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X-Ray Diffraction Technique: A Powerful Method of Characterization of Minerals from Mamuniyat Formation Concession NC174, Murzuq Basin, SW Libya

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A B S T R A C T

This study provides a comprehensive geochemical and mineralogical analysis of sediments from different wells in the Mamuniyat Formation Concession NC174, Murzuq Basin, located of South West Libya. The mineralogy of a series of twenty-two samples has been evaluated by X-ray diffraction (XRD) on a quantitative basis using the SIROQUANT data processing technique. Based on these principles. The results show that eight minerals have been identified: quartz, microcline, kaolinite, illite, muscovite, chlorite, dolomite and siderite. The most common minerals are quartz, kaolinite, siderite, and illite. The diffraction patterns demonstrated that quartz is the dominant mineral phase in most samples, indicating high sedimentary maturity and strong resistance to chemical and mechanical weathering during transportation and deposition processes. kaolinite is the most abundant clay mineral within the formation and is mainly associated with the chemical alteration of potassium feldspars under acidic diagenetic fluids during early diagenesis. The inverse relationship observed between microcline and kaolinite indicates progressive dissolution and mineralogical transformation. illite represents a more advanced diagenetic stage associated with increasing burial pressure and structures, whereas clay minerals exhibit broader temperature ranges, while chlorite reflects depositional and diagenetic conditions enriched in iron and magnesium. Siderite and dolomite occur in limited amounts, suggesting reducing and oxygen-deficient environments during certain depositional and post-depositional stages.

Keywords: *X-Ray diffraction, Mineral characterization, Mamuniyat Formation, crystal, Libya*

تقنية حيود الأشعة السينية: طريقة فعالة لتوصيف المعادن من تكوين المأمونيات، امتياز NC174، حوض مرزق، جنوب غرب ليبيا

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الملخص

تقدم هذه الدراسة تحليلاً جيوكيميائياً ومعدنياً شاملاً لرواسب مستخرجة من آبار مختلفة ضمن "تكوين المأمونيات" في منطقة الامتياز NC174 بحوض مرزق، الواقع في جنوب غرب ليبيا. وقد جرى تقييم التركيب المعدني لسلسلة مكونة من اثنتين وعشرين عينة باستخدام تقنية حيود الأشعة السينية (XRD) وبأسلوب كمي يعتمد على تقنية معالجة البيانات "SIROQUANT" والمبادئ المتبعة في هذا السياق. وأظهرت النتائج هيمنة ثمانية معادن تم تحديدها، وهي: الكوارتز، والميكروكلين، والكاولينيت، والإيليت، والمسكوفيت، والكلوريت، والدولوميت، والسيدريت. وتُعد معادن الكوارتز والكاولينيت والسيدريت والإيليت هي الأكثر شيوعاً. كما بيّنت أنماط الحيود أن الكوارتز يمثل الطور المعدني السائد في معظم العينات، مما يشير إلى نضج رسوبي عالٍ ومقاومة قوية للتجوية الكيميائية والميكانيكية أثناء عمليات النقل والترسيب.

كما يُعد الكاولينيت أكثر معادن الطين وفرةً في هذا التكوين، ويرتبط بشكل أساسي بالتحول الكيميائي لفلسبارات البوتاسيوم بفعل السوائل التحولية (الدياجينية) الحمضية خلال مرحلة التحول المبكر. وتشير العلاقة العكسية الملاحظة بين الميكروكلين والكاولينيت إلى عمليات ذوبان وتحول معدني مستمرة. بينما يمثل معدن "الإيليت" (illite) مرحلة تحول صخري (diagenetic) أكثر تقدماً ترتبط بزيادة ضغط وعمليات الدفن، في حين تُظهر معادن الطين نطاقات حرارية أوسع، بينما يعكس معدن "الكلوريت" (chlorite) ظروفاً ترسيبية وتحولية غنية بالحديد والمغنيسيوم. أما معدنا "السيدرايت" (siderite) و"الدولوميت" (dolomite) فيتواجدان بكميات محدودة تشير إلى بيئات مختزلة وفقيرة بالأكسجين خلال مراحل معينة من الترسيب وما بعد الترسيب.

الكلمات المفتاحية: *حيود الأشعة السينية، توصيف المعادن، تكوين المأمونيات، بلورة، ليبيا.*

1. Introduction

XRD was used to determine the composition of the sandstones and was carried out on bulk samples. A total of 22 samples were selected and analysed using X-ray diffraction (XRD) to understand the nature and mineral composition of the Mamuniyat reservoir. X-ray diffraction is a powerful non-destructive technique for mineral characterization having

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widespread applications within major domains such as crystal structure and size, phase identification, crystallographic orientation, determining the lattice parameters, dislocation density, residual stress/strain, phase transformation, and thermal expansion coefficient [1].

In the context of the application of regional independence, which will soon take effect, local governments are encouraged to be independent in managing their regions. One of the mainstays of the region is mineral resources. One potential commodity that deserves attention is quartz sand or silica sand. Silica sand is one of the mineral materials whose existence in nature is very abundant and can be utilized in various applications. In the Mamuniyat Formation, there are deposits of silica sand that are quite abundant. The existence of silica sand in this area is expected to provide new income contributions, both to the local community and to local revenue.

2. Mamuniyat Formation background

The Mamuniyat Formation was defined after Jabil Al Mamuniyat (West of Gargaf) [2]; it has been described by both [3] and [4]. This formation is composed entirely of sandstones, which makes it very prominent and easy to recognize throughout the area. The composition of the Mamuniyat Formation is relatively simple and monotonous. Its consist of massive, cross-bedded, medium-grained to conglomeratic sandstones occasionally showing high percentages of kaolinitic matrix.

Generally, the origin of clay minerals is as subaerial weathering products of silicate minerals, usually abundant in weathered residue and soils [5]. The clay minerals group includes: kaolinite, illite, chlorite, smectite, and mixed-layer clay. This division of clay minerals is based on a structural rather than a compositional basis [6]. Detrital clays can indicate source area geology, climate, and weathering processes. Clay minerals form about 5% of most sandstones. They are characterized by their small size and are as abundant as a matrix. The phyllosilicate mineral group is characterized by two-dimensional layers, which are arranged in indefinitely extending sheets [7]. The volume of authigenic clay minerals in sandstone ranges from 1-2%. The prominent exception is the volcaniclastic sandstones that have high percentages of very unstable lithic fragments that are deposited near convergent plate margins in high heat flow areas and geothermal gradients [8]. Mafic silicates in many climates will weather to smectite, while illite forms in intermediate to humid climates. It fills the primary and secondary pore space.

Many factors affect the content of clay minerals: pressure (burial depth), temperature, time, tectonics, source rock, general deposition environment and major climate variations [9]. The chemistry of the formation waters and composition of the rock have a strong influence on the growth of authigenic clays [10]. All the major types of clay minerals in sandstone formed authigenically as a direct precipitate from formation waters (neoformation) or from reactions that occur between precursor materials and the contained waters (regeneration) [11].

Kaolinite in sandstone generally occurs as clusters of large "booklets" located between detrital grains; the dickite polytype occurs to depths of about 3900 m (180°C) in both sandstone and shale. Kaolinite transforms to dickite between 3000m and 3500m depth [12]. Kaolinite may be the most common mineral of the kaolinite group found in sandstones; however, the polytype dickite is also common [13].

Authigenic illite and mixed-layer illite-smectite generally post-date kaolinite authigenesis in sandstones. Moreover, the composition of illitic clay cements in sandstones is controlled by the porewater composition from which they have formed and is probably independent of temperature. Illite is usually associated with higher pH and more concentrated porewaters than kaolinite [14]. Illite can occur as flakes, filaments, or hair-like crystals. Mite occurs as polytypes that may reflect the different ways in which layers are stacked [15]. Generally, the occurrence of fibrous Blite as an authigenic phase may affect a reservoir and cause problems by baffling pore throats without a major reduction in pore volume. Smectite usually occurs as flakes curling up from an attachment zone on the detrital sand grain surface [16]. Chlorite occurs as a grain coating, appearing as boxwork with the chlorite crystals attached perpendicular to the grain surface.

Clay coatings apparently coat all detrital grains regardless of their composition [17]. Clay coating materials formed at an earlier stage of diagenesis are themselves diagenetic in origin [18]. Clay coats on sand grains can be detrital in origin and occur most commonly within embayed surfaces of sand particles [19]. Infiltrated clay coats are common in sandy meandering river deposits, but appear to be thinner than in braided river deposits. The one mechanism of grain coating clay is always by macro-organisms [20].

The purpose of this paper is to determine the geochemical composition of silica sand in the Mamuniyat Formation Concession NC174 area using X-Ray Diffraction (XRD).

3. X-RAY DIFFRACTION PRINCIPLE

When the X-rays impinge on solid materials, they get scattered by the electrons revolving around the nucleus of atoms. These scattered waves, emitted in multiple directions, interfere with each other. The nature of interference can be constructive or destructive, based on the direction and type of interaction of waves [21]. Diffraction is the constructive interference of scattered X-rays. It is worthy to note here that the orderly arrangement (periodicity) of atomic structures in solids causes constructive interference. It is, therefore, relatively easier to interpret the XRD graphs of crystalline substances as compared to amorphous ones. A strong correlation exists between periodicity and diffraction, i.e., higher diffraction angles are observed with shorter periodicity and vice versa. [22] established XRD graphs of amorphous and crystalline solids. Due to the absence of a periodic arrangement in amorphous materials, the XRD graph only indicates the maximum average peak at a certain diffraction angle, while crystalline materials show several distinct XRD peaks owing to the periodic arrangement of atoms. XRD is also a powerful technique for estimating the treatment effects on the crystallinity of materials. For example, a recent study [23] used XRD for understanding the effects of various treatments on the crystallinity of their sample material. XRD allowed them to identify that the combustion treatment of their sample would enhance the material's crystallinity to a relatively greater extent.

4. Material and Methods

4.1 Material

In this study, samples from 7 wells with burial depths ranging from 5102 to 7187 ft were selected for experimental research. The experimental items include clay mineral X-ray diffraction. The X-ray diffraction analysis and detection of clay minerals are based on "X-ray Diffraction Analysis Method of Clay Minerals and Common Non-clay Minerals in Sedimentary Rocks, and the experimental instrument is an X-ray diffraction analyzer Ultima IV.

4.2 Methods

X-ray diffraction of clay minerals. X-rays are light waves with very short wavelengths and have strong penetrating power. When X-rays are injected into the lattice of clay minerals, diffraction will occur. Different clay minerals and lattices have different structures and will produce different diffraction patterns. The X-ray diffraction analysis of clay minerals is based on the fact that different clay minerals have different crystal structures, and utilizes the layered structure of clay minerals and the principle of X-ray diffraction [24], [25]. From the diffraction peaks, the interplanar spacing is calculated, and then different mineral types are identified. The X-ray diffraction analysis of clay minerals was carried out on randomly oriented powders. Twenty-two hand-powdered whole-rock samples were analyzed. Samples were crushed for 90 seconds in a TEMA tungsten carbide disc mill, and the particle size of selected samples was checked using a CIS-11 laser particle size analyzer to ensure a particle size in the range of 5- 10 μm. [26]. Before preparation of the analyzed sample, the sample powders were homogenized by gentle agitation for ca. 30 seconds. X-ray diffraction analysis was carried out on a Bruker D8 Advance diffractometer using monochromatic Cu Kaa radiation (1 = 1.5406 Å), with the X-ray tube voltage and current set at 40 KV and 40 mA, respectively. The detector used was a scintillation counter. A 1mm divergent slit, a 0.2mm detector slit 1mm anti-scatter slit were used. Each sample was scanned between 5° and 70° with a step size of 0.02° and a count time of 4 seconds per step, and rotated during the scan to ensure random sample orientation. XRD was used to determine the composition of sandstones. The results of this were linked to the petrographic description of selected samples as shown in Table 1. Analysis of the powdered whole rock gives more information on the fine-grained c1astics. components, although XRD for the separated fine fraction from sandstone can provide more information about clay mineralogy [27]. Siroquant Analysis XRD was used to determine the composition of the sandstones and was carried out on bulk samples. 22 samples were selected and analysed using X-ray diffraction (XRD) to understand the nature and mineral composition of the Mamuniyat reservoir. Results are shown in the following Figures 1 to 7.

5. Results and Discussion

Based on the analysis results of the studied samples in Table 1, the diffraction patterns reveal the occurrence of constructive interference when X-rays of a given wavelength ($\lambda = 1.5406\, A°$) interact with crystalline materials. The incident X-rays are not only reflected from the surface but also penetrate the atomic planes and undergo diffraction at specific angles satisfying Bragg's law

$$n\lambda = 2d\ sin\theta:$$

The following physical considerations should be taken into account:

1. Each diffraction peak represents a physical fingerprint of the interplanar spacing (d-space) of the identified mineral phase.
2. The diffraction intensity is directly proportional to the square of the structure factor, allowing a physical estimation of the relative abundance of each mineral within the complex Mamuniyat sandstone mixture.
3. Thermal-energy-induced phase transformation may occur, where elevated temperatures (reaching approximately 180 C^o at a depth of 3900 m) lead to atomic rearrangement within mineral layers to minimize the free energy of the system. This process alters the observed diffraction pattern through changes in layer stacking arrangements (Polytypism)

5.1 Quartz

The occurrence of sharp and high-intensity diffraction peaks in most samples indicates that quartz possesses a highly ordered periodic crystalline structure with low crystal defects and minimal internal strain.

The quartz content ranges from 23.6% to 95.3% of the total rock volume Figures 1 to 7, samples 1 to 22. Such a high abundance reflects advanced sedimentary maturity and strong resistance to both chemical and mechanical weathering during transportation and deposition processes due to its high hardness and compressional resistance.

5.2 Clay Minerals

The study revealed that illite and chlorite are among the dominant clay minerals within the Mamuniyat Formation. XRD analyses of the clay fraction (<2 μm) showed that kaolinite and illite constitute the principal clay phases, as presented in Table 1. The XRD results confirmed characteristic kaolinite peaks with variable intensities and relatively broad diffraction profiles compared to quartz, reflecting lower crystallinity and smaller crystal size. The fine layered structure of clay minerals increases scattering effects and reduces the regularity of crystallographic reflections. Kaolinite content ranged from 2.2% to 28.7% Figures 1 to 7, samples 1 to 22, indicating variations in clay transformation processes among the studied samples. This suggests that kaolinite was mainly formed through the alteration of potassium feldspars under the influence of acidic groundwater-rich solutions. Kaolinite may fill pore spaces or accumulate along pore walls, resulting in reduced effective permeability.

The XRD patterns also exhibited weak to moderate illite peaks, representing the second most abundant clay mineral, with concentrations ranging from 0.0% to 7.9% Figure 2, sample 1 and Figure 4, sample 9. This indicates relatively advanced diagenetic alteration associated with increasing burial pressure and temperature.

Illite typically exhibits less sharp diffraction peaks compared to quartz due to the relatively disordered layered crystal structure of clay minerals. Furthermore, the occurrence of illite reflects the thermal evolution of the reservoir, where smectite progressively transforms into illite with increasing burial depth and temperature.

Fibrous illite may cause pore throat blockage even at relatively low volumetric concentrations, leading to a significant permeability reduction despite its limited effect on total porosity. XRD analysis shows that chlorite is only present in minor quantities in well B 1. At 0.1 – 0.8%, Figure 2 sample 3 and 4, this confirms that the chlorite is poorly crystallised. Its abundance suggests that it is probably detrital in origin.

5.3 Microcline

Microcline is one of the potassium feldspar minerals identified within the Mamuniyat Formation. Whole-rock XRD analyses revealed characteristic diffraction peaks of microcline with varying intensities, ranging approximately between 0.0% and 13.5% Figure 2 Sample 4, Figure 3; sample 3, Figure 4; sample 10, 12, Figure 5; sample 13 to 17, Figure 6; sample 18 to 20, Figure 7; samples 21 to 22.

Microcline crystallizes in the triclinic crystal system; therefore, it exhibits distinct diffraction peaks at specific diffraction angles resulting from the periodic atomic arrangement within the crystal lattice. Relatively sharp peaks observed in some patterns indicate good crystallinity and well-ordered crystal structures.

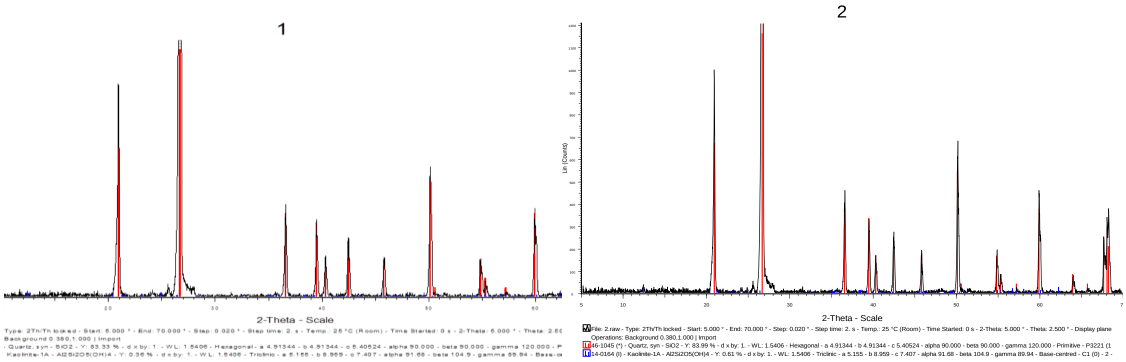

Figure 1. X-ray diffractogram of clay samples 1,2 (well A1)

The presence of microcline suggests that part of the primary detrital minerals was not completely altered during weathering and diagenesis, reflecting relatively stable geochemical conditions during certain geological stages. Its preservation in noticeable quantities may also indicate short sediment transport distances or direct input from igneous and metamorphic source rocks enriched in feldspars.

The results additionally demonstrate an inverse relationship between microcline and kaolinite in some samples, where acidic dissolution of microcline promotes kaolinite formation. Accordingly, decreasing microcline peak intensity accompanied by increasing kaolinite peaks reflects progressive diagenetic and mineralogical transformation within the sandstone reservoir.

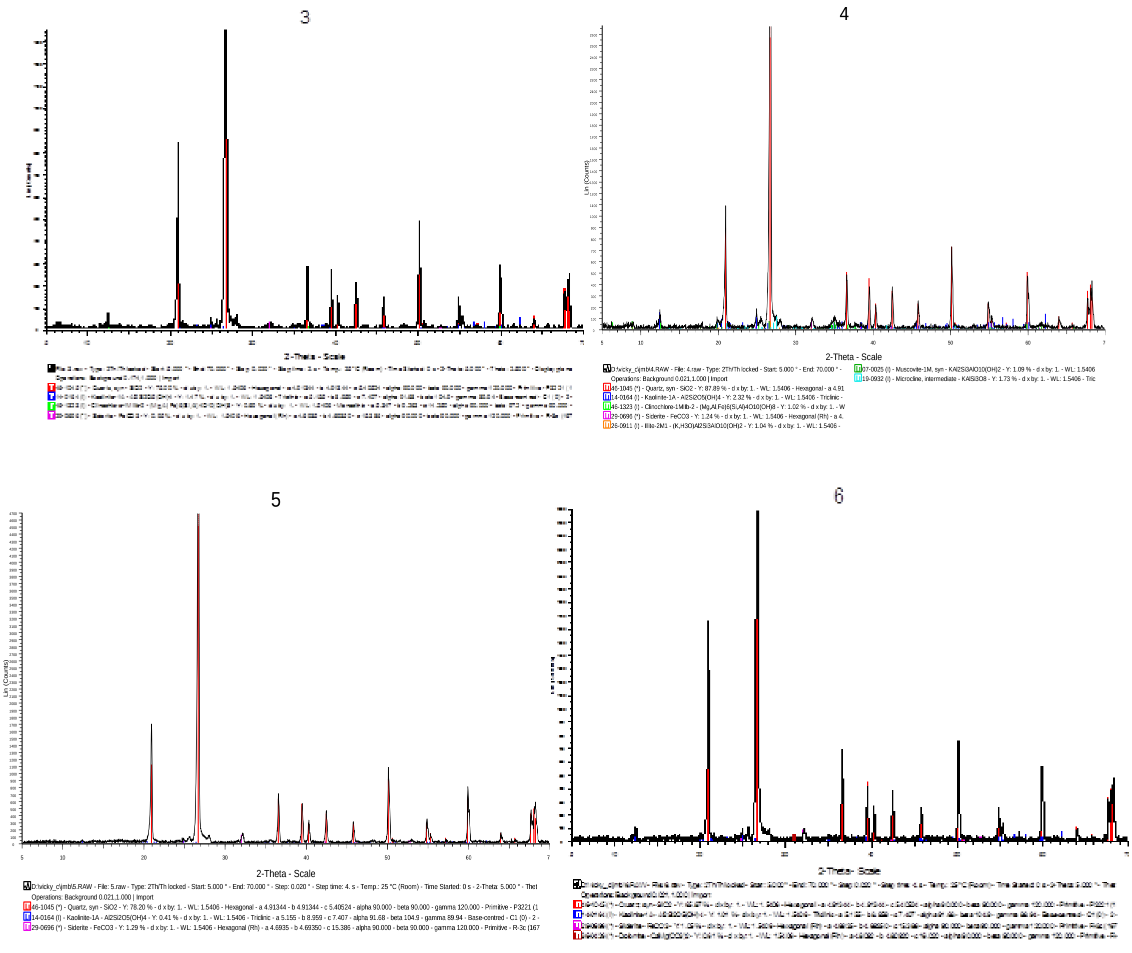

Figure 2. X-ray diffractogram of clay samples 3,4,5,6 (well B1)

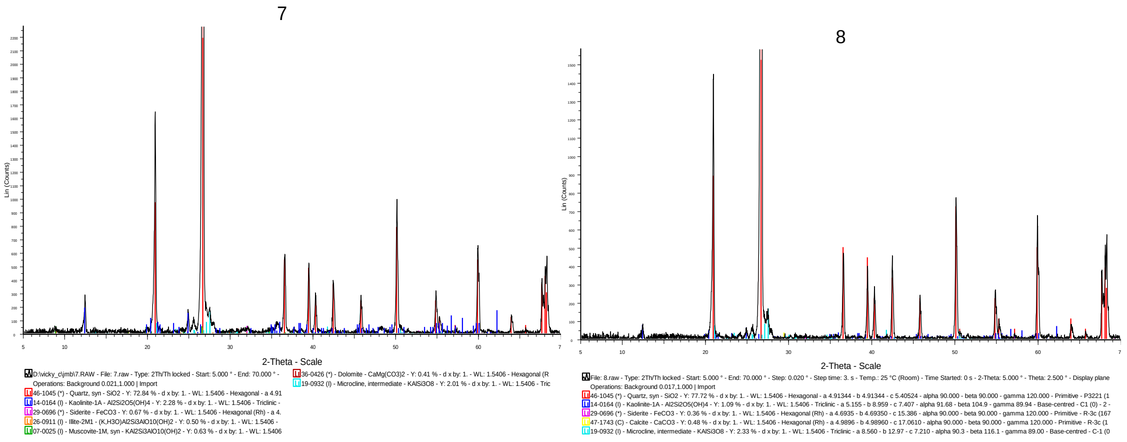

Figure 3. X-ray diffractogram of clay samples 7,8 (well F1)

From a reservoir-quality perspective, dissolution of microcline may generate secondary porosity through feldspar alteration; however, this porosity may subsequently become occluded by clay mineral precipitation or carbonate cementation within pore spaces.

Muscovite, on the other hand, is a platy mineral characterized by a two-dimensional layered crystal structure, resulting in strong but irregular reflections from certain crystallographic planes. Consequently, it appears as relatively broad peaks with moderate intensity and contributes to reduced permeability.

5.4 Siderite

XRD analyses confirmed the presence of limited siderite peaks. Siderite represents a carbonate cement phase within the sandstone samples, with concentrations ranging from 0.0% to 8% Figure 2, samples 3 to 6; Figure 3, sample 8; Figure 4, samples

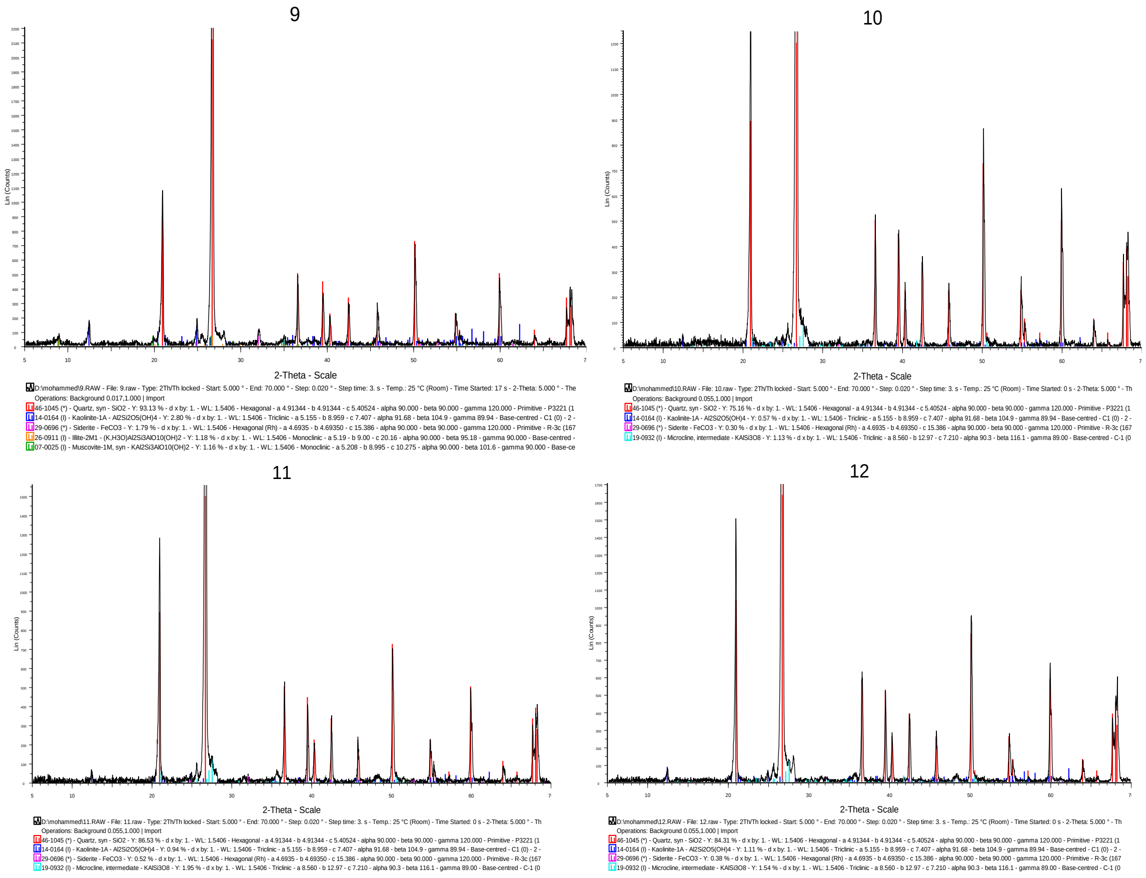

Figure 4. X-ray diffractogram of clay samples 9,10,11,12 (well F2)

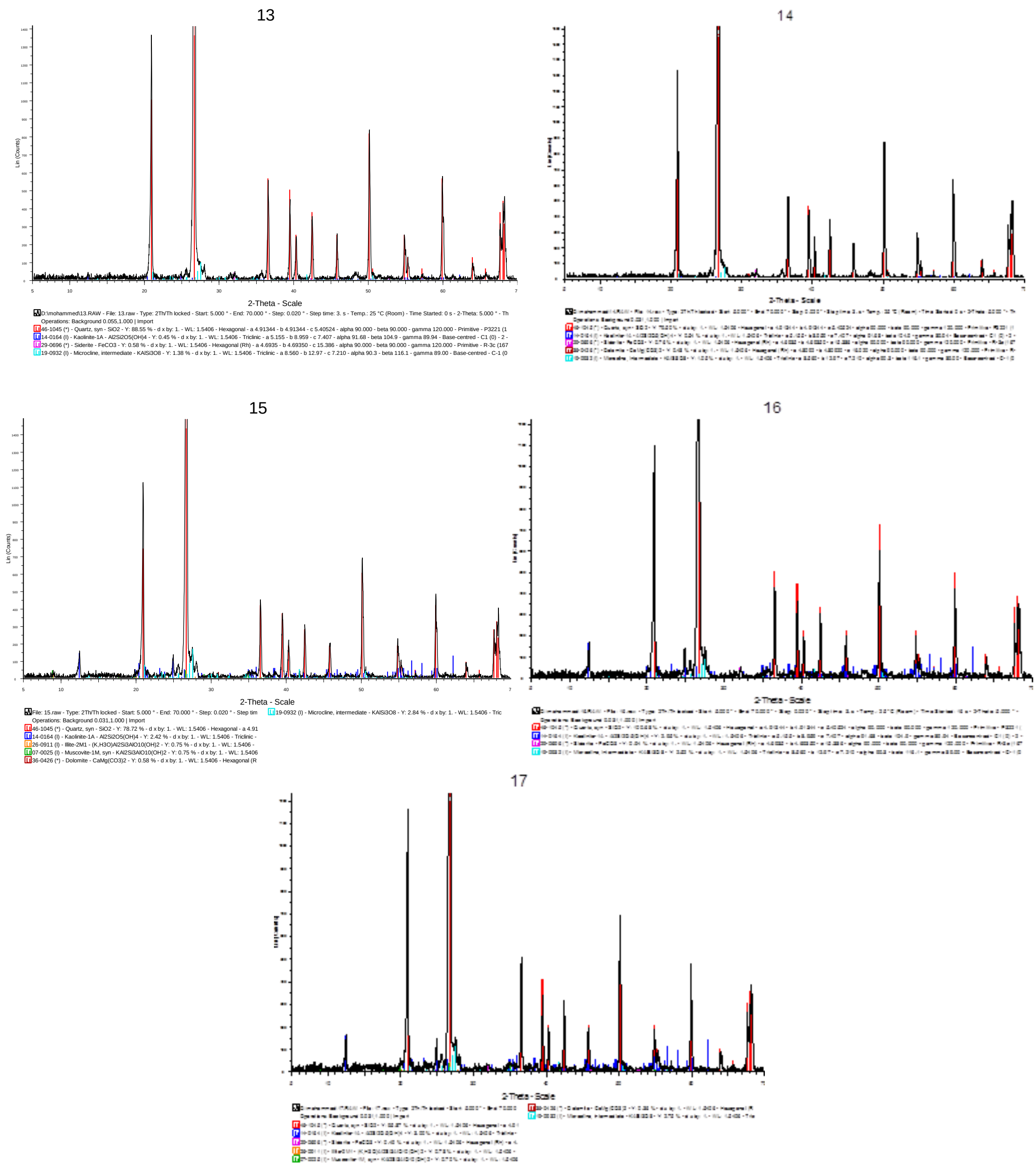

Figure 5. X-ray diffractogram of clay samples 13,14,15,16,17 (well F3)

9 and 10; Figure 5, samples 13, 14, 16 and 17; Figure 7, sample 21. Siderite formation is commonly associated with oxygen-deficient reducing environments. Its precipitation contributes directly to the reduction of both porosity and permeability.

5.5 Dolomite

XRD results recorded minor amounts of dolomite exclusively in well B1-NC174, with concentrations ranging from 0.0% to 0.7% in certain samples Figure 2, sample 6. This indicates limited activity of magnesium-rich fluids during the late stages of diagenesis. Carbonate minerals generally exhibit relatively sharp diffraction peaks owing to their higher crystallographic ordering compared to clay minerals.

5.6 Mica

The study demonstrated that detrital mica assemblages are dominated by muscovite, whose abundance ranges between 0.0% and 18.3% in the investigated Mamuniyat Formation samples Figure 2, sample 4; Figure 3, sample 7; Figure 4, samples 9 and 11; Figure 5, sample 15, with the highest concentration recorded in well F3. No clear relationship was observed between muscovite abundance and burial depth.

Muscovite constitutes an important component in some sandstone reservoirs. Its occurrence as thin, flaky, mica-rich sheets adversely affects permeability

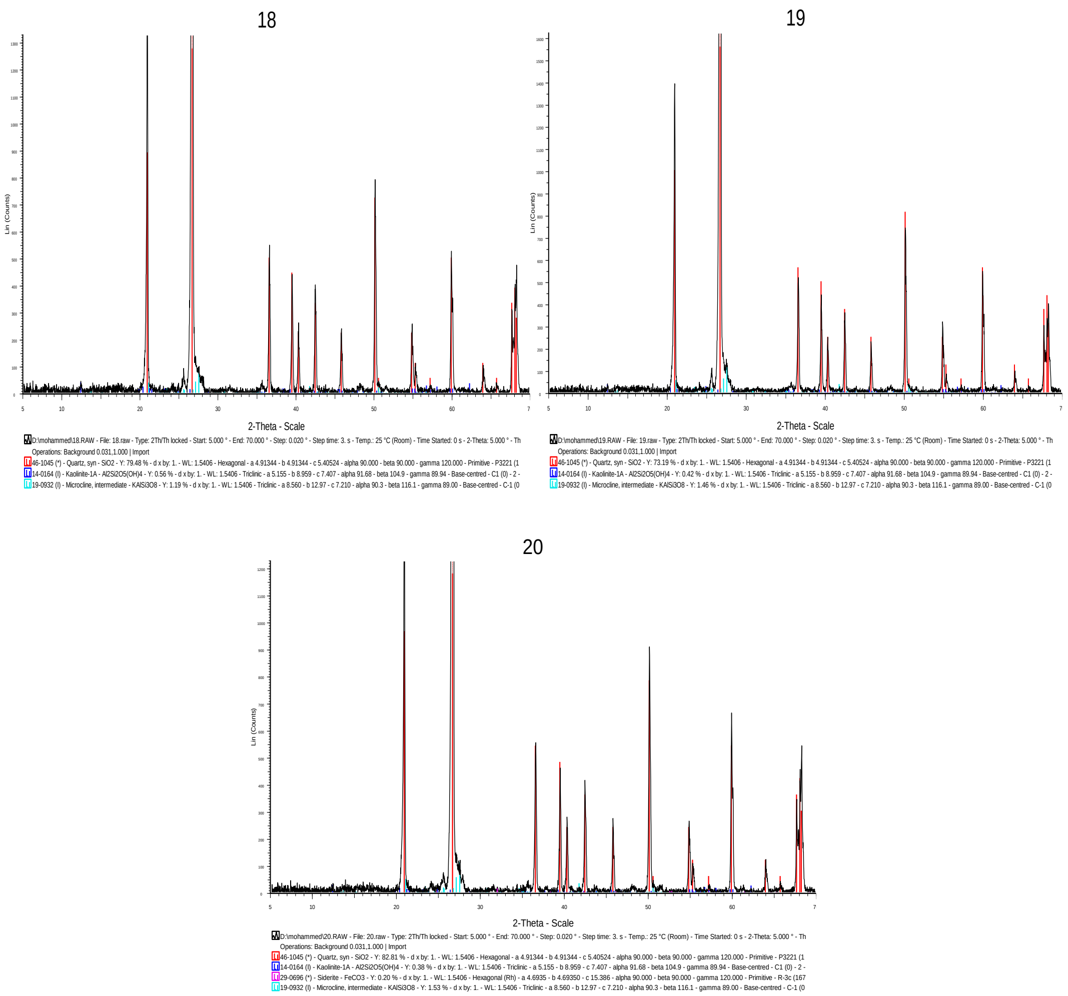

Figure 6. X-ray diffractogram of clay samples 18,19,20 (well F4)

by obstructing fluid flow pathways within pore systems. Variations in diffraction peak intensity reflect differences in mineral abundance, crystallinity, and crystal ordering among the studied samples.

The detrital mineral assemblages further suggest that the sediment source was mainly derived from coarse-grained metamorphic basement rocks associated with nearby tectonically active regions, possibly linked to the Ghat–Tikiumit Arch.

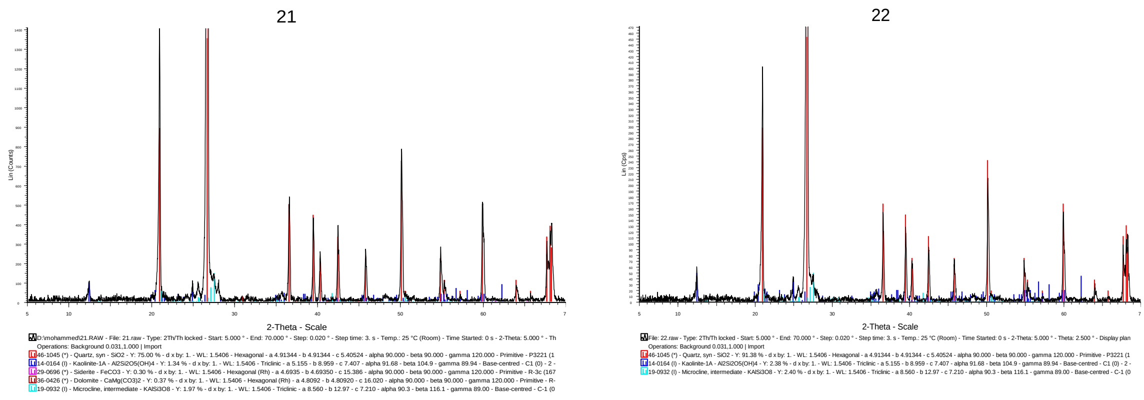

Figure 7. X-ray diffractogram of clay samples 21,22 (well F5)

Table 1. Mineral composition (%) of sandstone samples from the Mamuniyat Formation, NC174 concession

Sample No	well	Depth ft	Kaolinite %	Illite %	Chlorite %	Microcline %	Muscovite %	Siderite %	Dolomite %	Quartz %
1	A1	6370.6	4.7	0.0	0.0	0.0	0.0	0.0	0.0	95.3
2	A1	6395.0	5.3	0.0	0.0	0.0	0.0	0.0	0.0	94.8
3	B1	7096.5	6.8	0.0	0.8	0.0	0.0	1.5	0.0	90.9
4	B1	7127.9	7.1	1.2	0.1	7.8	6.6	1.5	0.0	75.0
5	B1	7156.7	5.1	0.0	0.0	0.0	0.0	1.9	0.0	92.9
6	B1	7175.8	5.5	0.0	0.0	0.0	0.0	1.0	0.7	92.8
7	F1	7163.0	7.1	0.0	0.0	12.0	3.5	0.0	0.0	77.3
8	F1	7187.0	5.4	0.0	0.0	0.0	0.0	0.5	0.0	94.0
9	F2	5102.0	8.8	1.8	0.0	0.0	7.3	2.4	0.0	79.7
10	F2	7167.4	3.3	0.0	0.0	10.5	0.0	0.2	0.0	86.0
11	F2	5310.5	4.1	0.0	0.0	0.0	12.9	0.0	0.0	83.0
12	F2	5426.0	4.4	0.0	0.0	12.1	0.0	0.0	0.0	83.5
13	F3	5377.7	3.5	0.0	0.0	11.1	0.0	0.4	0.0	84.9
14	F3	5398.0	3.6	0.0	0.0	10.9	0.0	0.7	0.0	84.9
15	F3	5434.7	7.3	0.0	0.0	12.4	4	0.0	0.0	76.3
16	F3	5438.8	7.2	0.0	0.0	12.8	0.0	0.6	0.0	79.4
17	F3	5478.0	7.3	0.0	0.0	12.9	4.2	0.1	0.0	75.6
18	F4	5478.0	2.5	0.0	0.0	9.4	0.0	0.0	0.0	88.1
19	F4	5372.4	2.2	0.0	0.0	9.6	0.0	0.0	0.0	88.3
20	F4	5415.0	2.8	0.0	0.0	11.2	0.0	0.0	0.0	86.0
21	F5	5504.0	4.5	0.0	0.0	11.7	0.0	0.2	0.0	83.6
22	F5	5549.5	6.9	0.0	0.0	12.6	0.0	0.0	0.0	80.5

6. Conclusion

X-ray diffraction (XRD) analyses of the investigated samples from the Mamuniyat Formation in the Murzuq Basin, southwestern Libya, revealed that the sandstone reservoir is predominantly composed of quartz, with variable proportions of kaolinite, illite, microcline, muscovite, siderite, dolomite, and chlorite The diffraction patterns demonstrated that quartz is the dominant mineral phase in most samples Figures 8 to 11., indicating high sedimentary maturity and strong resistance to chemical and mechanical weathering during transportation and deposition processes.

The sharp and high-intensity quartz peaks indicate good crystallinity and well-ordered crystal lattice structures that modified the mineralogical composition of the reservoir. From a petrophysical and reservoir-quality standpoint, high quartz content contributes to maintaining the mechanical stability and rigidity of the sandstone reservoir, whereas clay

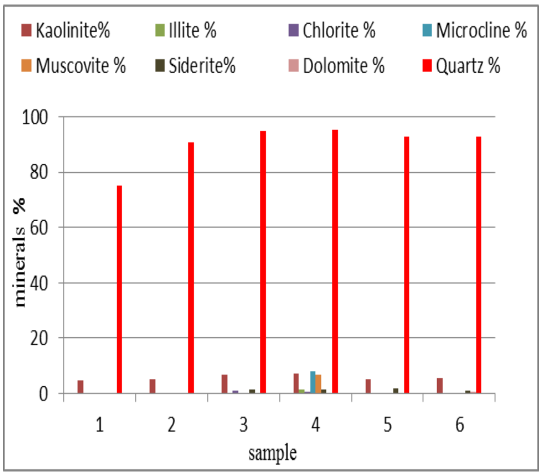

Figure 8. Bar graph representing the relative percentages of bulk minerals in the Mamuniyat Formation from samples 1 to 6, as shown in Table 1.

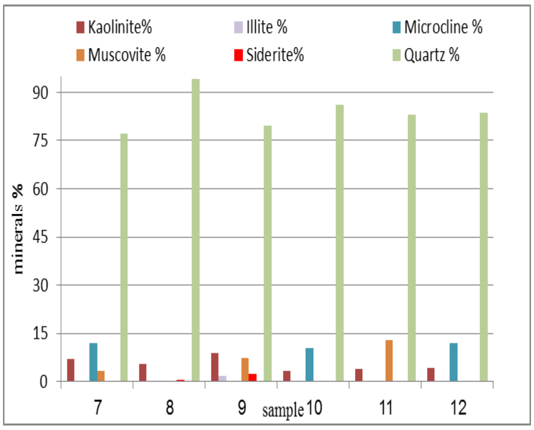

Figure 9 Bar graph representing the relative percentages of bulk minerals in the Mamuniyat Formation from samples 7 to 12 as shown in Table 1.

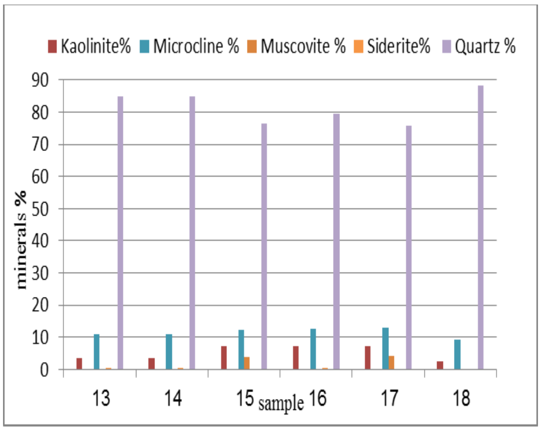

Figure 10. Bar graph representing the relative percentages of bulk minerals in the Mamuniyat Formation from samples 13 to 18 as shown in Table 1.

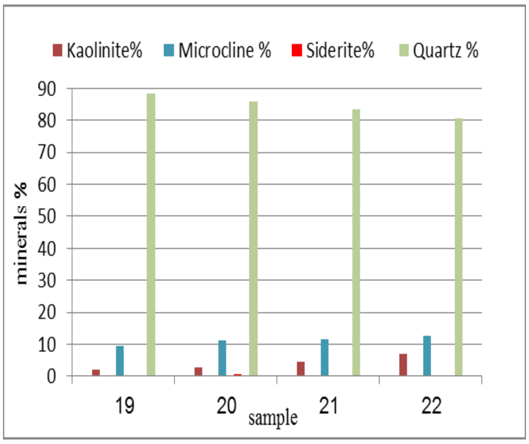

Figure 11. Bar graph representing the relative percentages of bulk minerals in the Mamuniyat Formation from samples 19 to 22 as shown in Table 1.

minerals and carbonate cement exert a negative influence on reservoir quality by reducing effective porosity and restricting fluid flow through pore networks.

These findings confirm that X-ray diffraction (XRD) is an accurate and effective technique for mineralogical characterization, diagenetic evolution assessment, and evaluation of the physical properties of reservoir rocks. Moreover, it provides an essential framework for understanding sandstone reservoir evolution and assessing petrophysical reservoir quality within the Murzuq Basin, with less intense peaks due to their smaller crystallite size and relatively disordered layered structures.

The study confirmed that kaolinite is the most abundant clay mineral within the formation and is mainly associated with the chemical alteration of potassium feldspars under acidic diagenetic fluids during early diagenesis. The inverse relationship observed between microcline and kaolinite indicates progressive dissolution and mineralogical transformation processes within the sandstone reservoir Figures 8 to 11.

XRD results further demonstrated that illite represents a more advanced diagenetic stage associated with increasing burial pressure and structures, whereas clay minerals exhibit broader temperature ranges Figures 8 and 9, while chlorite reflects depositional and diagenetic conditions enriched in iron and magnesium Figure 8.

Siderite and dolomite occur in limited amounts as carbonate cement phases within the sandstone matrix Figures 8 to 11, suggesting reducing and oxygen-deficient environments during certain depositional and post-depositional stages. These carbonate cements directly
reduce porosity and permeability through pore-filling processes. From a geological perspective, the identified mineral assemblages suggest that the sediments were primarily derived from ancient crystalline and metamorphic basement rocks enriched in feldspars and mica Figures 8 to 10, with significant contributions from chemical weathering and diagenetic alteration.

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