Application of Petrographic Image Analysis and Multivariate Statistical Techniques for Textural Studies of Oil Sand Samples*

Julie Dee Bell[1], Ovie Eruteya[1], and Oko Oono[1]

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[1] Petroleum Engineering, London South Bank University, London, United Kingdom (bellj@lsbu.ac.uk)

Abstract

Notably, Canadian oil sands are hosted within a quartz rich unconsolidated material and understanding the fabrics and textural characteristics of these oil sands is crucial to in-situ heavy oil production processes. This study is aimed at determining the characteristics of oil sand samples from the Upper McMurray Member and, more specifically, from an estuarine tidal depositional environment. Standard thin sections were prepared from outcrop samples collected from the Hangingstone River area near Fort McMurray, Canada. The thin sections were examined through a fabric analysis including composition and vectorial analysis. This analysis used an integrated petrographic image analysis (PIA) system consisting of a high-resolution petrographic microscope adapted with a digital camera for image acquisition and a commercial image analysis software package for image processing. The image analysis software was used to measure fundamental textural properties observed in thin section, using the modified Griffiths properties measurement rule $P= \Sigma$ (m,s,sh,o,p). Data sets were generated from the petrographic image analysis by means of point counting variables such as grain morphology, micromass, pore geometry and bitumen content. An estimate of grain sorting was derived from observing the spatial arrangements of the coarse and fine components along with the pores. The data sets were subject to multivariate statistical analysis using principal component analysis (PCA) and hierarchical cluster analysis (HCA) methods. From the PCA, the variable that contributed significantly to the textural fabric was the quartz content. The HCA showed that multi-groups existed, based on variations in textural properties. Quartz grains were arranged in a matrix of micromass with vugs and varying amounts of bitumen throughout. The micromass consisted of both silt and clay sized material and ranged from dark to light brown with some mixture of bitumen, which was mostly very dark brown. Multivariate statistical techniques provide an important tool for grain morphology studies of oil sands material and for delineating relationships of textural features. Integrated studies of this type could aid in locating sweet spots along production wells for enhanced heavy oil recovery processes.

Introduction

Oil sands represent one of the most strategic resources, and they are of extreme importance to North America and to the world as a whole. This is largely due to the declining reserves and increase in exploration difficulties associated with conventional oil. The Canadian oil sands represent the world's second largest hydrocarbon accumulation with 1.7 trillion barrels of heavy oil of which estimated 179 billion barrels is recoverable based on current technology (Canada National Energy Board, 2004).

Recent advances in petrographic studies, in particular the development of the computer aided petrographic image analysis (PIA) system, has proved to be a valuable method in examining oil sands reservoir qualities and the ability to rapidly characterize estimations of reservoir properties such as grain size distribution, along with porosity and permeability (Gordon et al., 2010; Coskun and Wardlaw, 1996). The application of PIA for the determination of oil sand properties and associated heterogeneities provides a window into reservoir quality. At micro-scale, these qualities include fabric composition and vectorial data that provide insight into overall reservoir quality. Applying multivariate statistical techniques in delineating textural characteristics of oil sand fabrics provides us with an important tool in establishing grain and pore morphology, as well as for delineating relationships between groups of samples. The focus of this study is to determine initial grain and pore morphology from petrographic analysis and apply petrographic image analysis (PIA) and multivariate statistical technique for oil sand fabric and textural analysis.

Material and Methods

The site selected for this study was the Hangingstone River area near Fort McMurray, Canada. This is a well-documented estuarine tidal depositional environment from the Upper McMurray Member (Hein et al., 2001). This formation lies at the base of the Lower Cretaceous Mannville group on an angular unconformity from the Devonian and is comprised of limestone and calcareous shale in the east and carbonate rocks in the west (Cant and Abrahamson, 1996). Sediments in the McMurray Formation were deposited in a north-south trending ridge and valley that was formed by fluvial processes. This later changed to a marginal marine setting during an Early Cretaceous sea-level rise.

Material

Overall, the McMurray Formation has very complex sedimentary relationships that vary considerably, both laterally and vertically, over short distances. This is indicative of complex depositional environments common with transgression and regression cycles (Hein et al., 2001). The McMurray Formation is divided into three members; Lower, Middle and Upper (Carrigy, 1959). Textural variations are well documented between the three members and characterised as the following: a conglomerate of poorly sorted and argillaceous sand, silt and clay in the lower member; overlain by a moderately well sorted, fine-grained sand and argillaceous silt in the middle member; and overlying is very fine grained sand and argillaceous silt in the upper member.

Methods

The fieldwork was carried out over two weeks in the summers of 2010 and 2011 in the study area located in the Hangingstone River area. Here, undisturbed oil sands samples were sampled from outcrops. Teflon tubes were used to ensure that samples retained an undisturbed and in-situ nature. Select samples were mapped and collected from regions of interest; more specifically, the study focused on sample areas that showed distinct sedimentary features and areas void of obvious sedimentary features and structures. In the field, the oil sands samples appeared as unconsolidated sands with bitumen cementing sand grains and agreed with other studies previously carried out (Mossop, 1980).

The thin sections were produced according to well-established methods from Jongerius and Heintzberger (1975) and Fitzpatrick (1984). Methods were modified as necessary to accommodate the delicate nature of the oil sands with a view to preserving its integrity and minimizing alterations of the oil hosted in the quartz rich samples during the course of thin section production. The major objective in the laboratory was to investigate the undisturbed nature of the material, including a fabric composition and vectorial analysis.

The slides were observed under plain polarized light with the sole objective to undertake a fabric study to gain both compositional data by identifying coarse components (including quartz grains, micromass, pore spaces, and bitumen) and vectorial or scalar data by measuring select components. Samples and thin sections were first observed for composition and those that portrayed distinct features associated with bioturbation were considered heterogeneities and not included in the textural study. Bioturbation features are well documented in the field by Pemberton et al. (1982) and in thin section by Jongerius and Schelling (1960) and DeConinck et al. (1974). These features will be investigated in a later study.

Measurements involved determining the spatial distribution of select components along with the minimum intermediate and maximum dimensions. The goal was to provide insight into the nature of the oil sands reservoir material in order to understand reservoir quality. Point counting was conducted under a 10X magnification lens fitted to an Olympus BH 2 microscope. Morphometric analysis was performed systematically by tracking a pre-calibrated cross hair in the microscope’s field of view, during which pre-determined parameters were measured. Point counting occurred on a 1 mm scale and, as the stage was advanced 1mm, components were point-counted and observations were recorded at each location. The point counting involved 6,000 total point counts. The representative elementary area (REA) was calculated for the samples according to VandenBygaart and Protz (1999) and 6,000 points were counted in order to meet the statistical requirements for grain data of this nature.

A Cannon A560 Powershot digital camera was used for image acquisition, thin sections viewed under the microscope were focused and important variables observed and measured. Photographs were taken before advancing the point counting scale by 1 mm for the process to be repeated. Magnification, light source intensity and polarity were standardized for the whole of the point-counting process to ensure uniformity and compatibility of methods and procedure so that results from different thin sections can be correlated.

The dataset generated from the point counting and image analysis of the grain morphology and pore morphology were treated to PCA and HCA using PAST. These measurements allow for a quantitative analysis and characterization that include determining the frequency distribution of oil sands individual components. The size of the grains, including maximum and minimum length and diagonal axis logged in µm. The optical area, including coarse components and micromass, void, and area occupied by bitumen was also recorded for each square micron.

The point count analysis of the thin section involved logging of the observed components by adopting Griffiths' (1961) measurement of properties (Figure 1). The relative percentage distribution of components was then calculated. For each component that falls under the microscopic cross hair, the major, minor and intermediate axis length was determined using the PIA and recorded to provide an estimate of the size (s) of the component. The shape (sh) of the component observed in thin section was determined from the value of roundness derived from the PIA system using Image J.

Results and Discussion

Thin section analysis is important as reservoir properties can be directly observed and key details regarding reservoir conditions better understood. Ultimately, key details regarding reservoir quality can aid in the design of better and more efficient oil recovery methods. McCormack (2001) outlined the minimum reservoir requirements for a successful SAGD operation. He pointed out that the minimum requirements directly affected include the following properties: porosity, permeability, oil saturation, pay continuity, structural features and the presence of water and gas zones.

A micromorphologic fabric study, including both compositional and vectorial analysis, was carried out on oil sand samples from an outcrop of the Upper McMurray Member, notably the estuarine depositional environment. The environment of deposition controls the material deposited that, in turn, controls the reservoir properties. The Upper McMurray Member was deposited in meandering deep estuarine and point bar environments that were controlled by rapid sea level rises (Hein et al., 2007).

Bell et al. (2011) presented the initial results of the compositional fabric study. In keeping with thin section studies of sediments, thin sections were described according to Stoops (2003). During the course of the study, it was clearly noted that a range of c/f related distribution patterns from Enaulic to Gerfuric to Porphyric was observed. Major features observed in thin section consisted of the following: coarse components, as quartz grains; fine components or micromass; and voids, mostly vugs and bitumen.

The textural study involved measuring parameters of the main components observed in the fabric study, including determination of size and shape, and deduction of the relative abundance of constituents through petrographic image analysis (PIA). Data collected from point counting were subjected to statistical evaluations, the goal being to determine the principal grain elements of the grains that have a significant influence on reservoir properties, including porosity and permeability. Data sets from the PIA, including grain distribution parameters, were evaluated and tabulated (Table 1).

Coarse Components

Quartz was the principal mineral component observed in thin section (Figure 2). Overall, the quartz grains displayed little weathering. Some alterations of the grains were observed, mostly as fractures within the grains. In thin section, some grains displayed distinct fracturing, mostly interpreted to be weathering fractures although a few fractures observed may be attributable to the mechanical effect of thin section production.

Using 2D grain axis measurements from the petrographic microscope, the minimum grain size was tabulated and plotted as a frequency distribution curve (Figure 3). As observed in the thin section, the median grain size is 2.6 σ and the mean is 2.66 σ, which is 170 micron and 160 microns respectively. Due to the closeness of the mean and median grain sizes, the sample is understood to be normally distributed. The standard deviation σ is approximately 0.5, suggesting that grains are well sorted ($0.35<\sigma<0.5$) (Table 1). Skewness Skwhic is a measure of the symmetry of the grain size distribution from the mean particle size and a maximum possible size for skewness is 1 with a minimum size. A maximum value of -1; the value of skewness derived from the study was 0.1. Therefore, distribution can be referred to as fine skewed for Sk ($+0.1<Sk<+0.3$). The implication of this value of skewness is that the distribution has a high concentration of fine grain sized particles.

The shapes of the quartz grains were identified according to Pettijohn et al. (1973). Point counting results revealed that grain shapes varied from well rounded to very angular (Figure 4). The predominate shape, according to the point counting result, ranged from subrounded to subangular.

The packing density of grains is the spacing between the particles. It is a very important determinant of porosity depending on the degree of utilisation of space by the grains of a porous material. Porosity might vary from zero to more than 50 % respectively according to packing density (Cheel, 2005) (Figure 2). From thin section observation, the packing of grains had, on average, a porosity between 36% and 42%, which reflects the packing density of the materials; this was determined by estimating the ratio of the pore spaces to the matrix observed in thin section.

Micromass

The resolution of the petrographic microscope is such that some elements, including silt and sized particles, cannot be individually resolved. The fine mineral component of the groundmass as it is observed in thin section studies of sediments is the micromass and generally cannot be individually resolved by its optical characteristics (Karale et al., 1974). For this study, the size distribution limit between the coarse and fine components was set at 2 µm. The micromass ranged from dark to light brown and was of a speckled nature. From the point counting analysis, the micromass was estimated to be around 10% of the total constituents. Presence of micromass strongly suggests an environment with energy low enough for the deposition of fines mainly silt and clay particles. This is consistent with an estuarine depositional environment described by Hein et al. (2000).

Bitumen

Bitumen has very complicated chemical and physical properties, being made up of several chemical elements. Its composition and behaviour was observed to vary between thin sections slides. This variation could be due to changes in grades of bitumen present in the sample. Bitumen occurred as inter-granular infillings and observed within large vugs. The colour of the coarse components of bitumen was mostly a very dark brown and was infilling a majority of the pore spaces. Bitumen was also observed within the fractures of the weathered quartz grains. Within the micromass, bitumen was observed as very dark brown specks (Figure 2).

Voids

The porosity of Upper McMurray Member from the estuarine-tidal depositional environment is an important determinant of the reservoir quality. Pores spaces were classified into three major groups based on their size according to Rouquerol et al. (1994) as the following: pore spaces measuring 2 µm and less in width are classed as micropores; mesopores have widths between 2 and 50 µm; and macropores have widths larger than 50 µm. Pore spaces were grouped into the above sub-groups and point counted. From the thin section analysis, 16% of the pores analysed were of the size range 2-50 µm across (mesopores) while the remaining pores had a diameter larger than 50 microns (macropores). Importantly, this showed that, based on size, there are two groups of pores identified. Voids were identified predominately as vugs. There was no observable pore size orientation, appearing to be randomly distributed, although future work is ongoing concerning the spacing and orientation of pores. Pore spaces have very important controls on permeability and porosity of oil and, using visual descriptors, porosity was determined to range from 36% to 42%.

Summary and Conclusions

In the field, the Upper McMurray Member showed characteristics that define a transitional medium to low energy environment from fluvio to marine depositional settings. This deposit is characterized by highly biotubated, cross-bedded ripple sands with occasional mud flats, and shale breaks that may constitute barriers to flow on a macroscopic scale. As observed from microscopic studies, the fabric and textural characteristics including the grain size distribution and values for sorting, kurtosis, shape, form, and flatness index all lie within a favourable range for excellent flow. This flow would be achieved through utilization of the pore spaces, which have high value for pore connectivity, resulting in a projected high permeability value.

Due to the physical state of bitumen at reservoir conditions, and its occurrence within pore space and the unconnected vugs, flow without enhancement is impossible. Under enhanced conditions, bitumen will flow, but one must consider the textural arrangement due to the occurrence of micromass and fines that include clay and silt within the pores, as observed in the c/f related distribution. These textural relationships present a real issue to dynamic reservoir conditions, as they tend to modify permeability by clogging pore spaces. For example, when coming in contact with water, some clays can swell and block out pore spaces cutting off sections of the reservoir.

Ideally, an aim of determining oil sands fabrics (both compositional and vectorial) would be to identify “sweet” spots along reservoir intervals. Once identified, completion design factors (such as sand/clay control or temperature/pressure profile control between injector and producer) can be employed more effectively in the positioning of wells to target specific intervals for optimum production.

Acknowledgements

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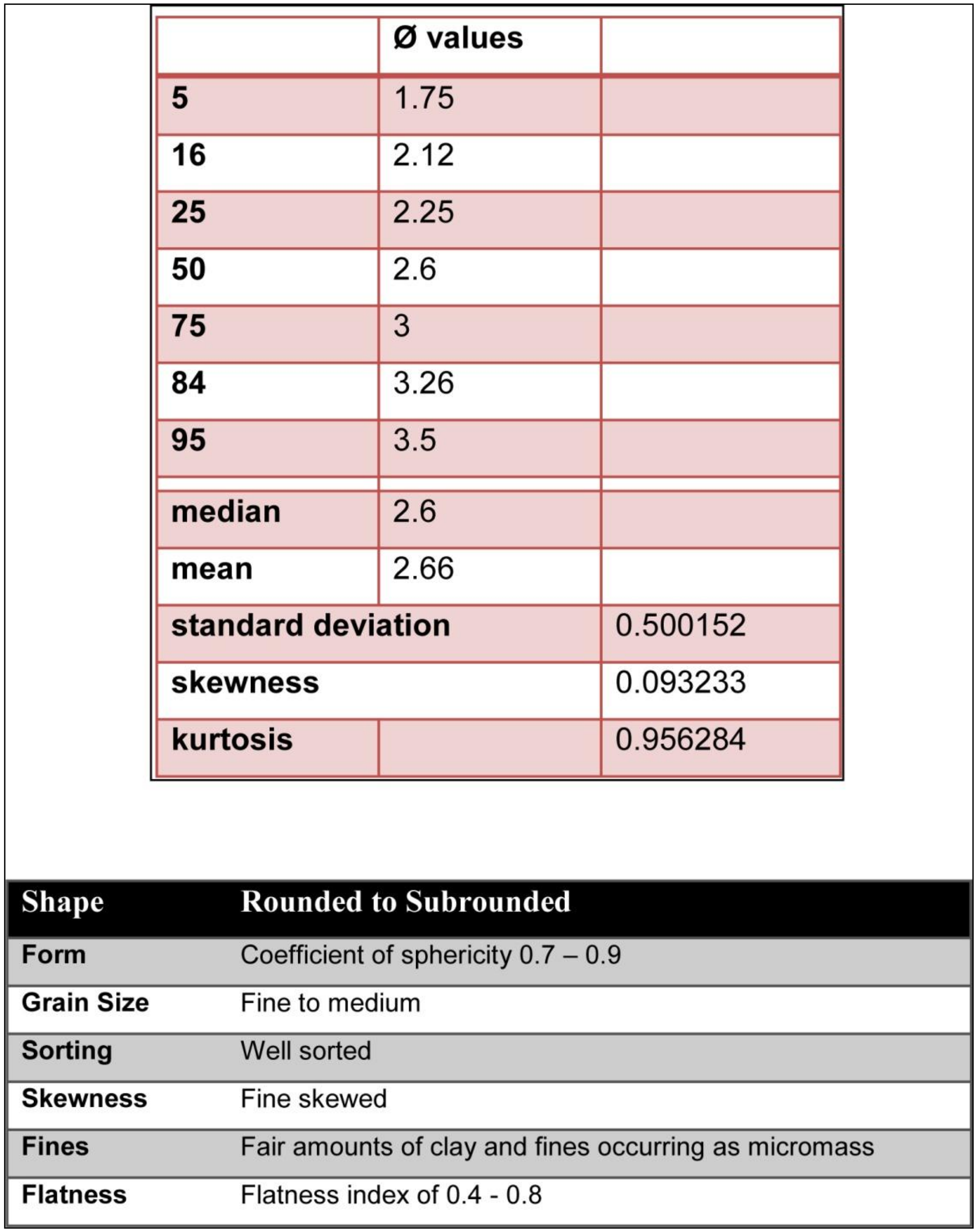
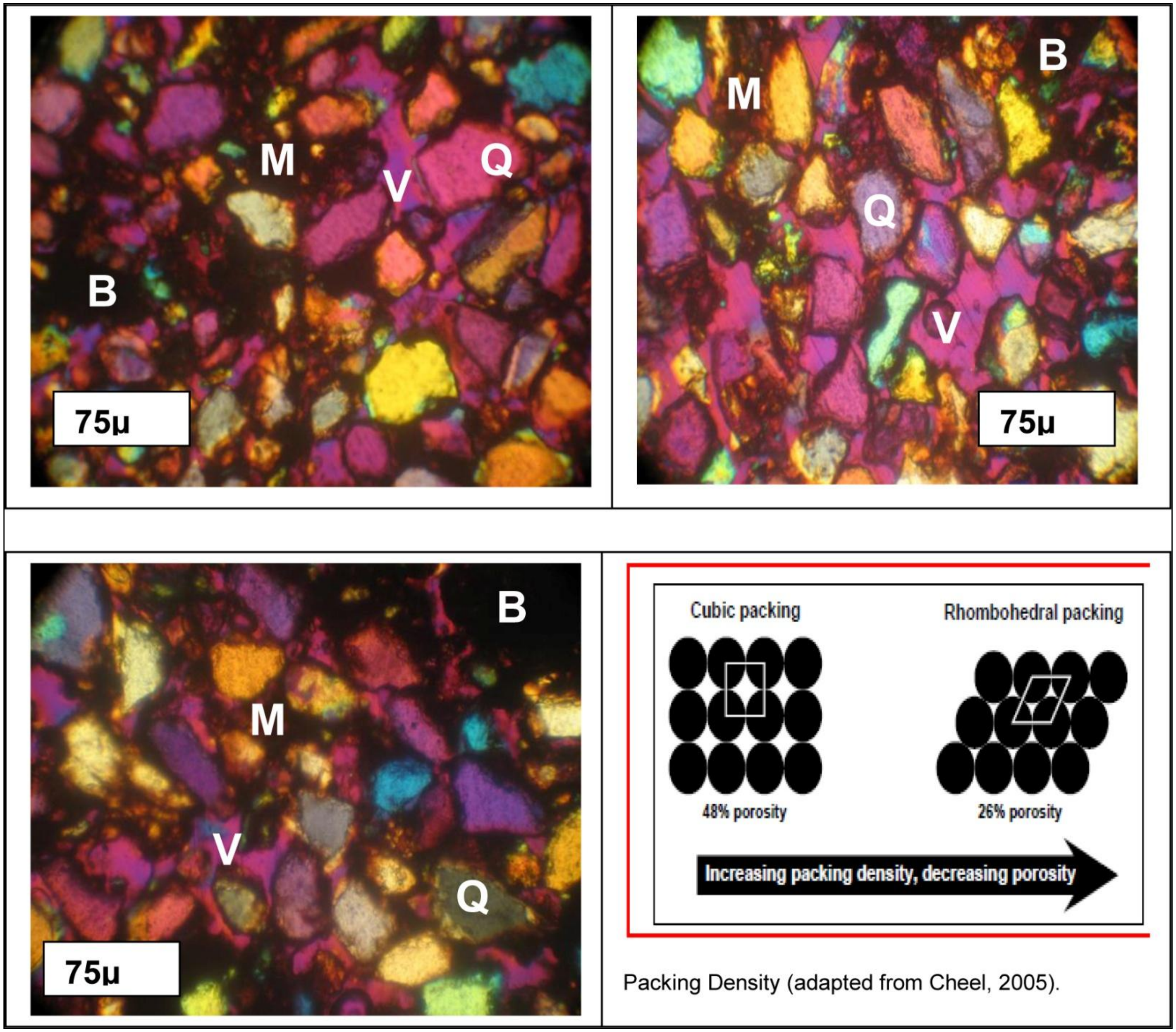


	Ø values	
5	1.75	
16	2.12	
25	2.25	
50	2.6	
75	3	
84	3.26	
95	3.5	
median	2.6	
mean	2.66	
standard deviation		0.500152
skewness		0.093233
kurtosis		0.956284

Shape	Rounded to Subrounded
Form	Coefficient of sphericity 0.7 – 0.9
Grain Size	Fine to medium
Sorting	Well sorted
Skewness	Fine skewed
Fines	Fair amounts of clay and fines occurring as micromass
Flatness	Flatness index of 0.4 - 0.8

Figure 1. The modified Griffiths properties measurement rule.



Packing Density (adapted from Cheel, 2005).

Figure 2. Coarse components were mostly quartz grains (Q) which was embedded in a micromass (M), although in some cases the micromass acted as a bridge between grains. Voids (V) were mostly vugs. Bitumen (B) was observed as coarse components and within the micromass.

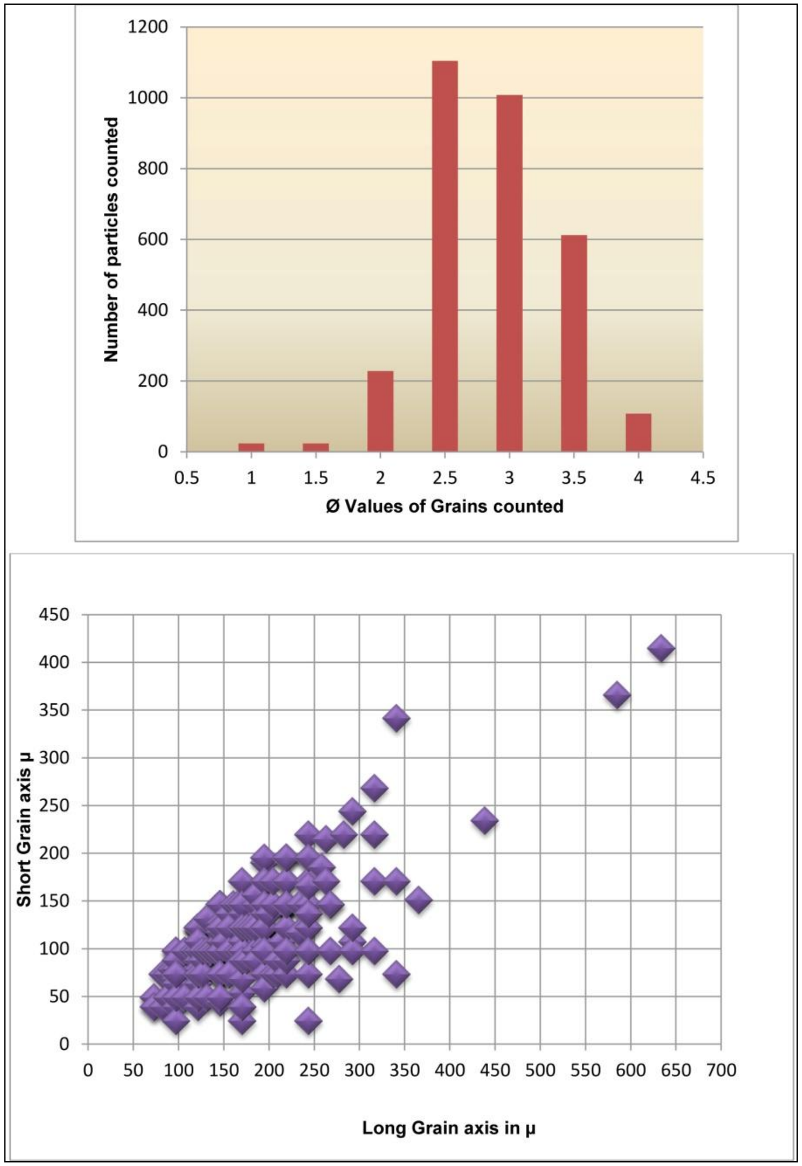
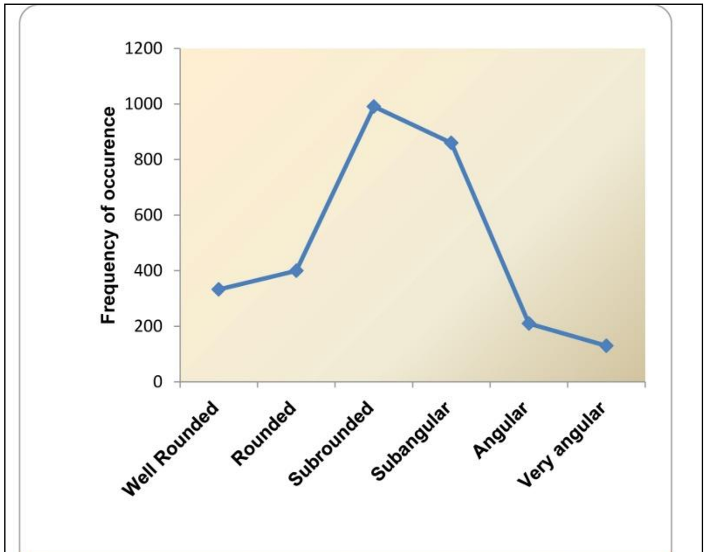
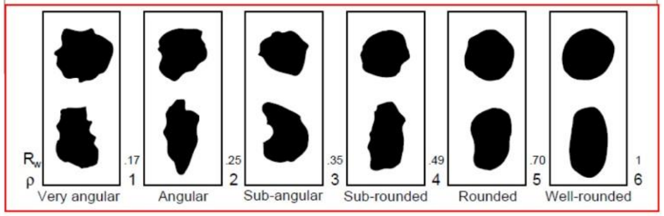


Figure 3. Frequency distribution chart showing Ø values of grains counted in regard to number of particles counted. Plot of grain dimensions with long grain axis and short grain in µ showing a primary predominate cluster although variation from that cluster indicating a flattening of grains. The red areas display a dominant grain and the dashed red-circled areas show a secondary grouping of grains evidencing that multi-groups exist based on variations in textural properties.





Visual Comparison Chart for Roundness Classes (Adapted from Petijohn et al., 1973)

Frequency Table

Nature of Grain	Frequency of occurrence
Well Rounded	**333**
Rounded	**400**
Subrounded	**991**
Subangular	**860**
Angular	**210**
Very angular	**130**

Figure 4. Quartz grain shapes were predominately subrounded to subangular.

$$P = \sum(m, s, sh, o, p) \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots .3.1$$

Where;

P = *is modified to be the population of the thin section*

m = *kinds and proportion of the elements composing the population*

s = *sizes of each element*

sh = *shape of each element*

o = *arrangement or orientation of each element.*

P = *sorting*

Table 1. Key parameter deduced from thin section analysis.