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GEOTECHNICAL ENGINEERING

Mechanical Properties as Predictors of Sand production: Case Study of the Mamuniyat Reservoir, Murzuq Basin-Libya

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ABSTRACT

Sand production is one of the instability issues in oil reservoirs within the oil industry. This research paper seeks to establish a methodology for detecting sand production in the Mamuniyat Reservoir (Upper Ordovician) across multiple oil fields in the northwest Murzuq Basin, Libya. Well logging data from five oil wells (1, 2, 3, 4, 5) in Fields 1 and 2 have been processed to calculate the Sand Production Indicator (SPI), which is based on the estimation of petrophysical and mechanical properties. The Mamuniyat reservoir is classified in ascending order into Clayey Mamuniyat and Clean Mamuniyat sandstone, based on a 25% shale baseline. Montmorillonite and illite are identified as the dominant clay minerals, as recognised by natural gamma-ray spectrometry (NGS) in the Mamuniyat reservoir. Additionally, the reservoir is classified from very low strength (E) to high strength (B) based on uniaxial compressive strength (UCS). The shale content (Vsh) has noticeable changes in the UCS, cohesion (Co), and friction angle (Φ) of the Clayey Mamuniyat sandstone rather than the Clean Mamuniyat sandstone, which is about 70 MPa, not exceeding 30 MPa, and 20 degrees of the UCS, Co, and Φ, respectively. Whereas the Clean Mamuniyat sandstone is ranged from 80 to 110 MPa of the UCS, about 20 MPa of Co and close to 40 degrees of Φ. Accordingly, the studied reservoir does not meet the threshold criterion for sanding problems according to the standard shear to compressibility modulus ratio (G/Cb), which is less than 8×10^{11} psi².

Keywords: Sand production indictor; Mamuminyat reservoir; Mechanical properties; Petrophysical; Murzuq basin; Libya.

Propiedades mecánicas como predictores de la producción de arena: caso de estudio del reservorio de Mamuniyat, en la cuenca de Murzuq, Libia

RESUMEN

La producción de arena es uno de los factores inestables de las reservas de petróleo. Este artículo de investigación busca establecer una metodología para detectar la producción de arena en el reservorio de Mamuniyat (Ordovícico Tardío) a lo largo de múltiples campos de petróleo en la cuenca de Murzuq, al noroeste de Libia. Se procesó la información de perforación de cinco pozos petrolíferos (1, 2, 3, 4, 5), en los campos 1 y 2, para calcular el Indicador de Producción de Arena (SPI, del inglés Sand Production Indicator), el cual se basa en las propiedades petrofísicas y mecánicas. El reservorio de Mamuniyat tiene clasificación de orden ascendente dentro de las areniscas arcillosas y las limpias de Mamuniyat, de acuerdo con su línea de base del 25 % de esquisto. Los minerales de montmorillonita e illita se identificaron como los dominantes, según se reconoce a través de la espectometría de rayos gamma natural en el reservorio de Mamuniyat. Adicionalmente, el reservorio se clasifica en los rangos de fuerza muy baja (E) y hasta de fuerza muy alta (B), de acuerdo con la prueba de resistencia a la compresión uniaxial (UCS). El contenido de esquistos (V sh) implica cambios significativos en la prueba UCS, en la cohesión (Co), y en el ángulo de fricción (Φ) de las areniscas arcillosas de Mamuniyat, más que en las areniscas limpias del reservorio, cuyas unidades son de 70 MPa en el índice UCS, sin superar los 30 MPa en la cohesión y de 20 grados en el ángulo de fricción. Mientras que las areniscas limpias tienen un rango de 80 a 110 MPa en el índice UCS, cerca de 20 MPa de cohesión y cerca de 40 grados en el ángulo de fricción. De acuerdo con esto, el reservorio estudiado no cumple con el margen de criterio para los problemas de producción de arena según la relación estándar entre corte y módulo de compresibilidad (G/Cb), que es menos de $8X10^{11}$ psi².

Palabras clave: Indicador de producción de arena; reservorio de Mamuniyat; propiedades mecánicas; petrofísica; cuenca de Murzuq; Libia

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Introduction

Sand production is defined as a yield of small or large amounts of sand together with the reservoir fluids in production wells. Most of the clastic oil and gas reservoirs contain sandy materials which may enhance problems at production stage of reservoir life history. In addition, operational cost of production, maintenance, as well as safety and environmental impacts are main reasons of the sand production investigation of wellbores (Moore, 1994). Mainly, two different mechanisms to understand the sand production occurring; mechanical instability and degradation of material around the wellbore, and hydromechanical instability which is related to pressure gradient of fluid flow within the porous media itself (Rahmati et al., 2013). Hence, Issa et al. (2022) reviewed sand production problem and remedial techniques and Veeken et al. (1991) summarized parameters influenced by sand production.

Many oil companies suffer from the sand production and try to get a solution that ensures continuity of reservoir productivity with fewer reservoir instability issues. Thus, Ben Mahmud (2020) demonstrates application techniques of sand production, evaluated risks of sand management and display a smart control of the sand production. Whereas, influence of oriented perforation on the flow rates and sand grain size taken in consideration to inhibit sand production of development wells in Krishna Godavari basin (Southern India) by finite element model (Kukshal et al., 2024). While, Dong et al. (2013) utilized logging data to calculate mechanical properties, which indicated that the Kexia formation is prone to sand production. Further, Khamehchi and Reisi (2015) used the shear modulus, bulk compressibility, and the ratio between shear modulus and bulk compressibility to estimate sand production potential at Kaki and Bushgan oil fields in Iran. They founded that production with a high water cut requires higher threshold value for G/C_b ratio greater than 0.8×10^{12} psi^2. Thus, discovering of the sand production problem in early stages of well production life allows to design and choose a suitable solution for its controlling and to make a strategic plan in both drilling and production future development wells.

In the Libyan region, Qiu et al. (2008) implemented the Sand Management Solution (SMS) in the Sarir field, operated by AGOCO, to address sand production issues in over 400 wells. Similarly, Elhaddad (2019) analyzed sand production in the Amal Oil Field, Block 12, in the Sirte Basin, demonstrating that Halliburton's modern three-layer filter gravel provided an effective solution to the reservoir's problem. Based on these studies, the estimation of the Sand Production Indicator (SPI) for the Mamuniyat reservoir in the Murzuq Basin (southwest Libya) was conducted for five wells across two oil fields. Additionally, the evaluation of the reservoir's dynamic elastic properties is crucial for understanding the mechanical behavior of in-situ stresses during well development operations. This study highlights the utility of well log data, which offers a quick, time-saving, and efficient method for achieving the research objectives.

Geological Background

Tectonic development of Libya has been generally outlined by researchers who summarized their work as (Hallett and Clark-Lowes, 2016). In early Palaeozoic Era, the late Pan-African activity produced a series of broad north-south troughs and swells. These troughs and swells are represented by the Tihemboka high, Murzuq- Jadu Trough, and Tripoli- Tibisti Uplift, which are controlled by the deposition followed by glacial and periglacial phenomena (late Ordovician to Silurian). During the mid- to late Devonian, the northwestern margins of Gondwana collided with Laurasia, and the effect of the collision increased in intensity throughout the Carboniferous in North African deformation. The peak of collision was reached in the Late Carboniferous, leading much of Libya to be uplifted, eroded, and deformed. This is a reflection of Hercynian Orogeny. Thus, a new set of east-west to northeast-southwest structural elements; Nafusah Uplift, Alqarqaf Arch, Sirt Arch, and Ennedi-Al Awaynat Uplift were superimposed over the earlier Pan- African structural trend (Klitzsch, 1971; Bellini and Massa, 1980; Rusk, 2002). The situation led to the formation of the Jifarah Trough, the Ghadamis basin, the Murzuq basin, and the Al Kufrah basin (Fig. 1a). However, Mamuniyat Formation (Upper Ordovician, Ashgillian) is considered a valuable hydrocarbon reservoir of the Murzuq Basin, SW Libya. Stratigraphically, the Mamuniyat Formation is composed of three members (lower, middle, and upper), which are overlain by the Silurian sequence (Fig. 1b). In addition, Table 1 is a concise a literature review of the studied formation. The Figure 1b displays a sketch of a stratigraphic sequence (Cambro – Ordovician) of the formation. Also, thickness of the Mamuniyat formation of each studied well is varied from 91 feet up to 332 feet, as well as these wells are belonging to two oil fields of concession 115 and 186 northwest Marzuq basin (Figure 1).

Table 1. Summary of a literature review of the Mamuniyat Formation

Reference	Summary of some previous studies
Echikh and Sola, 2000	They have published their works on the Gargaf Uplift and the western flanks of the Murzuq Basin and suggested that the Mamuniyat sediments were deposited in various fluvioglacial, deltaic, and shallow marine environments.
Alansari et al. 2018; Fello, 2001; Fello and Turner, 2004; Mohamed and Beshr, 2022; Alrabib et al., 2022; Shalbak, 2015.	They have studied and discussed sedimentology, depositional environment, diagenesis, and reservoir characteristics of the Mamuniyat formation. Also, they subdivided the formation into three members, which includes ten facies grouped in three different facies units.
Fello and Turner, 2004.	Core samples and petrographic studies were taken from four oil fields that demonstrate sublitharenites, arenites, and litharenites are mainly composed of the Mamuniyat formation. In addition, braided fluvial and shallow water marine sandstones form a petroleum potential of this formation.
Le Heron et al., 2006	Thye have reported Four disconformity-bound delineate stratigraphic units of the Upper Ordovician (Mamuniyat Formation).
Abdunaser, 2020.	Displays a sketch of a stratigraphic sequence (Cambro – Ordovician) of the formation.

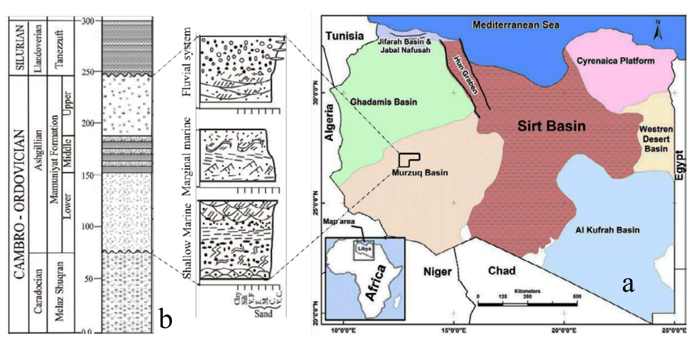

Figure 1. a: location of the main sedimentary basins of Libya, b: Cambro – Ordovician sequence of the study area (Abdunaser, 2020; Fello and Turner, 2004)

Materials and Methods

Logs and core samples are valuable measured data oil fields. Also, the logs are more available and continue than the core samples. Hence, radiation, electrical and acoustic logs are essential data that takes considered from five oil wells. These wells are producing from the Mamuniyat reservoir (Upper Ordovician) at different oil fields 1 and 2. However, the logs data has included gamma ray (GR), interval travel time (ΔT), neutron ($\O n$), Litho-Density log (bulk density, ρb and photoelectrical factor, PEF), caliper (CAL), and electrical resistivity (R). These recorded logs have been processed using Excel Microsoft program in order to evaluate the petrophysical and mechanical properties of the reservoir. In general, both petrophysical and mechanical properties results utilizes to calculate Sand Production Indicator (SPI).

Lithology determination is an early step to assess the petrophysical properties of any reservoir rocks. Thus, using combination of measured logs as cross plots, such as bulk density – neutron porosity, sonic – neutron porosity and bulk density– PEF logs are quick and very useful techniques to define lithology (Serra 1986).

Laboratory testing is a direct measurement of elastic properties by using rock samples and suitable empirical equations for indirect estimate these properties. Hence, most of the empirical equations based on measurements of interval travel times (ΔTc and ΔTs) or compressional and shear velocities (Vp and Vs), and bulk density (ρb) that illustrate acoustic properties of rocks of great interest in geomechanical interpretation. Hence, lacking of core samples of the studied reservoir induced the estimation of the elastic (mechanical) properties based on empirical equations 1, 2, 3 and 4 (Serra, 2008). However, young's modulus (E) is a stress-strain ratio, which measure a rock stiffness in pressure units, the shear modulus (G) gives the resistance of rock to shear without change in volume, and it decreases as the porosity of rocks increase. While, the bulk modulus (Kb) is a property of rocks explains required pressure to make the volumetric deformation. In other words, the E measures ability or disability of Elastic deformation, while Kb and G measure the strength of materials. Furthermore, Poisson's ratio (υ) is an essential mechanical property of rock that varies with burial of depth, lithology, porosity, confining pressure and pore pressure (Peng and Zhang, 2007).

$$\upsilon = \frac{1/2\left(\frac{\Delta ts}{\Delta tc}\right)^2 - 1}{\left(\frac{\Delta ts}{\Delta tc}\right)^2 - 1} \quad (1)$$

$$E = 2 \times G \times (1+\upsilon) \quad (2)$$

$$G = 1.34 \times 10^{10} \times \frac{\rho b}{\Delta Ts^2} \quad (3)$$

$$Kb = G\left[\left(\frac{\Delta Ts}{\Delta Tc}\right)^2 - \frac{4}{3}\right] \quad (4)$$

Where: ΔTc = compressional interval time (μsec/ft), ΔTs = shear interval time (μsec/ft) and ρb = bulk density (g/cc)

Uniaxial compressive strength (UCS) is also a mechanical property, which is maximum axial compressive stress or unconfined compressive strength of a material. It may give the ability to understand the sand production mechanism occurred within the rocks (Kim, 2012; Abass et al., 2002). However, both shear and tensile strengths provide reasons of common rock failure mechanisms. The McNally (1987) equation 5 is used to calculate the UCS of the Mamuniyat reservoir. Also, there are other factors affecting on the rock failure mechanism such as Cohesion (Co), internal Friction angle (Φ), formation depth, heterogeneity of rocks and pore pressure of fluid formation. Issa et al. (2022) briefly explained the mechanism of cohesion failure, which happen when a frictional force higher than cohesion strength between grains of rock due to increase of a fluid flow. While, the Φ gives an indication of rocks resistance to shear, and controlling of Mohr's envelope line (Peng and Zhang, 2007). Also, both Co and Φ are an indicator of the confining pressure and help in wellbore stability analysis. However, the following Plumb (1994) of the Friction angle equation 6 is used.

$$UCS = 1200 \times Exp(-0.036 \times \Delta Tc) \quad (5)$$

$$\Phi = 26.5 - 37.4\,(1 - \emptyset - V_{sh}) + 62.1\,(1 - \emptyset - V_{sh})^2 \quad (6)$$

Consequently, Stein and Hilchie (1972) and Tixier et al. (1975) used techniques to predict formation strength based on the mechanical properties estimated from logs that indicate whether the sand state will produce or not. Whereas Khamehchi and Reisi (2015) concluded that the shear and compressibility modulus (G/Cb) ratio is considered a good indicator of the sand production in a normal reservoir condition. Therefore, the shear and bulk compressibility (G/Cb) ratio is selected as the sand production index (SPI) of the Mamuniyat formation (Equation 7). Where, if the ratio is exceeded (8×10^{11} Psi^2), the sand production occurs (Liu 2017).

$$SPI = G/Cb = G \times Kb \quad (7)$$

Where: G = shear Modulus (Psi), Kb = bulk modulus (Psi) and and Cb = Bulk compressibility (1/Psi).

Results and discussion:

Lithology delineation of the Mamuniyat Formation manifests clean and clayey units by the bulk density (ρb) versus neutron porosity (Øn) cross plot (Figures 2a and 2b), and correlation between wells by the photoelectrical factor (PEF) logs (Fig. 3). Hence, Figure 2a reveals the most plotted points on and around the sandstone (green) line that an apparent matrix parameter (ρma) equal to 2.65 g/cc in the clean Mamuniyat. Also, some points are plotted towards the limestone (blue) line and excessed dolomite (magenta) line that may indicate increasing of the Vsh (>25%) and carbonate calcium as cementing material within the clean Mamuniyat unit. While the plotting points have shifted below the sandstone line and gradually moved into the dolomite line (Fig. 2b), which illustrates the high and influences of shale content on the Clayey Mamuniyat unit. In addition, the points above the sandstone line (Figures 2a and 2b) reveal the presence of a light hydrocarbon (Priisholm and Michelsen, 2015). Whereas, the measuring PEF logs of the Mamuniyat Formation are compared with a standard value of the sandstone that is equal to 1.8 b/e. Figure 3 displays a correlation of the PEF log between wells, which emphasizes the Clean Mamuniyat unit is closed to the 1.8 b/e, while the Clayey one is higher than the standard value. According to that, the volume of shale (Vsh) higher than 25 % is considered a shale baseline of the petrophysical and mechanical properties evaluation.

Porosity and water saturation are the most petrophysical results that depend on the lithology type, shale content and type, cementation factor (m), tortuosity (a), and apparent matrix parameters. Hence, the average of the total porosity (Ønd), shale content (Vsh), and water saturation (Sw) by arithmetic average (Equation 8) that summarized in Table 1. The Clean Mamuniyat has lower average values of the Ønd and Vsh, and as well, the water saturation is increasing within the Clayey Mamuniyat unit. Based on that, the Clean Mamuniyat unit is considered as the reservoir rock (Upper Ordovician) of the studied oil fields. Moreover, the clay types within the Clean and Clayey Mamuniyat are defined by Natural Gamma Ray Spectrometry (NGS): potassium (K) – Thorium (Th) concentration cross plot (Figures 4a and 4b). It is noticeably the Clean Mamuniyat Th-K plotting points are above Th/K ratio line of 2 and less than Th/K ratio line of 3.5, with slightly scattered values above the Th/K ratio line of 3.5. While the extensive points of the Clayey Mamuniyat are located below the Mica line and exceed the Th/K ratio of 3.5 up to 100% Illite line. Therefore, Montmorillonite and Illite clay minerals are dominant clay minerals have concentrated within the Mamuniyat reservoir.

$$\text{Arithmetic average} = \frac{\sum_{i=1}^{n} X}{n} \quad (8)$$

Where: X = calculated property, n = number of samples.

Generally, the above petrophysical evaluation is helpful for assessment and interpretation of the dynamic elastic properties evaluation of the Mamuniyat reservoir. Additionally, arithmetic average results of the calculated mechanical properties are also included in Table 1. Therefore, the Clean Mamuniyat has higher values of the E and G modulus and lower values of the Kb than the Shaly Mamuniyat, with an exception of well 4. As well, the Poisson's ratio (PR) that reflects the compressibility of the rock and works as a fracture indicator of rocks; rocks with a high υ are more likely to have fractured than those with a low PR. The average PR of the Mamuniyat reservoir is located within a typical range of 0.18 to 0.22 of deeper, highly compacted, cemented sandstone (Alberty and McLean, 2001).

The uniaxial compressive strength (UCS) of the Mamuniyat reservoir does not exceed 150 MPa, which is located with a typical range value of sandstone rock (Backers, 2013; Attewell and Farmer, 1976). Based on Hoek and Brown (1997), the Mamuniyat reservoir is classified from very low strength (E) to high strength (B). Whereas the calculated internal friction angle (Φ) and cohesion (Co) parameters results reveal decreased values against increasing of the total porosity and volume of shale values. Then, the Clayey Mamuniyat shows lower values of Φ than the Clean Mamuniyat and inversely the Co. An average value of the Co of the Mamuniyat is included in Table 1. These average values are closer to published data of Berea sandstone, Bartlesville sandstone, and Pottsville sandstone by Goodman (1991). Therefore, it is clearly the mechanical properties of the Mamuniyat reservoir are affected by the petrophysical properties.

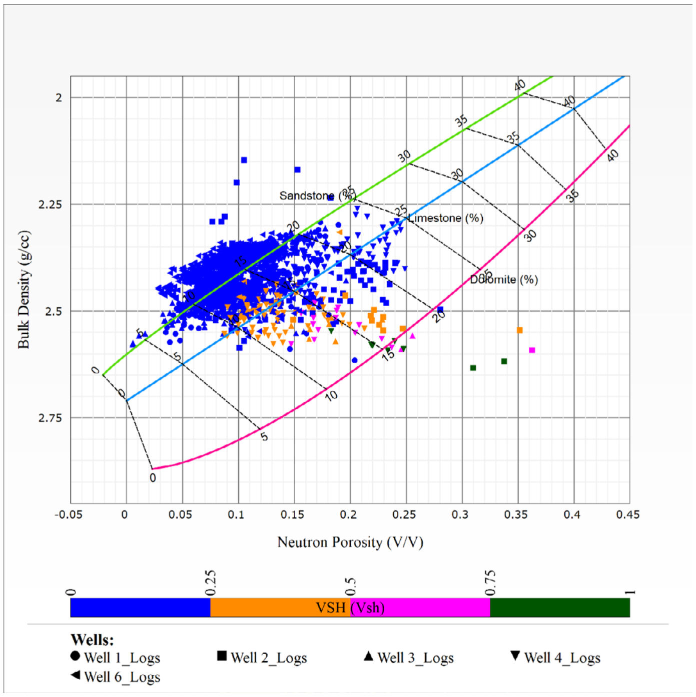

Figure 2a. Bulk density versus Neutron porosity cross plot of the Clean Mamuniyat unit.

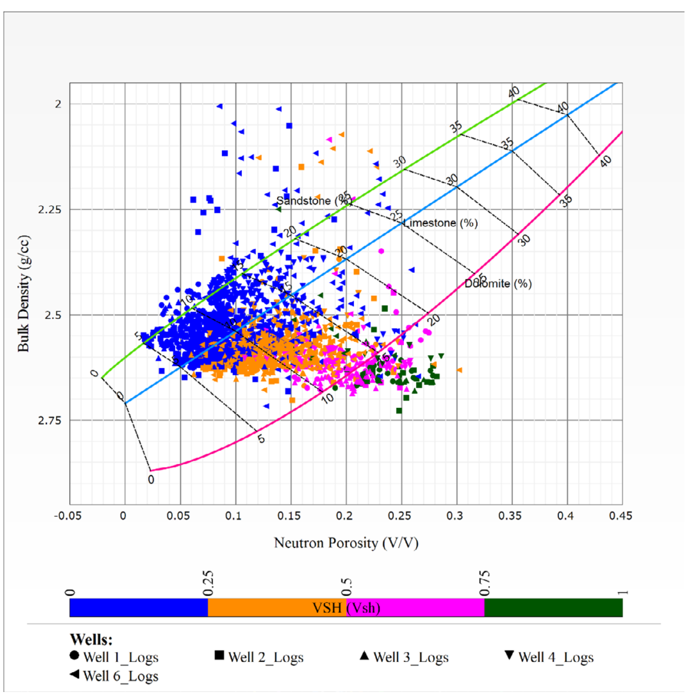

Figure 2b. Bulk density versus Neutron porosity cross plot of the Clayey Mamuniyat unit.

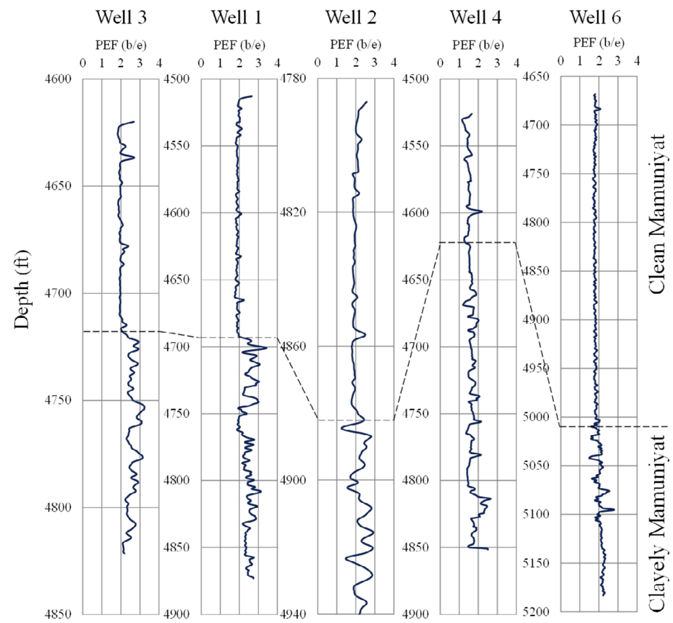

Figure 3. Photoelectrical factor (PEF) logs correlation between wells, field 1 and 2.

Table 1. Average porosity (Ønd), shale content (Vsh) and dynamic elastic properties of the Mamuniyat reservoir

		Field 1			Field 2	
		Well				
		1	2	3	4	6
Ønd (%)	C	11	13	11	15	12
	S	9	12	8	11	12
Vsh (%)	C	7	11	8	4	5
	S	33	36	33	26	26
Sw (%)	C	31.5	57	39	15	38
	S	100	81	100	79	37
PR	C	0.22	0.15	0.21	0.21	0.21
	S	0.22	0.18	0.22	0.21	0.20
E (MPa)	C	3.85E+04	4.32E+04	4.22E+04	4.02E+04	4.03E+04
	S	3.82E+04	3.94E+04	4.09E+04	4.15E+04	4.53E+04
G (MPa)	C	1.58E+04	1.88E+04	1.75E+04	1.67E+04	1.67E+04
	S	1.56E+04	1.67E+04	1.68E+04	1.72E+04	1.89E+04
Kb (MPa)	C	2.27E+04	1.91E+04	2.37E+04	2.29E+04	2.29E+04
	S	2.29E+04	2.36E+04	2.39E+04	2.37E+04	2.50E+04
UCS (MPa)	C	85	84	92	90	90
	S	79	86	84	88	97
Co (MPa)	C	21	22	23	23	22
	S	23	25	24	25	29
Φ (◦)	C	37	35	37	37	38
	S	30	29	30	31	27

C = Clean Mamuniyat S = Clayey Mamuniyat

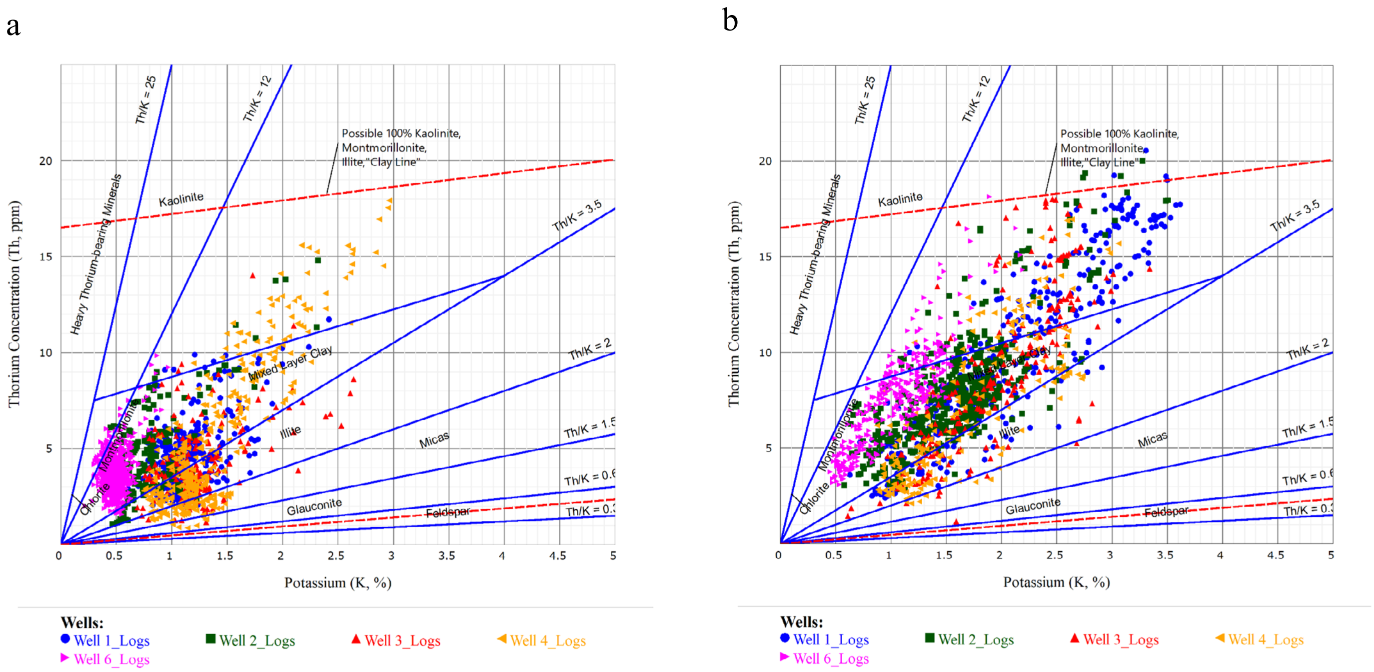

Figure 4. Natural Gamma Ray Spectrometry (NGS): potassium (K) – Thorium (Th) concentration cross plot of a: Clean Mamuniyat unit, and b: Clayey Mamuniyat unit.

Each sand production technique has specific conditions that determine whether it should be applied in a given situation. Thus, if the shear and compressibility (G/Cb) modulus ratio is less than 8×10^{11} psi^2 (3.80E+07 MPa^2) that means a formation is stable and there is no sand production. Otherwise, the G/Cb ratio is greater than 8×10^{11} psi^2, which means a formation is unstable and sand production could occur (Liu, 2017). Then, Figure (5) displays a correlation of the gamma ray and borehole geometry (caliper) logs and results of the SPI, UCS, Co, and Φ of the Mamuniyat reservoir of well 4. Also, the same correlation between the studied wells is recognized of wells 1 and 2 from field 1 (Figure 6a), and wells 3 and 6 from field 2 (Figure 6b). Then, evaluation of the sand production indicator (SPI) results of the Mamuniyat reservoir reveals it has no sand production problem. Hence, this result is consistent with the elastic property findings of the Mamuniyat reservoir.

Conclusion

Prediction of the sand production in the early stages of the reservoir production life history is a significant step to save time for treatment procedures in oil fields. This issue of oil fields is strongly related to the mechanical properties of rocks, in turn considering the petrophysical properties. However, based on the gamma ray and photoelectrical factor logs and 25% of the shale base line (Vsh), the Mamuniyat reservoir (Upper Ordivician) is divided into Clean and Clayey Mamuniyat. Also, the Clean Mamuniyat has a good total porosity (Ønd) and lower volume of shale (Vsh) and water saturation (Sw) than the Clayey Mamuniyat. Hence, these petrophysical properties have an impact on the elastic properties.

The average value of the UCS of the Mamuniyat Formation does not exceed 100 MPa, where the low values of the UCS respond to the high values of the Ønd and Vsh. Also, these UCS values are located between the very low strength (E) and high strength (B) classifications of the Mamuniyat reservoir rock. Furthermore, the Mohr-Columb failure criteria parameters: cohesion (Co) and internal friction angle (Φ) also have low values in the Clayey Mamuniyat rock. Therefore, the sand production indicator (SPI) of the Mamuniyat reservoir of two oil fields has not reached the threshold value of sand production, which is less than 8×10^{11} psi^2.

Consequently, the early evaluation of the sand production problem is a safer and less coasting technique to understand failure criteria and in-situ stresses of the oil fields. Moreover, the Mechanical Earth Model (MEM) of the Mamuniyat reservoir is necessary, and it gives a prediction of the ability to increase production rates without causing the instability problem (sand production).

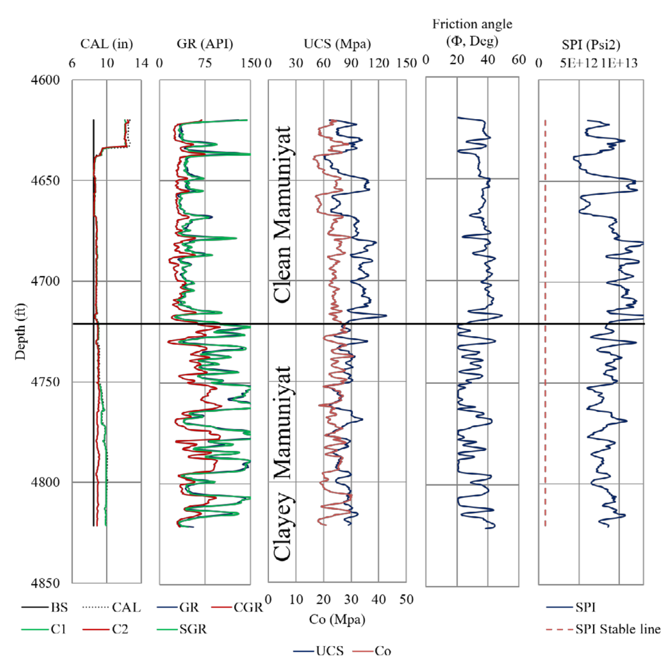

Figure 5. Gamma ray and geometry logs and mechanical properties results of well 4, field 1

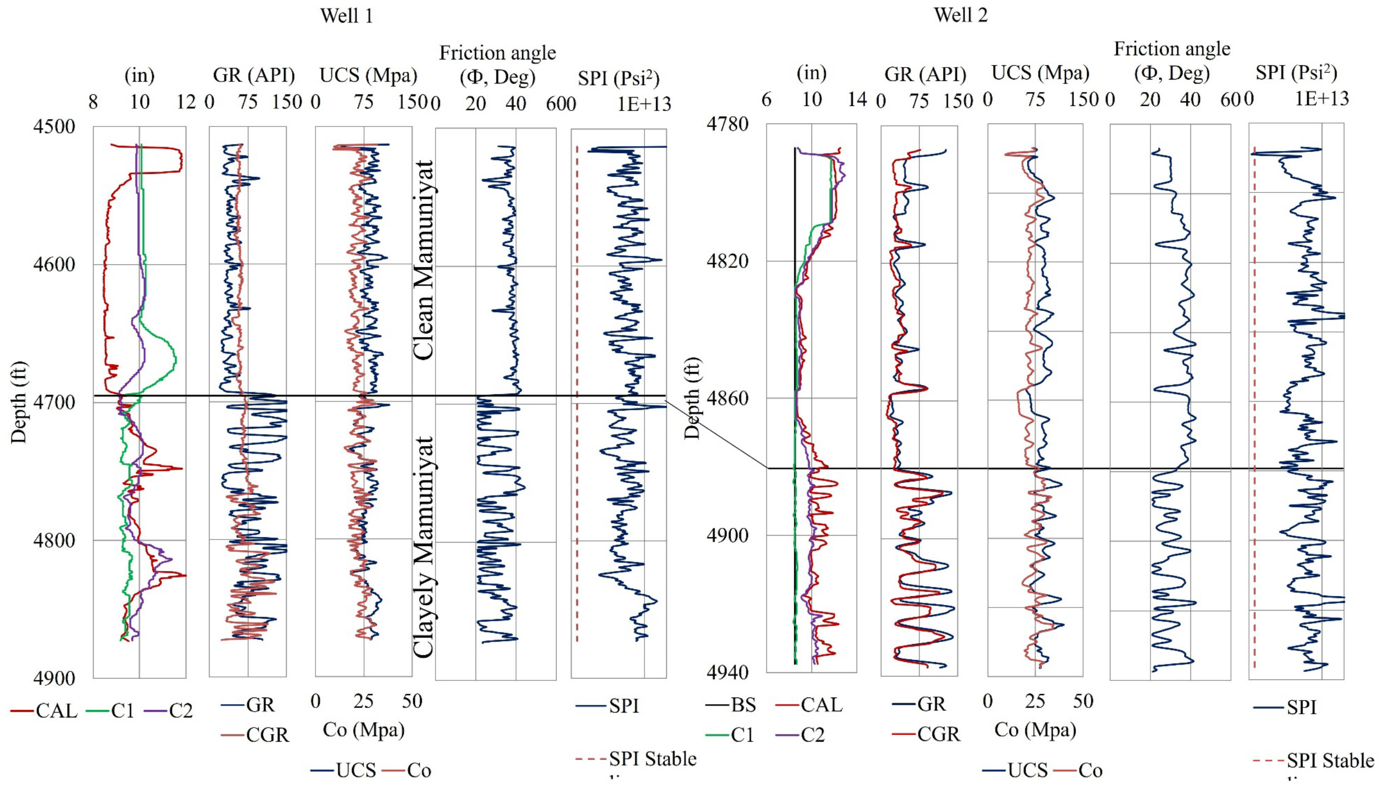

Figure 6a. Gamma ray and geometry logs and mechanical properties results of wells (1 and 2), field 1

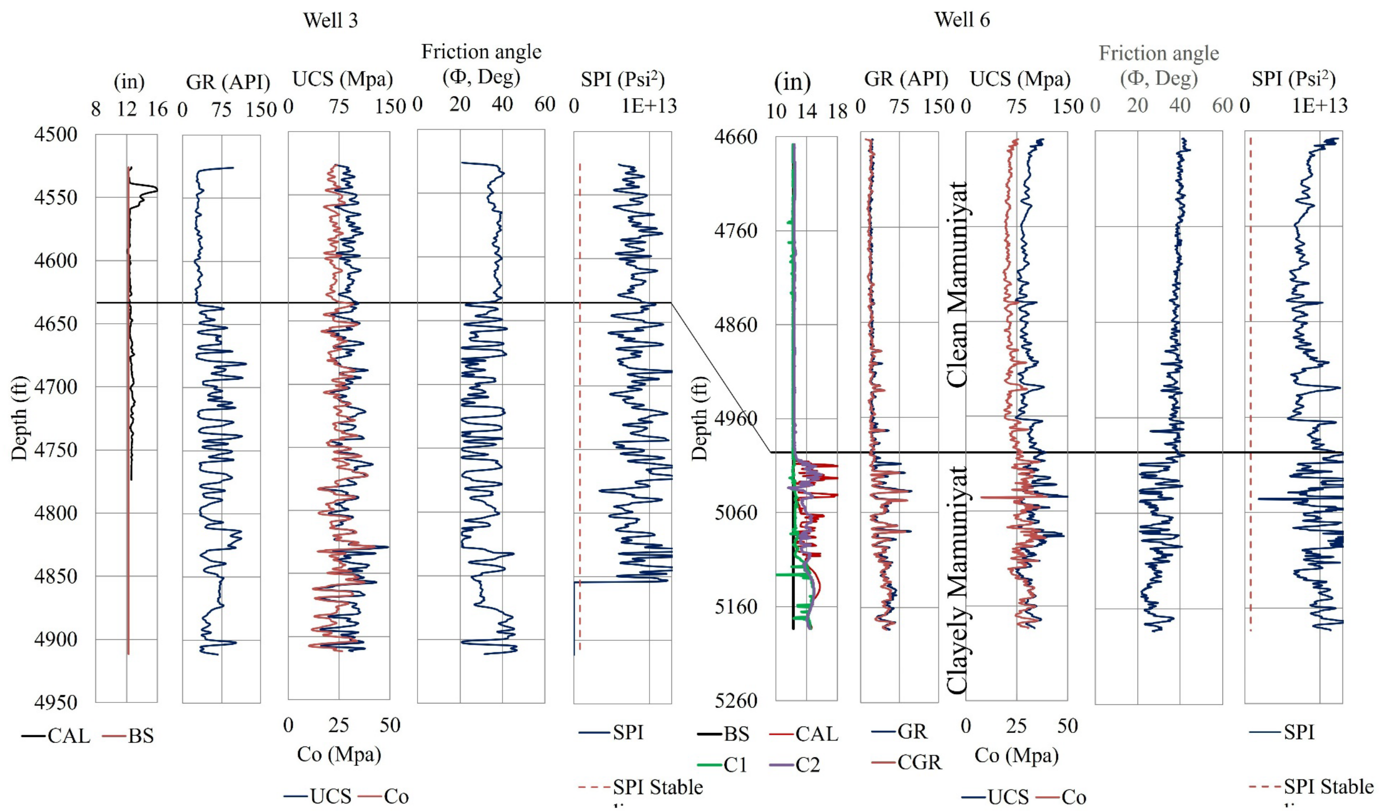

Figure 6b. Gamma ray and geometry logs and mechanical properties results of wells (3 and 6), field 2

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