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A Cross-Plot–Based Petrophysical Workflow for Lithology Discrimination and Shale–Clay Typing

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سير عمل بيتروفيزيائي قائم على التخطيط المتقاطع لتمييز الصخور وتصنيف الطين والشيل

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Abstract:

Petrophysical evaluation of sandstone reservoirs is often complicated by shale distribution and clay mineral variability, which significantly affect porosity and fluid saturation estimates. This study presents the implementation of integrated petrophysical cross-plot methods for lithology identification, shale characterization, and clay type analysis in the Messla sandstone reservoir, Sirte Basin, Libya using conventional well log data. Neutron–density, MID Matrix Identification Density Log, density–photoelectric factor (PEF), thorium–potassium (Th–K) cross-plots and Thomas-Stieber cross-plots were employed to discriminate sandstone lithology, evaluate shale distribution, and infer dominant clay minerals. The results demonstrate that cross-plot techniques provide reliable lithological separation and shale typing using log data only, offering a cost-effective and robust interpretation approach in the absence of core measurements. The proposed workflow improves reservoir characterization and reduces uncertainty in petrophysical interpretation of sandstone formations. The results indicate that the Messla reservoir is dominated by quartz-rich sandstone with variable shale content, mainly occurring as laminated and dispersed shale. Clay typing analysis suggests the predominance plot of a kaolinite-dominated clay assemblage with minor mixed-layer contributions in cleaner sandstone intervals. The proposed workflow demonstrates the effectiveness of cross-plot methods as a rapid and reliable approach for petrophysical characterization in data-limited environments and provides valuable input for reservoir quality assessment and completion planning in Libyan sandstone reservoirs.

Keywords: Petrophysical cross-plots; Lithology discrimination; Shale distribution; Clay typing; Sandstone reservoir; Messla Field; Sirte Basin; Libya.

الملخص:

غالبًا ما يكون تقييم الخصائص البتروفيسية لخزانات الرمل الرملي معقدًا بسبب توزيع الصخر الزيتي وتغيرات المعادن الطينية، والتي تؤثر بشكل كبير على تقديرات المسامية وتشبع السوائل. تقدم هذه الدراسة تنفيذ طرق مخططات متقاطعة بيتروفيزيائيه متكاملة لتحديد الصخور، وتصنيف الصخر الزيتي، وتحليل نوع الطين في خزان الرمل الرملي مسله، حوض سرت، ليبيا باستخدام بيانات سجل الآبار التقليدية. تم استخدام مخططات متقاطعة لنيوترون–الكثافة، وتحديد مصفوفة MID، والكثافة–عامل الفيزياء الكهربية (PEF)، والثوريم–البوتاسيوم (Th–K)، ومخططات توماس-ستيبير للتمييز بين صخور الرمل الرملي، وتقييم توزيع الصخر الزيتي، واستنتاج المعادن الطينية السائدة. توضح النتائج أن تقنيات المخططات المتقاطعة توفر فصلًا موثوقًا للتركيبة الصخرية وتصنيف الصخر الزيتي باستخدام بيانات السجل فقط، مما يقدم نهج تفسير

فعال من حيث التكلفة وموثوقًا في غياب قياسات النوى. يحسن سير العمل المقترح خصائص الخزان ويقلل من عدم اليقين في التفسير البتروفزيائي لتكوينات الحجر الرملي. تشير النتائج إلى أن خزان المسلة يهيمن عليه الحجر الرملي الغني بالكوارتز مع محتوى متغير من الصخر الزيتي، يظهر بشكل رئيسي على شكل صخر زيتي طبقي ومنتشر. تشير تحليلات تصنيف الطين إلى غلبة مجموعة الطين الغني بالكاولينيت مع مساهمات ثانوية من الطبقات المختلطة في فترات الحجر الرملي الأنظف. يوضح سير العمل المقترح فعالية طرق الرسم البياني المشترك كنهج سريع وموثوق للتوصيف البتروفزيائي في البيئات محدودة البيانات ويقدم مدخلاً قيمًا لتقييم جودة الخزان وتخطيط الاستكمال في خزانات الحجر الرملي الليبية.

الكلمات المفتاحية: مخططات قطعية بيتروفيزيائيه، تحديد الصخور، توزيع الصفائح الطينية، تصنيف الصفائح الطينية، خزان الحجر الرملي، حقل مسلة؛ حوض سرت، ليبيا.

Introduction:

Sandstone reservoirs in mature hydrocarbon provinces commonly exhibit variable shale content resulting from depositional heterogeneity and diagenetic alteration. In the southeastern Sirte Basin, Libya, the Sarir Formation of the Messla Field is a prime example of such complexity, comprising fluvial to shallow-marine sandstones interbedded with shale layers of variable thickness and continuity [1, 2]. The presence and distribution of shale and clay minerals exert a fundamental control on effective porosity, permeability, and water saturation through bound water effects, microporosity, and electrical conductivity, making accurate shale and clay characterization essential for reliable reservoir evaluation [3, 4].

Conventional petrophysical interpretation techniques often rely on single-log indicators, particularly the gamma-ray log, to estimate shale volume and infer lithology. While practical, such approaches are inherently limited, as gamma-ray responses cannot distinguish between laminated and dispersed shale nor identify clay mineral types with different petrophysical behaviors [5, 6]. Empirical shale volume models further assume uniform shale properties, which is rarely valid in heterogeneous sandstone reservoirs such as the Sarir Formation, where mixed clay assemblages introduce significant uncertainty into porosity and saturation calculations.

Petrophysical cross-plot methods provide a robust alternative by integrating multiple conventional well-log measurements into a coherent interpretive framework. Cross-plots such as neutron–density, MID, photoelectric–density, thorium–potassium and Thomas-Stieber model enable quantitative lithology discrimination, shale distribution assessment, and clay mineral typing without reliance on core data [7, 8]. The objective of this study is to implement an integrated cross-plot–based petrophysical workflow to evaluate lithology, shale distribution, and clay mineral types in the Sarir Formation sandstone reservoir of the Messla Field using conventional wireline logs only, demonstrating its effectiveness in reducing interpretation uncertainty in shale-heterogeneous sandstone systems.

Geological Setting:

The Messla Field is located in the southeastern part of the Sirte Basin, Libya Figure (1), one of the most prolific hydrocarbon provinces in North Africa. Structurally, the field lies on a gently faulted platform margin, where hydrocarbon accumulations are controlled by subtle structural closures combined with stratigraphic heterogeneity [9]. The basin evolution and tectonic framework have strongly influenced sediment distribution and reservoir architecture, with direct implications for petrophysical log responses. The primary reservoir unit in the Messla Field is the Cretaceous Sarir Formation, which is composed predominantly of fluvial to shallow-marine sandstone successions. These sandstones are interbedded with varying proportions of shale, reflecting depositional environments ranging from braided and meandering fluvial channels to marginal-marine and deltaic settings. This depositional variability results in laterally and vertically heterogeneous reservoir units, characterized by alternating clean sandstone intervals and shale-rich layers [10].

From a petrophysical perspective, the Sarir Formation exhibits significant heterogeneity in porosity and clay content due to the presence of both laminated and dispersed shale. The shale intervals commonly contain mixed clay mineral assemblages, which exert a strong influence on neutron, density, and gamma-ray log responses. Such heterogeneity complicates lithology discrimination and shale volume estimation when using single-log interpretations

Stratigraphically, the Sarir Formation is underlain by older continental clastics and overlain by marine shales, forming a regionally extensive reservoir–seal pair. Internal stratification within the formation, driven by depositional cycles and diagenetic overprinting, produces variable reservoir quality across the field. These characteristics make the Sarir Formation in the Messla Field an ideal case study for applying integrated cross-plot–based petrophysical workflows aimed at improving lithology discrimination, shale distribution analysis, and clay type identification [11].

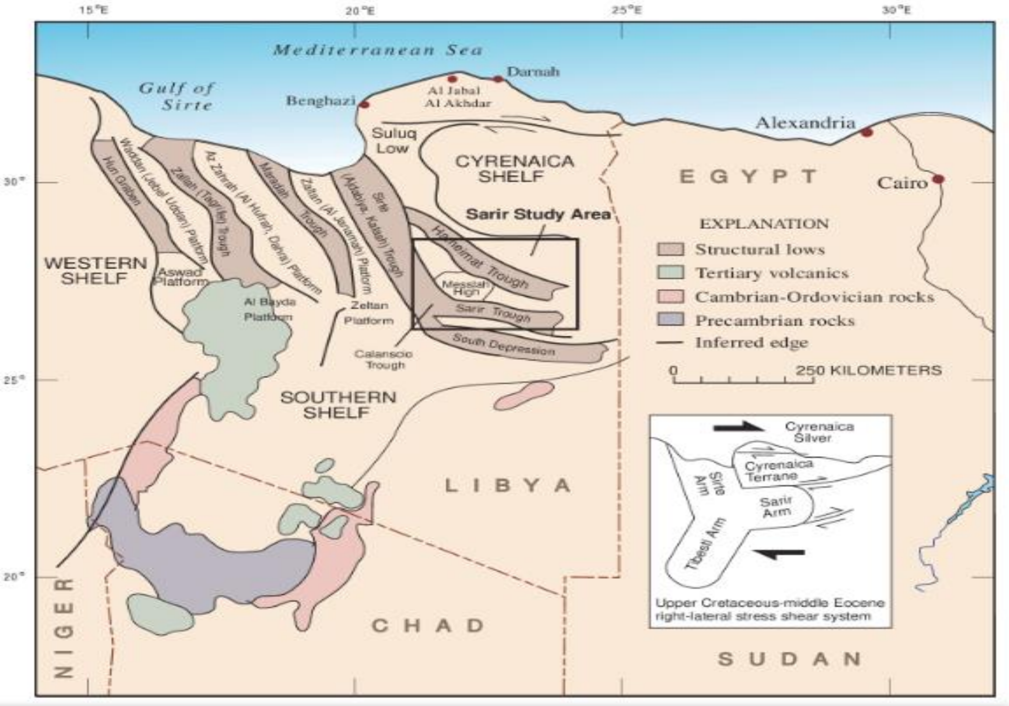

Figure (1): Location of the Sarir Field in the Sirte Basin.

Literature Review:

Petrophysical evaluation of sandstone reservoirs has long recognized the critical impact of shale content and clay mineralogy on reservoir quality and fluid-flow behavior. Early studies demonstrated that the presence of shale introduces bound water and electrically conductive pathways that significantly affect porosity, permeability, and water saturation estimates [3, 4]. Subsequent research emphasized that not only the volume of shale, but also its spatial distribution laminated, dispersed, or structural plays a key role in controlling reservoir performance and log responses [12].

Traditional shale evaluation methods have relied heavily on single-log interpretations, particularly gamma-ray–based shale volume models. While widely applied, these approaches assume uniform shale properties and fail to capture the mineralogical diversity of clay assemblages commonly present in sandstone reservoirs [13]. Several authors have shown that empirical shale volume models can lead to significant uncertainty in porosity and saturation calculations when clay type and shale distribution are not explicitly considered.

To overcome these limitations, petrophysical cross-plot techniques were developed as integrative tools that combine multiple log responses to improve lithology and shale characterization. The neutron–density cross-plot has been extensively used for lithology discrimination and shale identification in clastic reservoirs, particularly where shale effects obscure porosity trends. The MID cross-plot further enhanced matrix identification by minimizing porosity effects and isolating mineralogical signatures using density, and sonic measurements [7].

Spectral gamma-ray logging introduced additional capability for clay mineral identification through thorium, potassium, and uranium measurements. Numerous studies have demonstrated the effectiveness of Th–K cross-plots in distinguishing illite-, kaolinite-, chlorite-, and mixed-layer clay assemblages in sandstone reservoirs [14]. These techniques have proven particularly valuable in data-limited fields where core and X-ray diffraction analyses are unavailable or sparse, allowing clay typing to be inferred directly from well logs.

Despite the widespread application of individual cross-plot techniques, relatively few studies have integrated neutron–density, MID, photoelectric–density, spectral gamma-ray and Thomas-Stieber cross-plots into a single, systematic workflow tailored to heterogeneous sandstone reservoirs. In complex settings such as the Sarir Formation of the Messla Field, southeastern Sirte Basin, reservoir heterogeneity and mixed clay mineralogy necessitate a multi-log, cross-plot–driven approach to reduce interpretation uncertainty. This study builds on previous methodologies by presenting an integrated cross-plot–based petrophysical workflow that simultaneously addresses lithology discrimination, shale distribution, and clay mineral typing using conventional wireline log data.

Methodology:

This study applies an integrated petrophysical cross-plot–based methodology to evaluate lithology, shale distribution, and clay mineral types in the Sarir Formation sandstone reservoir of the Messla Field, southeastern Sirte Basin. The workflow relies exclusively on conventional wireline log data and is designed to minimize interpretation uncertainty in shale-heterogeneous sandstone systems where core data are limited or unavailable. The methodology consists of data preparation, shale volume estimation, lithology discrimination using multi-log cross-plots, and clay mineral typing based on spectral gamma-ray responses [15].

Data Set and Log Preparation:

The analysis utilizes a suite of conventional open-hole wireline logs acquired over the Sarir Formation interval, including gamma ray (GR), bulk density (RHOB), neutron porosity (NPHI), compressional sonic transit time (Δt), photoelectric factor (PEF), and spectral gamma-ray measurements (thorium, potassium, and uranium). All logs were quality controlled to remove spurious measurements related to borehole enlargement, tool malfunction, or poor hole conditions. Environmental corrections were applied according to service-company standards to ensure consistency among neutron, density, and sonic responses.

Depth matching and normalization were performed prior to cross-plot construction to reduce tool-to-tool and well-to-well variability. Log responses were examined in conjunction with caliper data to exclude intervals affected by severe washouts, particularly in shale-rich sections, where neutron and density measurements are known to be unreliable.

Shale Volume Estimation:

Shale volume (Vsh) was initially estimated from the gamma-ray log to provide a reference shale indicator for cross-plot color-coding and quality control. The linear gamma-ray index method was applied:

$$I_{GR} = \frac{\left(GR_{\log} - GR_{min}\right)}{\left(GR_{max} - GR_{min}\right)}$$

$$V_{sh} = I_{GR}$$

where GR_{min} and GR_{max} represent clean sandstone and shale reference values, respectively, determined from log intervals within the Sarir Formation. Although gamma-ray–derived shale volume is known to have limitations, it serves in this study as an initial qualitative indicator rather than a definitive shale quantification tool [14].

Lithology Discrimination Using Cross-Plots:

Lithology discrimination was carried out using a sequence of complementary cross-plots that integrate neutron, density, sonic, and photoelectric responses.

The neutron–density (NPHI–RHOB) cross-plot was first employed to distinguish clean sandstone from shale-rich and mixed lithology intervals. Reference lithology trends for quartz sandstone, limestone, and dolomite were overlaid, and data points were color-coded by shale volume to visualize shale effects on log responses.

The photoelectric factor versus density (PEF–RHOB) cross-plot was used to confirm matrix composition and identify potential carbonate cementation. Quartz-rich sandstones were identified by PEF values near 2.0 b/e, whereas deviations toward higher PEF values were interpreted as localized carbonate influence.

MID Cross-Plot Analysis:

To further constrain matrix lithology while minimizes fluid effects and highlights matrix lithology, the MID is a mineral identification / lithology discrimination plot derived from the M–N concept, MID cross-plot was constructed using density, neutron and sonic measurements.

The MID cross-plot is a matrix-corrected M–N plot, where:

- **X-axis:** MID-X (matrix density influence).
- **Y-axis:** MID-Y (matrix sonic influence).

$$MID_X \propto \frac{\Phi_D - \Phi_N}{\rho_{ma} - \rho_f}, \qquad MID_Y \propto \frac{\Delta t - \Delta t_f}{\Delta t_{ma} - \Delta t_f}$$

Where Φ_D is the Density-derived porosity, ϕ_N is neutron porosity, ρ_{ma} is Matrix density (quartz, calcite, dolomite), ρ_f is Fluid density, Δt is the compressional transit time, $\Delta t_f\ is\ the$ Fluid sonic slowness and Δt_{ma} Matrix sonic slowness [16, 17].

Clay Mineral Typing Using Spectral Gamma-Ray Cross-Plots:

Clay mineral identification was performed using thorium–potassium (Th–K) cross-plots derived from spectral gamma-ray measurements. Reference clay mineral fields for illite, kaolinite, chlorite, mixed-layer clays and heavy thorium-bearing mineral were superimposed based on established empirical relationships. Data clustering within these fields was interpreted to infer dominant clay assemblages within shale-bearing intervals of the Sarir Formation.

Thomas–Stieber Cross-Plot for shale distribution:

The Thomas–Stieber cross-plot is a petrophysical interpretation method that uses a Neutron Porosity (NPHI) vs Bulk Density (RHOB) cross-plot to determine how shale occurs in a reservoir, not just how much shale is present.

Its key strength is that it distinguishes between different shale distribution styles, which have very different impacts on porosity, permeability, and producibility.

Integrated Workflow and Interpretation Strategy:

The final interpretation integrates results from all cross-plots to achieve consistent lithology discrimination and shale–clay characterization. Neutron–density and PEF–density cross-plots provide primary lithological constraints, MID analysis refines matrix identification, Th–K cross-plots define clay mineral types and Tomas-Stieber cross plot for shale distribution. The combined interpretation allows differentiation between clean sandstone, shale-laminated sandstone, and shale-dominated intervals, forming the basis for improved petrophysical evaluation of the Messla Field reservoir.

Cross-Plot Findings and Discussion:

Lithology Discrimination from Neutron–Density Cross-Plots:

Figure 2. Neutron porosity (NPHI) versus bulk density (RHOB) cross-plot for the Sarir Formation interval (7390–9190 ft) in the Messla Field. Data points are color-coded by shale volume (Vsh) derived from the gamma-ray log. Reference sandstone, limestone, and dolomite lithology lines are superimposed. The data cluster predominantly follows the quartz sandstone trend with progressive deviation toward the shale line as Vsh increases, indicating variable shale content and mixed lithology intervals.

The neutron–density (NPHI–RHOB) cross-plots indicate that the Sarir Formation reservoir in the Messla Field is dominantly quartz-rich sandstone, as evidenced by the strong clustering of data points along the clean sandstone trend. Clean reservoir intervals are characterized by relatively low neutron porosity and moderate bulk density values, consistent with well-sorted siliciclastic sands. Progressive deviation of data points toward the shale line correlates with increasing shale volume, confirming the sensitivity of the neutron response to clay-bound water in shale-bearing intervals.

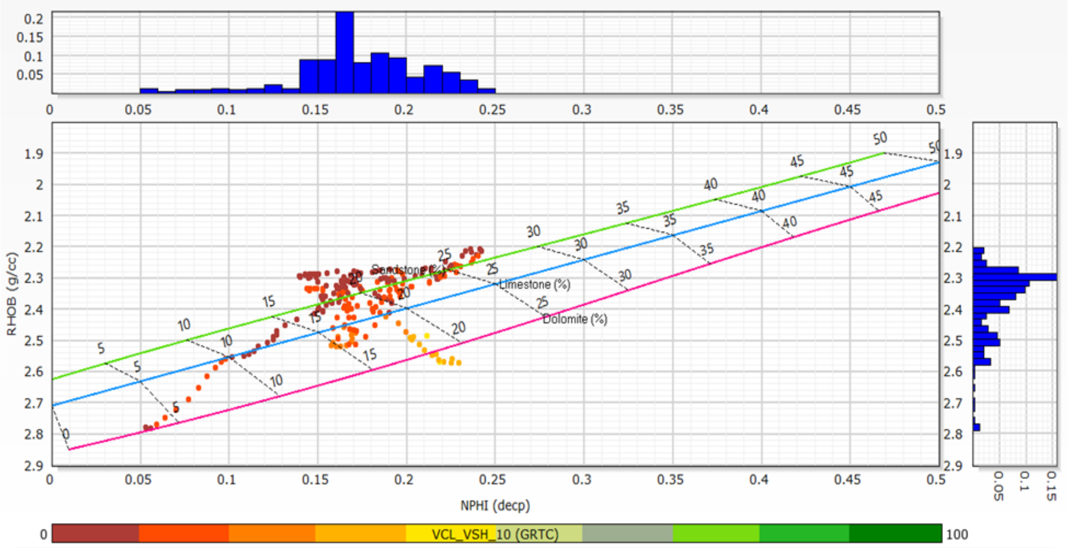

Figure (2): Neutron–Density (NPHI–RHOB) Cross-Plot for the Sarir Formation.

The observed spread between clean sandstone and shale-rich clusters reflects variable shale distribution within the reservoir. Intervals exhibiting moderate neutron enrichment without significant density increase are interpreted as laminated shale within sandstone beds, whereas coincident increases in both neutron porosity and density suggest dispersed shale. This distinction

is critical for petrophysical evaluation, as laminated shale tends to preserve effective porosity and permeability better than dispersed shale, despite similar gamma-ray responses.

The cross-plot demonstrates a dominant clustering of data points along the quartz sandstone trend, confirming that the Sarir Formation reservoir in the Messla Field is primarily sandstone-dominated. Clean sandstone intervals are characterized by low neutron porosity (0.10–0.18 v/v) and bulk density values ranging between 2.30 and 2.45 g/cm³.

As shale volume increases, the data progressively deviate toward the shale line, reflecting the influence of bound water associated with clay minerals. This behavior is consistent with laminated to dispersed shale distribution within fluvial to shallow-marine sand bodies.

Matrix Confirmation from PEF–Density Cross-Plots:

Figure 3. Photoelectric factor (PEF) versus bulk density (RHOB) cross-plot for the Sarir Formation (7390–9190 ft), showing reference lithology trends for quartz sandstone, limestone, dolomite, anhydrite, and salt. Data points cluster tightly around the quartz sandstone field, with limited dispersion toward carbonate trends, indicating minor carbonate cementation and confirming the siliciclastic nature of the reservoir.

The photoelectric factor versus density (PEF–RHOB) cross-plots provide independent confirmation of matrix composition inferred from neutron–density analysis. Most data points cluster around PEF values of approximately 1.8–2.2 b/e, which is diagnostic of quartz-dominated sandstone. The limited dispersion toward higher PEF values suggests minor carbonate cementation, likely dolomitic, but this component is volumetrically insignificant and does not dominate reservoir lithology.

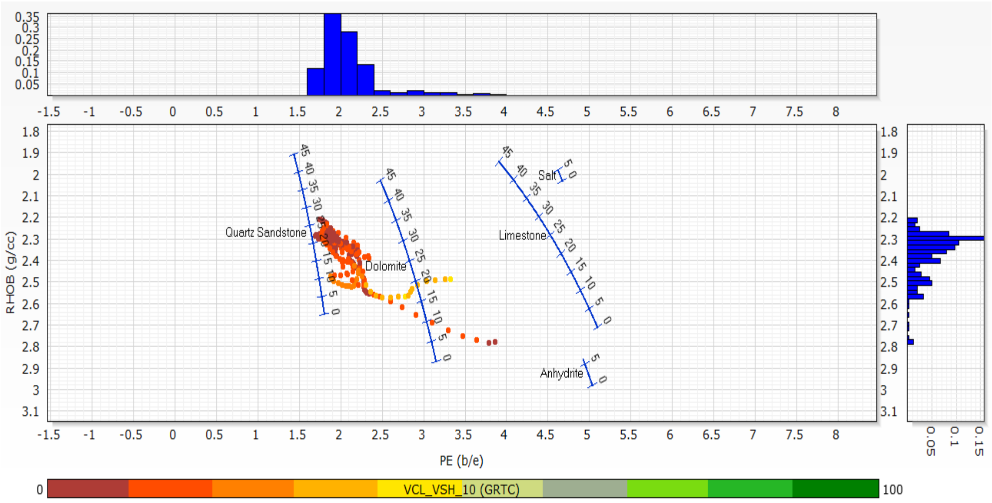

Figure (3): Photoelectric Factor (PEF) versus Density Cross-Plot for the Sarir Formation.

The clear separation of the dataset from evaporite and anhydrite reference fields rules out significant non-siliciclastic contributions. This finding supports the interpretation that variations in porosity and log response across the Sarir Formation are primarily controlled by shale content and clay mineralogy rather than changes in primary matrix lithology.

Matrix Lithology Refinement Using MID Cross-Plots:

Figure 4. Sonic transit time (Δt) versus bulk density (RHOB) cross-plot for the Sarir Formation (7390–9190 ft). Reference mineral points for quartz, dolomite, and anhydrite are shown. Data points trend parallel to the sandstone compaction line, with minor deviation indicating porosity reduction due to shale content and cementation. The inferred gas direction is shown for reference.

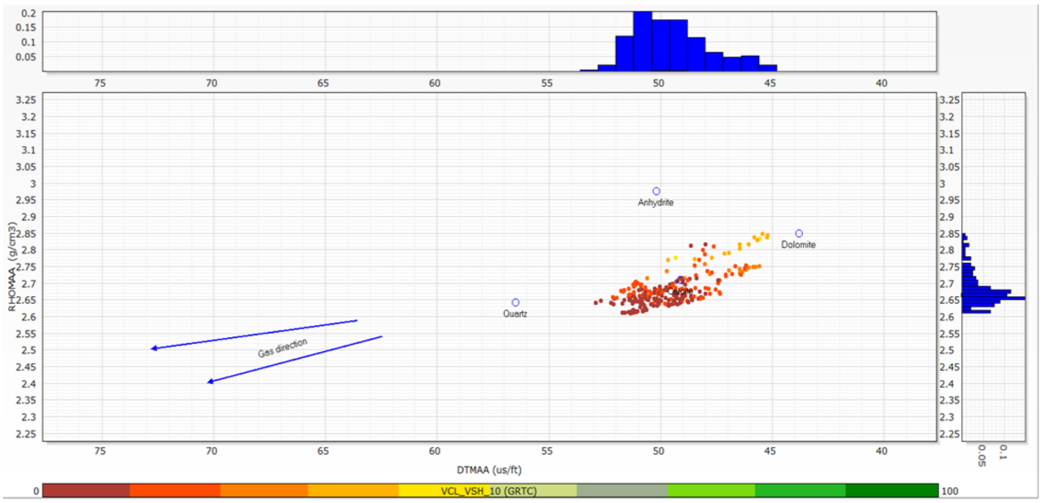

Figure (4): MID Cross-Plot for the Sarir Formation.

The cross-plot reveals a coherent trend consistent with normally compacted sandstone. Sonic transit times range between 45 and 55 µs/ft, corresponding to moderate porosity intervals. Minor upward deviation from the clean sandstone trend indicates the presence of shale and possible clay-related compaction effects.

The lack of systematic displacement in the gas direction suggests that free gas effects are minimal in the analyzed interval, supporting interpretations derived from the neutron–density cross-plot.

This behavior demonstrates the value of the MID method in distinguishing true lithological variation from porosity-related effects. In the Messla Field, the MID cross-plots corroborate interpretations derived from neutron–density and PEF–density analyses, providing a consistent and internally validated lithological framework.

Clay Mineral Typing from Th–K Cross-Plots:

Figure 5. Thorium (Th) versus potassium (K) cross-plot for the Sarir Formation (7390–9190 ft), used for clay mineral identification. Reference fields for kaolinite, illite, mixed-layer clays, chlorite, and mica are shown. Data points align close to the kaolinite field, High Th/K ratios indicate a clean, well-sorted fluvial–deltaic sandstones, some scatter trends toward mixed-layer clay.

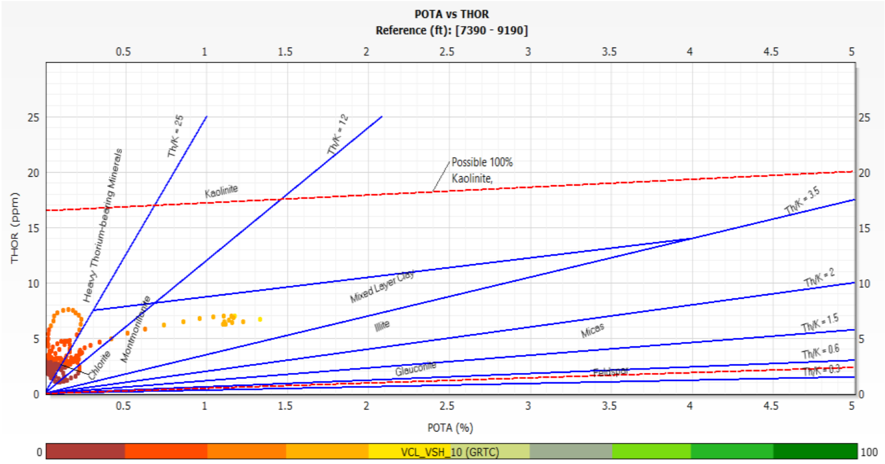

Figure (5): Thorium–Potassium (Th–K) Cross-Plot for Clay Typing of the Sarir Formation.

The POTA–THOR cross-plot indicates a kaolinite-dominated clay assemblage with minor mixed-layer contributions. The low potassium content and elevated Th/K ratios confirm an authigenic clay origin associated with clean sandstone reservoirs. The absence of glauconite and illitic trends suggests minimal diagenetic K-fixation and supports favorable reservoir quality, although with localized permeability reduction due to pore-filling kaolinite.

Shale distribution from Thomas-Stieber cross-plots:

Figure 6. Neutron Porosity (NPHI) vs Bulk Density (RHOB) cross-plot with a Thomas–Stieber shale model framework. The plot correctly defines three key lithological controls:

The plot correctly defines three key lithological controls:

○ **Clean Sand Point:**

- NPHI ≈ 0.20–0.22
- RHOB ≈ 2.15–2.20 g/cc
- Represents clean, well-sorted sandstone
- Dominated by intergranular porosity
- High reservoir quality baseline

○ **Structural Shale:**

- High NPHI (~0.55)
- Low RHOB (~2.1–2.2 g/cc)
- Indicates shale occurring as laminations or beds
- Minimal impact on matrix porosity
- Typical of bedded shale–sand sequences

○ **Dispersed Shale:**

- Low NPHI (~0.05)
- High RHOB (~2.65 g/cc)
- Clay minerals distributed within pore space
- Causes severe porosity and permeability degradation.
- Most detrimental shale type for reservoir quality

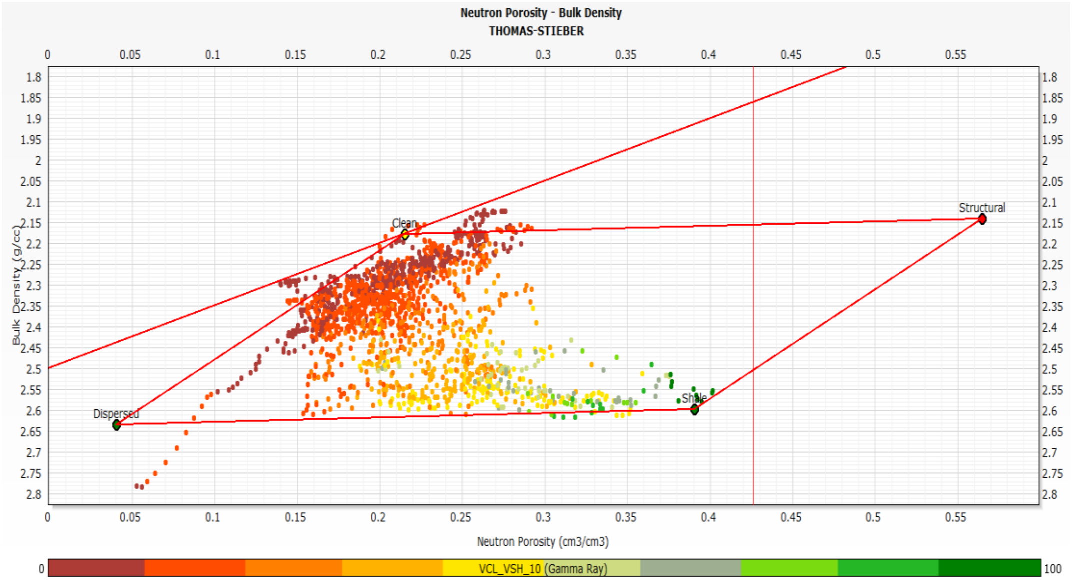

Figure (6): Thomas-Stieber Cross-Plot for the Sarir Formation

Data distribution and trends:

- **Main cluster (orange–red points)**
- **Concentrated around:**

\- NPHI: 0.15–0.25

\- RHOB: 2.20–2.45 g/cc

- **Indicates:**

\- Moderately shaly sandstone

\- Dominantly dispersed + mixed shale

\- Progressive porosity loss with increasing shale

This trend aligns closely with the dispersed shale line, not the structural shale trend.

The neutron–density cross-plot constrained by the Thomas–Stieber model indicates that the studied intervals are dominated by dispersed shale rather than structural shale. Data points trend away from the clean sandstone reference toward the dispersed shale end member, implying clay minerals are mainly pore-filling or grain-coating, leading to significant effective porosity degradation. Structural shale contribution appears minor, suggesting limited laminated shale influence on reservoir quality.

Integrated Interpretation and Reservoir Implications:

Integration of all cross-plot results demonstrates strong internal consistency and highlights the effectiveness of the proposed workflow. Neutron–density cross-plot define shale distribution and porosity trends, PEF–density and MID analyses confirm quartz-dominated lithology, and Th–K cross-plots resolve clay mineral types. Together, these findings indicate that reservoir quality variations in the Messla Field are primarily controlled by shale distribution and clay mineralogy rather than changes in primary sandstone composition.

The dominance of kaolinite and mixed-layer clays suggests increased bound water and reduced permeability in shale-rich intervals, emphasizing the need for shale-aware porosity and saturation models. The integrated cross-plot approach presented here provides a robust, log-based framework for reducing uncertainty in lithology discrimination and shale evaluation, particularly in data-limited sandstone reservoirs such as the Sarir Formation.

Conclusion:

Petrophysical cross-plot analysis of the Sarir Formation in the Messla Field indicates that the reservoir is dominantly quartz-rich sandstone with variable shale content. Neutron–density cross-plots show a strong clustering of data points along the clean sandstone trend, confirming the siliciclastic nature of the reservoir. Progressive deviation toward the shale line corresponds to increasing shale volume and reflects the presence of laminated to dispersed shale within sandstone intervals.

Photoelectric factor–density cross-plots further confirm quartz-dominated matrix composition, with most data points exhibiting PEF values near 2.0 b/e. Minor dispersion toward higher PEF values suggests localized carbonate cementation; however, this component is limited and does not significantly influence overall reservoir lithology. MID cross-plot results corroborate these interpretations by clustering near the quartz reference point while showing systematic displacement in shale-rich intervals. Spectral gamma-ray Th–K cross-plots reveal that kaolinite-dominated clay assemblage with minor mixed-layer contributions dominate the shale component of the Sarir Formation. These clay assemblages explain the observed neutron enrichment and porosity suppression in shale-bearing intervals and highlight the strong influence of clay mineralogy on reservoir quality, where Thomas–Stieber model indicates that the studied intervals are dominated by dispersed shale rather than structural shale.

This study demonstrates the effectiveness of an integrated, cross-plot–based petrophysical workflow for lithology discrimination, shale distribution analysis, and clay mineral typing in a heterogeneous sandstone reservoir using conventional wireline log data only. Application of neutron–density, PEF–density, MID, Th–K and Thomas-Stieber cross-plots to the Sarir Formation in the Messla Field confirms that the reservoir is predominantly quartz-rich sandstone with variable shale content.

The results show that shale distribution, rather than primary matrix lithology, is the principal control on porosity and reservoir quality in the studied interval. Cross-plot analysis allows differentiation between clean sandstone, shale-laminated sandstone, and shale-rich zones, which cannot be reliably achieved using single-log or gamma-ray–based methods alone. Clay mineral typing from spectral gamma-ray data indicates a dominance of kaolinite and mixed-layer clays, explaining the observed bound-water effects and porosity reduction in shale-bearing intervals.

The proposed workflow provides a robust and internally consistent framework for reducing petrophysical uncertainty in data-limited sandstone reservoirs. Its successful application in the Messla Field suggests that the methodology is transferable to similar fluvial to marginal-marine sandstone systems in the Sirte Basin and comparable basins worldwide, offering practical value for reservoir characterization, net pay evaluation, and static reservoir modeling.

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