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

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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 Formation, 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 for a fabric analysis including composition and vectorial analysis using 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 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 appreciably approaching extreme importance to North America and on the world stage at large due to the declining reserves and increase in exploration difficulties associated with conventional oil. The Canadian oil sands represent the worlds' second largest hydrocarbon accumulation with 1.7 trillion barrels of heavy oil and an 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 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 grain size distribution along with porosity, permeability (Gordon et al., 2011; Coskun and Wardlaw, 1995). The application of PIA for the determining properties of oil sand and associated heterogeneities provides a window into reservoir quality at the micro-scale fabrics including fabric composition and vectorial data that provide insight to reservoir quality. The application of multivariate statistical techniques in delineating textural characteristics of oil sand fabrics is the ability to serve as an important tool in establishing grain and pore morphology, also 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.

The site selected for this study was the Hangingstone River area near Fort McMurray, Canada and is a well-documented estuarine tidal depositional environment from the Upper McMurray Formation (Hein et al., 2001). This formation lies at the base of the Lower Cretaceous Mannville Group on an angular unconformity from the Devonian 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 ridge and valley system trending north-south that were formed by fluvial processes but 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, indicating 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 characterized as the following: a conglomerate, 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 field work was carried out over two weeks in the summers of 2010 and 2011 in the study area located in the Hangingstone River area where 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, 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 according to Jongerius and Heintzberger (1975) and Fitzpatrick (1984) although 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 in order to provide insight into the nature of the oil sands reservoir material 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 microscopes field of view during which pre-determined parameters were measured. Point counting occurred on a 1mm scale and as the stage was advanced 1mm, components were point-counted and observations were recorded at each location. The point counting involved a total of 6000 total point counts. The representative elementary area (REA) was calculated for the samples according to VandenBygaart and Protz (1999) and 6000 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 1mm 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 to include determining the frequency distribution of oil sands individual components. Measurements recorded include: the determination of the size of the grain; including the maximum and minimum length, also the diagonal axis were logged in µm; and the optical area for coarse components and micromass, void, and area occupied by bitumen were recorded for each square micron.

The point count analysis of the thin section involved the logging of the components observed in thin section by adopting Griffiths (1961) in measurement of properties refer to Figure 1. The relative percentage distribution of components was then calculated. For each component that falls under the microscopic cross hair the major, minor axis and intermediate axis length were determined using the PIA and recorded to provide an estimate of the size(s) of the component. The shape (sh) of the component observed under the thin sections was determined from the value of the 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 that 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 on oil sand samples from an outcrop of Upper McMurray Formation, notably the estuarine depositional environment. The environment of deposition has powerful controls on the material deposited in the reservoir properties. The Upper McMurray Formation was deposited in a meandering deep estuarine and point bar environments that were controlled by rapid sea level rises (Hein et al., 2007).

The initial results of the compositional fabric study were presented by Bell et al. (2011). All thin sections were described according to Stoop (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; voids, mostly vugs and bitumen.

The textural study involved measuring parameters of the main components observed in the fabric study including determining the size and shape, and deducing the relative abundance of constituents by petrographic image analysis (PIA). Data collected from point counting were subjected to statistical evaluations with a view to determining the principal elements of the grains that can significantly influence reservoir properties including porosity and permeability. Data sets from the PIA, including grain distribution parameters, were evaluated and tabulated, refer to 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 2.6σ and the mean is 2.66σ which is 170 micron and 160 microns respectively and in agreement with a similar work by (Carrigy, 1966). 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 grains is 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 value of -1; the value of skewness derived from the study was 0.1, approximately, and thus 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 Petijohn 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 and a very important determinant of porosity depending on the degree of utilization 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 such as silt and sized particles cannot be individually resolved. The fine mineral component of the groundmass 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 an estimated to be around 10% of the total constituents. Presence of micromass strongly suggests a low energy environment with energy low enough for the deposition of fines mainly silt and clay particles which 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 behavior 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 color of the coarse components of bitumen was mostly a very dark brown and infilling a majority of the pore spaces. Bitumen was also observed within the fractures of the weathered quartz grains. Within the micro-mass, bitumen was observed as very dark brown specks (Figure 2).

Voids

The porosity of Upper McMurray Formation 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 widths are classed micropore, mesopores have widths between 2 and 50 µm, and macropores have widths larger than 50 µm. Pores spaces were grouped into the above sub-groups and point counted. From the thin section analysis, 16% of the pores analyzed were of the size range 2-50 µm across (Mesopores) while the remaining pores had a diameter larger than 50 microns (Macropores), importantly showing that there were two groups of pores identified based on size. All voids were identified as vugs. There was no observable pore size orientation and appeared to be randomly distributed, although future work is ongoing in regard to the spacing and orientation of pores. Pore spaces have very important controls on permeability and porosity of oil and using visual descriptors, porosity was determine to range from 36% to 42%.

Summary and Conclusion

In the field the Upper McMurray Formation showed characteristics that define a transitional environment (medium to low energy environments), from fluvial to marine depositional settings, characterized by a highly bioturbated 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 favorable range for excellent flow utilizing the pore spaces with an estimated high value of porosity and pore connectivity as expected is moderate, therefore a high permeability value are expected.

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, although the fabric and textural arrangement due to the occurrence of micromass fines including clay and silt within the pores observed in the c/f related distribution these relationship present a real issue to dynamic reservoir conditions as they tend to modify permeability by clogging pore spaces, for example some clays on coming in contact with water can swell and block out pore spaces cutting off sections of the reservoir.

Ideally, the aim of determining fabrics both compositional and vectorial would be to identify “sweet” spots along reservoir interval where 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.

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

Where;

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

m = kinds and proportion of the elements composing the population

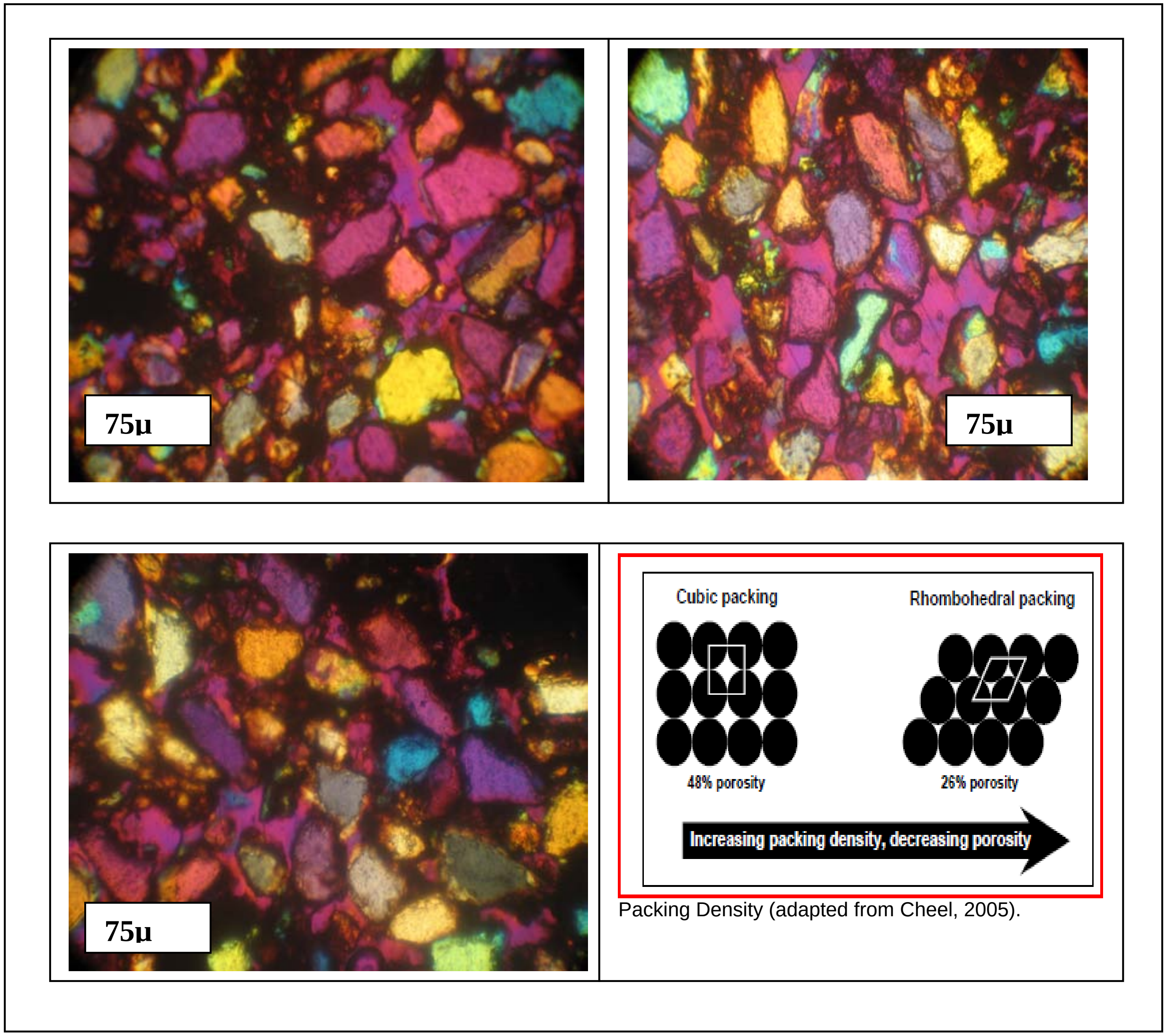
s = Sizes of each element

sh = shape of each element

o = arrangement or orientation of each element.

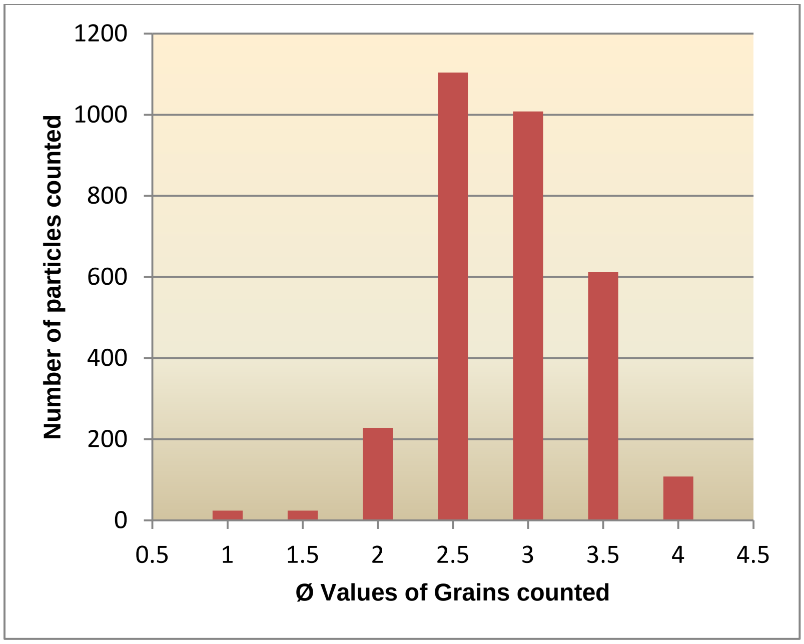
P = Sorting

Figure 1. The modified Griffiths properties measurement rule.



Packing Density (adapted from Cheel, 2005).

Figure 2. Coarse components were mostly quartz grains (**Q**) which were 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.



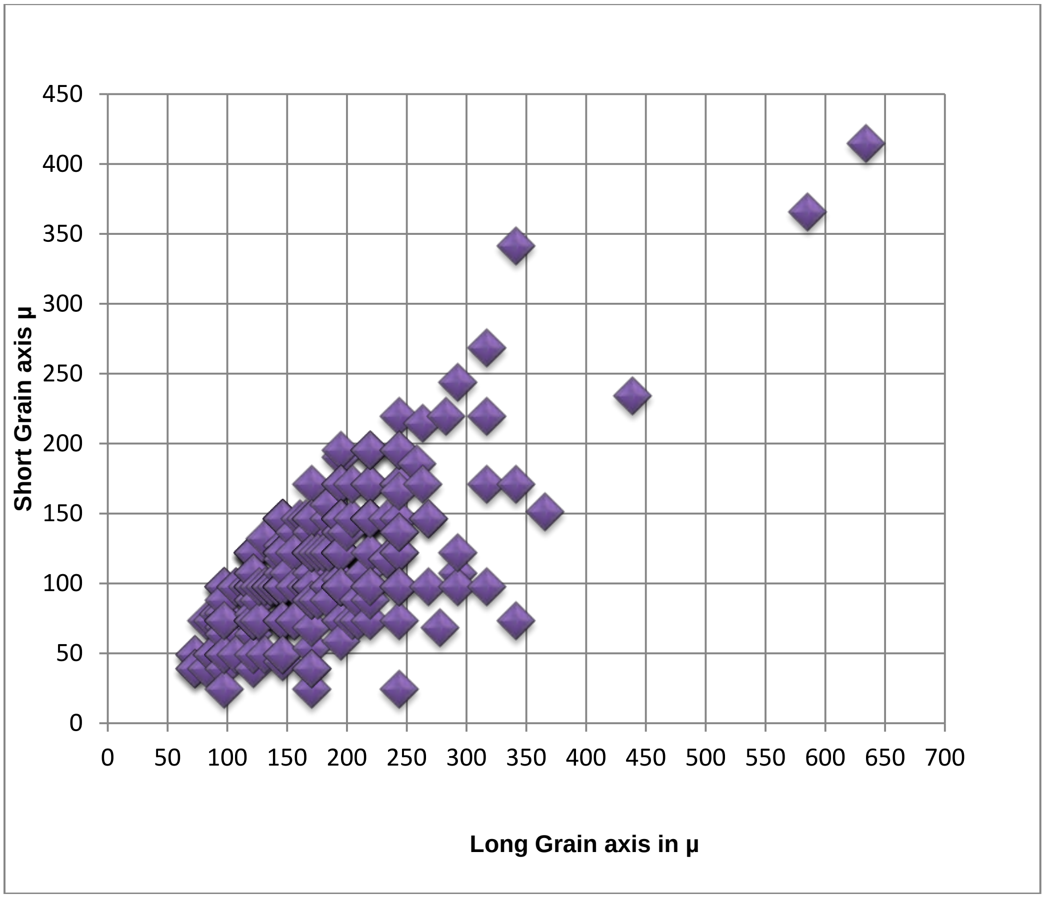
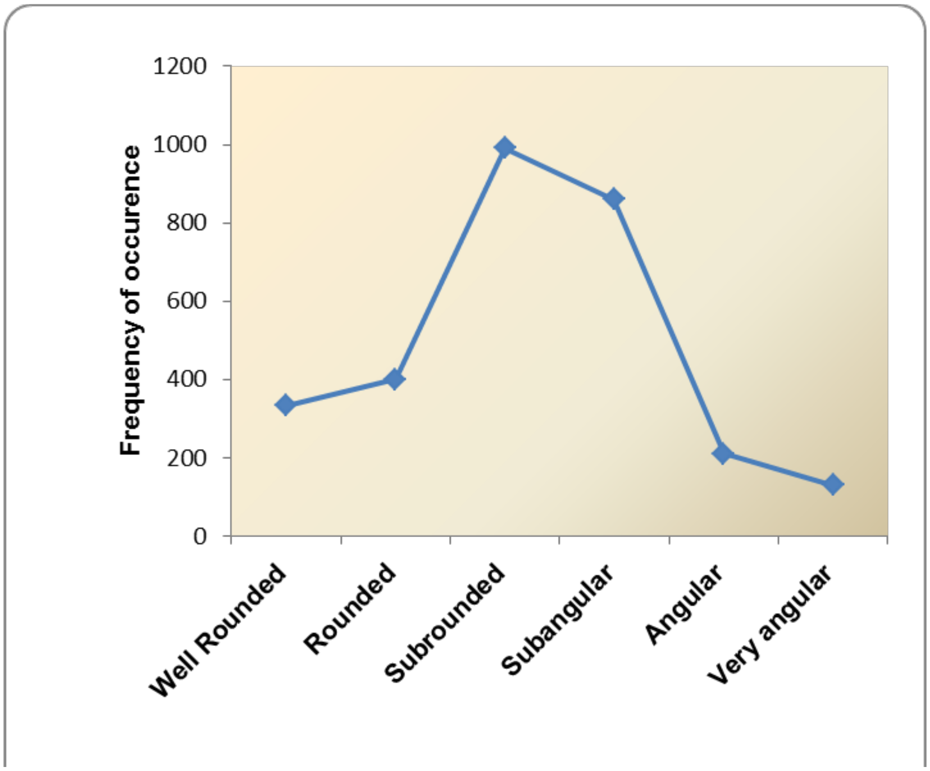
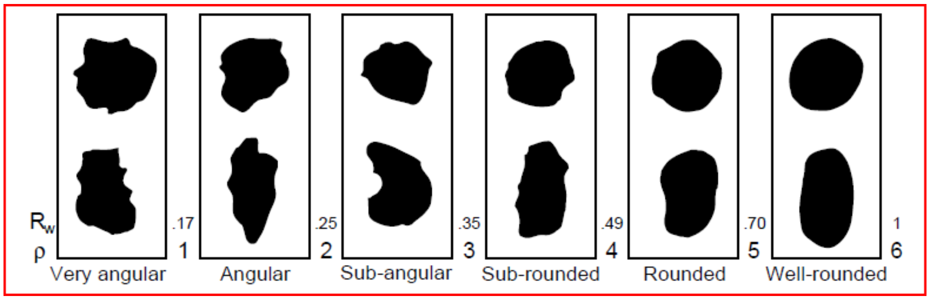


Figure 3. Frequency distribution chart showing Ø values of grains counted in regard to number of particles counted. Plot of grain dimensions with long grain axis and short grain in µ showing a primary predominate cluster although variation from that cluster indicating a flattening of grains. The red 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.





Powers' Visual Comparison Chat 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.

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 shpericity 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

Table 1. Key parameter deduced from thin section analysis.