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Variance in reservoir quality due to diagenesis: A study from tidal deposits, Nyalau Formation, Sarawak, East Malaysia

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Abstract: Prediction of reservoir quality is challenging due to complexities caused by pore geometry. Here diagenesis plays an important role in providing a better understanding of the controls on reservoir quality. This research focuses on determination of pore geometry and diagenetic alterations in the Nyalau Formation, Borneo. This has been achieved by a combination of traditional, macroscopic field sedimentology and microscopic thin-section study, along with grain size analysis and porosity-permeability determination on 26 samples taken from outcrops. Represented outcrops from the study area show sedimentary features such as herringbone lamination, cross-bedding, flaserbedding, wavybedding and bioturbation structures. The outcrop samples are mainly very fine to fine grained, with petrographic visible porosity ranging from 15% to 35%, indicating reservoir quality of the outcrop is good to very good. Permeability of the sandstone facies ranges from 50 to 1000 millidarcies (mD). Petrographic analysis shows the sorting to be very poor to fair depending on facies type, with common quartz overgrowths indicating diagenetic reduction of reservoir quality. Integrating the results of these analyses shows which factors affect the diagenesis of the tidal sandstones in the Nyalau Formation, which is considered as an analogue for a good quality hydrocarbon sandstone reservoir.

Keywords: Sedimentology, diagenesis, reservoir quality, petrography, porosity-permeability

INTRODUCTION

Background

Situated in the south of Balingian province, the Nyalau Formation is interpreted to have formed in an onshore depositional environment that developed during the late Oligocene to early Miocene. The Nyalau Formation mainly comprises sandstone.

The Sarawak Basin is classed geomorphologically as a foreland basin (Hutchison, 2005), and displays the common features associated with a foreland basin which formed in a zone of overloading (James, 1984). The study area is dominated by shallow marine and deltaic marine sediments (Mazlan & Rahman, 2007). During the early Miocene, a major tectonic event caused NW Borneo to be uplifted, resulting in erosion of some sediments (Balaguru & Lukie, 2012). This event led to a change in depositional environment to shallower water deltaic settings. The area can also be interpreted as open-coast tidal flats due to the presence of shallow marine and deltaic sediments. Common structures found in Nyalau Formation include tide-generated herring bone lamination and bioturbation structures, in addition to overlying mud-rich sediments (Siddiqui *et al*., 2016).

Study area

The base map (Figure 1) shows the study area along with the two outcrops locations, and is annotated with 15-meter topographical contours. Outcrop 1 coordinates are 3º4'8.13" N, 113º0'31.48" and outcrop 2 coordinates are 3º7'33.99" N, 113º2'21.05". Based on the map, the outcrops are easily accessible, as the locations are beside the main road, although they are surrounded by some vegetation. The elevation of outcrop 1 is 203m above Mean Sea Level (MSL) while outcrop 2 is 53 m above MSL.

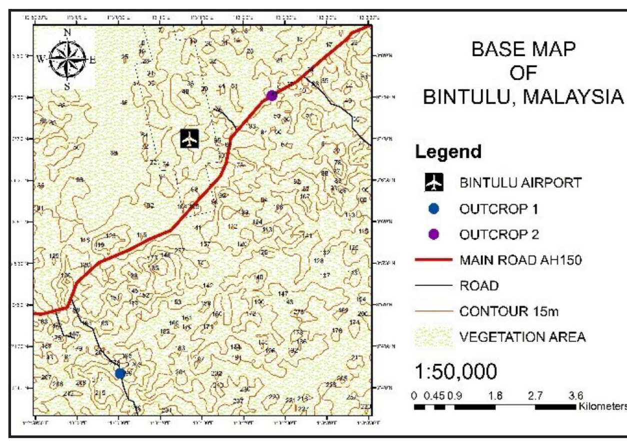


Figure 1: Base map of study area with outcrop locations.

LITERATURE REVIEW

Diagenesis is defined as physical, chemical and biological post-depositional processes and the reactions of the interstitial pore waters in the process of attaining textural and geochemical equilibrium with their environment (Curtis *et al*., 1977; Burley *et al*., 1985). Based on Worden & Burley (2003), any process involved in making sediments into sedimentary rock, from weathering to compaction during deep burial, is considered as diagenesis (Worden & Burley, 2003). There are three types of diagenesis: Eodiagenesis, Mesodiagenesis and Telodiagenesis. Eodiagenesis occur during early burial of sediments (Table 1). Early diagenesis develops at or near surface of the sediments where the chemistry of the interstitial waters is controlled mainly by the depositional environment (Berner, 1980; Chapelle, 1993). Mesodiagenesis occurs after sufficient burial has rendered the sediment and its pore fluids free from impact of the depositional environment (Worden & Burley, 2003),

Table 1: The stages and process of diagenesis, along with the resulting primary sedimentation alteration, reproduced from Worden & Burley (2003).

	Diagenesis Stage	Diagenesis Process	Result
Burial	Eogenesis	Bioturbation	Destruction of primary sedimentary structures; formation of mottled bedding and other traces.
		Cementation and replacement	Formation of pyrite (reducing environments) or iron oxide; (oxidizing environments); precipitation of quartz and feldspar overgrowths, carbonate cements, kaolinite, or chlorite.
Burial	Mesodiagenesis	Physical compaction	Tighter grain packing; porosity reduction and bed thinning.
		Chemical compaction	Partial dissolution of silicate grains; porosity reduction and bed thinning.
		Cementation	Precipitation or carbonate (calcite) and silica (quartz) cements with accompanying porosity reduction.
		Dissolution by pore fluids	Solution removal of carbonate cements and silicate framework grains, creation of new (secondary) porosity by preferential destruction of less stable minerals.
		Mineral replacement	Partial to complete replacement of some silicate grains and clay matrix by new minerals (e.g., replacement of feldspars by calcite).
		Clay mineral authigenesis	Alteration of one kind of clay mineral to another (e.g. Smectite to illite or chloride, kaolinite to illite).
Uplift	Telodiagenesis	Dissolution, replacement, oxidation	Solution or carbonate cements, alteration of feldspars to clay minerals, oxidation of iron carbonate minerals to iron oxides, oxidation of pyrite to gypsum, solution of less stable minerals (e,g. pyroxenes, amphiboles).

whereas telogenesis occurs after uplifting of strata back towards the surface.

Porosity changes due to diagenesis are the main objective of research regarding diagenesis and reservoir quality. Diagenetic effects on porosity can be described in terms of (1) origin, (2) amount, (3) subsurface distribution, (4) pore-size distribution, (5) pore shape, (6) surface area and (7) attendant permeability (Hayes, 1979). Originally, when transported by wind or water, the primary porosity of a clean sandstone should be around 35 to 40 percent (Chapelle, 1993). Diagenesis will alter the original pore network of the formation, with the fundamental mechanisms affecting the reservoir quality including compaction, cementation, dissolution and recrystallization. In order to verify the various diagenetic effects, detailed microscopic analysis was required for validating the interpretation.

STATEMENT OF THE PROBLEM

Sandstone of the Nyalau Formation is interpreted to have formed in a tidally influenced depositional environment, the reservoir quality of which has been affected by diagenesis. Although diagenetic features and their impact on reservoir quality has previously been described from the Nyalau Formation as part of broader studies (Amir Hassan *et al*., 2013), the impact of the varying diagenetic phases on facies in this formation had yet to be documented. Here we expand on this research and present a focused study on the diagenetic phases and impact on the sedimentary tidal sandstone features from this formation. Therefore, the main objective of this study is to provide a detailed explanation of diagenetic alteration in the Nyalau Formation, and in doing so further the investigation of the effects of diagenesis on reservoir quality.

OBJECTIVES AND SCOPE OF STUDY

The main objective of this project is to study the diagenesis in Nyalau Formation and identify the diagenetic alteration in tidal sandstone deposits. A prediction of the Nyalau Formation reservoir quality with respect to diagenesis will be included in the final results. As this study focuses more on diagenesis, a correlation between facies and diagenesis types is presented in the paper for a deeper understanding of diagenetic alteration in the Nyalau Formation. Thin section analysis was used to investigate and measure the pore spaces in the samples, while air permeability was measured using the TinyPerm2 device.

METHODOLOGY

There are two parts to the main experimenting this study: sedimentology determination and petrophysical analysis. 26 samples were taken from the two outcrops for laboratory analysis, which included sieve analysis (to determine grain size) and petrography analysis. Sedimentological determination was performed during fieldwork at the outcrop, and petrophysical analysis was run on the samples collected.

Sedimentary logging

The sedimentary log was drawn at the outcrop, with the structural geometry and the dimensions of the strata recorded at meter scale and tabulated to determine the facies distribution and distribution of lithologies.

Petrophysical analysis

All the outcrop samples taken during field work were submitted for petrographic analysis and interpretation. The petrographic laboratory work employed thin sections in order to identify texture, mineralogy and alteration due to diagenesis. The thin sections were prepared by mounting the rock samples onto glass slides, then grinding them down with silicon carbide to a thickness of 0.03 mm (30 micrometers). The thin sections were viewed under a polarizing microscope in order to identify the mineralogy of grains, matrix and cements, and to determine visible porosity. Point counting was used to quantify porosity and perform grain size analysis (independent of sieve analysis).

Grain size analysis

The samples underwent two types of grain size analysis: sieve analysis and thin section analysis. As diagenesis can affect the smallest of grains, an investigation of the finest grain sizes was needed to ensure the results of the research. In this way, the microscale grain size was obtained by thin section and the macroscale by sieve analysis. Both data sets were further analysed using GRADISTAT software. Steps for Sieve Analysis were as follows:

- Each sediment sample was dried for one day until the water content was removed.
- 100g of sediments were weighed and recorded.
- The sieves, ranging from 63µm to 2mm screen opening size, were cleaned using a brush to expel any sediment that had attached to the screen openings.
- Each sieve and bottom pan were weighed and recorded.
- All seven sieves were stacked on top of one another by placing the biggest size of screen opening on the top, with size of screen opening decreasing downward.
- The sediments were poured into the top sieve and the cap placed over it.
- The sieve stack was placed in the sieve shaker and shaken for 3 minutes. The shaking movement was then reversed.
- After removing the stack from the shaker, each sieve and the bottom pan with its retained sediment was weighed and recorded.
- The retained sediment was observed and recorded.
- Steps 2 to 9 are repeated for each sample.

Permeability

An air permeability tester was used for the quantitative and qualitative analysis of permeability of the outcrop (Figure 2). The device, TinyPerm2, was used to make in-situ permeability measurements. Flow rate and pressure were monitored as along with the results of the experiment. From the readings obtained by the TinyPerm2 machine, a series of calculations were used to convert from TinyPerm pressure readings to permeability. The formula for this conversion is provided below:

$T = (-0.8206) \times log_{10}K + 12.8737$

where *T = Tiny Perm 2 readings, K = Permeability*

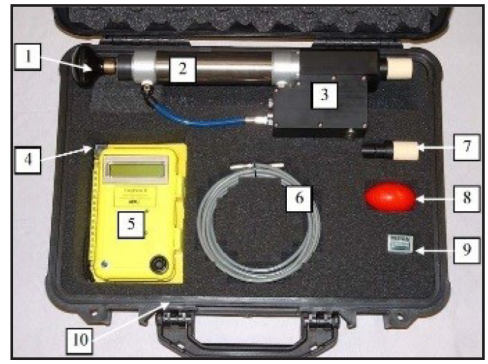


Figure 2: Tiny Perm 2 Instrument with its component. 1. Hanger and Plunger, 2. Vacuum Cylinder, 3. Pressure Transducer Enclosure, 4. Documentation and Calibration, 5. Microprocessor and Control Unit, 6. Electrical Cable, 7. Spare Nozzle, 8. Silly Putty, 9. Artist's Eraser, and 10. Bag.

RESULTS AND DISCUSSION

Sedimentary log

Figure 3 presents the sedimentary logs for Outcrop 1 and Outcrop 2 with stratigraphic thickness of 42 m and 34 m, respectively. Both outcrops contained similar facies characteristics. In outcrop 1, two meters of hummocky cross stratified sandstone and three meters of herringbone cross-stratified sandstone can be seen while outcrop 2 have hummocky cross stratification at bottom from 0-2.6m. The outcrop sections are divided into four to five units as shown in Figure 3, together with descriptions.

Petrography analysis

Figure 4 below shows summarization of the petrography results, along with a prediction of the diagenetic stages for each sample. Samples starting with SB are from outcrop 1 and samples starting with QB are from outcrop 2. The location of each sample is indicated on the sedimentary logs in Figure 3. Thin section photographs and brief descriptions are provided in the accompanying notes.

Grain size analysis

From the ternary diagram in Figure 5, it clearly can be seen that these outcrops have mainly 5% to 30% of sand with less than 20% gravel. This leads us to conclude that the sandstone of the Nyalau formation are gravelly sand. The average grain size for the whole outcrop samples ranges from fine to very coarse, which is consistent with tidal depositional environments, since they include both continental and marine sourced sediment. Sorting average for the samples is poor to very poor. As a measure of symmetry distribution, the skewness measurement for all the samples is coarse to very coarse skewed, indicating a dominance of coarse material. The ranges from mesokurtic to extremely leptokurtic, where the spreading is very flat to very peaked (Figure 6).

Porosity permeability graph

The graph for porosity versus permeability is shown in Figure 7 below. Porosity ranges from 15% to 35%, considered as good to high, and permeability from more than 50mD to almost 1000mD, which can be described as high permeability. The red colors indicate coarse grained samples, while black indicates fine grained samples. Tidal sandstone deposits can contain both fine and coarse sediment,

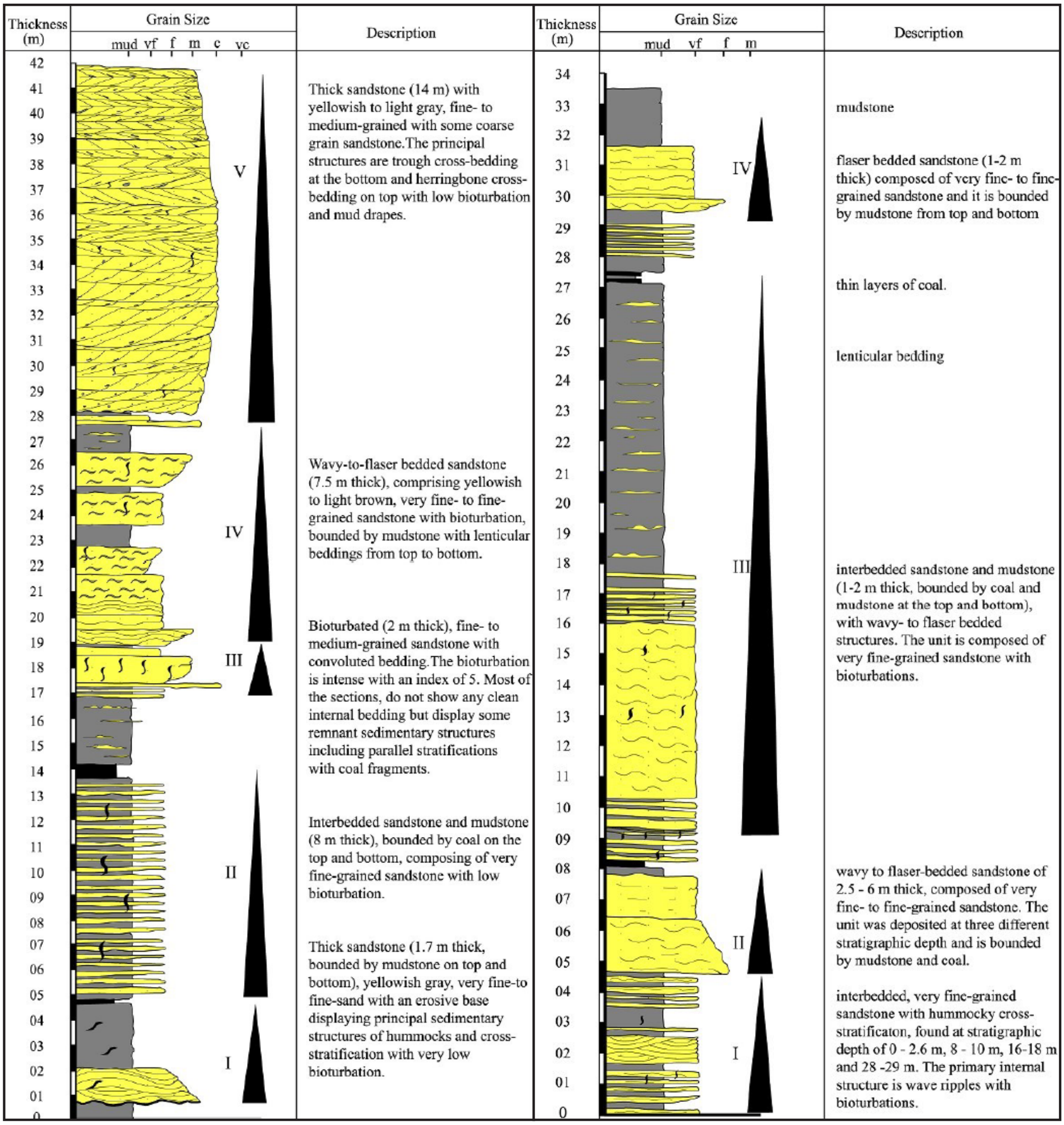


Figure 3: Stratigraphic logs of Outcrop 1 (left) and Outcrop 2 (right) showing facies description, sedimentary structures and grain sizes with units.

with the finer grains coming from the marine environment while coarse grains are from continental environments. Coarse grained samples show higher porosity than fine grained samples, although permeability is generally similar for the two grain sizes.

CONCLUSION

The facies logs for outcrop 1 and outcrop 2 show common tidal sedimentary structures in the sandstone. Facies types observed include hummocky cross bedding, herringbone cross bedding, trough cross bedding, planar cross bedding, along with wavy, lenticular, and flaser sedimentary structures and bioturbation. Grain size is consistent with tidal deposits containing continental and marine-sourced sediment.

Thin section analysis (Figure 4) summarizes the diagenetic alterations in the formation along with the percentage of porosity. These outcrops show all three stages of diagenesis: Eodiagenesis, Mesodiagenesis and Telodiagenesis. Telodiagenesis eventually affected outcrop due to tectonic uplifting in Borneo, causing the samples to be weathered, thus most of the upper samples show loosened pores and high porosity.

Based on facies characteristics, the following diagenetic alteration can be seen in these types of facies:

Bioturbation could be considered as very early diagenetic alteration, causing redistribution of grain size, and some loosened pores observed due to activity by micro-organisms.

Hummocky Cross Bedding showing poorly sorted grains in thin section but high porosity, however in outcrop 2 this type of facies has been highly compacted grains with resulting reduction of porosity.

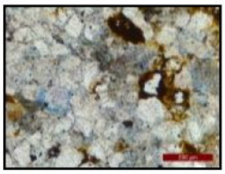
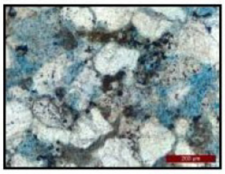
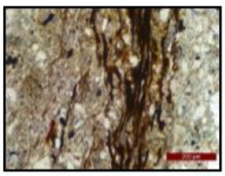
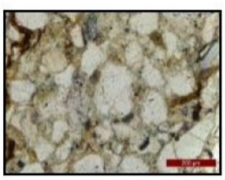
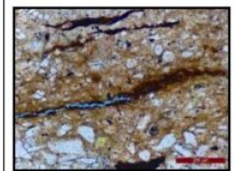
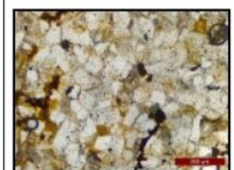
Sample	Photomicrograph	Facies and description	Diagenesis
QB9		Wavy High porosity (more than 20%), loose to compacted grains, poor sorting, matrix accumulations.	Eodiagenesis • Microquartz overgrowth
QB5		Flaser High porosity (more than 20%), less compacted, poor sorting. Quartz overgrowth can be observed.	Eodiagenesis • Microquartz overgrowth
QB3		Bioturbidite Good porosity (more than 15%), compacted grains in the middle but porous at the right side, fracture presents due to bioturbidation, some quartz overgrowth can be seen.	Mesodiagenesis • Fibrous illites • High compacted grains • Quartz overgrowth
QB2		Through Cross Bedding Very high compacted grains due to smaller sediments filling up the spaces, still fair porosity to almost 15% porosity existed in the samples.	Mesodiagenesis • High compacted grains • Quartz overgrowth
QB1		Planar Cross Bedding Very compacted but lesser than sample QB2 (facies characteristic effect), quartz overgrowth exists, however porosity quite high which is more than 20%.	Mesodiagenesis • High compacted grains • Albitized feldspar • Quartz overgrowth
SB8		Bioturbidite Good porosity (more than 15%), compacted grains started to loosen in the fracture presents due to bioturbidation, some quartz overgrowth can be seen.	Mesodiagenesis. • Fibrous illites • High compacted grains
SB4		Wavy Very high compacted grains due to smaller sediments filling up the spaces, still fair porosity to almost 15% porosity existed in the samples, high matrix accumulations.	Mesodiagenesis • High compacted grains
SB1		Hummocky Cross Bedding Very compacted but lesser than sample SB4 (facies characteristic effect), high quartz overgrowth exists, however porosity still higher than 15%	Mesodiagenesis • High compacted grains • Albitized feldspar • Quartz overgrowth
QB10		Flaser High porosity (more than 20%), loose to compacted grains, poor sorting, minor matrix accumulations.	Eodiagenesis • Microquartz overgrowth • Feldspar overgrowth

Figure 4: Summary of petrographic studies for each facies sample.

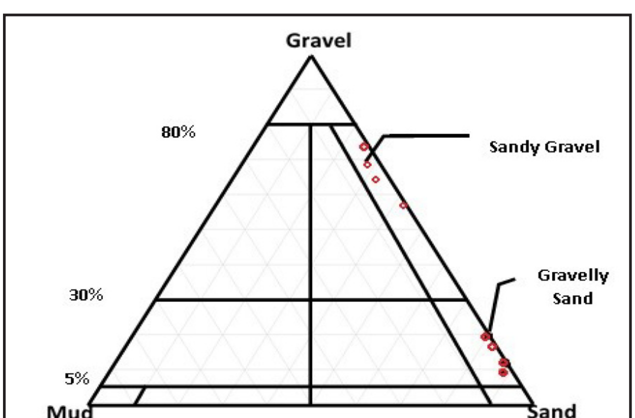


Figure 5: Ternary diagram for grain size distribution.

Herringbone cross bedding located at the top layer shows high porosity values with less compacted grains. The grains are poorly sorted with mixture of fine to coarse grains.

It can be concluded that based on the reservoir quality of these tidal sandstone deposits, the Nyalau formation is a good reservoir. Eodiagenesis has higher porosity compared to Mesodiagenesis and Telodiagenesis. As Nyalau formation is a good reservoir, thus most of the results for the porosity on all types of diagenesis is a good reservoir. The Porosity-Permeability graph shows high permeability and high porosity of sediments in both fine and coarse grains.

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SAMPLE STATISTICS

SIEVING ERROR: 0.0%

ANALYST & DATE: retest - 16th June 2017

SAMPLE TYPE: Unimodal, Poorly Sorted

TEXTURAL GROUP: Gravel Sand

SEDIMENT NAME: Very coarse gravel very fine sand

	μm	ϕ
MODE 1:	106.5	3.363
MODE 2:		
MODE 3:		
D_{10}:	20.14	1.360
MEDIAN or D_{50}:	104.3	3.261
D_{90}:	389.5	5.634
(D_{90} / D_{10}):	19.34	4.142
$(D_{90} - D_{10})$:	369.4	4.274
(D_{75} / D_{25}):	2.245	1.441
$(D_{75} - D_{25})$:	88.68	1.167

GRAIN SIZE DISTRIBUTION

GRAVEL:	0.0%	COARSE SAND:	13.1%
SAND:	83.1%	MEDIUM SAND:	9.3%
MUD:	16.9%	FINE SAND:	19.7%
		V FINE SAND:	44.9%
V COARSE GRAVEL:	0.0%	V COARSE SILT:	2.8%
COARSE GRAVEL:	0.0%	COARSE SILT:	2.8%
MEDIUM GRAVEL:	0.0%	MEDIUM SILT:	2.8%
FINE GRAVEL:	0.0%	FINE SILT:	2.8%
V FINE GRAVEL:	0.0%	V FINE SILT:	2.8%
V COARSE SAND:	1.3%	CLAY:	2.8%

	METHOD OF MOMENTS			FOLK & WARD METHOD		
	Arithmetic μm	Geometric μm	Logarithmic ϕ	Geometric μm	Logarithmic ϕ	Description
MEAN ($\bar{x}$):	176.7	88.21	3.503	112.9	3.147	Very Fine Sand
SORTING (σ):	196.8	3.479	1.799	2.802	1.487	Poorly Sorted
SKEWNESS (Sk):	3.589	1.733	-1.733	-0.007	0.007	Very Coarse Skewed
KURTOSIS (K):	11.403	3.186	3.186	2.144	2.144	Very Leptokurtic

Figure 6: Grain size distribution with Mean, median, mode and sorting in average samples.

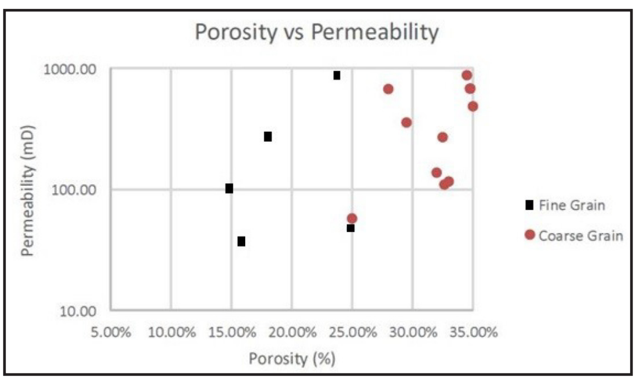

Figure 7: Porosity-permeability cross plot representing the fine grain and coarse grain distribution.

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