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STUDY OF DEPENDENCE BETWEEN CLAY MINERAL DISTRIBUTION AND SHALE VOLUME IN RESERVOIR ROCKS USING GEOSTATISTICAL AND PETROPHYSICAL METHODS

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Abstract. Identify and obtain a detailed understanding of shale and its clay minerals in three segments; exploration, drilling and reservoir in the oil industry are very important. The study of the formation clay minerals in terms of depth and layers of earth is done through X-ray tests on samples taken from the reservoir which in comparison with logging requires a lot more time and cost and also can't provide continuous results because continuous sampling from the whole well is not possible. NGS (Gamma-ray Spectrometry) log is used to identify formation clay minerals that is an indicator of three radioactive elements thorium, uranium and potassium and the amount of each of these elements and according to amount of each of these elements and their ratio gives a description of clay minerals of each zone. CGR log represents the sum of two elements Thorium and potassium that are present in the shale and uranium has no effect on it. The CGR log is usually used as a shale indicator and it is an essential tool for determining the Shale volume in well logging operation. In this study the relationship between shale volume shown by the CGR log and the type of formation clay mineral was investigated. A very clear relationship between the shale volume and formation clay minerals was observed. In intervals with low shale volume the amount of active clay minerals, especially montmorillonite was higher and in intervals with high shale volume, inactive clay minerals were more. In order to investigate the spatial relation between the logging data, frequency distribution and correlation between logging data was studied. By using logging data and identifying the type of clay minerals in each zone and also the spatial correlation between logging data a suitable program for drilling and exploitation of oil fields in different areas can be proposed.

Keywords: clay minerals, logging, shale volume, frequency distribution, variogram.

Introduction

Approximately 75% of Earth's upper crust is composed of sedimentary rocks and the greater part of the world's hydrocarbon reserves can be extracted from these rocks. In drilling oil and gas wells, we come in contact with various sedimentary rocks including sandstone, carbonate rocks and mudstones. The shale has formed the thickest sedimentary sequences in geology courses. Mineralogical composition of shale is not fixed but can be said that clay minerals, quartz, feldspars, carbonates, amorphous silica, pyroclastic materials, and organic matter of shale are frequently shale components. Shale has been formed of silt (50%) and clay minerals (15%). Other minerals present in the shale are commonly known as authigenic minerals. Among these clay minerals have significant

effects on the physical behavior of shale in contact with aqueous solutions. Among the clay minerals, illite typically seen more than other minerals and chlorite are common. The smectite can be seen in the younger rocks and Mesozoic rocks and kaolinite is a pretty rare clay mineral. Changes in the mineralogical composition of shale affects other properties of it, therefore shale properties are highly variable (Ellis, Singer 2008). The wide variations in shale properties are very important in exploration, drilling, and well completion and most important of all in formation evaluation using well logging. The difference between shale and other components of rock is due to the presence of clay minerals which have different chemical and physical properties with other minerals. The presence of shale in hydrocarbon reservoir has a large impact on

estimation of reservoir storage and production rates. Presence of clay in shale makes it difficult to determine porosity and water saturation. Small amounts of clay in porous media can heavily influence the permeability (Prothero, Schwab 2004). Without adequate information about the type of clay minerals in the rock it is possible to encounter fundamental problems by using unsuitable drilling mud.

Clay minerals due to their own characteristics such as softness, plasticity, swelling and ion exchange have always been emphasized and the need to review and study their properties in various sciences including geological, geotechnical, and oil drilling is inevitable. The importance of shale and clay minerals in petroleum geology and reservoir studies can be classified in three sections: exploration (source rock, cap rock, etc.), drilling (drilling mud, drilling problems and prospects in shale, etc.) and reservoir (effect on reservoir quality, capillary pressure, electrical logs, etc.). Hence the evaluation of behavior and performance of shale and its clay minerals in different conditions and also dealing with problems arising from them is essential.

1. Clay minerals

Clay minerals are composed of particles with small crystals and based on crystalline structure are classified into different groups. Due to improper sorting in evaporite sedimentary environments, most sandstone reservoirs are containing clay minerals. A large part of the sedimentary sequences are clay minerals and their origin can be the following:

- Clay minerals that were derived from older rocks and sediments.
- Clay minerals which are formed from conversion and alteration in unstable minerals, due to changes in environmental conditions (such as PH and temperature changes).
- Clay minerals that are formed in situ form the composition of pores water.

There are hundreds of clay minerals that based on structure and composition; they all can be divided into five groups: kaolinite, and mica (illite), smectite (montmorillonite), chlorite and vermiculite (Murray 1991).

1.1. Kaolinite

This type of clay minerals consists of two layers clay with structural formula $\text{Al}_2\text{O}_3 \cdot 2\text{Si}_2\text{O} \cdot 2\text{H}_2\text{O}$. Its structure consists of a tetragonal silica sheet and an octagon alumina sheet. Kaolinite particles are connected with

hydrogen bonding and the distance between layers is about 2.76 Å. This hydrogen bond is strong enough to separate the water from the clay surface. As a result, kaolinite is non-swelling clay and has a CEC range of 3–15 meq/100g (Murray 1991; Kale 2009).

1.2. Chlorite

Chlorite is 3-layers clay with a structural formula $\text{Mg}_5(\text{Al}\cdot\text{Fe})(\text{OH})_8(\text{Al}\cdot\text{Si}_4)\text{O}_{10}$ that are separated by a layer of brucite. There is a strong bound between the layers hence the chlorite is a typically non-swelling clay mineral. Cation exchange capacity of chlorite is between 10 to 40 meq/100g (Murray 1991; Kale 2009).

1.3. Illite

Illite is a hydrous mica and 3-layers clay with structural formula $\text{K}\cdot\text{Al}_2(\text{OH})_2(\text{Al}\cdot\text{Si})_3(\text{O}_2\text{OH}_{10})$. Illite is structurally similar to montmorillonite. Due to not having an expandable network, water cannot be placed between layers of illite. Illite has formed by an octagon alumina layer that placed between two tetragonal silica layers. Electrical deficiency caused by the replacement of silicon atoms with aluminum atoms is compensated by the placement of potassium in the layers. Sometimes the replacement of silicon by aluminum is limited and potassium will be replaced with bivalent cations such as potassium, calcium and magnesium in which case the illite may tend to be swollen like montmorillonite. Illite CEC is in the range between 10 to 40 meq/100g (Murray 1991; Kale 2009).

1.4. Smectite (Montmorillonite)

Smectites are 3-layers Clay with structural formula $(\text{Mg}\cdot\text{Ca})\text{O}\cdot\text{Al}_2\text{O}_3 \cdot 5\text{SiO}_2 \cdot \text{NH}_2\text{O}$ that also including montmorillonite. This group includes an octagonal alumina sheet which is surrounded by two tetrahedral silica sheets. Electrical imbalance due to the possible replacement of aluminum atoms with magnesium atoms and iron in the middle layer caused the cations accumulation on the surface of particles. This cation can be monovalent or bivalent. Cation exchange capacity determines the swelling level of montmorillonite. CEC range in the smectite is between 60 to 150 meq/100g (Kale 2009).

1.5. Mixed clay layers

Mixed-layer clay minerals are materials in which different kinds of clay layers alternate with each other. Commonly described mixed-layer clays include: illite-vermiculite, illite-smectite, chlorite-vermiculite

(corrensite), chlorite-smectite, and kaolinite-smectite. Mixed-layer clays can form by weathering involving the removal or uptake of cations (e.g. K), hydrothermal alteration, or removal of hydroxide interlayers, and, in some cases, may represent an intermediate stage in the formation of swelling minerals from non-swelling minerals or vice versa (Kale 2009).

Each of these clays has its own characteristics and somehow they cause errors in the petrophysical evaluation process. Some of the important and significant effects on petrophysical parameters are:

- Reducing the permeability and porosity.
- Displacement of the rock grains when the shale begins to lose water.
- Increasing in water absorption during the hydration process and contact with water (i.e., formation of mud filtrate which reduces the permeability and effective porosity).
- Negative impact on sampling or logging tools (for example, a severe impact on neutron porosity due to hydrogen in clay minerals)

Unique effects of clays on logs are due to their layered structure. Water that is trapped between the layers affects the conductivity and porosity measurements but it is not a part of the effective porosity. The presence of negative charges on the clay surface allows them to attract cations (Sondhi 2011; Kale *et al.* 2010). Cation exchange capacity (CEC) is an intrinsic factor of clay minerals and it is related to their specific surface area. Clays have high specific surface area, which expresses their physical properties (Kale *et al.* 2010; Hunnur 2006). Specific surface area of some clay minerals is listed below in Table 1:

Table 1. Specific surface area of various clay minerals

Clay minerals	Specific surface area (m ² /G)
Smectite	700–800
Illite	113
Chlorite	42
Kaolinite	15–40

2. Data used and the study area

In this study logging data has been used to examine the distribution of clay minerals in shaly zones. The data used, including Calliper log, sum Gamma Ray log (SGR), Corrected Gamma Ray log (CGR), Photoelectric effect (PEF) and Natural Gamma Ray Spectrometry log (NGS). These data have been obtained from Marun field, one of the most important

fields in southwest of Iran. Oil fields in southwest Iran have carbonate formations which generally formed of dolomite, limestone and laminated shale. However, in some fields layers of sandstone between carbonate rocks have been observed.

3. Study of wells clay minerals

In this study, three random wells of Marun field have been studied. Formation's clay minerals were examined by NGS log. Figure 1 shows clay minerals identification crossplots in zones with low shale volume. Clay minerals identification crossplots of zones with high shale volume are showed in Figure 2.

In these wells shaly and non-shaly zones were identified by using CGR log and clay minerals in each of these zones were evaluated. Figure 3 shows the correlation of CGR logs and Th/K ratios in studied wells. Among these three wells in zones with a high percentage of shale, Well (C) was distributed more uniformly than the other two samples. It was observed that in areas with Gamma Ray above 50 API, active clay minerals such as montmorillonite rarely exist. In areas with low shale volume (i.e. areas with Gamma Ray less than 50 API); minerals such as montmorillonite are widely observed. Consequently a direct relationship between shale volume and type of clay minerals can be observed. Results of CGR logs obtained from these wells are shown in the Table 2.

3.1. X-Ray Diffraction

In this study for more accurate results, by using XRD experiments the type of clay minerals in cores taken from these three wells has been determined (Fig. 4). The study of cores also indicated a high percentage of montmorillonite in areas with low gamma ray values (areas with low shale volume) and a high percentage of illite in areas with high shale volume (High CGR values). Results of XRD tests on these cores are shown in Table 3.

3.2. Frequency Distribution

In general, geostatistics is the study of the change of phenomena in space or time. The essential components in geostatistics are:

- (1) Evaluation of the distribution of data (normalization analysis).
- (2) Variogram analysis.
- (3) Kriging.
- (4) Stochastic simulation (Abdideh, Bargahi 2012).

Most of geostatistical studies have assumed that the data distribution is normal. However, it is difficult to obtain a normal exponential distribution histogram in the reservoir due to other variable environmental parameters such as lithology (Diggle 2003; Webster, Oliver 2007). Normal distribution curve is a bell-shaped curve with zero skewness and kurtosis equal to 3 (Webster, Oliver 2007; Deutsch 2002). Preliminary review of data (CGR data of the three wells A, B and C) didn't show normal distribution. By using logarithmic normalization method, the most normal distribution of data for examining the structural relationship between CGR values obtained. Skewness is usually

occurs due to higher level of frequency distribution of data in the lower or upper boundary (Deutsch, Journal 1998). Positive skew means that the mass of the distribution is concentrated on the left of the figure. It has relatively few high values. The distribution is said to be right-skewed, right-tailed, or skewed to the right. In negative skew the left tail is longer; the mass of the distribution is concentrated on the right of the figure. It has relatively few low values. The distribution is said to be left-skewed, left-tailed, or skewed to the left (Houlding 2000; Christakos 2001).

By using logarithmic normalization method, the data of Well (A) in normalized form had a positive skew 0.82,

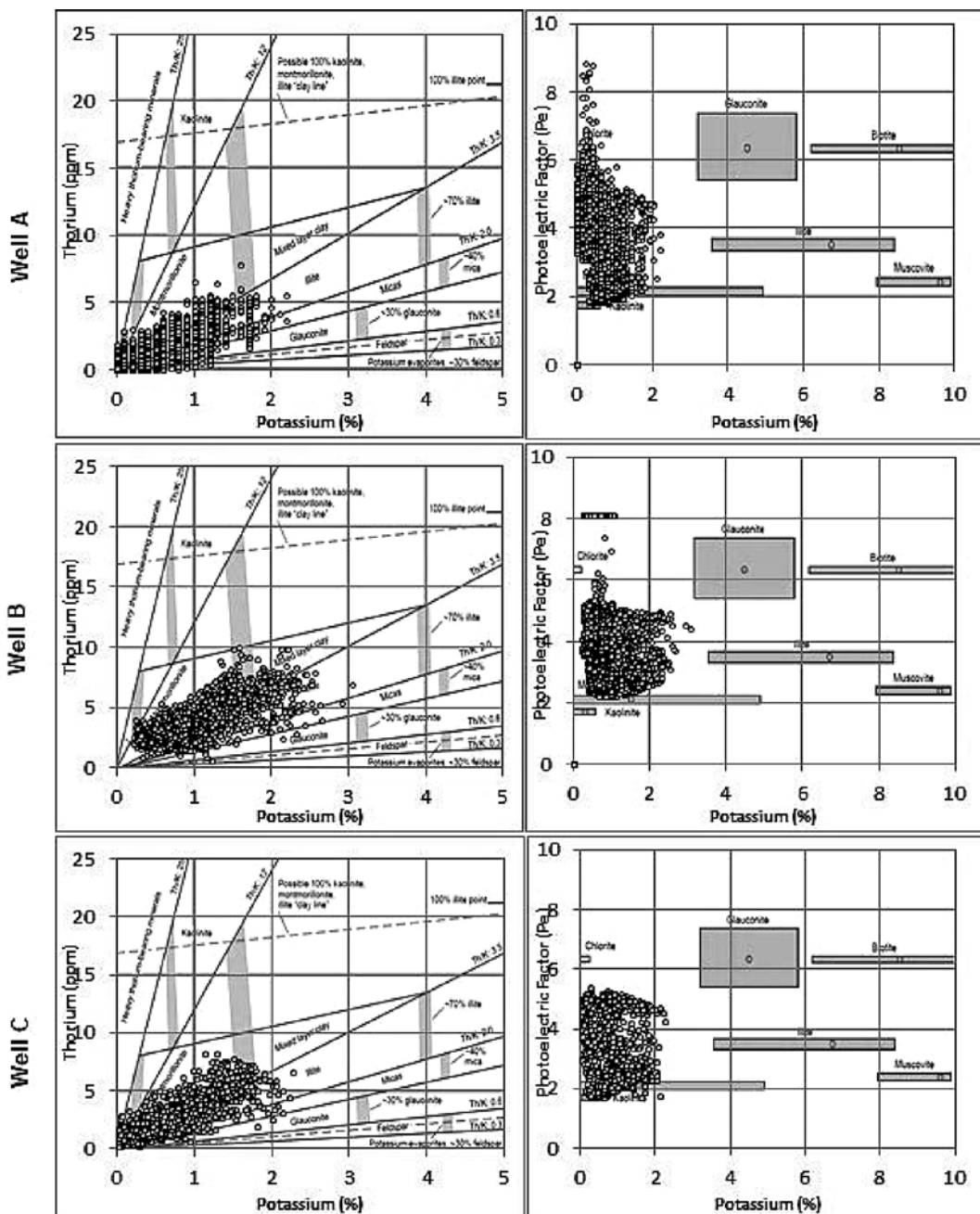


Fig. 1. Clay minerals identification cross plots of zones with Gamma-ray less than 50 API

well (B) had a positive skew 0.25 and well (C) had positive skewness equivalent to 0.16 (Fig. 7). Skewness of these histograms showed that areas with high percentage of shale have less frequency distribution. However this indicates that the distribution of active clay minerals in these wells is more than inactive minerals.

3.3. Wells Variograms

Variogram is used as a tool for determine the data spatial correlation by examining the difference between adjacent values (Abdideh 2014). Variogram can be plotted separately for each area of the well and structural correlation between data in different zones

can be investigated. The sill is indicative of the overall variance.

Experimental Variograms often continuously increase with lag distance; however, the Variogram is not restricted to such monotonic form and decreasing segments or cyclicity can be observed (Remy *et al.* 2009; Hansen *et al.* 2006).

Non-monotonic Variogram structures are identified as “hole-effect” structures. These structures may be bounded by a sill or occur without a sill, be dampened or undampened and be isotropic or anisotropic (Fig. 5). Although hole-effect structures are often ignored, their presence provides valuable information

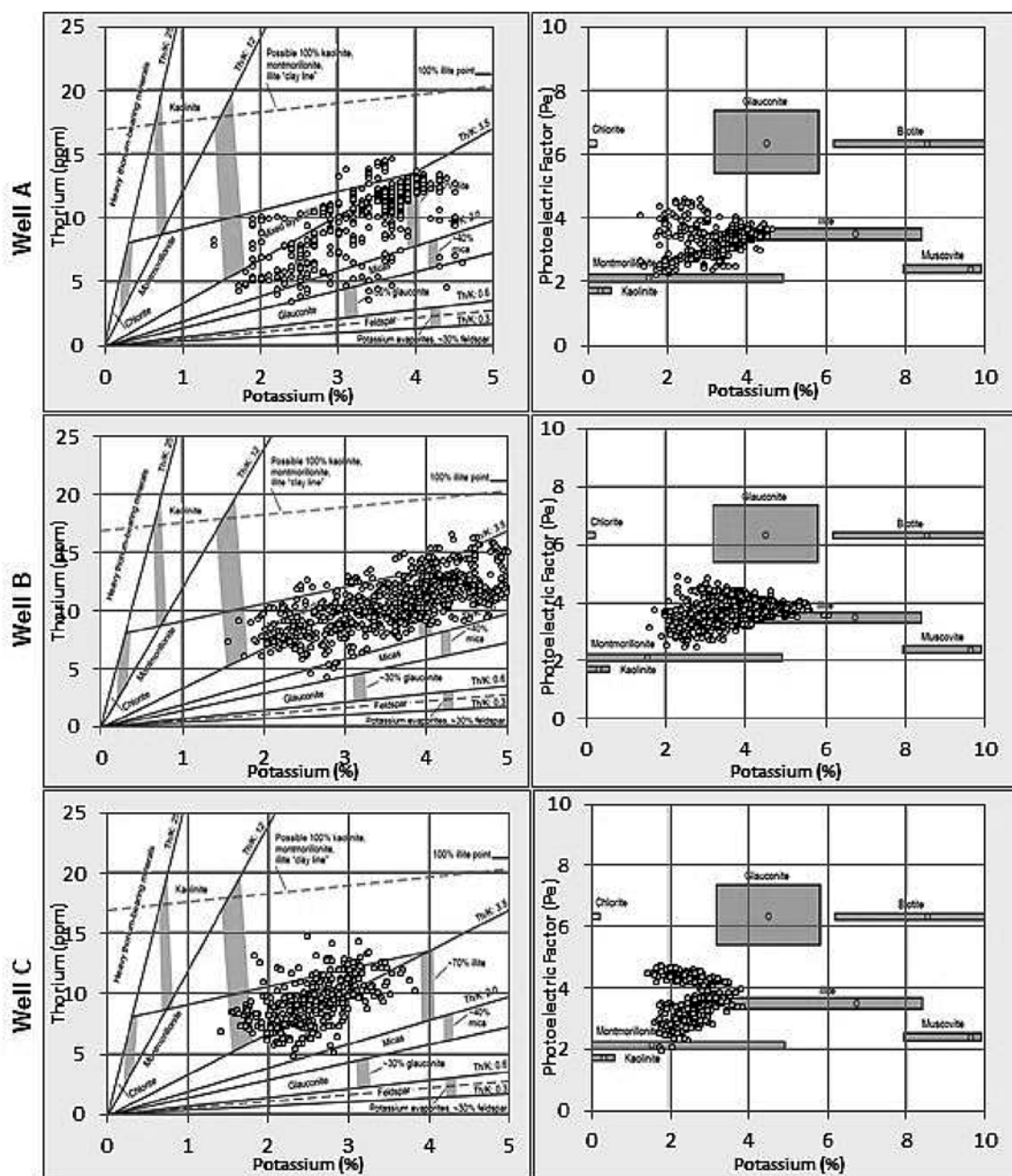


Fig. 2. Clay minerals identification cross plots of zones with Gamma-ray above 50 API

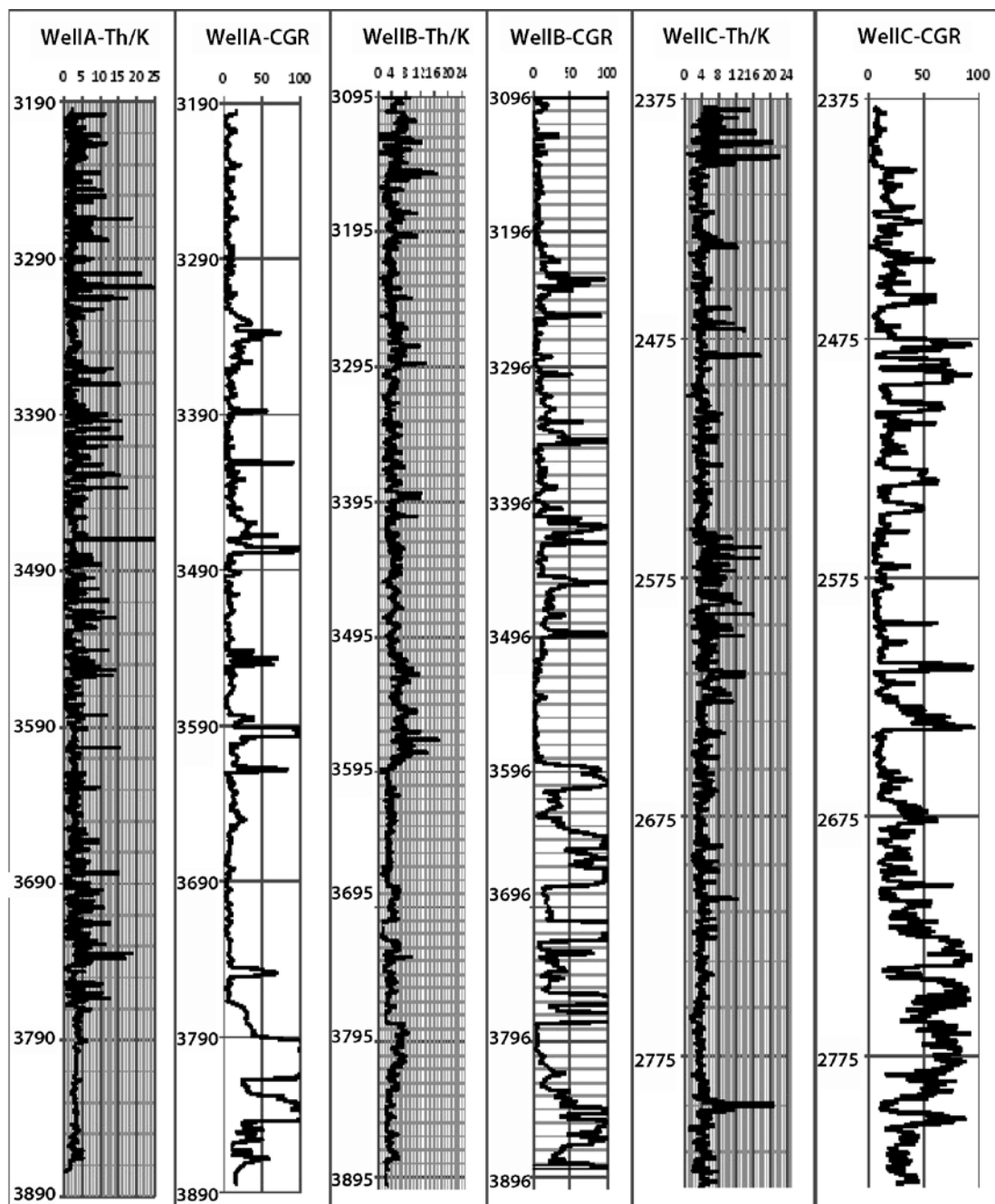


Fig. 3. Correlation of CGR logs and Th/K ratios in studied wells

Table 2. Results of clay minerals identification cross plots in areas with high and low shale volume

Clay Minerals	Well (A)		Well (B)		Well (C)	
	CGR>50API	CGR<50API	CGR>50API	CGR<50API	CGR>50API	CGR<50API
Illite	78.2%	8%	82.2%	12%	40.8%	14%
Mixed Layer Clay	15%	4%	17%	18%	59%	13%
Kaolinite	0%	5%	0%	0%	0%	0%
Glauconite	0.9%	5%	0.3%	0%	0%	3%
Micas	5%	3%	0.5%	2%	0.2%	4%
Montmorillonite	0.9%	60%	0%	67.5%	0%	51%
Chlorite	0%	15%	0%	0.5%	0%	15%
Total recorded points	446	3550	998	4062	635	2322
Error points	28	221	136	302	44	74

concerning spatial variability hole-effect structures most often indicate a form of cyclicity or periodicity, which is a common and legitimate spatial characteristic in geology (Remy *et al.* 2009; Hansen *et al.* 2006). Ignoring these nonmonotonic structures may result in unrealistic heterogeneity models that do not reproduce the observed patterns of variability.

The form and character of hole-effect structures is indicative of the spatial setting. After observing many spatial configurations and their respective Variograms, the following generalizations are reached (Fig. 6) (Hansen *et al.* 2006):

Regular strata: (1) the lag distance of the first peak is an indication of the average thickness of the

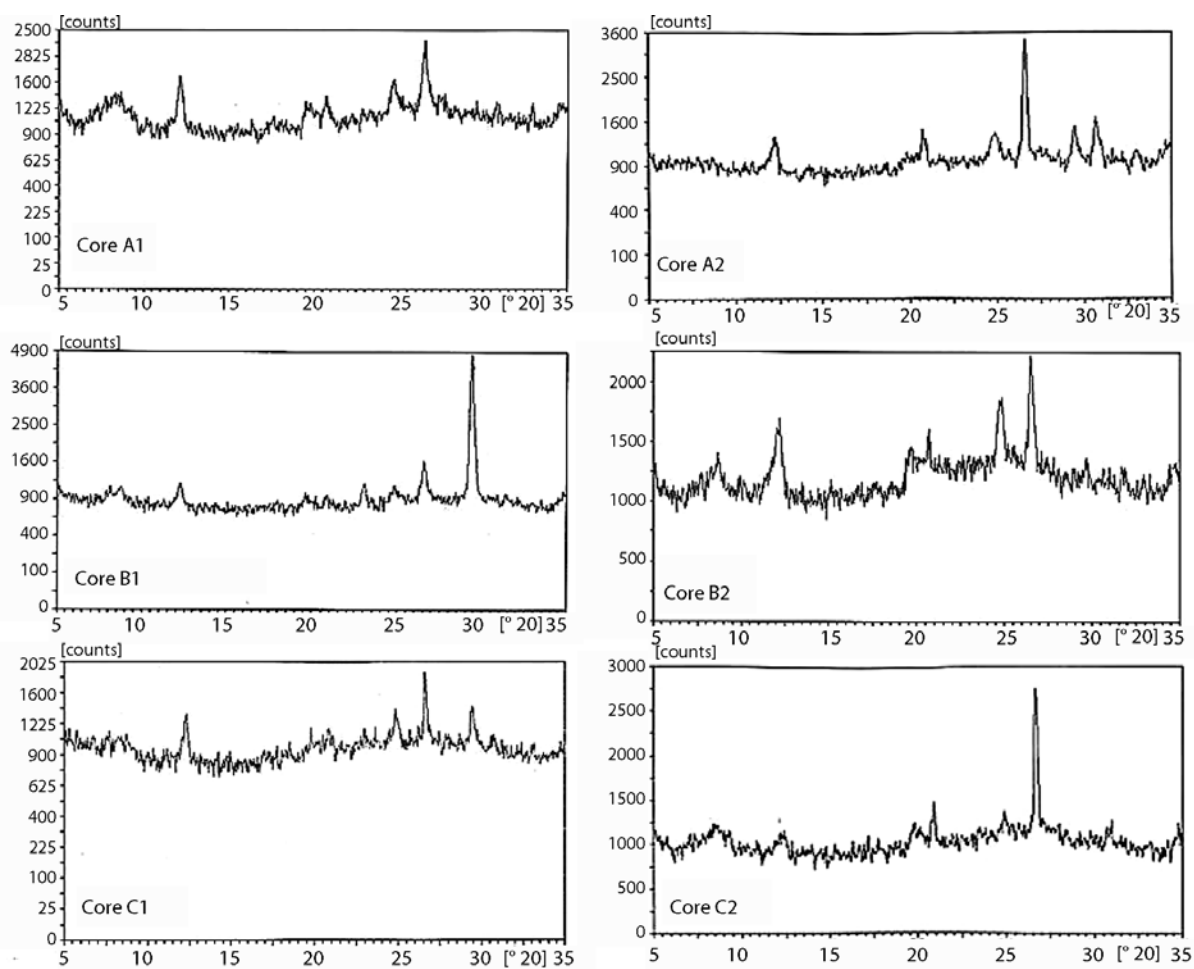


Fig. 4. X-ray diffraction diagrams in cores taken from these wells

Table 3. Results of XRD tests on cores

	Core A1	Core A2	Core B1	Core B2	Core C1	Core C2
Depth	3802 m	3695 m	3510 m	3605 m	2772 m	2584 m
CGR	CGR>50API	CGR<50API	CGR<50API	CGR>50API	CGR>50API	CGR<50API
Illite	35%	17.8%	9.9%	45%	33.1%	20.3%
Montmorillonite	15%	60.2%	49.7%	15%	19.4%	40%
Kaolinite	10%	5.5%	10.6%	17%	22%	10.4%
Chlorite	15%	-	9.9%	13%	-	--
Illite-Montmorillonite	25%	6.5%	-	10%	15.4%	14.2%
Montmorillonite-Chlorite	-	-	19.9%	-	-	-
Vermiculite	-	10%	-	-	-	15.1%
Sepiolite	-	-	-	-	10.1%	-

bedding, and (2) the lag distance of the first trough is twice the “bed thickness”.

Irregular strata: (1) cyclicity is observed if there is a continuously repeating series and the peaks are attenuated over the distribution of bedding widths in each

unit sequence, and (2) in the absence of a perfectly repeating series, dampening occurs.

After examining the frequency distribution of normalized data, the overall Variogram of wells were plotted (Fig. 7). Minimum hole-effect was observed in

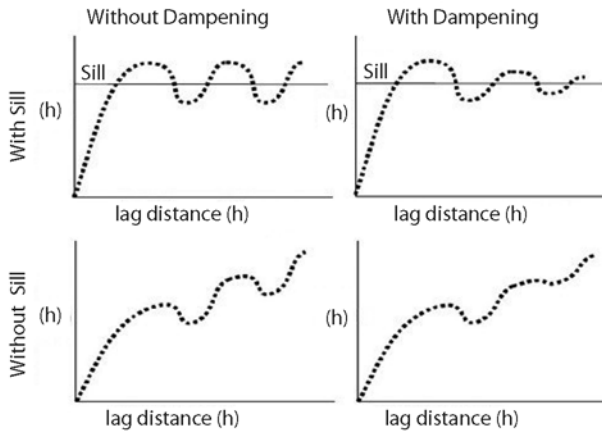


Fig. 5. Hole effect configurations (Deutsch 2002)

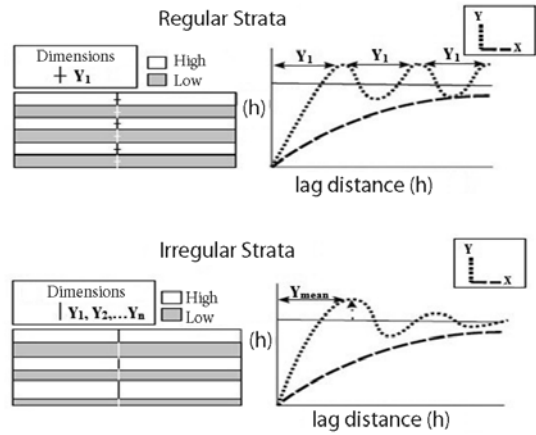


Fig. 6. Hole effect interpretations in regular strata and irregular strata based on indicator data (Deutsch 2002)

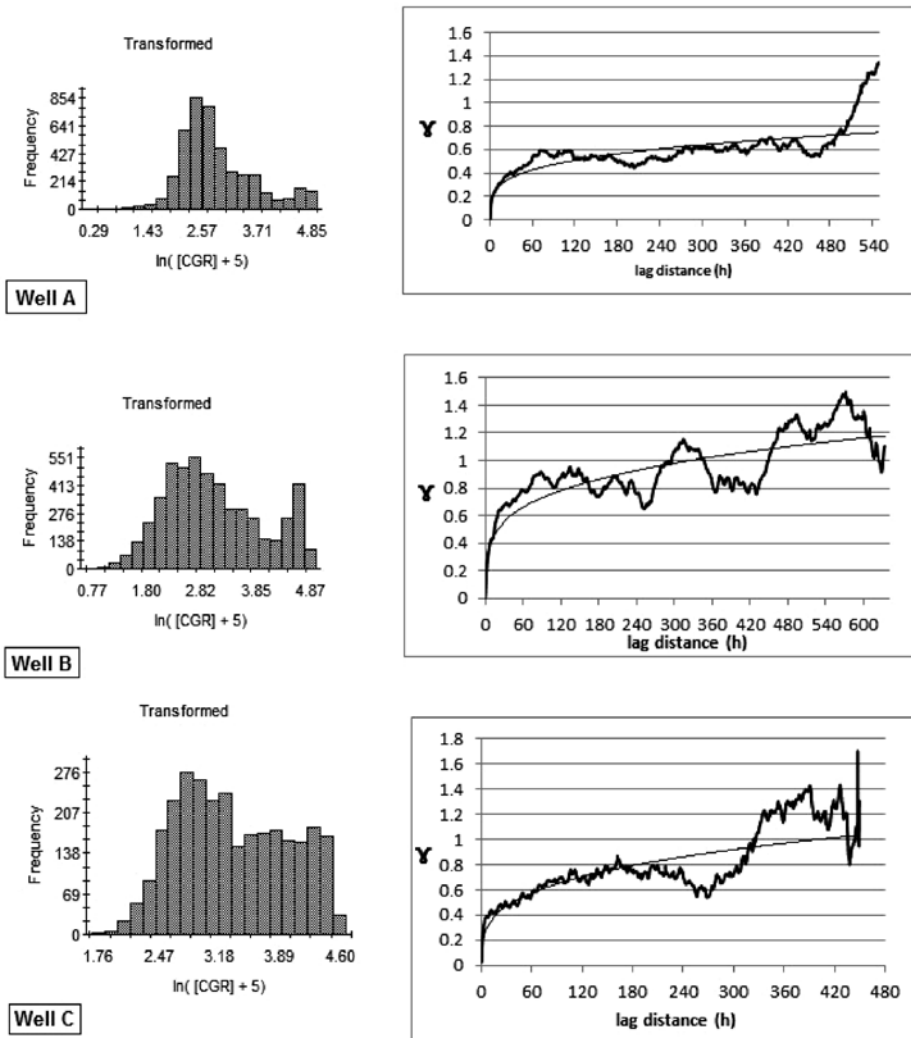


Fig. 7. Histograms and Variograms of studied wells

well (A) that had the best histogram. This well had an undampened Variogram with sill, which represents a uniform distribution of high grade and low grade shale layers in the well.

Greatest and most obvious hole-effect was seen in well (B). Its Variogram was without sill so no overall variance has been obtained. This indicated that the distribution of high and low grade shale layers is not uniform.

In well (C) there was hole-effect only in a few areas that were far from the origin; however Variogram at lag distances far from the origin had no sill. This means that dissonance occurs in regions far from the origin. By observing these Variograms an overview of CGR data correlation and changes in the layers grade was obtained.

Conclusions

In Marun field Oil-based mud is used. Distribution of clay minerals in each sample was almost similar to each other. The most abundant clay mineral in areas with more than 50 API Gamma-ray in the two wells A and B were belonging to illite mixed-layer clay minerals in wells (C) had the highest frequency. The amount of other minerals in these areas was very low. In areas with Gamma-ray less than 50 API, montmorillonite rate was very high and compared to areas with high Gamma-ray; there was a very significant difference. Amounts of illite and mixed-layer clay minerals in these areas were much lower than areas with a high shale volume. Montmorillonite is the major swelling clay mineral in contact with water and most of well bore chemical instability in drilling shale prospects is due to the presence of this clay mineral. As a result, according to the relationship between CGR log and the type of clay minerals it was observed that in areas with low percentage of shale active minerals such as montmorillonite are very common and areas with a high percentage of shale contain more illite.

Frequency distribution was investigated to identify the existing data and obtain an understanding of how CGR values distributed in the entire wells. Thus it became clear that the distribution of active clay minerals is greater than inactive clay minerals in these wells. The plotted Variograms have showed a close relationship between the distribution of clay minerals and the layers grade. These Variograms determined the effective range of data and the correlation between them. With identification and evaluation of clay

minerals and shale in the field, more accurate planning for drilling operations in the field can be obtained.

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