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Grain Size Distribution (GSD) and its Effect on Porosity and Permeability: The Hulett Sandstone, PRB #1 test well, Wyoming.

Davin Bagdonas, J. Fred McLaughlin,
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DIRECTOR: DR. J. FRED MCLAUGHLIN

Grain Size Distribution (GSD) and its Effect on Porosity and Permeability: The Hulett Sandstone, PRB #1 test well, Wyoming.

By Davin Bagdonas, Fred McLaughlin, Yuri Ganshin, and Scott Quillinan

Introduction

Characterizing underground geological formations is a tedious task for at least three reasons: geological heterogeneity, limited data and measurement uncertainty. Improving measurement tools and technologies can mitigate measurement uncertainties. Inferential uncertainties can be mitigated by acquiring more data. Within this context, a key point is to integrate and reconcile all available data - geological, geophysical and hydrologic data - into reservoir models. There is a clear need for advanced techniques to adjust the reservoir model at any level of the workflows and strengthen its consistency with data.

Grain size is one of the most important descriptive parameters of sedimentary rocks. The grain size and sorting of clastic sediment exerts a profound influence on reservoir properties. Accordingly, the grain size analysis is a vital sedimentological tool used to texturally classify sedimentary rocks, unravel the hydrodynamic conditions, and define depositional environments. With respect to mineralogical grain size measurements, Grain Size Distribution (GSD) can be defined as frequency of occurrence of grains' diameters over a given area or volume. Several methods exist for measuring the grain size of siliciclastic particles, which depend on the sizes of particles and their degree of consolidation. The conventional technique for measuring sand- and coarse-silt-size grains in consolidated rocks remains measurement in rock thin sections by use of a petrographic microscope fitted with an ocular micrometer. The grain size determined in this way is the section diameter of randomly oriented grains (Boggs, 2009). An alternative method of measuring the size of particles is by using digital images of thin sections (photomicrographs) produced by a video digitizer that converts the analog signal to digital format. Whichever instrument is used, a glass slide inscribed with a metric scale must be used to determine a conversion factor for converting unitless data to millimeters or micrometers (µm).

General Geology

The Hulett Sandstone/Lower Sundance was deposited in the ancient Jurassic seas that covered modern Wyoming during a period when the sea levels fell. This sandstone was laid down in offshore bars, as beach and dune sands were pulled out into the ocean by near-shore waves and tidal forces. Though a sand body with zones of decent porosity and permeability, the Hulett Sandstone has never truly been a target of subsurface (basin-wide) exploration or study. As the silty/shaly formations above the Hulett have very little organic content and the Triassic redbeds below are barren, the Hulett was sealed from being charged with hydrocarbons for over 150 million years. As such, it presents an ideal target for carbon sequestration studies as there are no minerals to disturb, but having never been an exploration target, there is scarce available data.

Data and Methods

The data (well logs and core) used for this study were obtained from UW PRB #1 stratigraphic test well drilled in the Northern Powder River Basin of Wyoming. The core plugs were extracted from the Hulett stratigraphic interval and were further analyzed at Core Laboratories (Denver, CO) and the University of Wyoming at the net confining pressure of 1000 psi (both porosity and permeability measurements). To minimize the depth correlation errors between core and logs, a gamma log of the core was completed at Core Laboratories and matched to the downhole gamma log. Sample characteristics of sandstones are summarized in Table 1. The porosity ranges from approximately 4% to 17%, and permeability values demonstrate a wide extent (three orders of magnitude) from approximately 0.01 to more than 10 millidarcy.

The conventional technique for measuring samples of sand- and coarse-silt-size grains is a measurement in thin section by use of a petrographic microscope provided with an ocular micrometer. In this study, a microscope with objectives of 5x and 10x with circular rotating stage and scales was used (?) to manually measure diameter of randomly oriented grains in selected thin sections. Plane polarized light and cross polarized light (?) was used to identify the minerals and voids. The grain size determined in this way is the section diameter of randomly oriented grains.

Image analysis was carried out automatically, using in-house software, on twenty-four RGB-domain photomicrographs of the Hulett thin sections. The image analysis used the pixel color and intensity from the photomicrograph to differentiate between various minerals and void spaces. The user needs to select the red, green, and blue color intensity corresponding to a specific grain type or a group of grains. The process of color selection with subsequent filtering and image binarization is done interactively by comparing the results in different windows. Those parameters that allow the best segregation of grain contours in binary (black & white) format, are used for building the GSD and statistical parameters estimation. The binary image is composed of 'ones', representing the grains of interest, and zero values appointed for everything else (Figure 1). The grain size is determined by finding the maximum grain diameter among the four predefined directions 0˚, 45˚, 90˚, and 135˚. A grain diameter is defined by counting a continuous number of 'ones' along the above-mentioned directions at each pixel of the thin section. There is also an optional high-cut filter to delimit the measurements over small-scale features.

The data obtained from the analysis of grain size are represented graphically in the form of frequency distribution curves (histograms) plotted in metric (linear) size scale. The parameters used to describe a grain size distribution fall into three principal groups: those measuring (1) the average size, (2) the spread (sorting) of the sizes around the average, and (3) the symmetry or preferential spread (skewness) to one side of the average. Optionally, the degree of concentration of the grains relative to the average (kurtosis) can be used as an additional descriptive parameter.

We used the logarithmic Udden-Wentworth (Udden, 1914, and Wentworth, 1922) grade scale and class terms for clastic sediments that is adopted by most sedimentologists (Boggs, 2009). In this scale the boundaries between successive size classes differ by a factor of two. To facilitate statistical manipulation of grain size frequency data, we also used a logarithmic transformation of the Udden-Wentworth scale, introduced by Krumbein (1934) and known as the Phi-scale, which is the most used measure of grain size:

$$\phi = -log_2 d$$

, where d is grain diameter in millimeters. Correlation between metric grain size classification and the corresponding Phi-scale ranges is graphically shown in Figure 2.

To characterize the grain size distributions obtained in this study, we used statistical parameters and formulae proposed by Folk and Ward (1957). The parameters calculated for these analyses include:

- "median" – corresponds to the 50th percentile on cumulative curve, where half the particles by frequency of occurrence are larger and half are smaller than median.
- "mean" – is the average grain size determined by the formula

$$M_z = \frac{\phi 16 + \phi 50 + \phi 84}{3}$$

, where $\phi 16$, $\phi 50$, and $\phi 84$ represent the Phi values at 16, 50, and 84th percentile of the cumulative distribution. In this study we measured the mean and median values in Phi units and further convert them to micrometers.

- "spread" or standard deviation – is the measure of the grain size dispersion. The grain size spread is determined as inter-percentile range covering approximately 68% of data by the formula

  $$\sigma = d84 - d16$$

  , where $d16$ and $d84$ represent the size at 16th and 84th percentiles. We measured the spread parameter in micrometers.

- "sorting" – the sorting of grain population represents the magnitude of the spread or scatter of grain sizes around the mean size. In this study we used the "inclusive graphic standard deviation" (Folk and Ward, 1957) as the sorting parameter, which is calculated as follows

  $$\sigma_{\mathbf{1}} = \frac{\phi 84 - \phi 16}{4} + \frac{\phi 95 - \phi 5}{6.6}$$

  , where $\phi 16$, $\phi 84$, $\phi 5$ and $\phi 95$ represent the Phi values at 16, 84, 5, and 95th percentiles. One of the reasons for using Phi values is because of the currently existing verbal classification: $\sigma_{\mathbf{1}}<0.35$: very well sorted; 0.35-0.50: well sorted; 0.50-0.70: moderately well sorted; 0.70-1.00: moderately sorted; and, 1.00-2.00: poorly sorted (e.g., Boggs, 2009).

- "skewness" – measures the degree to which a cumulative curve approaches symmetry. Folk and Ward (1957) introduced the "inclusive graphic skewness", which is determined by the equation

  $$sk_{\mathbf{1}} = \frac{\phi 16 + \phi 84 - 2\phi 50}{2(\phi 84 - \phi 16)} - \frac{\phi 5 + \phi 95 - 2\phi 50}{2(\phi 95 - \phi 5)}$$

  , where the Phi values represent the same percentages as those for sorting. A verbal classification for skewness suggested by Folk and Ward (1957) includes: from 0.1 to -0.1 as nearly symmetrical; -0.1 to -0.3 as coarse-skewed when a coarse tail is present; and, 0.1 to 0.3 as fine-skewed when an excess of fine particles is present in a sample.

Results and Discussion

We have completed grain size analysis of 24 digital images of thin sections representing 72 feet of thick Hulett sandstone drilled by the PRB #1 well at the Dry Fork Station location with the major results shown in Table 1. The important conclusions drawn are as follows.

The Hulett sedimentary unit is mostly composed of very fine to fine grained sands, which point to relatively low energy conditions of deposition. Almost all the histograms show a unimodal nature as in example shown in Figure 3. The mean grain size varies considerably in the upper part of the studied formation from 8276 to 8321-feet depth. The corresponding spread (standard deviation) of grain sizes in this depth interval is much higher compared to the middle Hulett interval from 8321 to 8348 feet depth (Table 1). The sorting parameter expressed as inclusive standard deviation in Phi units, also indicates an abrupt change in sediment sorting at about 8321-feet depth. The grains above this depth value are moderately sorted, while those below this depth mark tend to be moderately well sorted (Table 1). The majority of grain size distribution curves are characterized with the presence of coarse tails, and only GRD's corresponding to the middle Hulett interval with relatively well-sorted samples (the highlighted area in Table 1) are closer to a symmetrical shape (Figure 3). This may be inferred to as the change in depositional facies. The variation in sorting from moderately sorted to moderately well sorted in the samples of the study area can be indicative of high energy fluctuation of the depositing agent in a mixed environment.

In the light of the above information obtained from the GSD's and statistical parameters of grain size, it can be summarized that the Hulett sandstone unit of the study area is not restricted to a single depositional environment. It can be broadly inferred that these sediments were deposited in a mixed environment or the transitional environment.

We compared the results of statistical analysis of grain sizes obtained for the Hulett sandstones with porosity-permeability measurements from the 24 core plugs that were cut at the corresponding depths. An obvious correlation can be observed between the grain sorting type and porosity/permeability magnitude in the Hulett core samples (Table 1). The cores with poorly and moderately sorted grains do not exceed 10.5% porosity and 1.5 mD permeability, while moderately well sorted grains in the depth range from 8321 to 8349 feet have porosity values from 12% to 17% and permeability values in excess of 10 mD. The same trend of relatively increased porosity/permeability values in the depth range from 8321 to 8349 feet can be also observed in the combinable magnetic resonance (CMR) logs from the PRB #1 well (Figure 4). Variations in the gamma-ray, density, and deep resistivity log-readings may also indicate depositional processes and the resultant facies change within the Hulett sandstone at about 8325 feet depth (Figure 4). This depth marker separates the upper Hulett from the middle Hulett unit. The lower Hulett unit, below the 8350-feet depth interval, represents a transition zone from very fine sands to coarse silts, where porosity/permeability drops to the values characteristic to shales (Table 1).

The study revealed a pronounced dependence of porosity/permeability on grain sorting for the Hulett sandstone samples. This observation is in accord with laboratory measurements of porosity on various packing arrangements of spherical grains. It was shown empirically that porosity of a collection of uniform spheres is independent of the grain size (sphere diameter). However, if smaller spheres are mixed among the spheres of either system, the ratio of pore space to the solid framework becomes lower and porosity is reduced (Tiab and Donaldson, 2011). Hence, if smaller particles of silt or clay are mixed with larger sand grains, the effective porosity will be considerably reduced as shown in Table 1 and Figure 4.

The grain size distribution algorithm used in this study is a robust method to find the GSDs from 2-D binary images. We validated it by comparing the results with manually measured grain diameters. The statistical outcomes of manually measured grain sizes of selected thin sections of the Hulett sandstone are shown in Table 2. The overall mean grain size and spread values are of the same order of magnitude as the corresponding statistical parameters from Table 1. However, no facies change nor change in depositional trend can be derived from the manually measured grain diameters. This is likely because manual measurements in this study do not provide a representative sample of the grain population, which makes them statistically insignificant. Using the automated application can significantly reduce the time and increase the accuracy of acquiring the grain size distribution.

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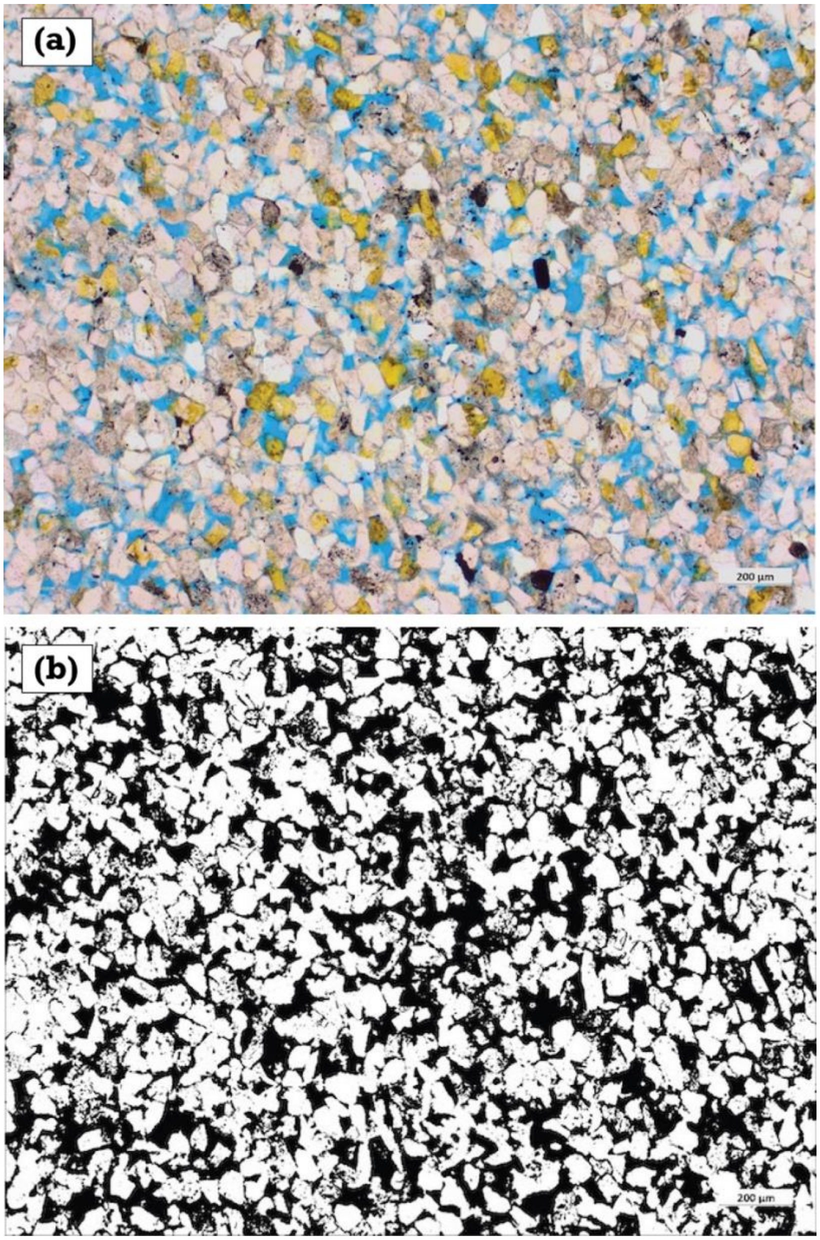

Figure 1. (a) 5x photomicrograph of Hulett Formation sand sample derived from 8,335.8-feet depth. In this image quartz is white/pink, potassium feldspar is yellow, Fe-bearing minerals are black, and pore space is blue. (b) Binary petrographic image of (a). Note that quartz and feldspar mineral grains are white-colored, while everything else remains black.

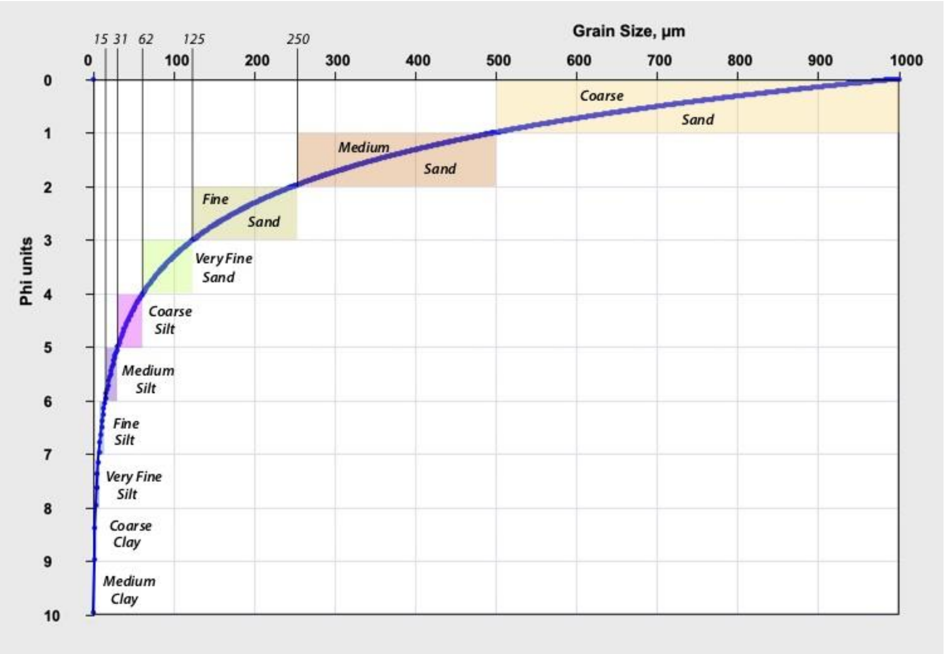

Figure 2. Interpretive grade scale chart relating rocks' grain size (in micrometers) to the logarithmic Phi scale. Based on Udden-Wentworth (1914 and 1922) and Krumbein's (1934) publications.

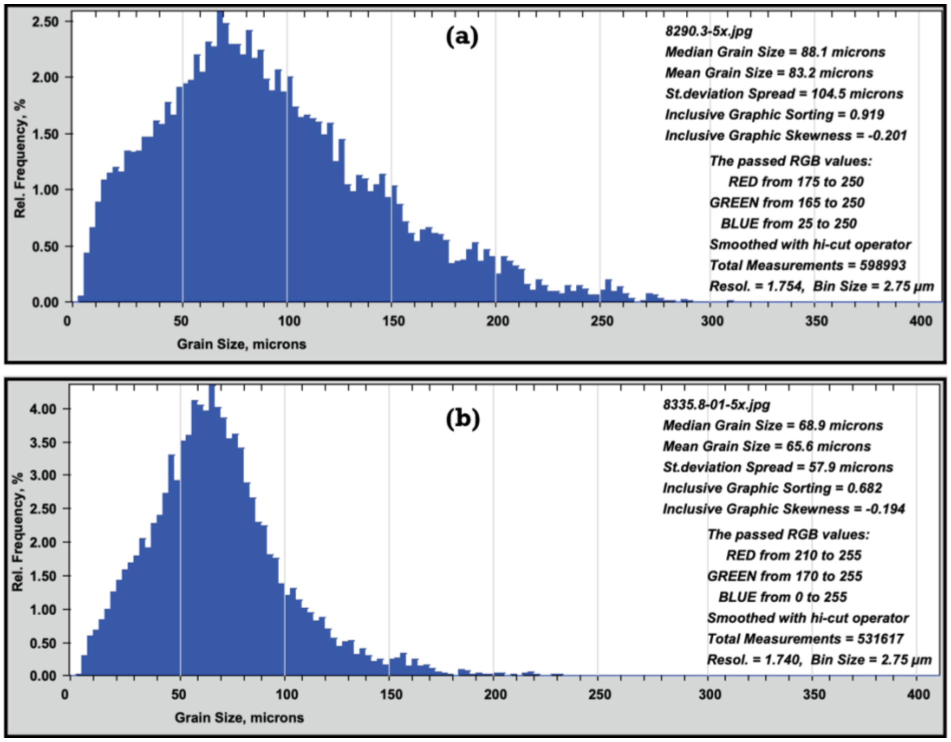

Figure 3. A comparison of GSDs obtained from the Hulett Sandstone photomicrograph images from 8,290-feet depth (a) and from 8,335-feet depth. Note the same grain-size grade for both images (very fine sand) but significantly different spread of standard deviations and sorting parameters.

Depth, feet	Mean grain size M_z, µm	Grain size description	Spread σ, µm	Sorting, Phi units	Sorting description	Core Measured porosity, %	Core Measured Perm., mD
8276.6	120	very fine sand	143	0.854	moderately sorted	6.27	0.011
8282.8	127	fine sand	144	0.832	moderately sorted	10.28	0.124
8285.8	69	very fine sand	85	0.898	moderately sorted	6.25	0.062
8286.3	158	fine sand	194	0.909	moderately sorted	5.55	0.014
8287.3	134	fine sand	147	0.843	moderately sorted	4.68	0.011
8288.3	173	fine sand	210	0.868	moderately sorted	7.33	0.025
8290.3	83	very fine sand	105	0.919	moderately sorted	6.63	0.011
8290.8	179	fine sand	210	0.841	moderately sorted	7.01	0.037
8294.6	94	very fine sand	115	0.859	moderately sorted	7.18	0.017
8298.1	138	fine sand	180	0.917	moderately sorted	8.81	0.046
8300.5	155	fine sand	200	0.892	moderately sorted	6.93	0.024
8304.8	78	very fine sand	98	0.894	moderately sorted	7.80	0.045
8307.7	74	very fine sand	93	0.913	moderately sorted	9.14	0.124
8312.6	70	very fine sand	90	0.952	moderately sorted	10.33	1.442
8316.9	132	fine sand	145	0.810	moderately sorted	6.84	0.013
8321.6	74	very fine sand	72	0.746	moderately sorted	15.25	10.875
8324.4	68	very fine sand	63	0.702	moder. well sorted	13.98	10.282
8327.9	77	very fine sand	80	0.768	moderately sorted	15.09	11.294
8335.8	66	very fine sand	58	0.682	moder. well sorted	14.41	4.534
8336.2	74	very fine sand	60	0.655	moder. well sorted	13.70	1.928
8340.3	63	very fine sand	56	0.691	moder. well sorted	17.28	6.693
8348.9	57	coarse silt	61	0.788	moderately sorted	12.08	0.122
8351.3	54	coarse silt	60	0.822	moderately sorted	5.51	0.013
8357.3	43	coarse silt	45	0.764	moderately sorted	5.36	0.011

Table 1. A comparison of parameters associated with automatically derived grain-size distributions from analyses of digital images and the corresponding core-measured porosity from the Hulett sandstone samples. The highlighted area corresponds to a relatively well-sorted grain size distributions matching high-porosity core samples.

Depth, feet	Mean grain size M_z, µm	Spread σ, µm	# samples
8304.8	79	36	150
8307.7	81	52	50
8312.6	83	32	50
8324.4	84	62	50
8327.9	87	53	100
8335.8	78	42	50
8340.3	75	38	100
8348.9	49	35	50

Table 2. Statistical parameters derived from manual measurements of grain diameters in thin sections from the Hulett sandstone samples.

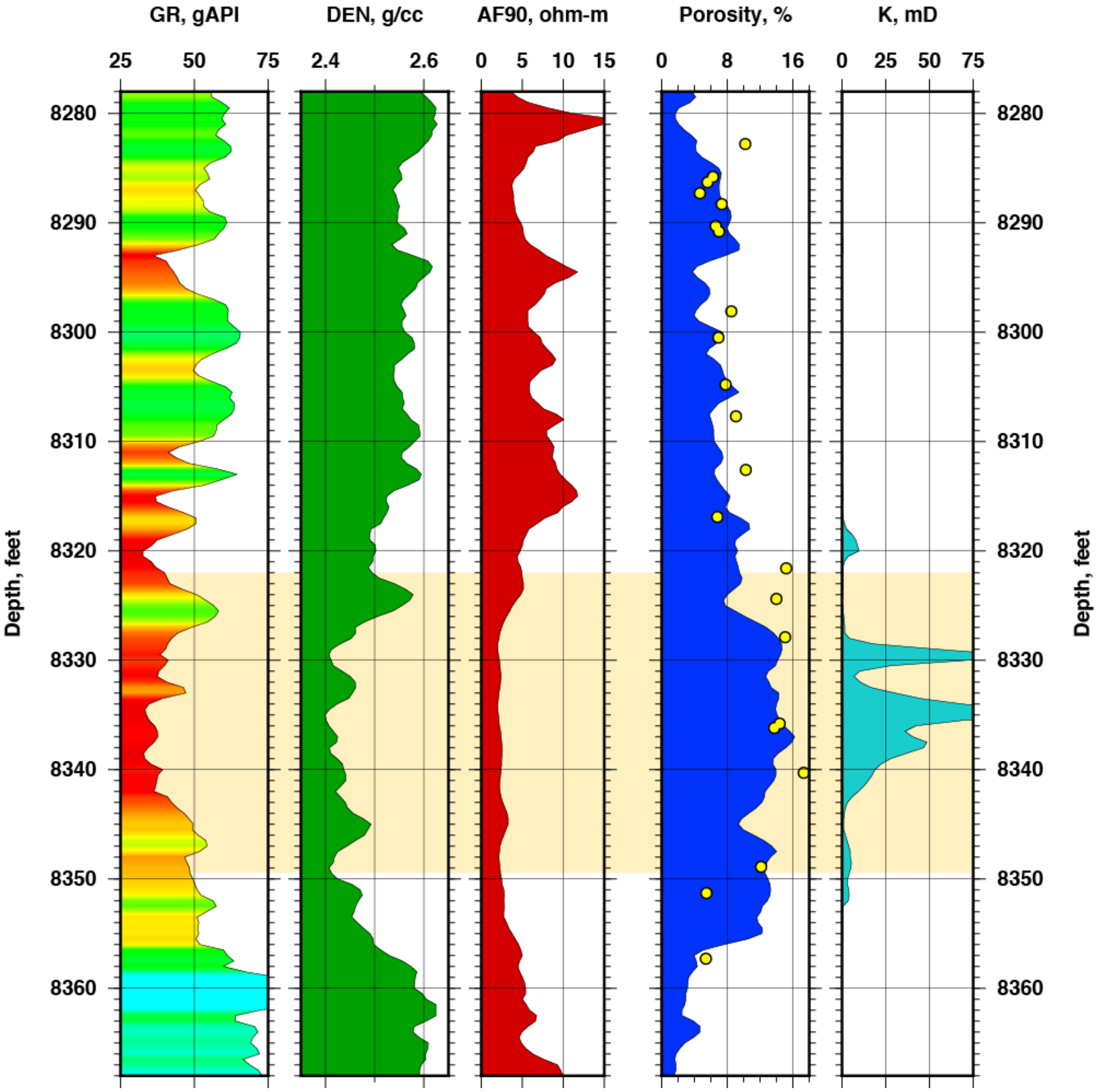

Figure 4. A composite log display for the Hulett Sandstone stratigraphic interval of the PRB #1 well. From left to right, the panels are gamma-ray log, density, deep resistivity, CMR-T2 porosity, and the Timur/Coates permeability. The yellow circles in Porosity panel indicate core-measured porosities. The color-coded gamma-ray values increase from left (red color) to right (green and cyan colors). The highlighted area corresponds to a relatively well-sorted grain size distributions from petrographic analysis of the digital thin section images (compare to Table 1).