PARTICLE SIZE ANALYSIS OF SOME SIDEWALL CORES FROM KU-1 WELL, OFFSHORE BENIN BASIN, NIGERIA.

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ABSTRACT

Lithologic description and particle size analyses had been carried out on eight (8) sidewall cores obtained from the reservoir sands of KU-1 Well, offshore Benin Basin, Nigeria. High resolution core images of the samples under simulated natural and ultraviolet lightning conditions revealed that seven of the samples were saturated with hydrocarbon in varying degrees. The lithologic description showed that four (4) of the studied samples were medium to fine-grained, poorly to moderately sorted and moderately consolidated while the remaining four (4) were predominantly fine to very fine-grained, moderately to well sorted and moderately consolidated. The particle size analysis indicated that the sands were predominantly fine to very fine-grained (70 – 230 US mesh). Some cores contained significant medium-grained (40 – 60 US Mesh) fractions while a few had coarse-grained (20 – 30 US mesh) fractions. Silt/clay sized fractions were also substantial, averaging about 30 wt% of the studied core samples. The obtained average grain size for each core provided an invaluable data for gravel packing operation and screen size selection for oil production within the reservoir from which these cores were obtained.

Keywords: Sidewall Core, Particle Size, Reservoir Sands, Gravel Packing, Screen.

INTRODUCTION

Coring operations are an essential part of oil exploitation with the main objective of gathering information that leads to more efficient oil and gas production. Cores are cylinder-shaped rock sample obtained from an oil or gas well. Cores provide information in the areas of geology, petrophysical and reservoir engineering as well as those used for drilling and completion operations. Geological information obtained from cores include those related to lithology such as rock types, depositional environment, pore type and mineralogy/geochemistry. Cores also provide information for making geologic maps and give clues on fracture orientation. Valuable information for petrophysical and reservoir engineering from cores include those on permeability (permeability and porosity correlation and, relative permeability), capillary pressure data as well as data for refining log calculations (electrical properties, grain density, core gamma log, mineralogy and cation exchange capacity, enhanced oil recovery studies, reserve estimates – porosity and fluid saturations). For drilling and completion operations, core data are utilized for fluid/formation compatibility studies, grain size data for gravel pack design and rock mechanics.

Two main types of cores, commonly available for study, include conventional cores and sidewall cores. Sidewall cores are usually of relatively small size diameter and length and obtained from the sidewall of a well by a wireline tool or gun after the well has been drilled. Percussion sidewall cores are obtained by firing a hollow core recovery bullet into the sidewall and are typically 2.5 cm in diameter and 4.4 cm long. Rotary sidewall cores are obtained by mechanically drilling (sidewall boring) and are typically 2.3 cm in diameter and 5.1 cm long.

By far the most important physical property of particulate samples is particle size. Measurement of particle size distributions is routinely carried out across a wide range of industries and is often a critical parameter in the manufacture of many products. Grain size analysis, also known as particle-size analysis or granulometric analysis is perhaps the most basic sedimentological technique to characterize and interpret sediments and sedimentary rocks. Grain size analyses are carried out in sediments/soils for various purposes. It is important to determine the percentage of different grain sizes contained within a sediment or soil. The distribution of different grain sizes affects the engineering properties of the soil. Grain size analysis provides the grain size distribution, and it is required in classifying the soil. Scientists often classify soil particles into different categories including sand, silt, and clay, and this is important in defining a sample's texture. Each particle has various characteristics; clay, for example, increases soil stability and water retention, while sand offers better drainage and aeration.

Grain size analysis on sedimentary rocks is performed in the oil industry for several purposes including provenance and paleoenvironmental studies, porosity and permeability determination among others. The particle size of reservoir rocks is routinely measured for a number of reasons, including sand control selection. In many wells, especially shallow ones, hydrocarbon production causes sand production. Unconsolidated sandstones with permeability over 0.5 Darcies are most susceptible to sand production, which may start during first flow, or later when reservoir pressure has fallen or, when water breaks through. Sand production strikes with varying degrees of severity, not all of which requires action. The rate of sand production may decline with time at constant production conditions and is frequently associated with clean-up after stimulation. Sand production may be tolerated depending upon operational constraints like resistance to erosion, separator capacity, ease of sand disposal and the capability of any artificial lift equipment to remove sand-laden fluid from the well. The production of formation sand with hydrocarbon from sandstone reservoirs is dangerous and with serious cost implications. Production of sandy oil may result in loss of production while the accumulated sand may shut off the production entirely. There could be erosion damage to downhole tubulars and equipment. Production casing may collapse or buckle while the sand disposal problems may be extremely costly (Coberly and Wagner, 1938; Suman *et al.*, 1985; Sparlin and Hagen, 1991).

Sand screen selection relies on accurate particle size information for the sands that need to be controlled. Particle/grain size analysis helps in describing the population of formation sand grain size, as well as characterize the formation sand and the gravel to be used to control sand production in gravel packing and production screen selection. This study was carried out to examine the grain size distribution on sidewall cores obtained from the multiple reservoir sands of the KU-1 Well for the purpose of gravel packing and screen selection thereby reducing sand production to the barest minimum from the wellbore. KU-1 Well is located offshore Benin Basin, Nigeria.

Geology and Stratigraphy of Dahomey Basin

The Dahomey Basin, also known as Benin Basin was believed to have been initiated during the Mesozoic in response to the separation of the African – South American land masses and the subsequent opening of the Atlantic Ocean. The Basin covers the area from the Okitipupa Ridge in south western Nigeria through southern Benin Republic and southern Togo to south eastern Ghana in the West (Whiteman, 1982). Deposition was initiated in fault-controlled depressions on the crystalline Basement Complex. The depressions were a result of rift-generated basement subsidence during the Early Cretaceous (Neocomian). The subsidence gave rise to the deposition of a very thick sequence of continental grits and pebbly sands over the entire basin (Lehner and Ruiter, 1977). Further discussion on the tectonic framework of the basin was made by various authors including Billman (1976), Omatsola and Adegoke (1981) and Adediran and Adegoke (1987). The stratigraphy of the eastern margin of the Cretaceous to Tertiary sedimentary basin which unconformably overlies the basement complex includes the following: the Abeokuta Group, Imo Group, Ilaro Formation and the Coastal Plain Sands (Benin Formation). Jones and Hockey (1964) assigned the Abeokuta Formation to the mainly arenaceous strata with mudstone, silt, clay and shale interbeds that outcrop onshore in the Nigerian sector of the basin. Omatsola and Adegoke (1981) assigned the Cretaceous sediments to the Abeokuta Group and subdivided it into three formal formations: Ise Formation (oldest), Afowo Formation and Araromi Formation (youngest) based on the lithologic homogeneity and similarity in origin. The Ise and Afowo Formations were dated Neocomian (Valanginian) and Albian-Turonian respectively by these workers. The continental Ise

Formation consists of conglomerate at the base, gritty to medium grained loose sand capped by kaolinite clay (Omatsola and Adegoke, 1981). The Afowo Formation which indicates the commencement of deposition in a transitional environment is composed of interbedded fine to medium grained sands, shale and clays. The Araromi Formation is composed of clastic fine grained and thin interbeds of limestones, clay and lignite beds (Omatsola and Adegoke, 1981).

The Tertiary Imo Group which consists of two lithostratigraphic units (Ewekoro and Akinbo Formation) directly overlies the Abeokuta Group. The predominantly shaly Imo Formation lies unconformably on the Ewekoro Formation. The formation consists of fine-textured dark micromicaceous shale, locally silty with glauconitic marl and conglomerate at the base. The greenish-grey variety of the shale, encountered in the subsurface of most inland areas of Western Nigeria and which in the Ewekoro quarry disconformably overlies the Ewekoro Formation, was named Akinbo Formation by Ogbe (1972). The formation has been dated Lower-Middle Eocene. The Oshosun Formation overlies the Akinbo Formation across a gradational boundary and is composed of green to greenish grey clays and glauconitic shales interbedded with loose sand. The formation has been assigned a Late Paleocene to Early Eocene age (Bankole *et al.* 2005). The formation is conformably overlain by the Ilaro Formation which is characterized by coarse to fine-grained sands, clays and shales with occasional thin bands of phosphate beds. This was overlain by the Coastal Plain Sands (Benin Sand Formation). The formation consists of very poorly, clayey, pebbly sands, sandy clay and rare thin lignite (Reyment, 1965). The Benin Formation was dated Upper Miocene to Recent.

MATERIALS AND METHODS

Eight labelled sidewall core samples {1678.50 m, 1688.22 m, 1835.40 m, 1842.80 m, 1851.00 m, 1857.20 m, 1932.04 m and 1939.21 m (measured depth)} from three stacked reservoir intervals from KU-1 Well, offshore Dahomey Basin were employed for this study. The coordinates of the well were not made available for proprietary reasons. Figure 1 shows the approximate location of the studied well, offshore Benin Basin

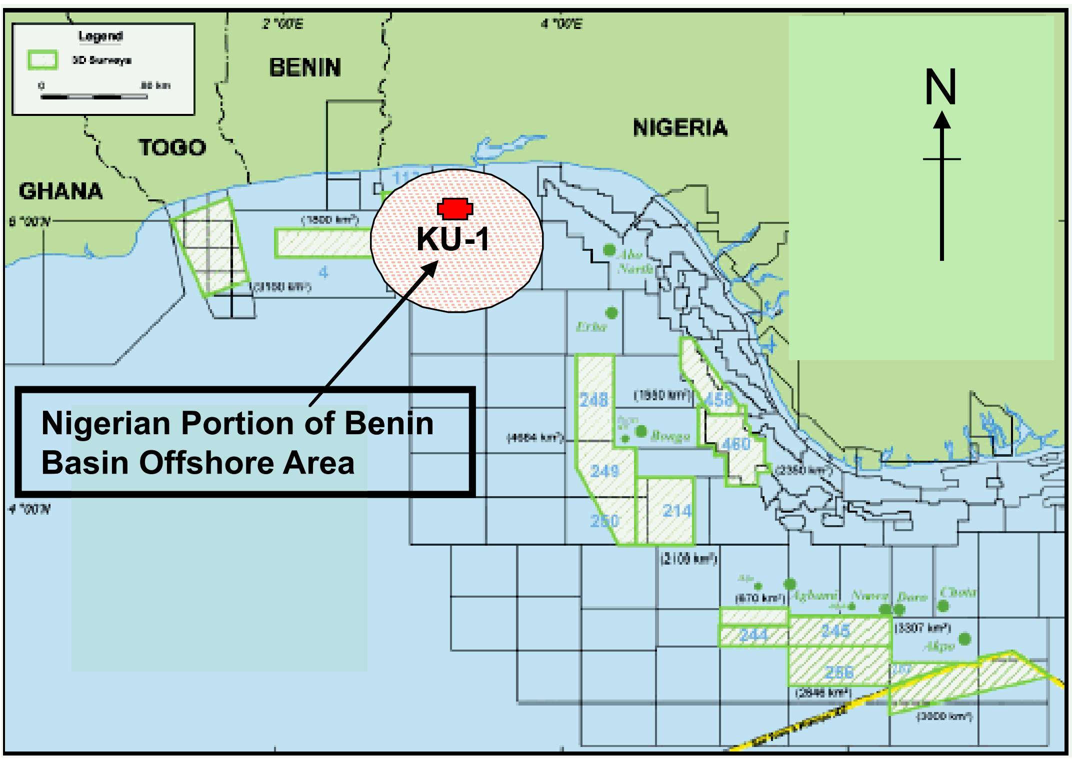


Figure 1: Approximate Location of the Offshore Benin Basin (Nigerian portion) where KU-1 Well was Drilled.

High resolution core images of the fresh sidewall cores were taken under simulated natural and ultra-violet lighting conditions prior to cleaning. A portion of the core was cleaned of drilling mud and a lithologic description detailing the lithology, colour, grain size, degree of sorting and consolidation were made for each core sample. The accessory index minerals present were also recorded.

For the granulometric analysis, a good mix of each sample was taken and connected to a vacuum pump. The sample was then washed of hydrocarbon using toluene. This process was repeated until the sample was clean of hydrocarbon with the indication of colorless residual toluene in the funnel. This was followed by methanol treatment to leach out the salts while hydrochloric acid was also used to liberate calcium carbonate from the sample. The sample was then air-dried for about eight hours and later oven-dried at about 115°C. The dried sample was then transferred into the desiccators for cooling. Cooled samples were individually weighed using a calibrated weighing balance and the weight recorded in the sieve analysis worksheet. Varied screen sizes were selected based on the perceived grain sizes from lithologic description. Selected screens were weighed cumulatively and the weight recorded. They were then sorted according to particle size using a sonic device, and separated into twenty-three (23) fractions (at 0.25 incremental phi values) using screen sizes most appropriate for the analysis of the sample. After sieving, each screen plus sample was weighed and the resultant data evaluated. The percentage passing through each screen size was calculated gravimetrically on the basis of the total sample weight. Statistical calculations of various particle size parameters were made using the following equations:

Median Grain Size, $(Md_\phi) = \phi_{50}$ *(1)*

Mean Grain Size, $(Me_\phi) = (\phi_{16} + \phi_{50} + \phi_{84})/3$ - *(2)*

Where:

ϕ_{50} = the fiftieth percentile

ϕ_{16} = the sixteenth percentile

ϕ_{84} = the eighty-fourth percentile

The mean grain size conversion to millimeters:

Mean Grain Size, $(N\ mm) = 2^{-\phi}$ *(3)*

i.e., $-\phi \log 2 = \log N$ *(4)*

Therefore,

$-\phi = (\log N) / (\log 2)$ *(5)*

Where:

N = the mean grain size diameter, (mm)

Skewness, $(Sk\phi) = (Me_\phi - Md_\phi)/(\delta_\phi)$ - *(6)*

Inman's Sorting Coeff., $S_\phi = (\phi_{84} - \phi_{10})/4 + (\phi_{95} - \phi_5)/6.6$ - *(7)*

Trask's Sorting Coeff., $S_o = (M_{25}/M_{75})^{0.5}$ - *(8)*

Kurtosis, $K_\phi = (\phi_{95} - \phi_5)/2.44(\phi_{75} - \phi_{25})$ - *(9)*

Where:

ϕ_5 = fifth percentile

ϕ_{10} = tenth percentile

ϕ_{25} = twenty-fifth percentile

ϕ_{75} = seventy-fifth percentile

ϕ_{95} = ninety-fifth percentile

M_{25} = the mean grain size diameter in millimeter at the intersection of the 25 percent line and the cumulative frequency curve.

M_{75} = the mean grain size diameter in millimeter at the intersection of the 75 percent line and the cumulative frequency curve.

M_{50} = the median grain size diameter in millimeter at the intersection of the 50 percent line and the cumulative frequency curve.

δ = standard deviation

The degree of sorting is interpreted based on Inman's (1952) Sorting Coefficient (S_{ϕ}) as shown below:

0.35 ϕ	very well sorted
0.35 – 0.50 ϕ	well sorted
0.50 – 0.71 ϕ	moderately well sorted
0.71 – 1.00 ϕ	moderately sorted
1.00 – 2.00 ϕ	poorly sorted
2.00 – 4.00 ϕ	very poorly sorted
> 0.4.00 ϕ	Extremely poorly sorted

RESULTS

Direct Capture Digital Sidewall Imaging

The photographs from the high resolution core imaging of the fresh core samples under the natural and ultra violent lightning conditions are as shown in Figures 2 – 9.

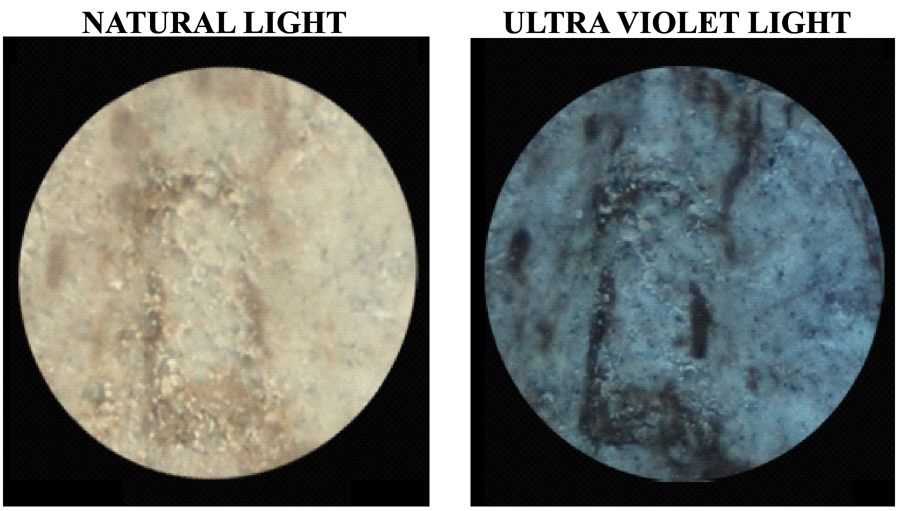


Figure 2: Direct Capture Image of Sidewall Core No. 1 (1678.50 m) under Natural and Ultra Violet Light Illumination

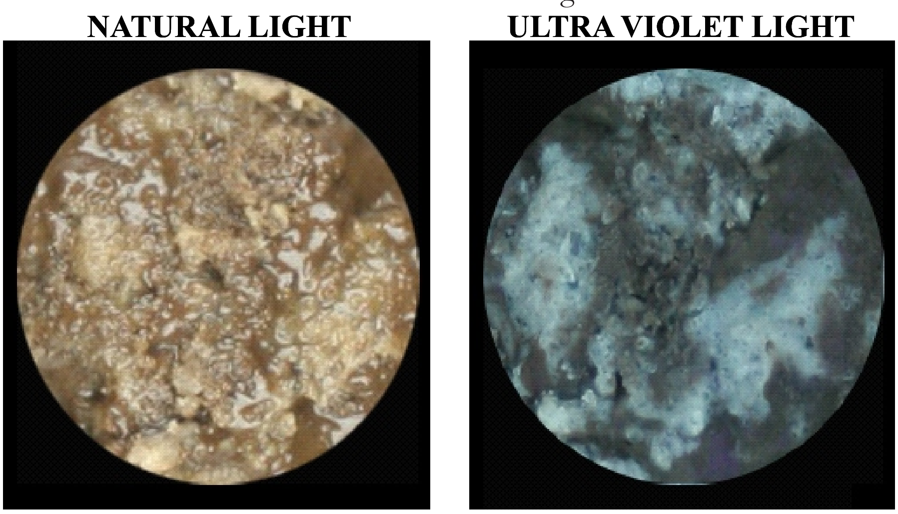


Figure 3: Direct Capture Image of Sidewall Core No. 2 (1688.22 m) under Natural and Ultra Violet Light Illumination.

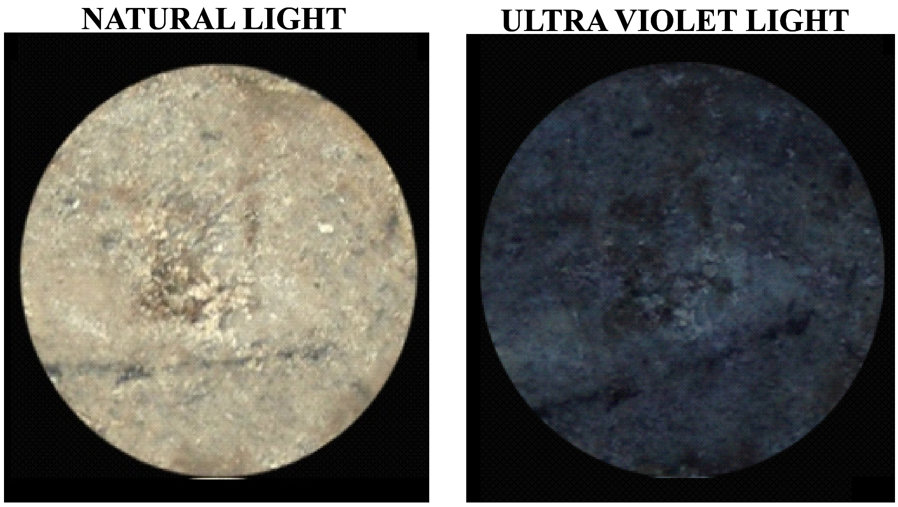


Figure 4: Direct Capture Image of Sidewall Core No. 3 (1835.40 m) under Natural and Ultra Violet Light Illumination.

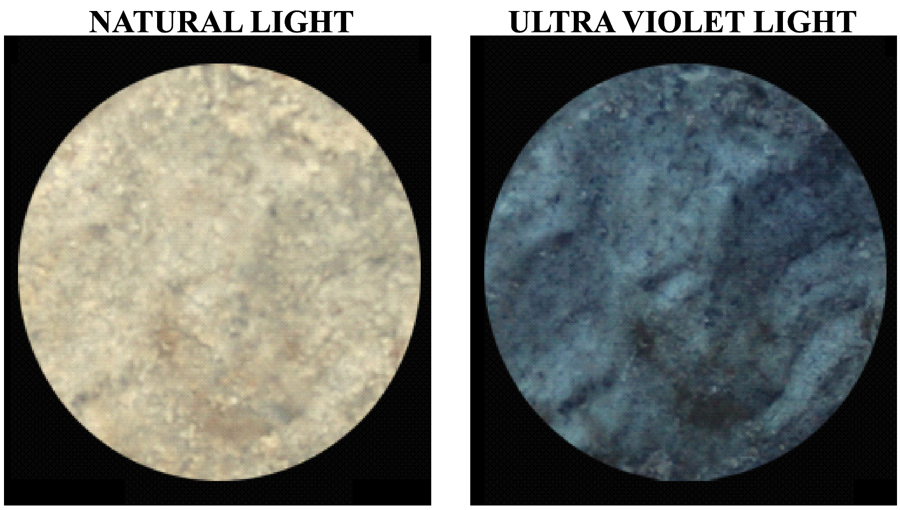


Figure 5: Direct Capture Image of Sidewall Core No. 4 (1842.88 m) under Natural and Ultra Violet Light Illumination.

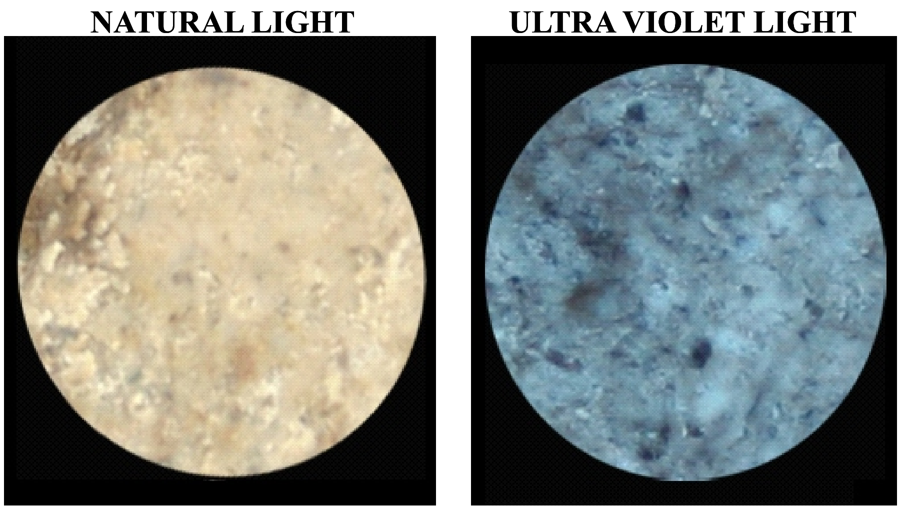


Figure 6: Direct Capture Image of Sidewall Core No. 5 (1851.00 m) under Natural and Ultra Violet Light Illumination.

NATURAL LIGHT **ULTRA VIOLET LIGHT**

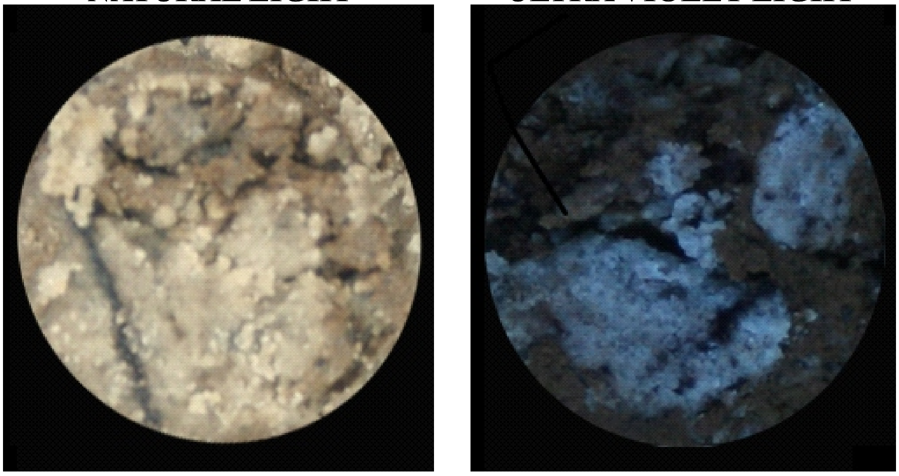


Figure 7: Direct capture image of Sidewall Core No. 6 (1857.20 m) under Natural and Ultra Violet Light Illumination.

NATURAL LIGHT **ULTRA VIOLET LIGHT**

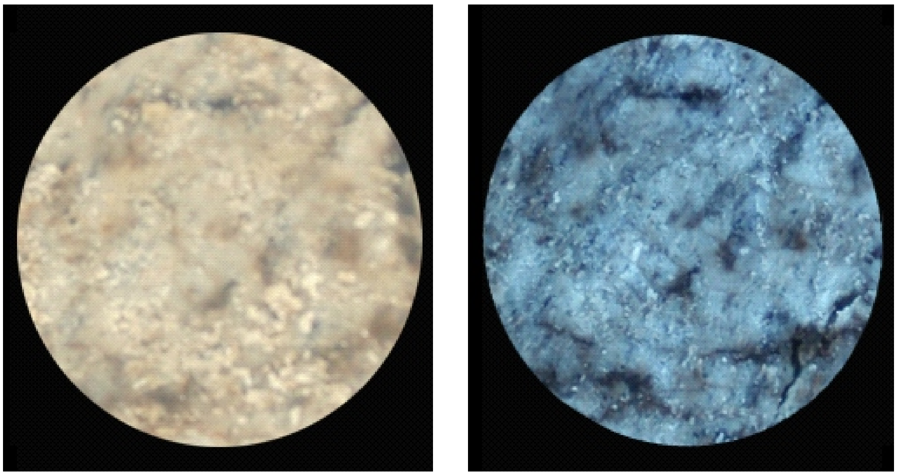


Figure 8: Direct Capture Image of Sidewall Core No. 7 (1932.04 m) under Natural and Ultra Violet Light Illumination.

NATURAL LIGHT **ULTRA VIOLET LIGHT**

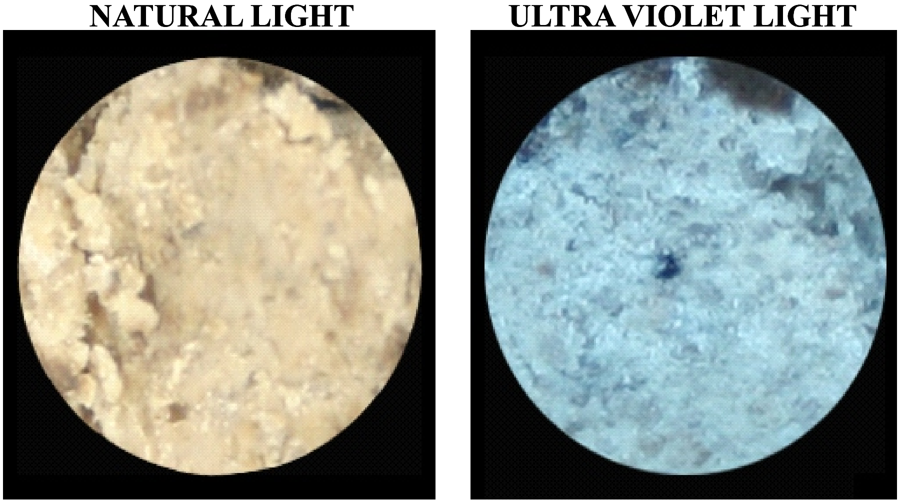


Figure 9: Direct Capture Image of Sidewall Core No. 8 (1939.21 m) under Natural and Ultra Violet Light Illumination.

Lithologic Description

The result of the detailed lithologic description carried out on the eight sidewall cores with the aid of a reflected light stetreo-binocular microscope is as shown below:

S/N	Core Depth (metres)	Description
1.	1678.50	Sandstone; light brown, medium to fine-grained, poorly sorted, moderately consolidated with accessory mica flakes, fluoresce.
2.	1688.22	Sandstone; light brown, medium to fine-grained, poorly sorted, moderately consolidated, fluoresce
3.	1835.40	Sandstone; light brown, fine-grained, moderately sorted, moderately consolidated.
4.	1842.80	Sandstone; light grey, medium-grained, moderately sorted, moderately consolidated, fluoresce.
5.	1851.00	Sandstone; light grey, very fine-grained, well sorted, moderately consolidated, fluoresce.
6.	1857.20	Sandstone; light grey, very fine-grained, well sorted, moderately consolidated, fluoresce
7.	1932.04	Sandstone; light grey, fine-grained, moderately sorted, moderately consolidated, fluoresce.
8.	1939.21	Sandstone; light brown, fine-grained, moderately sorted, moderately consolidated, fluoresce.

The description indicated that the reservoir sands of the KU-1 well are predominantly light brown to light grey in color, fine grained, moderately well sorted, moderately consolidated and fluoresce.

Particle Size Analysis

The results from the particle size and granulometry analysis are graphically depicted in Figures 10 to 17.

Core Sample No. 1 (1678.50 meters)

This sample cuts across the coarse sand to silt/clay size fractions. The sample is dominated by fine sand to very fine sand-sized fractions (70 – 230 US mesh) and constituting 41.9 wt% of the analyzed sample. The medium sand-sized fraction (40 - 60 US mesh) constitutes 14.6 wt% while the coarse sand-sized fraction (20 - 35 US mesh) constitutes 10.1 wt%. The remaining 33.4 wt% ranges from the coarse silt to clay size (270 – Pan US mesh). The grain size proportion in the sample is made up of coarse sand - 10.1%, medium sand - 14.6%, fine sand - 21.8%, very fine sand - 20.1%, coarse silt - 8.2%, silt - 25.2% (Figs. 10A and 10B).

Core Sample No. 2 (1688.22 meters)

This sample ranges from coarse sand to silt/clay size fractions. The size grade averages from coarse sand, medium sand, fine sand and very fine sand (20-230 US mesh) in approximately equal proportions resulting in a total of 67.3 wt%. The silt/clay fraction (270 – Pan US mesh) constitutes 32.6 wt%. The grain size proportion in the sample is made up of coarse sand - 15.3%, medium sand - 16.9%, fine sand - 17.4%, very fine sand - 17.7%, coarse silt - 8.9%, silt - 23.7% (Figs. 11A and 11B).

Core Sample No. 3 (1835.40 meters)

This sample ranges from coarse sand to silt/clay size fractions. The medium sand to very fine sand fractions (40 – 230 US mesh) constitute 59.4 wt% of the total weight analysed for the sample. The coarse sand fraction (20 – 35 US mesh) constitutes 13.5 wt% while the silt/clay fractions (270 – Pan US mesh) constitute the remaining 27.1 wt%. The grain size proportion in the sample is made up of coarse sand - 13.5%, medium sand - 18.5%, fine sand - 21.0%, very fine sand - 19.9%, coarse silt-8.0%, silt-19.1% (Figs. 12A and 12B).

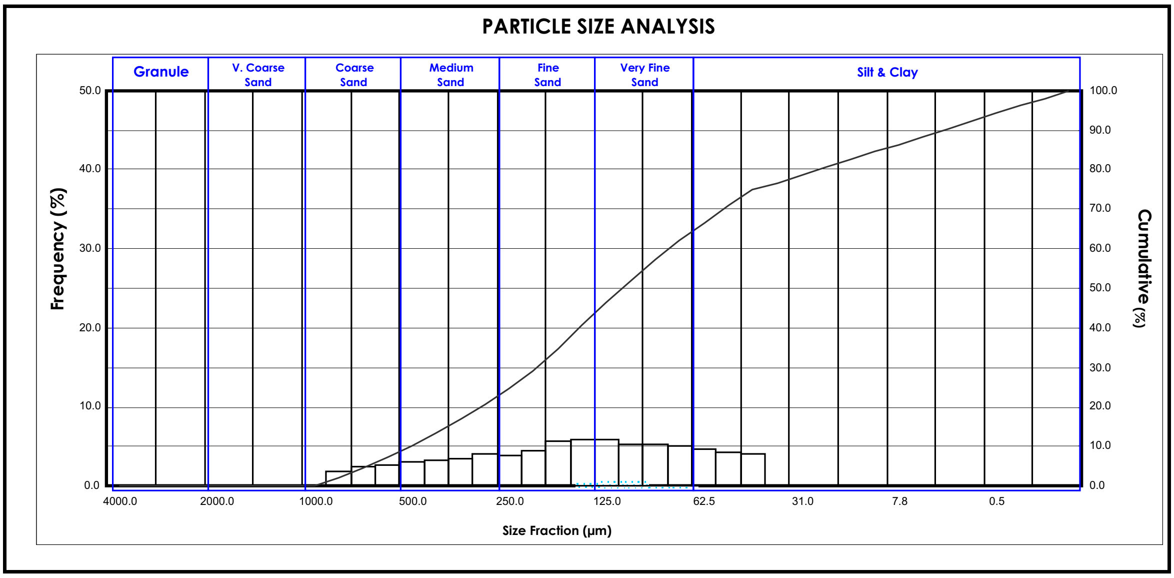


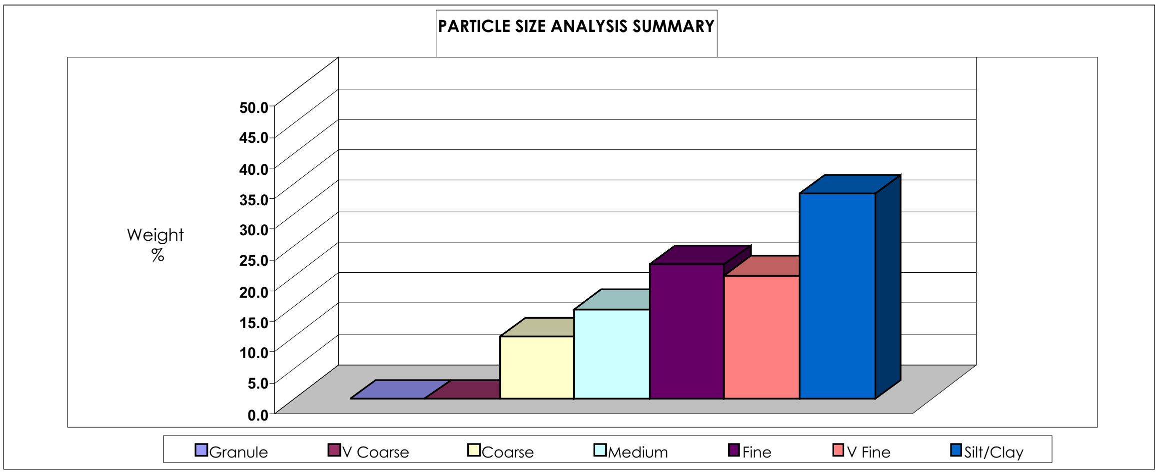
Figure 10A: Particle Size Analysis and Grain Size Distribution of Core Sample No. 1 (1678.50 m)

GRANULOMETRY DATA SUMMARY

Sieve (Mesh) Sizes												
mm	**4.00**	**2.00**	**1.00**	**0.50**	**0.36**	**0.25**	**0.18**	**0.13**	**0.09**	**0.06**	**0.05**	**0.04**
inches	0.16	0.08	0.04	0.02	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.00
phi	-2.00	-1.00	0.00	1.00	1.50	2.00	2.50	3.00	3.50	4.00	4.25	4.50
CUMULATIVE WEIGHT, PERCENTAGE (%)												
	0.0	0.0	0.0	10.1	16.8	24.7	34.7	46.5	57.1	66.6	70.8	74.8

STATISTICAL DATA								
$Ø_5$	$Ø_{10}$	$Ø_{16}$	$Ø_{25}$	$Ø_{50}$	$Ø_{75}$	$Ø_{84}$	$Ø_{90}$	$Ø_{95}$
(0.34)	0.27	0.84	1.53	3.05	4.51	5.13	5.61	6.08

CALCULATED STATISTICAL PARAMETERS					
Median (Md) (f)	Mean (Mz) (f)	Trask's Sorting Coeff. So	Skewness Sk	Kurtosis K	Standard Deviation (mm) SD
3.05	3.01	2.05	-0.04	0.88	1.49



Granule	V Coarse	Coarse	Medium	Fine	V Fine	Silt/Clay
0.0	**0.0**	**10.1**	**14.6**	**21.8**	**20.1**	**33.40**

Figure 10B: Granulometry Data Summary of Core Sample No. 1 (1678.50 m)

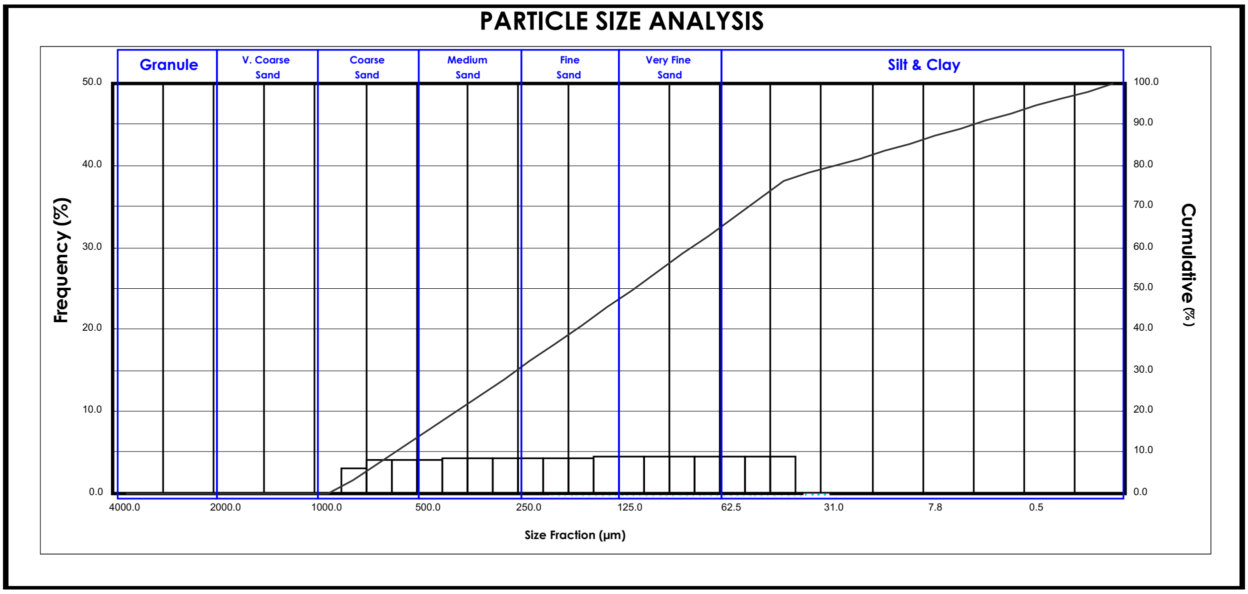


Figure 11A: Particle Size Analysis and Grain Size Distribution of Core Sample No. 2 (1688.22 m)

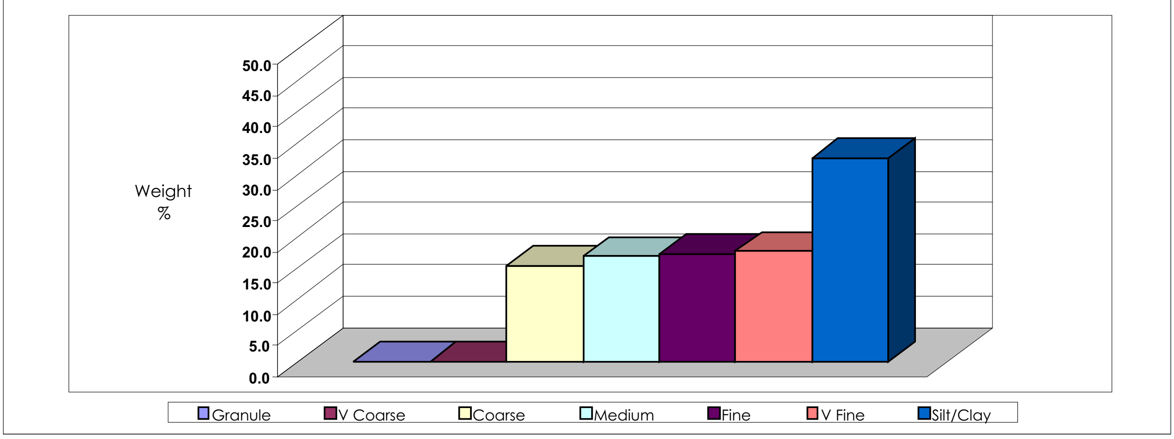
GRANULOMETRY DATA SUMMARY

Sieve (Mesh) Sizes												
mm	4.00	2.00	1.00	0.50	0.36	0.25	0.18	0.13	0.09	0.06	0.05	0.04
inches	0.16	0.08	0.04	0.02	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.00
phi	-2.00	-1.00	0.00	1.00	1.50	2.00	2.50	3.00	3.50	4.00	4.25	4.50
CUMULATIVE WEIGHT, PERCENTAGE (%)												
	0.0	0.0	0.0	15.3	23.7	32.2	40.9	49.6	58.4	67.3	71.8	76.3

STATISTICAL DATA								
$\varnothing_5$	$\varnothing_{10}$	$\varnothing_{16}$	$\varnothing_{25}$	$\varnothing_{50}$	$\varnothing_{75}$	$\varnothing_{84}$	$\varnothing_{90}$	$\varnothing_{95}$
0.37	0.68	1.04	1.58	3.02	4.43	4.93	5.27	5.55

CALCULATED STATISTICAL PARAMETERS					
Median (Md) (f)	Mean (Mz) (f)	Trask's Sorting Coeff. So	Skewness Sk	Kurtosis K	Standard Deviation (mm) SD
3.02	3.00	1.76	-0.02	0.74	1.43

PARTICLE SIZE ANALYSIS SUMMARY



Granule	V Coarse	Coarse	Medium	Fine	V Fine	Silt/Clay
0.0	0.0	15.3	16.9	17.4	17.7	32.67

Figure 11B: Granulometry Data Summary of Core Sample No. 2 (1688.22 m)

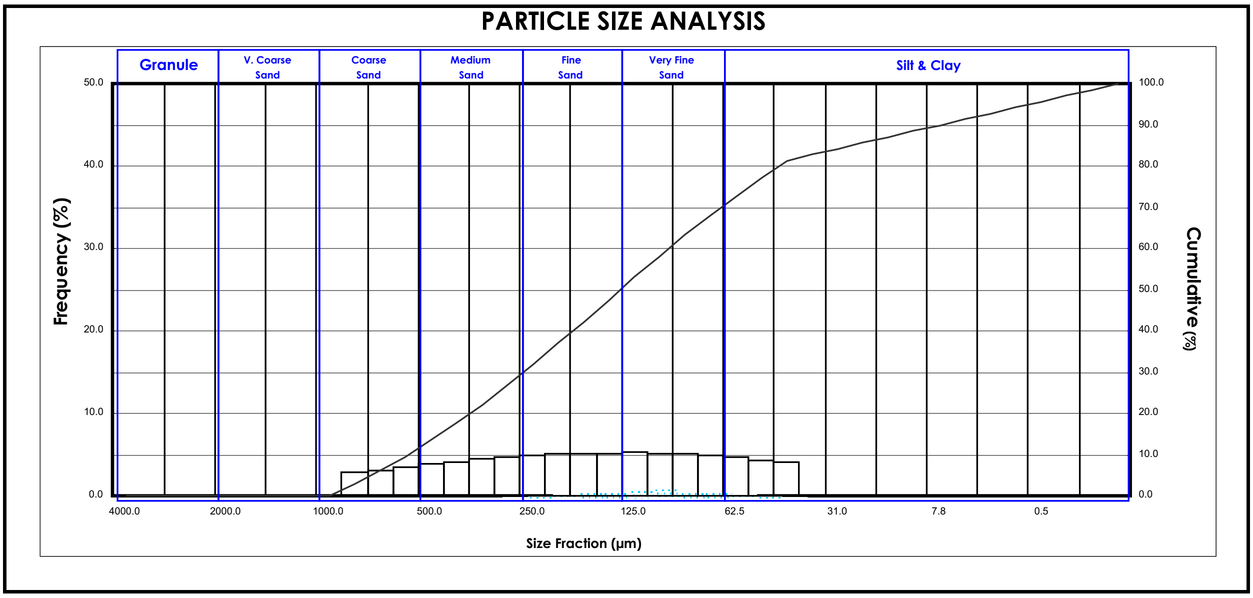


Figure 12A: Particle Size Analysis and Grain Size Distribution of Core Sample No. 3 (1688.22 m)

GRANULOMETRY DATA SUMMARY

Sieve (Mesh) Sizes

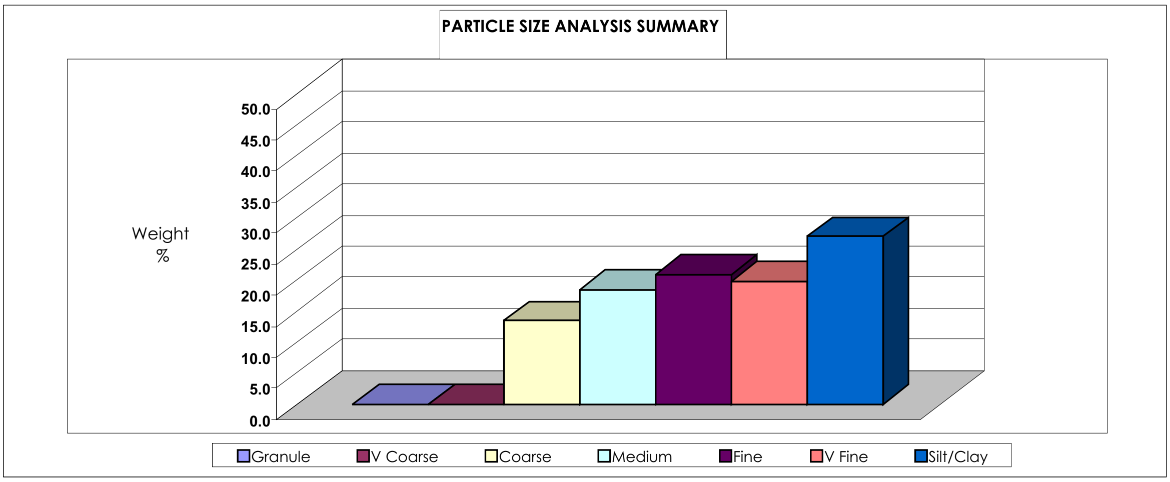
mm	4.00	2.00	1.00	0.50	0.36	0.25	0.18	0.13	0.09	0.06	0.05	0.04
inches	0.16	0.08	0.04	0.02	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.00
phi	-2.00	-1.00	0.00	1.00	1.50	2.00	2.50	3.00	3.50	4.00	4.25	4.50
CUMULATIVE WEIGHT, PERCENTAGE (%)												
	0.0	0.0	0.0	13.5	22.3	32.0	42.4	53.0	63.3	72.9	77.3	81.5

STATISTICAL DATA

$Ø_5$	$Ø_{10}$	$Ø_{16}$	$Ø_{25}$	$Ø_{50}$	$Ø_{75}$	$Ø_{84}$	$Ø_{90}$	$Ø_{95}$
0.21	0.64	1.06	1.60	2.86	4.12	4.67	5.10	5.55

CALCULATED STATISTICAL PARAMETERS

Median (Md) (f)	Mean (Mz) (f)	Trask's Sorting Coeff. So	Skewness Sk	Kurtosis K	Standard Deviation (mm) SD
2.86	2.86	1.71	0.01	0.87	1.26



Granule	V Coarse	Coarse	Medium	Fine	V Fine	Silt/Clay
0.0	0.0	13.5	18.5	21.0	19.9	27.10

Figure 12B: Granulometry Data Summary of Core Sample No. 3 (1835.40 m)

Core Sample No. 4 (1842.80 meters)

This sample ranges mainly from the medium sand to the silt/clay size fractions with the fine to very fine sand (70 – 230 US mesh) constituting 47.6 wt% of the total weight analyzed for the sample. The medium sand fractions (40 – 60 US mesh) constitute 15.5 wt% while the coarse sand fraction (20 – 35 US mesh) constitute only 3.2 wt%. The silt/clay fractions (270 – Pan US mesh) constitute the remaining 33.7 wt%. The grain size proportion in the sample is made up of Coarse sand - 3.2%, medium sand - 15.5%, fine sand - 23.1%, very fine sand - 24.5% coarse silt - 10.4%, silt - 23.3% (Figs 13A and 13B).

Core Sample No. 5 (1851.00 meters)

This sample grain size ranges from the medium sand to the silt/clay size fractions with the fine to very fine sand (70 – 230 US mesh) constituting 54.1 wt% of the total weight analyzed for the sample.

The medium sand fractions (40 – 60 US mesh) constitute 10.5 wt% while the silt/clay fractions (270 – Pan US mesh) constitute 35.4 wt%. The grain size proportion in the sample is made up of medium sand - 10.5%, fine sand - 22.8%, very fine sand - 31.3%, coarse silt - 13.6%, silt - 21.8% (Figs. 14A and 14B).

Core Sample No. 6 (1857.20 meters)

This sample ranges mainly from the medium sand to the silt/clay size fractions dominated by the fine to very fine sand (70 – 230 US mesh) which constitutes 45.8 wt% of the total weight analyzed for the sample. The medium sand fractions (40 – 60 US mesh) constitute 8.9 wt% while the coarse sand grade (20 – 35 US mesh) constitutes 1.6 wt% and the silt/clay fractions (270 – Pan US mesh) constitute 43.7 wt%. The grain size proportion in the sample is made up of coarse sand - 1.6%, medium sand - 8.9%, fine sand - 19.0%, very fine sand - 26.8%, coarse silt - 13.3%, silt - 30.4% (Figs. 15A and 15B).

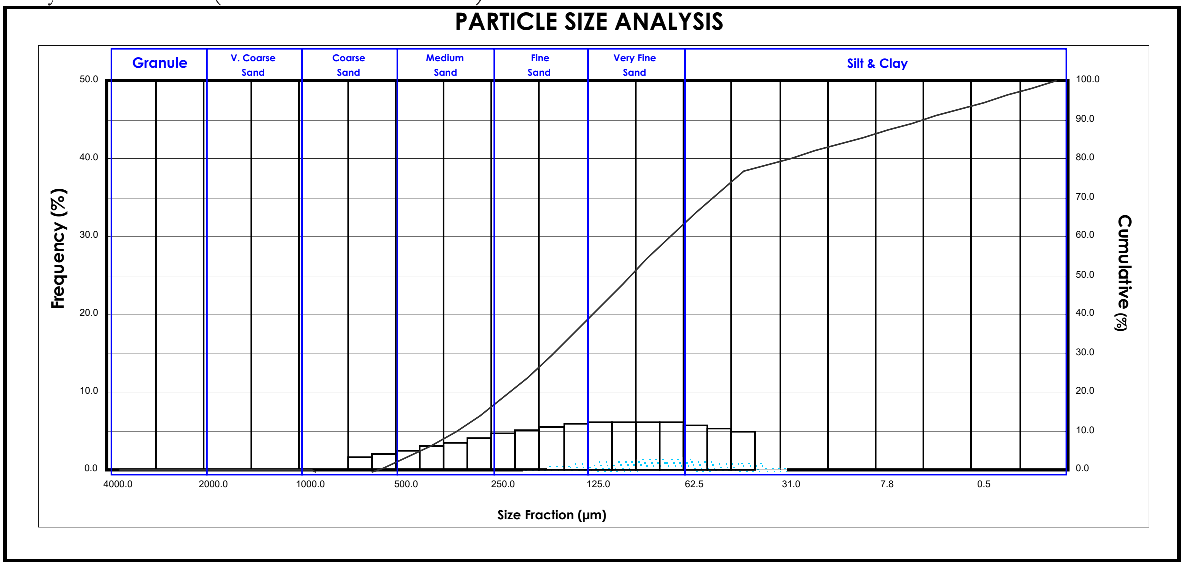


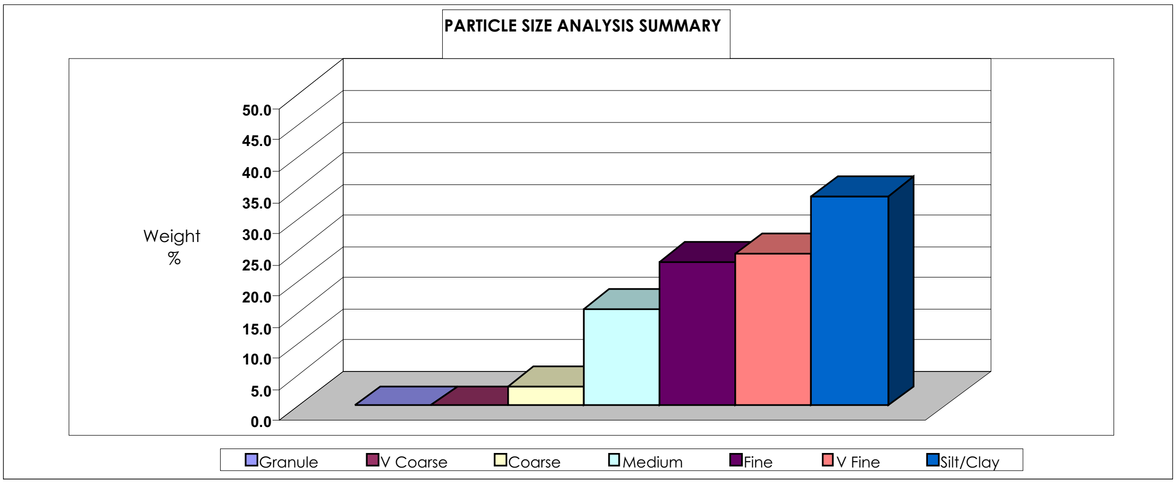
Figure 13A: Particle Size Analysis and Grain Size Distribution of Core Sample No. 4 (1842.80 m)

GRANULOMETRY DATA SUMMARY

Sieve (Mesh) Sizes												
mm	4.00	2.00	1.00	0.50	0.36	0.25	0.18	0.13	0.09	0.06	0.05	0.04
inches	0.16	0.08	0.04	0.02	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.00
phi	-2.00	-1.00	0.00	1.00	1.50	2.00	2.50	3.00	3.50	4.00	4.25	4.50
CUMULATIVE WEIGHT, PERCENTAGE (%)												
	0.0	0.0	0.0	3.2	9.9	18.8	29.6	41.8	54.4	66.3	71.8	76.7

STATISTICAL DATA								
$\varnothing_5$	$\varnothing_{10}$	$\varnothing_{16}$	$\varnothing_{25}$	$\varnothing_{50}$	$\varnothing_{75}$	$\varnothing_{84}$	$\varnothing_{90}$	$\varnothing_{95}$
1.15	1.51	1.86	2.30	3.33	4.41	4.93	5.39	5.95

CALCULATED STATISTICAL PARAMETERS					
Median (Md) (f)	Mean (Mz) (f)	Trask's Sorting Coeff. So	Skewness Sk	Kurtosis K	Standard Deviation (mm) SD
3.33	3.37	1.49	0.07	0.93	1.06



Granule	V Coarse	Coarse	Medium	Fine	V Fine	Silt/Clay
0.0	0.0	3.2	15.5	23.0	24.5	33.68

Figure 13B: Granulometry Data Summary of Core Sample No. 4 (1842.80 m)

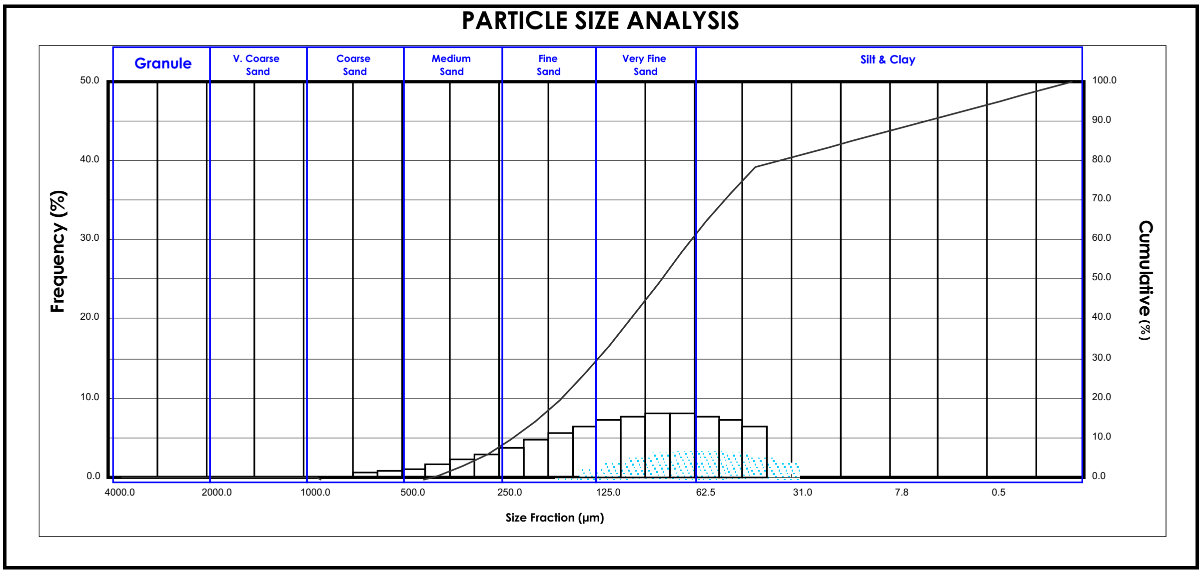


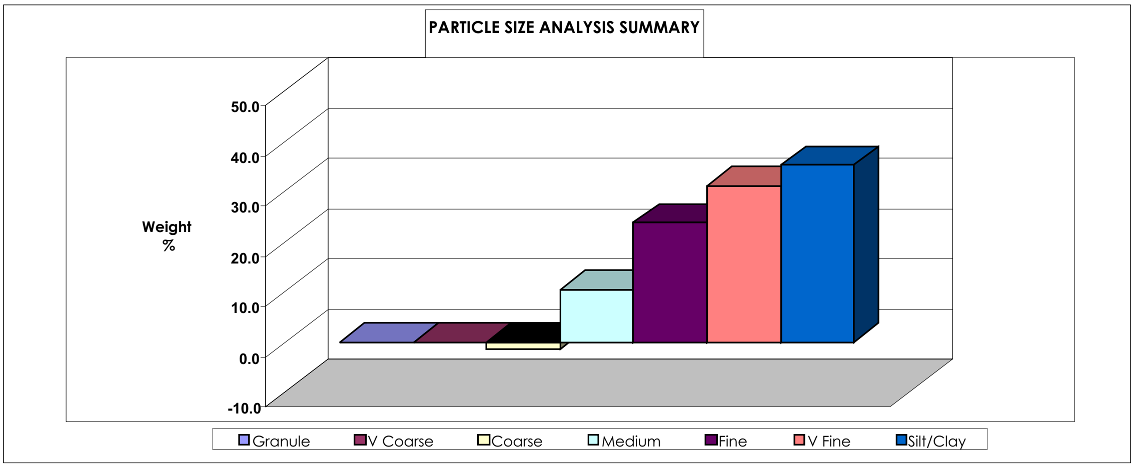
Figure 14A: Particle Size Analysis and Grain Size Distribution of Core Sample No. 5 (1851.00 m)

GRANULOMETRY DATA SUMMARY

Sieve (Mesh) Sizes												
mm	4.00	2.00	1.00	0.50	0.36	0.25	0.18	0.13	0.09	0.06	0.05	0.04
inches	0.16	0.08	0.04	0.02	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.00
phi	-2.00	-1.00	0.00	1.00	1.50	2.00	2.50	3.00	3.50	4.00	4.25	4.50
CUMULATIVE WEIGHT, PERCENTAGE (%)												
	0.0	0.0	0.0	-1.1	2.7	9.4	19.7	33.3	48.9	64.6	71.8	78.2

STATISTICAL DATA								
Ø5	Ø10	Ø16	Ø25	Ø50	Ø75	Ø84	Ø90	Ø95
1.70	2.04	2.34	2.71	3.53	4.37	4.76	5.10	5.50

CALCULATED STATISTICAL PARAMETERS					
Median (Md) (f)	Mean (Mz) (f)	Trask's Sorting Coeff. So	Skewness Sk	Kurtosis K	Standard Deviation (mm) SD
3.53	3.55	1.18	0.03	0.94	0.83



Granule	V Coarse	Coarse	Medium	Fine	V Fine	Silt/Clay
0.0	0.0	-1.1	10.5	23.9	31.3	35.39

Figure 14B: Granulometry Data Summary of Core Sample No. 5 (1851.00 m)

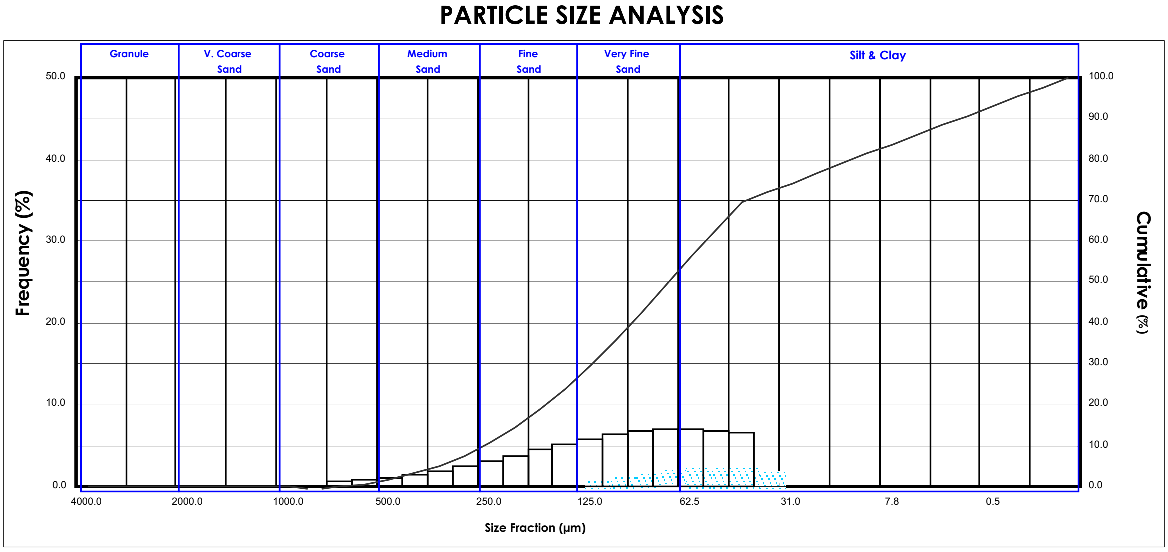


Figure 15A: Particle Size Analysis and Grain Size Distribution of Core Sample No. 6 (1857.20 m)

GRANULOMETRY DATA SUMMARY

Sieve (Mesh) Sizes

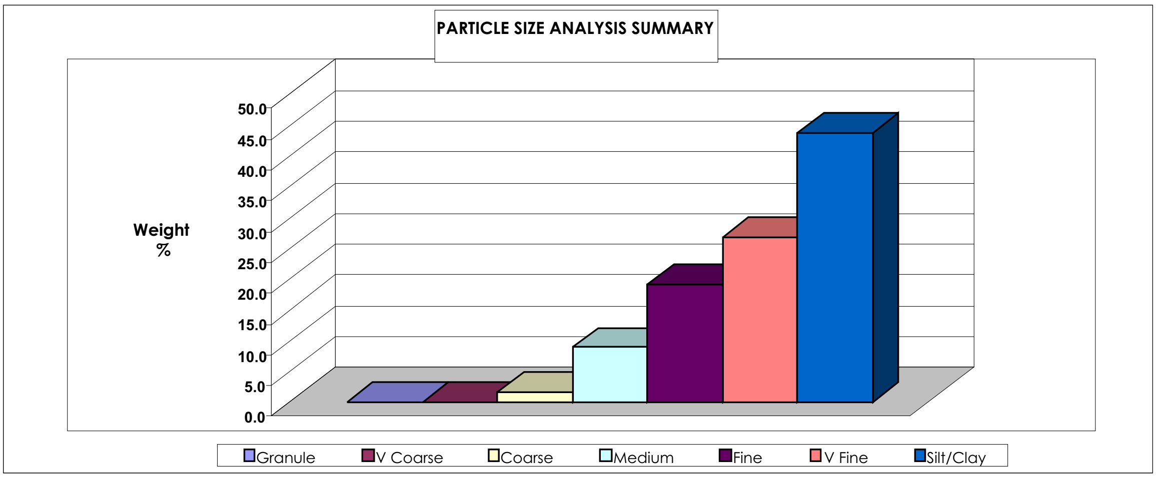
mm	4.00	2.00	1.00	0.50	0.36	0.25	0.18	0.13	0.09	0.06	0.05	0.04
inches	0.16	0.08	0.04	0.02	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.00
phi	-2.00	-1.00	0.00	1.00	1.50	2.00	2.50	3.00	3.50	4.00	4.25	4.50
CUMULATIVE WEIGHT, PERCENTAGE (%)												
	0.0	0.0	0.0	1.6	5.0	10.5	18.7	29.5	42.4	56.3	63.1	69.6

STATISTICAL DATA

$Ø_5$	$Ø_{10}$	$Ø_{16}$	$Ø_{25}$	$Ø_{50}$	$Ø_{75}$	$Ø_{84}$	$Ø_{90}$	$Ø_{95}$
1.51	1.96	2.36	2.81	3.77	4.72	5.15	5.50	5.88

CALCULATED STATISTICAL PARAMETERS

Median (Md) (f)	Mean (Mz) (f)	Trask's Sorting Coeff. So	Skewness Sk	Kurtosis K	Standard Deviation (mm) SD
3.77	3.76	1.36	-0.03	0.94	0.96



Granule	V Coarse	Coarse	Medium	Fine	V Fine	Silt/Clay
0.0	0.0	1.6	8.9	19.0	26.8	43.71

Figure 15B: Granulometry Data Summary of Core Sample No. 6 (1857.20 m)

Core Sample No. 7 (1932.04 meters)

This sample ranges from the coarse sand to the silt/clay size fractions and dominated by the medium to very fine sand (40 – 230 US mesh) which constitutes 56.7 wt% of the total weight analyzed for the sample. The coarse sand fractions (20 – 35 US mesh) constitute 9.2 wt% while the silt/clay fractions (270 – Pan US mesh) constitute 34.1 wt%. The grain size proportion in the sample is made up of coarse sand - 9.2%, medium sand - 16.6%, fine sand - 20.3%, very fine sand - 19.8%, coarse silt - 8.4%, silt - 25.7% (Figs. 16A and 16B).

Core Sample No. 8 (1939.21 meters)

This sample ranges mainly from the coarse sand to the silt/clay size fractions and dominated by the medium to very fine sand (40 – 230 US mesh) which constitutes 62.5 wt% of the total weight analyzed for the sample. The coarse sand fractions (20 – 35 US mesh) constitute 8.5 wt%

while the silt/clay fractions (270 – Pan US mesh) constitute 29.0 wt%. The grain size proportion in the sample is made up of coarse sand - 8.5%, medium sand - 18.3%, fine sand - 22.5%, very fine sand - 21.7%, coarse silt - 9.0%, silt - 20.0% (Figs. 17A and 17B).

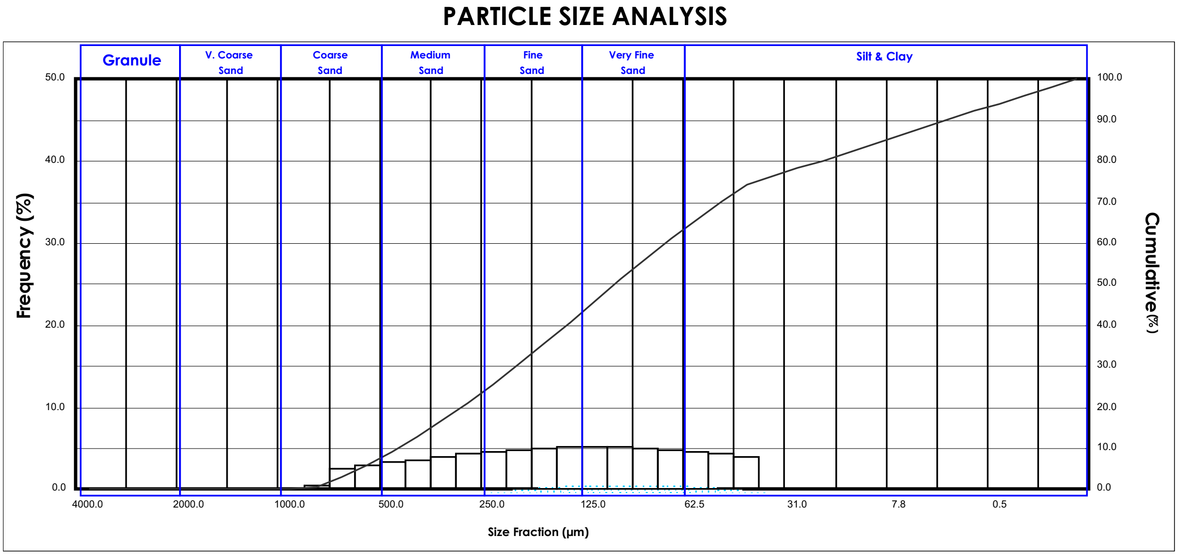


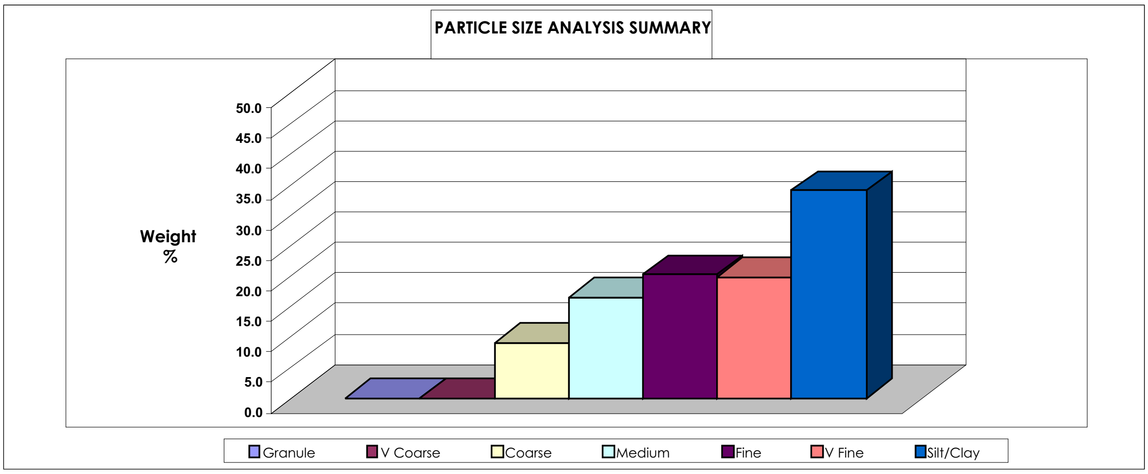
Figure 16A: Particle Size Analysis and Grain Size Distribution of Core Sample No. 7 (1932.04 m)

GRANULOMETRY DATA SUMMARY

Sieve (Mesh) Sizes												
mm	4.00	2.00	1.00	0.50	0.36	0.25	0.18	0.13	0.09	0.06	0.05	0.04
inches	0.16	0.08	0.04	0.02	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.00
phi	-2.00	-1.00	0.00	1.00	1.50	2.00	2.50	3.00	3.50	4.00	4.25	4.50
CUMULATIVE WEIGHT, PERCENTAGE (%)												
	0.0	0.0	0.0	9.2	16.8	25.8	35.7	46.1	56.3	65.9	70.3	74.3

STATISTICAL DATA								
Ø5	Ø10	Ø16	Ø25	Ø50	Ø75	Ø84	Ø90	Ø95
0.68	1.06	1.45	1.96	3.19	4.55	5.23	5.88	6.82

CALCULATED STATISTICAL PARAMETERS					
Median (Md) (f)	Mean (Mz) (f)	Trask's Sorting Coeff. So	Skewness Sk	Kurtosis K	Standard Deviation (mm) SD
3.19	3.29	1.88	0.13	0.97	1.29



Granule	V Coarse	Coarse	Medium	Fine	V Fine	Silt/Clay
0.0	0.0	9.2	16.6	20.3	19.8	34.10

Figure 16B: Granulometry Data Summary of Core Sample No. 7 (1932.04 m)

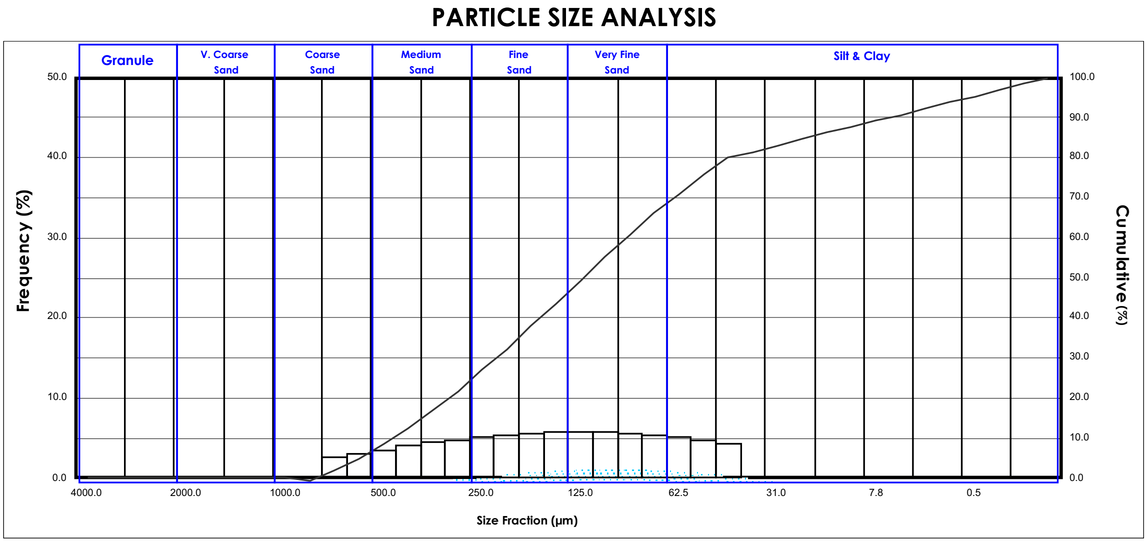


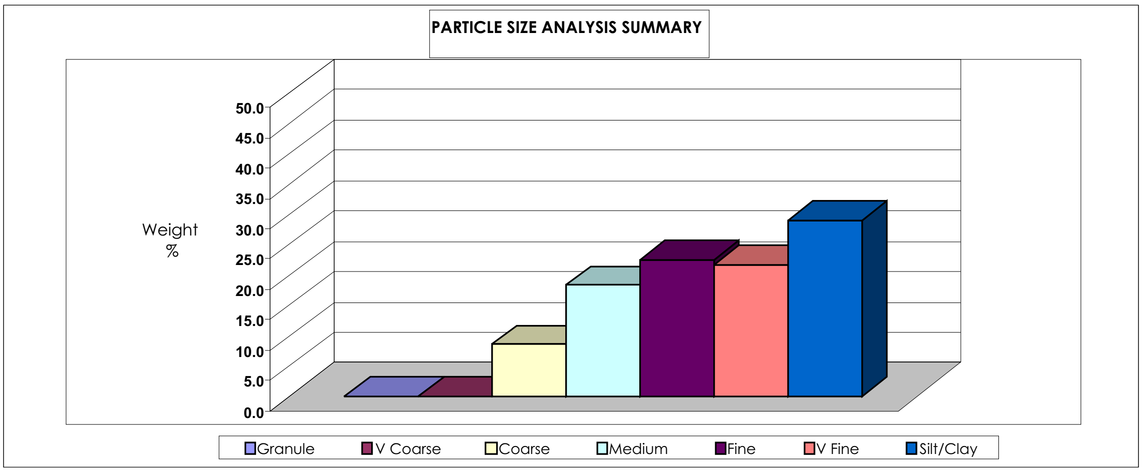
Figure 17A: Particle Size Analysis and Grain Size Distribution of Core Sample No. 8 (1939.21 m)

GRANULOMETRY DATA SUMMARY

Sieve (Mesh) Sizes												
mm	**4.00**	**2.00**	**1.00**	**0.50**	**0.36**	**0.25**	**0.18**	**0.13**	**0.09**	**0.06**	**0.05**	**0.04**
inches	0.16	0.08	0.04	0.02	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.00
phi	-2.00	-1.00	0.00	1.00	1.50	2.00	2.50	3.00	3.50	4.00	4.25	4.50
CUMULATIVE WEIGHT, PERCENTAGE (%)												
	0.0	0.0	0.0	8.6	17.0	26.9	37.9	49.4	60.7	71.1	75.7	80.0

STATISTICAL DATA								
$\varnothing_5$	$\varnothing_{10}$	$\varnothing_{16}$	$\varnothing_{25}$	$\varnothing_{50}$	$\varnothing_{75}$	$\varnothing_{84}$	$\varnothing_{90}$	$\varnothing_{95}$
0.75	1.09	1.45	1.91	3.03	4.21	4.76	5.22	5.74

CALCULATED STATISTICAL PARAMETERS					
Median (Md) (f)	Mean (Mz) (f)	Trask's Sorting Coeff. So	Skewness Sk	Kurtosis K	Standard Deviation (mm) SD
3.03	3.08	1.58	0.07	0.89	1.15



Granule	V Coarse	Coarse	Medium	Fine	V Fine	Silt/Clay
0.0	0.0	8.6	18.3	22.5	21.7	28.95

Figure 17B: Granulometry Data Summary of Core Sample No. 8 (1939.21 m)

DISCUSSION

Photographs of the eight sidewall core samples employed in this study provides the first check on the presence/absence of hydrocarbon in the stacked reservoirs in the KU-1 well section. Seven out of the eight sidewall cores studied have been confirmed to show florescence thereby confirming the presence of hydrocarbon. Presence of hydrocarbon in core samples is more visible in photographs than can be observed with the naked eye. Under the white light, traces of hydrocarbon can be seen and where saturation is high, streaming can be observed. The observed presence of hydrocarbon is more enhanced under the ultra violet light illumination as seen in the photographs. Hydrocarbon saturation on the core samples can be seen under the ultra violet light illumination with the intensity of fluorescence higher in the more saturated cores. This intensity has been found to be in the following order: core no. 8 (1939.21 m) > core no. 7 (1932.04 m) > core no. 5 (1851.00 m) > core no. 2 (1688.22 m) > core no. 1 (1678.50 m) > core no. 4 (1842.88 m) > core no. 6 (1857.20 m) > core no. 3 (1835.40 m). (Figs 2 – 9). This order shows that, care must be taken while viewing cores under the white light in trying to determine the presence of hydrocarbon as some samples may have some fluids that may be mistakingly interpreted as hydrocarbon, such as in core No. 2 (1688.22 m; Fig. 3).

The lithologic description from this study provides useful information for reservoir evaluation and production planning. Core no. 1 (1678.50 m) has been found to be poorly sorted and this may slightly be a hinderance to the porosity. The particle size analysis (Figs. 10A and 10B) indicated the presence of almost all size grades in appreciable quantity from coarse sand - 10.1%; medium sand - 14.6%; fine sand - 21.8%; very fine sand - 20.1%; coarse silt - 8.2% to silt - 25.2%. With the presence of all the size grades in the stated percentages, the porosity and permeability will be reduced as the smaller particles will block the pore spaces in between the larger grains. However, the moderately consolidated nature of the sample may be an added advantage in terms of the porosity and permeability of the reservoir at this interval. For recovery enhancement, the reservoir engineers may look at a possibility of fracturing or other permeability enhancing technique. Core no 2 (1688.50 m) has also been found to be poorly sorted having all the size grades from coarse sand - 15.3%, medium sand - 16.9%, fine sand - 17.4%, very fine sand - 17.7%, coarse silt - 8.9% to silt - 23.7% (Figs. 11A and 11B) . The implication of this is a probable low porosity and permeability. This situation can be helped with the moderately consolidated nature of the sand in the core. Core sample no. 3 (1835.40 m) is moderately sorted having the medium sand to very fine sand fractions constituting 59.4 wt% of the total weight analysed for the sample. There was a reduction in the silt/clay fractions constituting about 27.1 wt% as compared to the 33.4 wt% and 32.6 wt% in core nos. 1 and 2 respectively. The grain size proportion in the sample is made up of coarse sand - 13.5%, medium sand - 18.5%, fine sand - 21.0%, very fine sand - 19.9%, coarse silt-8.0%, silt-19.1% (Figs. 12A and 12B). The moderately sorted nature of the sediments in core no. 3 has an implication of an improved porosity and permeability over cores 1 and 2. Consequently, a smoother fluid flow is expected in core no 3. Core no. 4 (1842.88 m) having the fine to very fine sand constituting 47.6 wt% of the total weight analyzed for the sample and just 3.2 wt% of the coarse fraction is well sorted and moderately consolidated. As expected, fluid flow within the reservoir around this core is expected to be more effective than those in core samples 1 – 3. The grain size proportion in the sample is made up of coarse sand - 3.2%, medium sand - 15.5%, fine sand - 23.1%, very fine sand - 24.5% coarse silt - 10.4%, silt - 23.3% (Figs 13A and 13B). In a similar vein, core sample no. 5 (1851.00 m) with the fine to very fine sand fractions constituting 54.1 wt% of the total weight analyzed for the sample and without coarse fraction is also well sorted and is expected to have a smooth fluid flow. The grain size proportion in the sample is made up of medium sand - 10.5%, fine sand - 22.8%, very fine sand - 31.3%, coarse silt - 13.6%, silt - 21.8% (Figs. 14A and 14B).

Core samples no. 6 (1857.20 m) is moderately sorted being dominated by the fine to very fine sand which constitutes 45.8 wt% of the total weight analyzed for the sample and a negligible percentage of the coarse fraction. The grain size proportion in the sample is made up of coarse sand - 1.6%, medium sand - 8.9%, fine sand - 19.0%, very fine sand - 26.8%, coarse silt - 13.3%, silt - 30.4% (Figs. 15A and 15B). Core sample no. 7 (1932.04 m) is moderately sorted and dominated by the medium to very fine sand which constitutes 56.7 wt% of the total weight analyzed for the sample. The grain size proportion in the sample is made up of coarse sand - 9.2%, medium sand - 16.6%, fine sand - 20.3%, very fine sand - 19.8%, coarse silt - 8.4%, silt - 25.7% (Figs. 16A and 16B). Core no. 8 (1939.21 m) is also moderately sorted and dominated by the medium to very fine sand fractions which constitutes 62.5 wt% of the total weight analyzed for the sample. The grain size proportion in the sample is made up of coarse sand - 8.5%, medium sand - 18.3%, fine sand - 22.5%, very fine sand - 21.7%, coarse silt - 9.0%, silt - 20.0% (Figs. 17A and 17B).

The moderately sorted and moderately consolidated core samples 6, 7 and 8 are expected to have an average porosity and permeability which can easily be enhanced by cheap and less stressful methods for production within the reservoirs where the cores were obtained.

Sand production must be minimized as much as possible during hydrocarbon recovery. Several techniques are available for minimizing sand production from wells. The choices range from simple changes in operating practices to expensive completions, such as sand consolidation or gravel packing. The sand control method selected depends on site-specific conditions, operating practices and economic considerations. Some of the sand control techniques available are - maintenance and workover, rate exclusion, selective completion practices, plastic consolidation, high energy resin placement, resin coated gravel, stand-alone slotted liners or screens and gravel packing (Dees and Handren, 1994). The last two techniques (stand alone slotted liners or screens and gravel packing) employ the particle size of the reservoir. The slotted liners or screens have been known to function as filters. The slot width, or the screen gauge, is sometimes sized to be equal to the formation sand grain size at the 10-percentile point of the sieve analysis. The theory is that because the larger 10% of the sand grains will be stopped by the openings of the screen, the larger sand will stop the remaining 90% of the formation (Hollabaugh and Dees, 1993).

Gravel packing consists of placing a screen or slotted liner in a well opposite the completion interval and placing gravel concentrically around it. The gravel is actually large-grained sand that prevents sand production from the formation but allows fluids to flow into the well. The slotted liner or screen retains the gravel. The gravel is sized to be about 5 to 6 times larger than the median formation sand size. Gravel packing creates a permeable downhole filter that allows the production of the formation fluids but restricts the entry and production of formation sand.

For maximum productivity, one of the most important aspects of designing a gravel pack is the selection of the gravel to be used. Where formation samples are not available, a blanket recommendation would appear to be to use the smallest gravel possible without restricting productivity. When representative samples are available, size selection is based on formation particle-size distribution. To assure effective sand control and longer-lived gravel packs, it appears that the gravel should be sized to prevent invasion of the gravel pack by the finest formation sand (Sparlin, 1974; Gurley *et al.* 1977).

Screen opening (slot/micron rating) is dependent on the particle-size distribution. The particle size analyses of the cores in KU-1 well have been given in weight percentage of the total weight analysed for the different size classes. From the particle size distribution of the formation sands, adequate screen sizes can be selected for production in the different reservoir intervals from which the cores were obtained. Core sample no. 1 (1678.50 m) is dominated by fine to very fine sand-sized fractions (70 - 230 US mesh) which constitutes 41.9 wt% of the analysed sample. The dominating mesh size (70 – 230) is the determining factor in the screen size selection for the reservoir interval for core no. 1, while the other size grades will also be considered depending on their distribution. Core sample no. 2 (1688.50 m) has the size grades averaging coarse sand, medium sand, fine sand and very fine sand in approximately equal proportions totalling 67.3 wt% of the analysed sample. This grain size covers the 20 – 230 US mesh size. Selecting the sieve sizes for gravel packing within this interval is clumsy because of the wide size ranges. However, adequate screen size will still be selected but this may have some impact on the production rate as well as the recovery life which may result in the repeated screen changes/maintenance. Also, core sample no. 3 (1835.40 m) has a wided size range from medium sand to very fine san fractions (40 – 230 US mesh). A similar scenario comes to play here as we have in core sample no. 2. Core samples nos. 4 (1842.88 m), 5 (1851.00 m) and 6 (1857.20 m) were in the range of the 70 – 230 US mesh size with the fine to very fine sand predominating. Adequate screen sizes can be selected for the reservoirs where these cores were obtained while the minor size grades should also be taken into consideration. Core samples nos. 7 (1932.04 m) and 8 (1939.21 m) were dominated by the medium to very fine sand grain sizes and with a slightly wider mesh size (40 – 230 US mesh). These grain size ranges (medium to very fine) however constitute a very high total weight percent - 56.7 wt% and 62.5 wt% for core samples nos. 7 and 8 respectively. The high weight percentage is with the advantage that the other size grades are smaller in population and the chosen screen size here will be easy to manage.

CONCLUSION

The lithologic description and digital image capture of the eight sidewall cores analysed revealed that seven of the eight core samples were saturated with hydrocarbon. The recognition of the degree of saturation was enhanced by the digital photographs taken under the ultraviolet light illumination as shown by the intensity of fluorescence. The order of saturation was core no. 8 (1939.21 m) > core no. 7 (1932.04 m) > core no. 5 (1851.00 m) > core no. 2 (1688.22 m) > core no. 1 (1678.50 m) > core no. 4 (1842.88 m) > core no. 6 (1857.20 m) > core no. 3 (1835.40 m). The lithologic description showed that, core samples no. 1 (1678.50 m), 2 (1688.22 m), 3 (1835.40 m) and 8 (1939.21 m) were brownish in colour, medium to fine-grained, poorly to moderately sorted and moderately consolidated. Core samples no. 4 (1842.80 m), 5 (1851.00 m), 6 (1857.20 m) and 7 (1932.04 m) were light grey in colour, fine to very fine-grained, moderately to well sorted and moderately consolidated. Core sample no. 3 was predominantly fine-grained while core sample no. 4 was predominantly medium grained. The particle size analysis revealed that the sands were predominantly fine to very fine-grained (70 – 230 US mesh). Some cores contained significant medium-grained (40 – 60 US Mesh) fractions while a few had coarse-grained (20 – 30 US mesh) fractions. Silt/clay sized fractions were also substantial averaging about 30 wt% of the studied core samples. The grain size distribution in each sample had been used to interpret the degree of sorting and consequently the porosity and permeability. The average grain size from each core would be a determinant factor for gravel packing operation and screen size selection for oil production within the reservoir from which these cores were obtained.

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