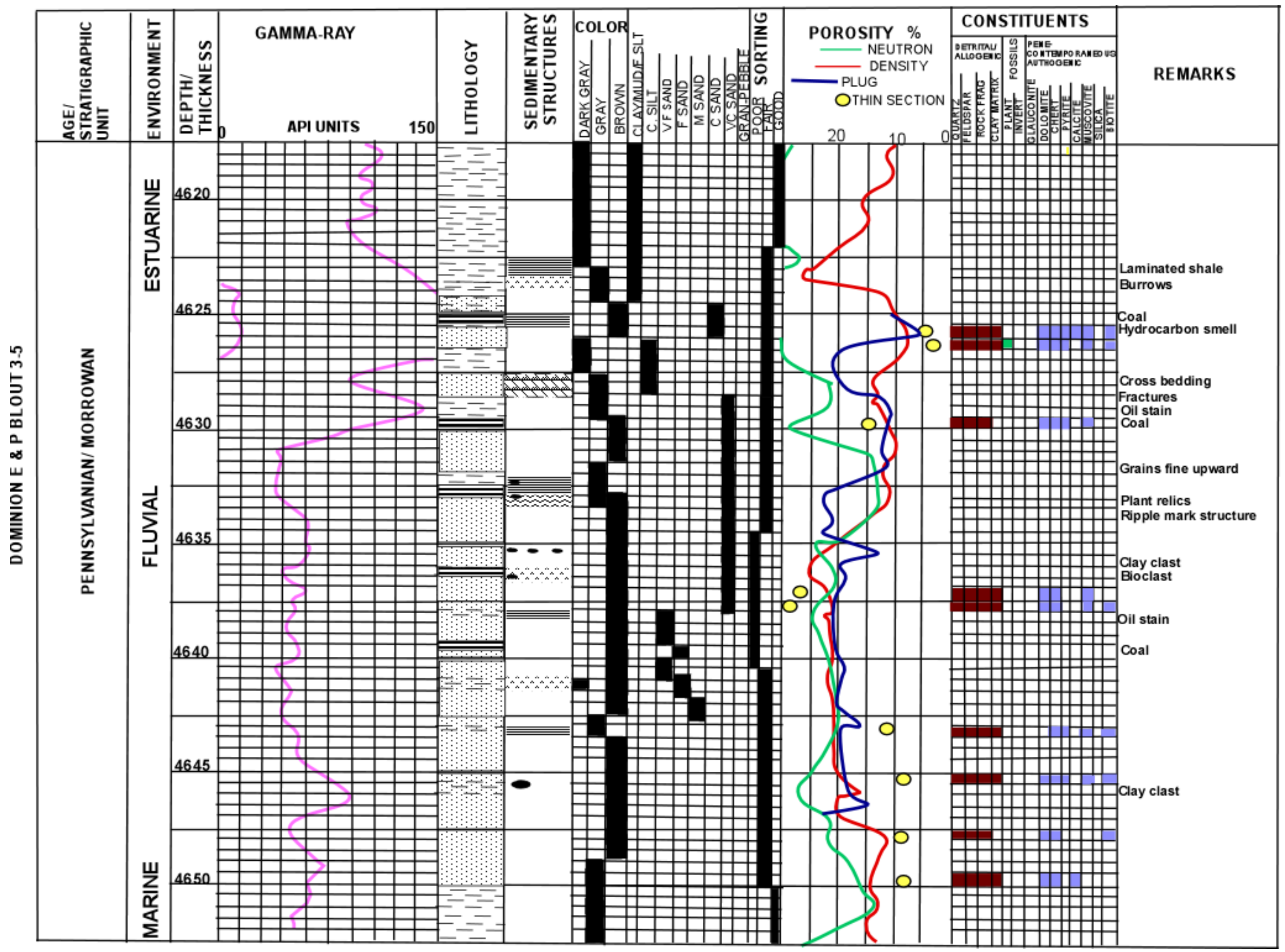
Appendix C. Facies assemblages



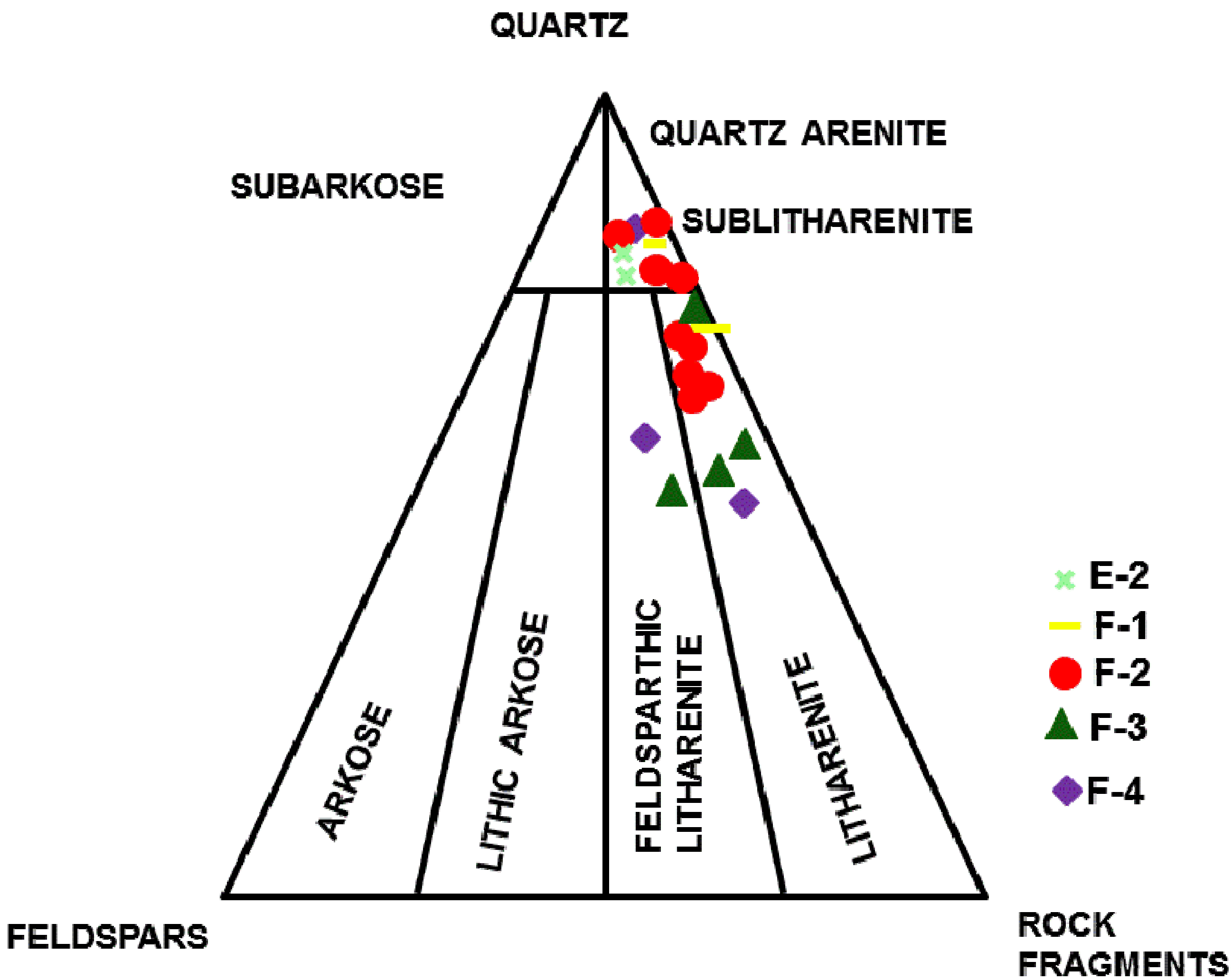
Appendix A. Petrolog for the Dominion Blout 6-5 showing gamma-ray, lithology, sedimentary structure, rock properties, porosity from thin section, core and log



Appendix A. Petrolog for the Dominion Blout 7-5 showing gamma-ray, lithology, sedimentary structure, rock properties, porosity from thin section, core and log



Appendix A. Petrolog for the Dominion Blout 3-5 showing gamma-ray, lithology, sedimentary structure, rock properties, porosity from thin section, core and log



Appendix B. Classification of the upper Morrow sandstone using the Folk (1962) classificatiion

Appendix C: Facies Assemblages.

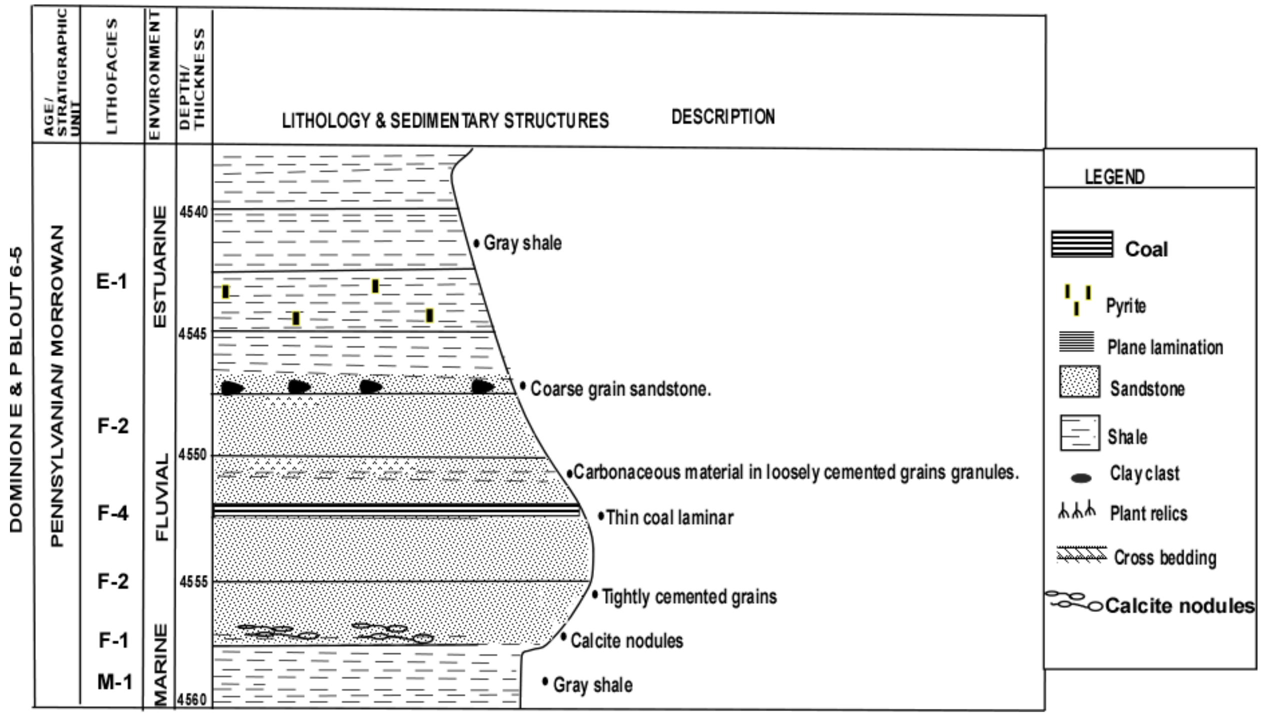
Eight main lithofacies assemblages occupy the incised valley fill in the region East Mustang Field: fluvial facies (F-1, F-2, F-3 and F-4), estuarine (E-1and E-2) and Marine (M-1 and M-2). These facies assemblages alternate and transgress in to each other without demarcated boundary conditions.

Fluvial facies assemblages

Fluvial facies is the most important reservoir facies in the East Mustang Field. The fluvial assemblage is approximately 25 ft sandstone with as much as 28% porosity. Fluvial facies is represented in the cores as fine to coarse-grained granule sandstone. Based on thin section microscopy, majority of the sandstones were classified as litharenitic using Folk, 1962 classification.

Blout 6-5

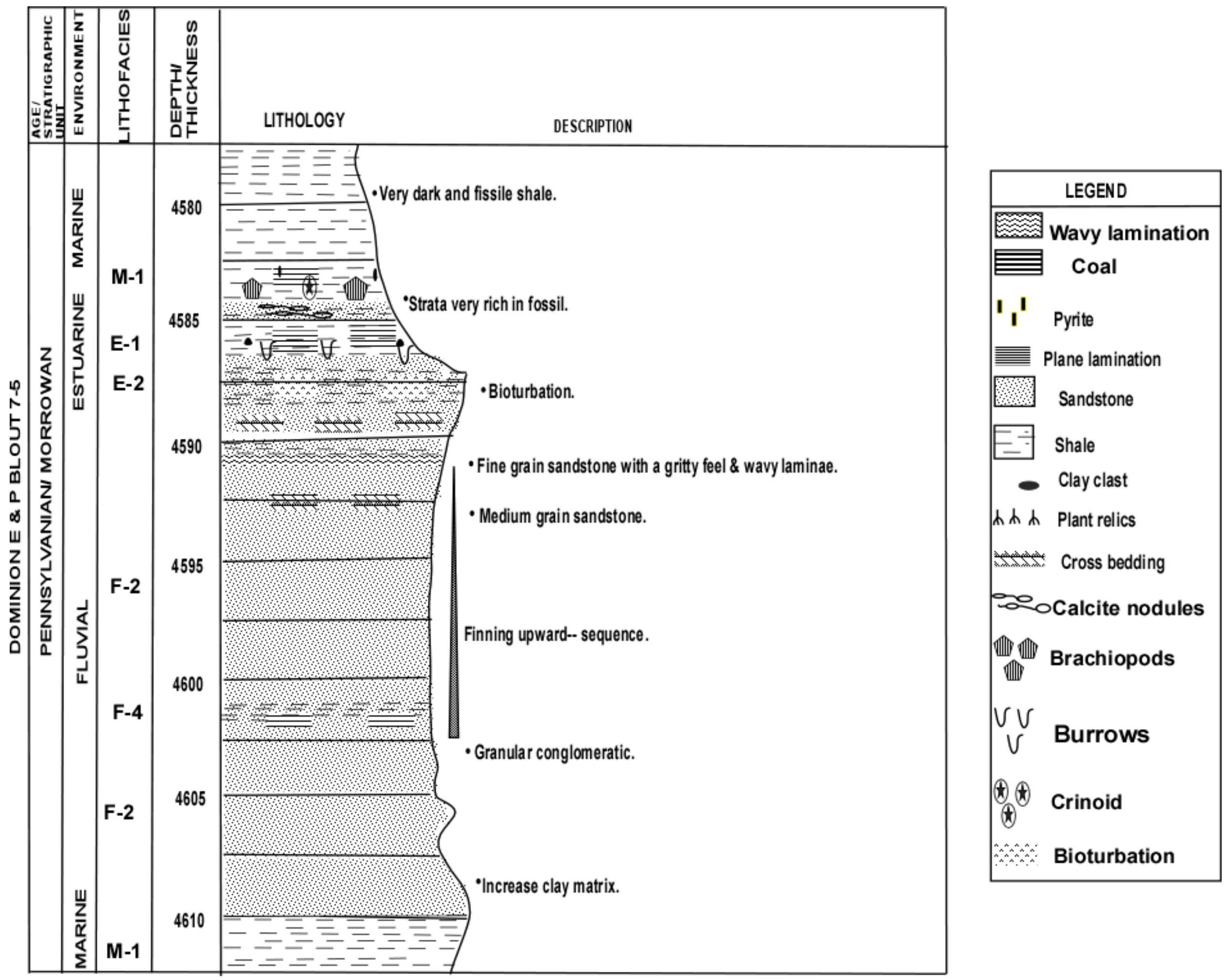
Blout 6-5 reveals that fluvial lithofacies F-1 occupies depths 4557.3 to 4556ft. F-3 occupies depth 4556 ft to 4555 ft, F-4 precedes at an interval of 4555ft to 4553.8ft. Clay matrix is high and so is carbonate cement therefore accounting for the low porosity recorded for F-1 lithofacies. Fluvial facies ends with F-2 from 4553.3 ft to 4546.8ft. These lithofacies at these depths have very high porosities that read between 3.5% (F-1) to 28.3 %, (F-2) for measured plugs, 7 % to above 30 %, for neutron log and density log reads between 7 % to 30 %. High porosity values reflected in the logs and plug results from the loosely cemented granule to coarse grains sandstone.



Appendix C. Schematic diagram of Blout 6-5 with a division of facies.

Blout 7-5

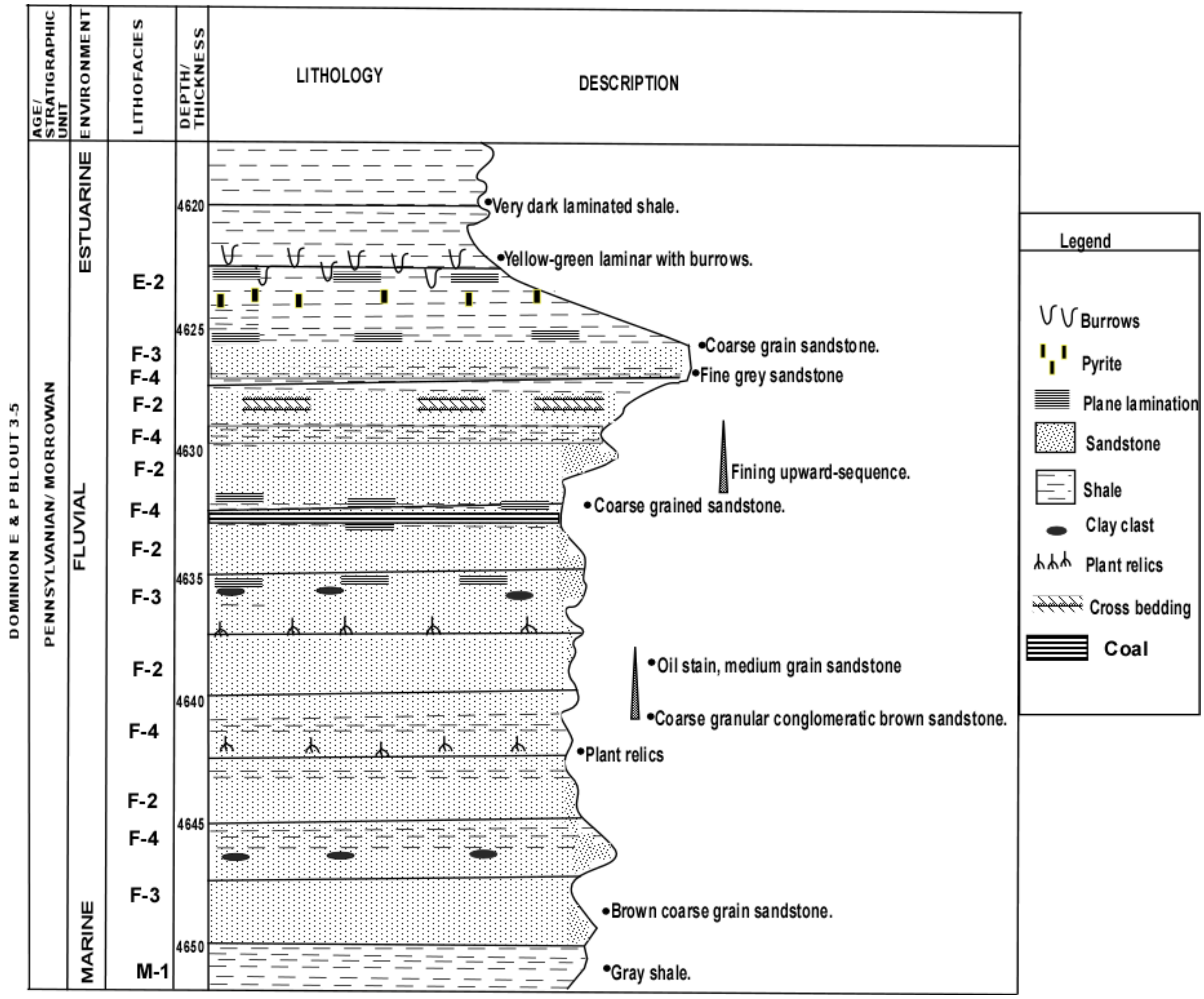
In Blout 7-5, F-2 lithofacies was the only fluvial facies indentified at intervals 4605.7 ft to 4603 ft and 4598.5 ft to 4591.5 ft. This fluvial facies forms a fining upward sequence with structures such as trough cross bedding in the fine-grained interval. F-2 lithofacies is characterized by coarse-grained sandstone with several areas with hydrocarbon staining. The porosity values for this lithofacies read between 13.4% to 26.8 %, for measured plugs, 12 % to above 28 %, for the neutron log and 8 % to 27 % for the density log. High porosity values reflected in the logs and plug results are from the loosely cemented coarse-grained sandstone.



Appendix C. Schematic diagram of Blout 7-5 with a division of facies

Blout 3-5

The fluvial core interval analyzed for Blout 3-5 contained F-2, F-3 and F-4 lithofacies. F-2 lithofacies was encountered at depths 4643.4 ft to 4636.7 ft, 4635.2 ft to 4634 ft, 4633.5 to 4632.5 and 4632.2 ft to 4627.6 ft. F-2 lithofacies are brown sandstones with coarse grains and fractures that form a fining upward sequence. Readings as much as 22% porosity for plugs and 23% porosity for neutron/density were obtained. F- 3 lithofacies were encountered at intervals 4648.3 ft to 4644 ft, 4646.5 ft to 4635.4 ft and 4626.8 ft to 4625.3 ft. Fine to medium grained sandstone with clay lenses and trough cross bedding was observed in this facies. Porosity measurements as much as 23% were measured from the core plugs and 15% for neutron density porosity. The sequence changes into fluvial F-3 lithofacies with high porosity (12.5 % - 23.5 %). This is oversized porosity from the dissolution of grains and fractures. F-4 lithofacies occurred at 4644 ft to 4643.4, 4636.7 ft to 4636.5, 4635.4 ft to 4635.2 ft, 4634 ft to 4633.5 ft 4633.5 ft to 4632.2 ft and 4627.6 ft to 4626.8 ft. These are fine- grained sandstones with coaly materials. Core plug porosity was low (7%) whereas density porosity was 15% from log.



Appendix C. Schematic diagram of Blout 3-5 with a division of facies

Estuarine Facies assemblages.

Estuarine lithofacies occupy a depth of 4546.8 ft to 4543 ft (E-1), for Blout 6-5, 4525.2 ft to 4523 ft (E-2) for Blout 3-5 and 4591.5 ft to 4587.3 ft (E-2) and 4587.3 ft to 4585 ft (E-1) for Blout 7-5. Core plugs revealed low to medium porosity (6% - 11%) This lithofacies has cracks filled with carbonaceous materials, interbedded clay and is highly burrowed accounting for the low porosity. Carbonate cement and interbedded with coal occur in estuarine facies.

Marine Facies Assemblages.

Marine lithofacies M-1 occupy depths of 4611.5 to 4609 ft 4585 to 4582ft and M-2 occupy depth 4603 to 4508.5 ft. These are laminated , fossiliferous shale, and sandstones. Core plugs obtained from M-2 facies reveal they have low porosity (6.1 to 8%) and permeability of 0.3 to 8md. No plugs were taken for M-1 lithofacies because they are not reservoirs.

VITA

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Thesis: IMPACT OF DIAGENETIC OVERPRINT ON RESERVOIR QUALITY AND HETEROGENEITY, UPPER MORROW SANDSTONE, MORTON COUNTY, KANSAS

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Name: Rita Dzeutsop Asoba Date of Degree: December, 2011

Institution: Oklahoma State University Stillwater, Oklahoma

Title of Study: IMPACT OF DIAGENETIC OVERPRINT ON RESERVOIR QUALITY AND HETEROGENEITY, UPPER MORROW SANDSTONE, MORTON COUNTY, KANSAS,

Pages in Study: 77 Candidate for the Degree of Master of Science

Major Field: Geology

Scope and Method of Study: The relationship between depositional environments, sedimentary features, diagenetic products and the evolution of porosity and intrareservoir seals was examined for the upper Morrow sandstone in Morton County, Kansas. These cores from the East Mustang Field were analyzed and sampled to determine textural properties, core plug porosity and permeability. Thin section and well log data were integrated to determine the relationship depositional facies and reservoir/ seal properties.

Findings and Conclusions: Integrated analysis of three cores along with well logs yielded eight distinct lithofacies associated with fluvial, estuarine and marine environments of deposition. The marine facies M-1 and M-2, which are fossiliferous shale and sandstone, are not reservoirs. The better reservoirs are F-2 facies which consists of coarse-grained sandstone to granule conglomerate with average porosity of 20.4% and permeability of 35.2md. F-2 sandstone represents braided stream deposits. Other fluvial facies are F-1 channel lag conglomerate, F-3 meandering stream sandstone and F-4 abandoned channel fill shale, siltstone and coal. F-1 facies are poor reservoirs due to carbonate cement and pseudomatrix. Average porosity in the F-1 facies is 7.3% and permeability is 2.3md. F-3 represent reservoirs and have average porosity of 15.4% and permeability of 17md. F-4 facies is generally low porosity and permeability due to the presence of silty and clay matrix. The average porosity for F-4 facies is 6-6% and permeability is 0.63md. Estuarine facies E-1 and E-2 have highly variable reservoir properties that depend on the amount of clayey material and burrowing that destroyed the original bedding. F-4, E-1 and E-2 facies tend to form flow barrier that contribute to reservoir heterogeneity. Mapping individual facies is critical to determine the distribution of reservoir (flow units) and sealing facies in the upper Morrow sandstone.

ADVISER'S APPROVAL: Dr. Jim Puckette