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بِسْمِ اللهِ الرَّحْمٰنِ الرَّحِيمِ

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This dedication would be the best way for me to honor you and show you how wonderful you have been.

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ABSTRACT

Clay minerals are a critical component of sedimentary rocks and can significantly impact oil and gas reservoirs. Clay migration and swelling are widely documented as the primary causes of oil recovery impairment. This study, conducted in the Gedinnean reservoirs of El Ouabed, aimed to examine the influence of clay minerals on permeability reduction. Through the use of X-ray powder diffraction (XRPD), hyperspectral camera analysis, logging interpretation, and laboratory experimental tests, it has been concluded that clay minerals, particularly non-swelling clay minerals such as kaolinite and illite, can migrate and block pore throats, causing permeability reduction in the reservoirs. Additionally, the use of oil-based mud can further impact reservoir permeability through alterations in wettability. These findings emphasize the significance of comprehending clay mineral behavior and its implications for effective reservoir management and oil recovery.

Key words: Clay, Migration, Swelling, Reservoir, Permeability, Inhibitions, Micro model.

RÉSUMÉ

Les minéraux argileux sont des composants essentiels des roches sédimentaires et peuvent avoir un impact significatif sur les réservoirs d'huile et de gaz. La migration et le gonflement des argiles sont largement reconnus comme les principales causes de la diminution de la récupération du pétrole. Cette étude, menée dans les réservoirs de Gedinnean à El Ouabed, visait à examiner l'influence des minéraux argileux sur la réduction de la perméabilité. Grâce à l'utilisation de la diffraction des rayons X sur poudre (DRX), de l'analyse par caméra hyperspectral, de l'interprétation des diagraphies et d'expériences en laboratoire, il a été conclu que les minéraux argileux, en particulier les argiles non gonflantes comme la kaolinite et l'illite, peuvent migrer et obstruer les pores, entraînant une réduction de la perméabilité dans les réservoirs. De plus, l'utilisation de boues à base d'huile peut également affecter la perméabilité du réservoir en altérant la mouillabilité des minéraux argileux. Ces résultats soulignent l'importance de comprendre le comportement des minéraux argileux pour une gestion efficace des réservoirs et une meilleure récupération du pétrole.

Mots clés : Argile, Migration, Gonflement, Perméabilité, Réservoir, Inhibitions, Micro modèle.

ملخص:

المعادن الطينية هي مكون حيوي في الصخور الرسوبية وتؤثر بشكل كبير على خزانات النفط والغاز. الانتقال والانتفاخ للمعادن الطينية موثقة على نطاق واسع كأسباب رئيسية لتقليل استعادة النفط. هدفت هذه الدراسة التي أجريت في خزاناتGedinnean ب El Ouabed إلى فحص تأثير المعادن الطينية على تقليل النفاذية. من خلال استخدام تقنيات مثل تفريق الأشعة السينية على مسحوق المعادن(XRPD) وتحليل الكاميرا فوق الطيف، وتفسير بيانات الحفر، والاختبارات التجريبية في المختبر، توصلت الدراسة إلى أن المعادن الطينية، وبخاصة المعادن الطينية غير الانتفاخية مثل الكاولينيت والإيليت، يمكن أن تهاجر وتسد ممرات المسام، مما يؤدي إلى تقليل النفاذية في الخزانات. بالإضافة إلى ذلك، يمكن أن يؤثر استخدام الطين القائم على الزيت على النفاذية في الخزان من خلال تغيير قابلية التبليل. تشير هذه النتائج إلى أهمية فهم سلوك المعادن الطينية وتأثيراتها على إدارة الخزانات واستعادة النفط بشكل فعال.

الكلمات المفتاحيّة: طين، هجرة، انتفاخ، النفاذية، الحقل، تثبيطات، نموذج المصغر

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LIST OF ABBREVIATIONS

WBM	Water-Based Mud
OBM	Oil-Based Mud
TO	Tetrahedral - Octahedral Layers
TOT	Tetrahedral - Octahedral - Tetrahedral Layers
TOTO	Tetrahedral - Octahedral - Tetrahedral - Octahedral Layers
CEC	Cation Exchange Property
PHPA	Partially Hydrolysed Polyacrylamide
PAC	Polyanionic Cellulose
PAG	Polyalkylene Glycols
HPWBM	High Performance Water-Based Mud
NE-SW	North East - South West
COT	Total Organic Carbon
FLEX	Formation Lithology Explorer
XRPD	X-Ray Powder Diffraction
BGO	Bismuth Germanate Oxygen
SGR	Natural Gamma Ray Spectroscopy
IR	Infrared
VNIR	Very Near Infrared
SWIR	Short-Wave Infrared
AIPEA	International Association for the Study of Clays
DLCC	Laboratories and Central Core Library Department
HMD	Hassi Messaoud

GENERAL INTRODUCTION

Formation damage mechanisms affect reservoir permeability especially in the near wellbore area and may happen during different operations such as drilling and production. It has been reported that approximately 97% of all petroleum reservoirs contain clay minerals and they are categorized into swelling and non-swelling groups. Non-swelling clays such as kaolinite may migrate during water flooding because of repulsive forces between clays and pore walls and block pores in the reservoir. Swelling clays such as montmorillonite may swell in contact with the invaded water up to 20 times the original volume, and may also migrate. Both these effects reduce porosity and permeability in the formation [1].

The reason for this special behavior of the clays is due to their unique structures. Three main mechanisms are used to reduce clay swelling or/and migration which are ion exchange, coating of the clay particles by stabilizers, and modification of surface affinity toward water. Zhou (1995) divided clay stabilizers into different classes and described their advantages and disadvantages [2].

It is generally recommended to avoid the use of water-based mud (WBM) in reservoirs containing swelling clays which have the tendency to absorb water and swell, leading to various issues in the reservoir and affecting oil recovery. On the other hand, oil-based mud (OBM) is commonly used as an inhibitor for reservoirs containing clay particles to prevent clay swelling or/and migration. However, it is important to consider the disadvantages of OBM, such as its negative environmental impact and its effects on altering reservoir properties. OBM is also more expensive compared to WBM [3].

In this study, the influence of clay in the Sillon Benoud basin reservoirs located in the Brezina region (bloc 313) will be investigated. The main mechanisms affecting well productivity in this region, along with the problems reducing permeability, porosity, and limiting oil recovery, will be explained. Different inhibition methods will be analyzed to understand their effects on altering reservoir properties. Through direct and indirect analysis techniques, as well as experimental micromodel tests, the mineralogy of the reservoir, particularly the predominant clay minerals, will be identified, and the mechanisms influencing permeability and porosity will be understood.

To achieve this objective, the following steps were undertaken:

Chapter I: This chapter is divided into four parts. We begin by defining Clays, discussing their origins and various transformations. Next, we delve into the classification of clay minerals, explaining their microstructures. We also present the famous clay groups, highlighting their physicochemical properties. Finally, the fourth part focuses on the major problems associated with clay and the inhibition methods used to address them.

Chapter II: This chapter is divided into three parts. Firstly, we conduct a literature review on clay studies, focusing on their problems and inhibition methods. Secondly, we present the main and essential problems caused by clay in Algeria. Lastly, we examine the different inhibition techniques employed to prevent these problems during drilling and production processes in Algeria.

Chapter III: This study consists of three sections. It starts with an overview of the regional geology of the Sillon Benoud basin, focusing on the Gedinnean and Silurian Clayey reservoirs. The chapter then presents an overview of the methods employed to study the clays in these reservoirs, with a specific emphasis on the micromodel test experiments. Finally, the results of these tests are analyzed to identify and characterize the clay types present in the reservoirs, and the main problem will be detected.

This work concludes with a general conclusion, presenting the main findings obtained and proposing recommendations and perspectives for future research.

Chapter 1

Clay: An Overview and Its Associated Problems

I.1. Introduction

Sedimentary rocks make up 5% of the Earth's crust but cover about 80% of the surface of the earth in which clays (including shales) form well over 40% of the sedimentary rocks. Clays are found in hydrocarbons-bearing formations and can be detrital or authigenic. Detrital clays are integrated into the matrix during deposition, while authigenic clays form later through chemical weathering or precipitation from formation water, they're more active and mobile.

Clays react with aqueous fluids including fluids that are native to and injected into the formation, such as stimulation fluids, completion fluids, drilling muds and the like. due to their surface's electrostatic charges, leading to changes in their properties and potential formation damage.

I.2. Definitions of Clays

The term "clay" can have different meanings based on its function. It is typically a fine-grained material that becomes plastic with some water and has a particle size of less than 4 microns. In reservoir engineering, clay refers to flat platelets with a crystalline structure and negative electrical charge, which can plug permeability due to their large surface area. Their diameter is usually less than 20 μ [4].

I.3. Origin of Clays

I.3.1. Inheritance and Alteration

The clay minerals resulting from the breakdown of rocks can either remain in place (residual clays, e.g., flint clays, decalcification clays) or be transported over long distances (e.g., clays from ocean floors). Depending on the parent rocks and the climate, the resulting clay minerals are different as shown in **Fig.I.1** [5].

- Cold climates result in illite and chlorite clay minerals,
- Hot and humid climates lead to the formation of kaolinite and smectites,
- Temperate, humid climates result in interstratified clays, degraded illites, chlorites, and vermiculite.

I.3.2. Neoformations in Confined Environments

Surface conditions can cause the dissolution of primary minerals present in the parent rock, including both clayey and non-clayey minerals. The resulting cations and anions enter the soil solution, and if the conditions are suitable for nucleation and growth, new clay minerals can form in the soil [5].

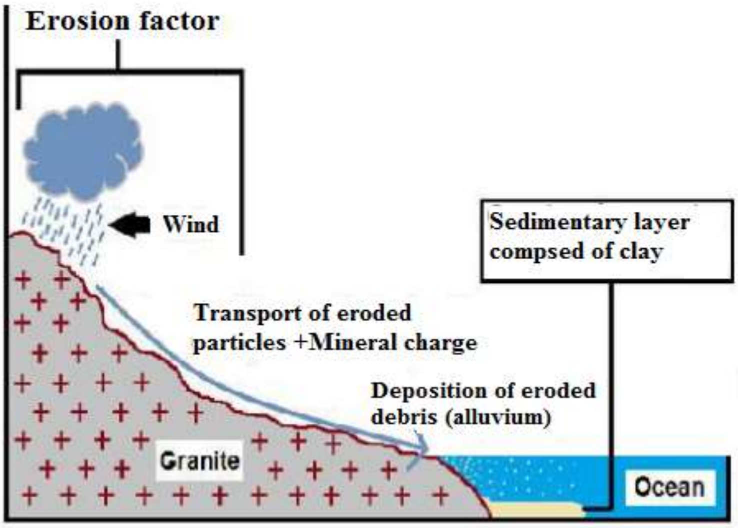

Fig.I.1: Process of clay formation *[6]*.

I.4. Transformations of Clay Minerals

The newly formed or inherited minerals can evolve to take on a new status in equilibrium with the new environment. There are transformations by degradation (subtraction of ions) and by aggradation (by fixing additional ions). These transformations occur both during weathering and diagenesis [7].

Example:

Kaolinite → Chlorite

Smectites → Illite

I.5. Nature of Clay Minerals

The nature of the source rock plays a role:

- The alteration of an acidic rock, such as granite, generally produces kaolinite,
- The alteration of a basic rock, such as basalt, generally produces smectites as shown in **Fig.I.2** [8].

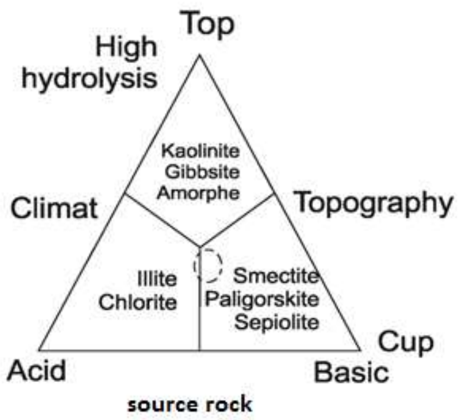

Fig.I.2: Main factors of alteration: climate, source rock, and topography *[8]*.

The topography, which controls drainage, also plays a role:

- On a slope, where drainage and leaching are good, the formation of kaolinite is favored,
- In a basin, a confined environment where solutions are concentrated, smectites are more likely to form [8].

I.6. Mineralogical Structure of Clays

Clay minerals are hydrated silicates (generally aluminum silicates but sometimes magnesium silicates) with a layered structure that places them in the phyllosilicate family. Most phyllosilicates are aluminosilicates (silicon and aluminum oxides) like zeolites and are classified according to their microscopic structure. the terminology used to define the structure of clays. Three levels of organization are distinguished as mentioned in **Fig.I.3** [9].

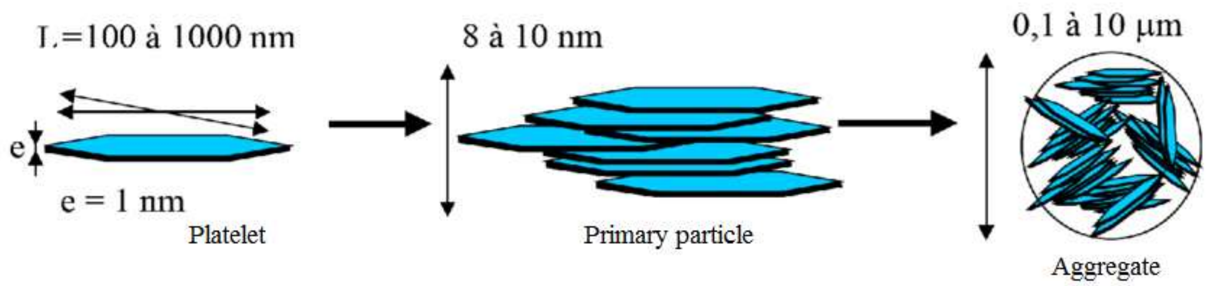

Fig.I.3: Multi-scale structure of a smectite - example of montmorillonite *[9]*.

I.6.1. Layer

The layer is the fundamental unit defining clay's mineralogical and physicochemical properties. Its thickness is typically around 1 nm, with lateral extension up to the micron level. The layer's shape depends on its composition, and its anisotropy gives it some flexibility as shown in **Fig.I.4** [10].

I.6.2. Primary Particle

The primary particle is composed of five to ten identical layers stacked and parallel to their basic planes, held together by attractive electrostatic forces between interlayer ions and the layers. It is generally 8 to 10 nanometers thick [11].

I.6.3. Aggregate

The aggregate is a set of primary particles oriented in all directions. The aggregates have a size that varies from 0.1 to 10 microns [10].

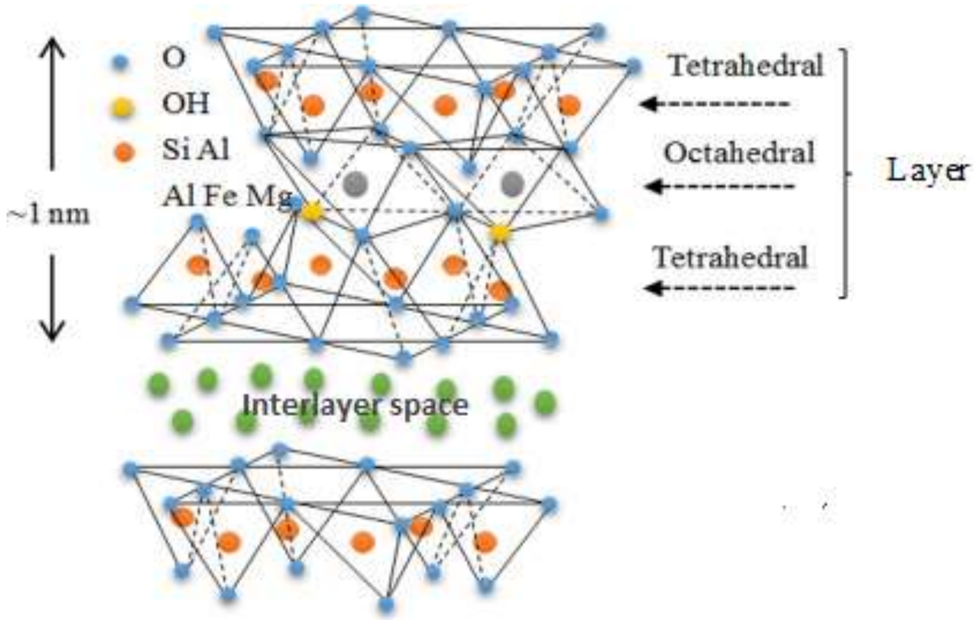

Fig.I.4: Schematic representation of the stacking of unit layers in a clay mineral case of a smectite *[12]*.

I.7. Organization of Pore Spaces

Understanding the organization of clay materials from the layer to the aggregate assembly requires considering the organization of the pore space. The pore space's size, shape, and distribution depend on several factors, including the particle size distribution of the clay material, its swelling properties, the interstitial fluid, and the constraints. Touret and Pons (1989) identified three types of space related to the solid phase organization as represented in **Fig.I.5** [13].

I.7.1. The Interlayer Space

Separates two layers in a stack. It is generally occupied by adsorbed water layers (1 to 4) and exchangeable cations, and its average thickness is between 1.5 and 2.5 nm [14].

I.7.2. The Interparticle Space

Separates the clay particles that form the aggregates. It may decrease to the value of the interlayer space for heavily compacted clays, and the double layer can develop in this space [15].

I.7.3. The Inter-Aggregate Space

Has an average section between 1.6 and 16 nm where water flows freely (free water), limiting the electrostatic effects of the double layer. The lenticular micropores are inside the particles, at the scale of a few nm [16].

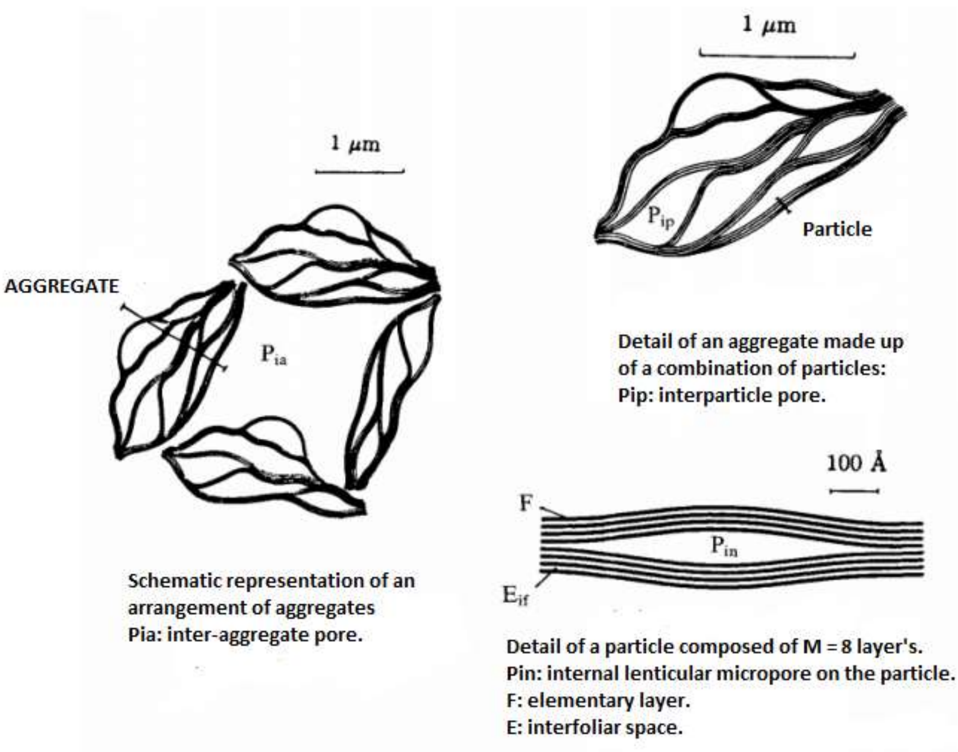

Fig.I.5: The different types of pore spaces *[10]*.

I.8. Classification of Clay Minerals

The classification of clays is based on their chemical composition and structural order. The AIPEA has different classifications for clays depending on the structural data. Two major families of minerals are distinguished based on the arrangement of tetrahedral and octahedral layers.

- Fibrous minerals which are species with pseudo layers, such as palygorskites,
- Phylliteous minerals with lamellar structures. The latter are the most widespread and studied.

Their classification is based on the mode of association of structural layers and the degree of occupation of octahedral layer sites (di- or tri-octahedral). According to the sequence of stacking of tetrahedral and octahedral layers, minerals of type 1/1 (T-O), 2/1 (T-O-T), and 2/1/1 (T-O-T-O) are distinguished as shown in **Table.I.1** [17].

Table.I.1: Classification of clay minerals according to the proportion and composition of T and O layers *[18]*.

Type of clay	Structural formula	Charge to be compensated	Group	Family
1/1	M_{2-3} Si_2 O_5 $(OH)_4$	0	Kaolinite, serpentine	Dioctahedral
				Trioctahedral
2/1	M_{2-3} Si_4 O_{10} $(OH)_2$	0	Pyrophyllite-talc	Dioctahedral
				Trioctahedral
		0.25-0.6	Smectite	Dioctahedral
				Trioctahedral
		0.6-0.09	Vermiculite	Dioctahedral
				Trioctahedral
		1	Micas	Dioctahedral
				Trioctahedral
		2	Brittle micas	Dioctahedral
				Trioctahedral
2/1/1	M_{2-3} Si_4 O_{10} $(OH)_2$-M-$(OH)_{2-3}$	Variable	Chlorite	---

I.8.1. Type TO (Tetrahedral Octahedral) Minerals

TO minerals consist of tetrahedral and octahedral layers forming sheets that are stacked with oxygen atoms in one sheet facing hydroxyl groups in the neighboring sheet, held together by hydrogen bonds. The arrangement of these sheets determines the mineral's crystal system. Examples of TO minerals include kaolinites, dickite, nacrite, and halloysite, which have a characteristic spacing of around 7.1A° and are electrically neutral as represented in **Fig.I.6** [19].

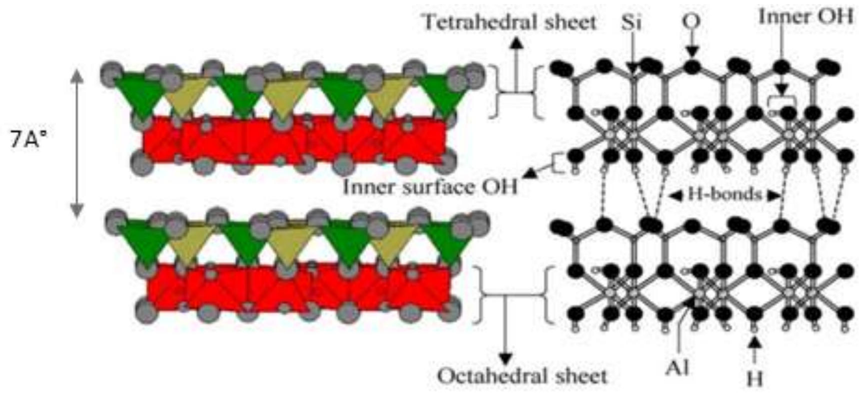

Fig.I.6: Representation of the stacking of siliceous tetrahedra and alumina octahedra in a TO-type mineral *[20]*.

I.8.2. TOT (Tetrahedral Octahedral Tetrahedral) Type Minerals

This type of mineral structure involves an octahedral layer situated between two tetrahedral layers. Substitutions in both layers lead to the presence of different cations required for electrical neutrality, which can modify the mineral's properties. The characteristic distance between layers ranges from 9.4 to 15A°, depending on the interlayer content. Talc, smectites, vermiculites, and micas are examples of this mineral type as represented **Fig.I.7** [19].

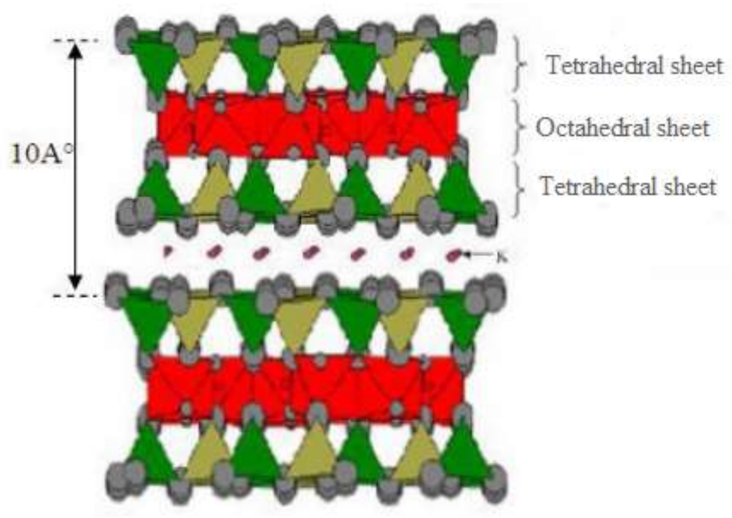

Fig.I.7: Schematic representation of the stacking of silicate tetrahedra and alumina octahedra in a TOT type mineral *[20]*.

I.8.3. TOTO (Tetrahedral Octahedral Tetrahedral Octahedral) Type Minerals

These minerals result from the combination of two octahedral layers with two tetrahedral layers. The charge of the sheet is compensated by an interlayer of octahedra containing aluminum and/or magnesium atoms. The characteristic equidistance is then about 14A°, and this type corresponds to the group of chlorites as represented in **FigI.8** [19].

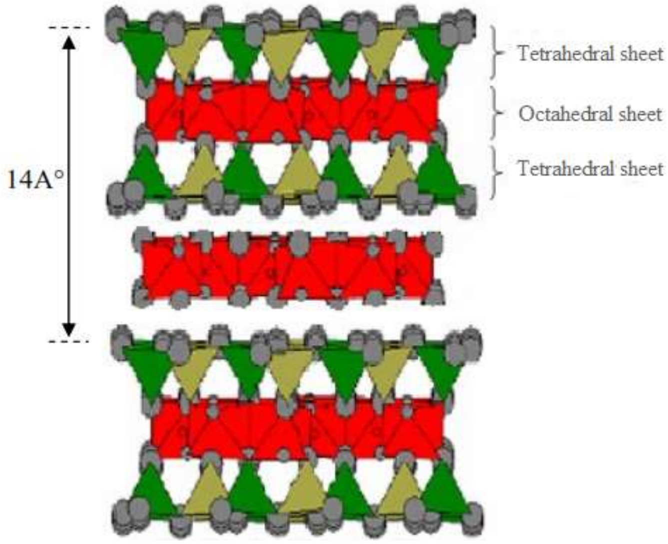

Fig.I.8: Representation of the stacking of silica tetrahedra and alumina octahedra in a TOTO-type mineral *[20]*.

I.9. Prominent Clay Groups

There are different prominent clay groups which are represented as the following:

I.9.1. Kaolinite

Kaolinite is a phyllosilicate mineral of the TO type that can be found in hydrated or non-hydrated form as shown in **Fig.I.9**. with a structural formula of $2[Si_2O_5Al_2(OH)_4]$. It does not swell in water due to hydrogen bonding and is difficult to disperse in water unless the ionic strength is low. Kaolinite has four crystallographic varieties: ideal kaolinite, nacrite, dickite, and metahalloysite [21].

Fig.I.9: Scanning electron microscope image of kaolinite crystals [7].

Physical and Chemical Properties:

Table.I.2 represents some of the physical and chemical properties of kaolinite.

Table.I.2: Physico-chemical properties of kaolinite [18] .

Density	**Hardness**	**Molecular mass (g/mol)**	**Specific surface area (m^2/g)**
2.4 -- 2.65	2 -- 2.5	258	10 -- 22

I.9.2. Halloysite ($Al_2O_3.2SiO_2.4H_2O$)

Halloysite is a type of mineral clay of the TO type in the kaolinite family with a similar structure and chemical composition to kaolinite, dickite, or nacrite. However, its layers are separated by a layer of water molecules, resulting in a 001 distance of 10.1A°, allowing the layers to roll up into tubes as shown in **Fig. I.10**. Dehydration at around 75°C to 80°C can cause the mineral to lose some of its water and transform into meta-halloysite [21].

Fig.I.10: Scanning electron microscope image of Halloysite crystals *[7]*.

I.9.3. Montmorillonite

Montmorillonite is a type of smectite clay mineral with a TOT structure consisting of an alumina layer sandwiched between two silica layers as shown in **Fig.I.11**. The octahedral sheets have a deficiency of net negative charge due to weak Van der Waals forces, allowing exchangeable ions to penetrate the structure and separate the layers. This results in an unstable structure that is highly influenced by the presence of water [22].

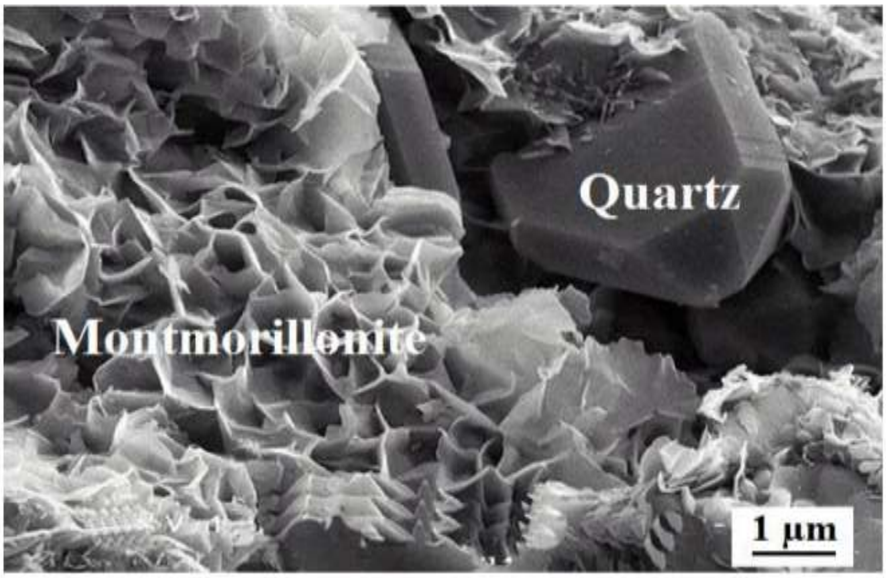

Fig.I.11: Scanning electron microscope image of Montmorillonite crystals *[7]*.

Physical and Chemical Properties:

Table.I.3 represents some of the physical and chemical properties of montmorillonite.

Table.I.3: Shows the physical and chemical properties of montmorillonite *[18]*.

Mean thickness of plates(μm)	**Density**	**Hardness**	**Molecular mass (g/mol)**	**Specific surface area (m^2/g)**	**General formula**
0.001 – 0.01	2.12 - 3 according to Goldman, 1980.	Very soft mineral, can be cut like soap.	814	800	(OH_4) $Si_8(A_{13}.34Mg_{0.66})$ O_{20}, nH_{20} or ($Na_{0.66}$ instead of $Mg_{0.66}$)

I.9.4. Illite

Illite is a type of clay mineral of composed of three layers (TOT), including an octahedral layer and two tetrahedral layers. The interlayer space contains poorly hydrated potassium ions, which prevent the clay from swelling. Illite is structurally similar to muscovite but has more silicon, magnesium, iron, and water. It is commonly found in sediments, soils, sedimentary clay rocks, and some metamorphic rocks as shown in **Fig.I.12** [23].

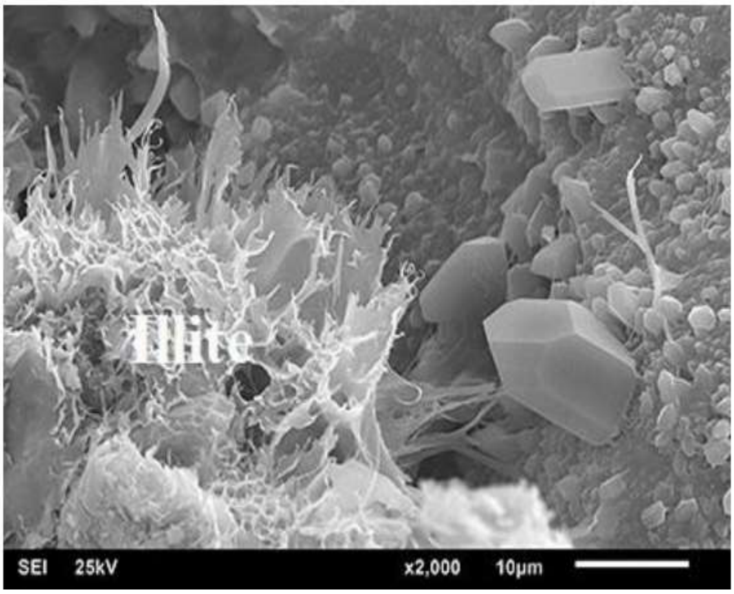

Fig.I.12: Crystals of illite seen under scanning electron microscope *[7]*.

Physical and Chemical Properties:

The physico-chemical properties of illite are summarized in **Table.I.4**.

Tabl.I.4: Shows the physical and chemical properties of illite *[18]*.

Mean thickness of plates (µm)	Density	Hardness	Molecular mass (g/mol)	Specific surface area (m^2/g)	General formula
00.1 – 0.3	2.12 - 3 according to Goldman, 1980.	2	814	100	$K_{0.5}(A_{10}.5Si_{3}.5O_{10})$ (OH)2

I.9.5. Chlorites

This clay is of the T-O-T type, and the interlayer spacing is 14 Å, filled with a layer composed of Mg and OH. Al is locally replaced by Fe. Chlorites exist as larger crystals in igneous rocks and are also formed during the diagenesis of sedimentary rocks. They are found as detrital elements in soils under less aggressive climates as shown in **Fig.I.13** [24].

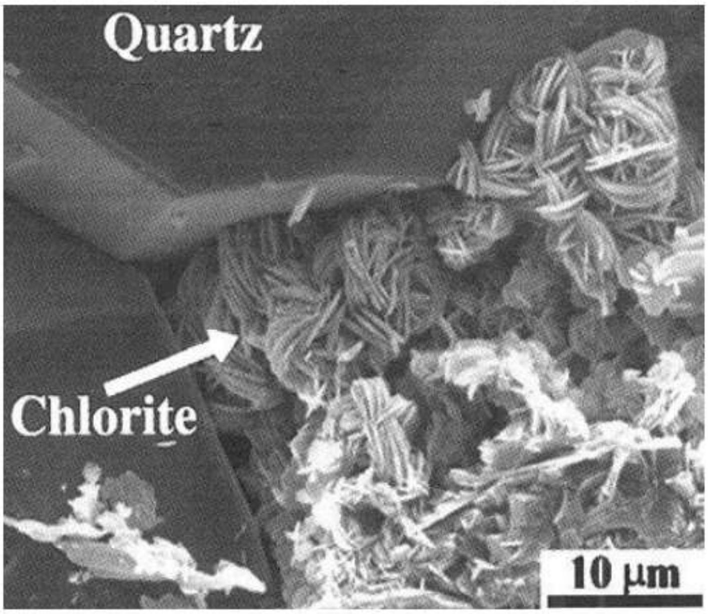

Fig.I.13: Crystals of chlorite seen under scanning electron microscope *[7]*.

I.10. Cation Exchange Property (CEC)

Cation exchange is a major property of clay minerals. The clay specific surface area is extremely large and reacts to changes in the water chemistry. Cations present in water adsorb to the surface of clays. The capacity of clay to adsorb cations is quantified by the cation exchange capacity. The higher the cation exchange capacity, the more colloidal activity the clay will exhibit as **Table.I.5** shows. This tendency leads to ion exchange between injected completion and stimulation fluids and the clays that are initially in equilibrium with formation fluids [25].

Table.I.5: Published cation exchange capacities for various clay minerals *[26]*.

Clay	Cation Exchange Capacity [Milliequivalents/100g of Dry Clay]
Montmorillonite	70-130
Vermiculite	100-200
Illite	10-40
Kaolinite	3-15
Chlorite	10-40
Attapulgite-Sepiolite	10-35

I.11. Clay Problems in Oil Production

Clays can cause problems with oil and gas reservoir production, primarily as a result of their large surface area. Two major clay problems are caused by clay migration and clay swelling, both of which result in a reduction of permeability. These problems can be caused by disturbing formation clays during drilling, completion or production.

I.11.1. Migratory Clays and Fines Migration

The movement of fines within a porous matrix can cause pore throat blockage and reduce permeability. These fines can come from the formation or external sources such as drilling fluids or contaminated fluids.

I.11.1.1. Characteristics of Migratory Fines

Clays, including illite, chlorite, and kaolinite, are the most common migratory fines. Gradually reducing fluid salinity can help control the cation exchange process and prevent permeability decrease. Fresh water injection can cause pH rise and clay dispersion, while fluids with low pH can minimize clay dispersion and pore throat plugging. Maintaining a pH below 10 is crucial when using low-salinity fluids to avoid damage as represented in **Fig.I.14** [27].

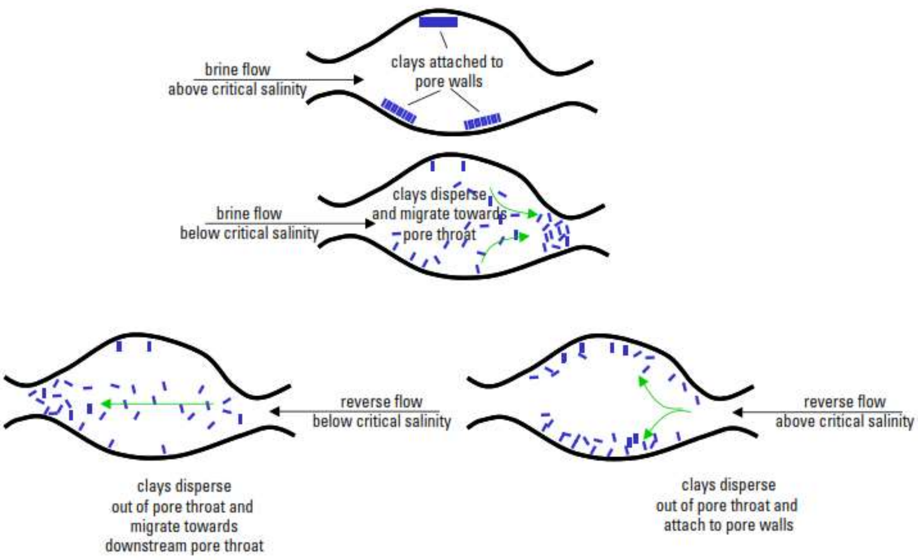

Fig.I.14: Schematic of fines migration experiment with forward and reverse flow of fresh and salt water *[28]*.

I.11.1.2. Physico-Chemical Fines Migration

Lab experiments found that lowering water salinity reduces core permeability by blocking pore passages with dispersed particles like kaolinite, illite, and chlorite. Pore lining clays are more mobile and easily entrained in fluid flow. The balance of forces holding clays in place can be disrupted by flowing fluids, and various forces like van der Waals attraction and electrical double layer affect particle-wall interaction [29] [30].

I.11.2. Swelling Clays

Clay expansion induces formation damage by reducing the hydraulic diameter of pore throats and pore bodies. It also can dislodge overlaying particles and cause them to migrate and become trapped in pore throats.

I.11.2.1. Characteristics of Swelling Clays

Swelling clays are clay minerals that can absorb large amounts of water and increase in volume. The most common swelling clays are the smectite group, including montmorillonite, beidellite, and nontronite. Other clays, such as vermiculite, attapulgite, illite, and chlorite, can also absorb water but have lower swelling capacities. Bentonites, composed of Na^-, Ca^-, and Mg-montmorillonite, are commonly used commercially due to their absorptive and swelling properties [31] [26].

I.11.2.2. Formation Damage

Like migrating clays, swelling clays substantially reduce formation permeability when aqueous fluid chemistry changes. Swelling clays, however, have three different contributions to damage: swelling, migration, and swelling induced migration. the mechanisms of permeability reduction caused by swelling clays as represented in **Fig.I.15** [27].

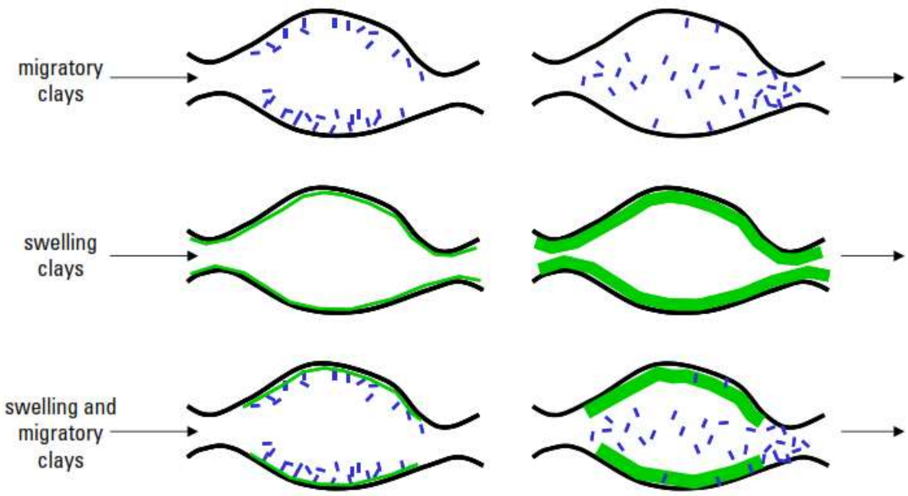

Fig.I.15: Three mechanisms of formation damage caused by swelling clays *[27]*.

Clay swelling can block fluid flow and plug downstream pore throats. The salt concentration needed to prevent formation damage is higher in cores with swelling clays, and pH control does not eliminate this damage. Swelling is influenced by ionic species and can occur via crystalline or osmotic swelling [27].

a. Crystalline Swelling:

Crystalline swelling is due to the balance between the repulsive hydration energy of exchangeable cations and electrostatic attractive forces. Cations with high charge density require greater force to displace the water of hydration and adsorb to clay surfaces. Adsorbed cations suppress the electric double layer, reducing the force of repulsion between basal surfaces removing adsorbed cations expands the electric double layer and forces basal spacing to increase, inhibiting formation damage [27].

b. Osmotic Swelling:

Clay basal spacing jumps at the critical salt concentration to around 40 Angstroms and increases linearly with sodium chloride concentration. Basal spacing can exceed 100 Angstroms, a 10 to 20-

fold volume increase. Weakly hydrated ions like potassium do not exhibit the transition to osmotic swelling as shown in **Fig.I.16**.

The transition from crystalline swelling to osmotic swelling is driven by an increase in electrostatic repulsion between the clay surfaces as the salt concentration decreases [27].

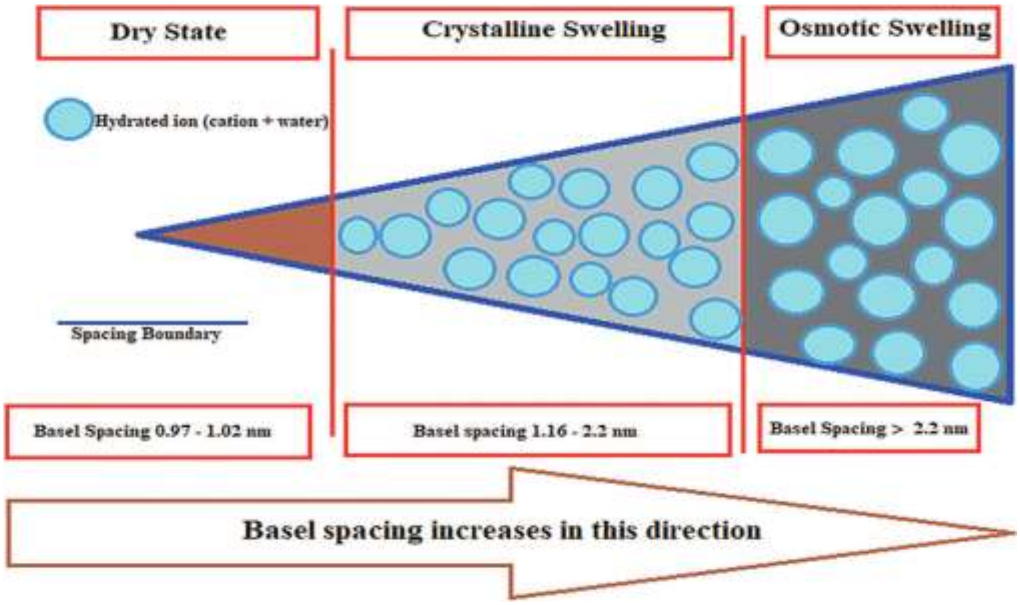

Fig.I.16: Crystalline swelling and osmotic swelling of clay minerals *[32]*.

I.11.2.3. Effect of Clay Surface Charge on Swelling Behavior

Swelling smectite clay's surface charge is due to element substitution and dissociating hydroxyl groups. Layer charge affects critical salt concentration needed to inhibit clay swelling and migration. The critical salt concentration shows a maximum as surface charge varies [33].

I.11.2.4. Effect of pH on Low Layer Charge Swelling Clays

Swelling clays expand with decreased salinity, even in low pH fluids, due to water adsorption along basal surfaces, while migrating clays are insensitive to low pH fluids. Swelling behavior at low pH results in formation damage in core flow tests where low pH fluids are injected into cores containing swelling clays [33].

I.12. Clay Inhibition

Clays can damage formation by swelling and migrating, influenced by changes in aqueous fluid ionic composition. This can occur during stimulation, drilling, completion, or secondary recovery operations. Mitigating the damage involves formulating fluids that preserve the force balance stabilizing the clays. Clay stabilizers are broadly classified into two categories: temporary clay stabilizers and permanent clay stabilizers.

I.12.1. Temporary Clay Stabilizers

Temporary stabilization of clays can be achieved through inorganic and organic stabilizers that neutralize repulsive forces between basal surfaces that cause swelling and migration. The concentration of stabilizers required depends on the type and quantity of clays, pH of the fluid, and severity of salinity change. Polyols such as glycols, glycerols, and polyethylene glycols are effective in inhibiting shale swelling in drilling mud, and their efficiency is enhanced by the presence of a salt like KCl [34] [35].

I.12.2. Permanent Clay Stabilizers

There are three types of permanent clay stabilizers that have been used:

- Inorganic polymers hydroxy-aluminum and zirconium oxy-chloride,
- organic polymers such as nonionic, cationic, and anionic polyacrylamides.

Inorganic multivalent cationic polymers and organic polymers are used to permanently stabilize clays. Inorganic polymers are permanently adsorbed to negatively charged surfaces, while organic polymers coat and link clays to the pore wall surface. Surface modification treatments can also be used to prevent clay migration. However, these treatments require specific application methods and may not be effective in low permeability formations as represented in **Fig.I.17** [36].

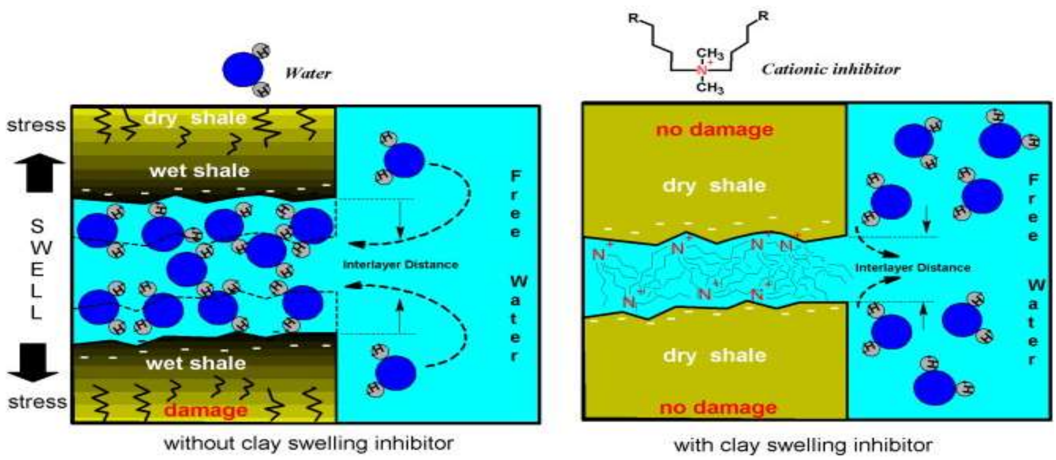

Fig.I.17: Swelling inhibition in water base drilling fluids *[37]*.

I.13. Conclusion

Clay minerals are important components in both source rocks and reservoir rocks, which respectively can generate and store oil and gas. The presence of clay minerals strongly influences the physical and chemical properties of conventional sandstone, carbonate, and unconventional shale, which can affect production. Therefore, efforts are made to prevent clay problems through the use of various inhibitions, which are continuously evaluated over time in order to optimize their effectiveness.

Chapter 2

Clay-related Challenges in Algeria

II.1. Introduction

Algeria's growing economy has led to increased demand for oil and gas, but the drilling environment is becoming more complex and problematic. Cementing, completion, and fracturing operations all require careful consideration of clay mineral effects on wellbore stability and reservoir permeability. The use of water-based drilling fluids, which are more environmentally friendly, can cause swelling and hydration of clay minerals, leading to instability and reduced permeability. Effective strategies and techniques are needed to address these challenges and ensure sustainable hydrocarbon exploration and production in Algeria.

II.2. Literature Review on Clay Problems Studies

An extensive literature review was undertaken as part of this research. The review was multidisciplinary and included literature from various fields and methodologies, to gain a fundamental understanding of the topic.

- **Simpson, Van et al., 1994** Explain that potassium salts have been used for a long time as swelling inhibitors in WBM. The inhibition is explained by the possible penetration of small non-hydrated ions into the porosity of the shale. And explain the reduction of the filtrate flow into shale by an increase of the viscosity leading to a reduction of shale permeability and a flow of mud filtrate into the shale driven by osmotic pressure [38].
- **Darley and Gray (1988), Ward et al. (1997), Van Oort et al. (1999), and Tare and Mody (2000)** The text describes PHPA, a synthetic polymer used for borehole stabilization in shale formations during drilling. The partially hydrolyzed (30%) polyacrylamide form is the most commonly used, and PHPA-clay slurries form a thin filter cake at the borehole wall, which is seen as an advantage. Silicate-containing fluids are also mentioned as having good shale swelling inhibition, low depletion rate, high rate of penetration, and being environmentally friendly [39].
- **Friedheim, Patel, et a in 2002** For laboratory tests, a typical mud contains several additives at concentrations commonly used, including a viscosifier (xanthan gumwith or without bentonite), a fluid loss reducer (polyanionic cellulose: PAC), and different polymeric swelling inhibitors such as partially hydrolysed polyacrylamide (PHPA), and polyalkyleneglycols (PAG or “glycol”) to improve shale stability [2].
- **Gupta and Santos, 2002; M.I. Corporation, 2002** Cuttings characterization is a key parameter to explain how salt added to WBM, affects shale stabilization. Recovered cuttings, generally contaminated by drilling fluid, are washed. Specialized laboratories recommend cuttings solvent washing. The washing could lead to positive effects such as plugging which reduces permeability

and filtration, or negative effects in inhibitive tests such as contamination of shale samples which affects polymer evaluation seriously [40].

- **Van Oort in 2003** Scarce research and few field tests have been conducted on Algerian fields to investigate WBM effects on drilling operations. Van Oort considered the replacement of OBM, currently used in some Algerian fields, by WBM. This author shows that the presence of additives in WBM, such as polymer and KCl, aims to reduce shale instability. Clay wettability and inhibition properties were studied by analyzing the behavior of water–clay–polymer–electrolyte systems. These properties are connected to the rheological and filtration characteristics for both mud and filtrate [3].
- **Abdolhamid, Peyman, Milad in 2015** This experimental study investigates the potential of metal oxide nanoparticles in remedying clay swelling, a common challenge in oil recovery. The research explores the interactions between clay particles and the surrounding medium, influenced by the ionic strength of the permeating fluid. By conducting core flood experiments, micro-model tests, and quantifying swelling indices, the study assesses the impact of nanoparticles on clay swelling. While nanoparticles can effectively stabilize clay migration, they have limited effectiveness in preventing clay swelling [1].
- **Abdou, M.I., Dahab, A.S., Abuseda, H., Abdulaziz, A 2015** The authors discuss the advantages of using water-based muds over oil-based muds, including environmental and cost considerations. covers laboratory testing methods for evaluating the effectiveness of high-performance water-based muds in inhibiting clay swelling (PHPA), such as using swelling pressure cells and permeability tests. The authors conclude that the use of high-performance water-based muds can be an effective way to control clay swelling and improve well productivity [41].
- **Sharifipour, M., Pourafshary, P., Nakhaee, A 2017** This article provides a review of the impact of clay swelling on well productivity. The authors discuss the mechanisms behind clay swelling and its impact on well performance, such as reducing permeability, inducing formation damage, and causing wellbore instability. The article also covers the different types of clay inhibitors available, including both chemical potassium chloride, quaternary ammonium salts, polymers, and glycols and mechanical methods, and their effectiveness in controlling clay swelling [42].

II.3. Clay Problems in Algeria

Due to borehole failure, accumulation of cuttings and swelling which often take place in different shale formations, drilling parameters may change significantly; which impact the reservoir quality, this may result in stuck pipe, difficulty in circulation and bottom hole cleaning efficiency [43]. There are several mechanisms involved in clays formation related instabilities including: pore pressure diffusion, anisotropy, capillary effects, osmosis, and physicochemical alterations [44].

II.3.1. Stuck Pipe and Borehole Instability

Stuck pipe is a general term which describes the problem of losing the ability of the drilling string to rotate and move up or down. Sticking can occur while drilling, making a connection, logging, testing, or during any kind of operation which may involves leaving the equipment in the hole [45].

II.3.1.1. Reactive Formations

Water sensitive shale is drilled with less inhibition than is required. The clay absorbs the water and swells into the well bore as shown in **Fig. II.1**. This mechanism normally occurs:

- When using WBM in shales and clays in young formations,
- When drilling with an incorrect mud specification. Particularly, an insufficient concentration of inhibition additives in OBM and WBM such as salts (KCI, $CaCl_2$), glycol and polymer [46].

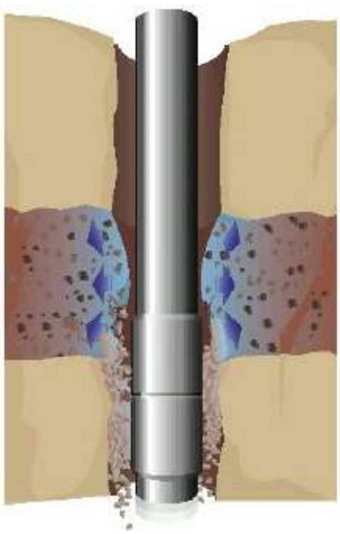

Fig.II.1: Reactive Formations *[46]*.

II.3.1.2. Naturally Over Pressured Shale Collapse

A naturally over-pressured shale is one with a natural pore pressure that exceeds the normal hydrostatic pressure gradient. This can be caused by geological phenomena such as under-compaction, removal of overburden due to weathering, and uplift. Insufficient mud weight in these formations can lead to hole instability and collapse as mentioned in **Fig.II.2**. This mechanism is more likely to occur in rapidly depositional clay sequences [46].

Fig.II.2: Naturally over-pressured shale collapse *[46]*.

II.3.1.3. Induced Over-Pressured Shale Collapse

Induced over-pressure clay occurs when the clay assumes the hydrostatic pressure of the well bore fluids after a number of days exposure to that pressure. When this is followed by no increase or a reduction in hydrostatic pressure in the well bore, the clay, which now has a higher internal pressure than the well bore, collapses in a similar manner to naturally over-pressured shale as shown in **Fig.II.3** [46].

Fig.II.3: Induced over-pressured shale collapse *[46]*.

II.3.1.4. Tectonically Stressed Shales

Well bore instability is caused when highly stressed clay formation is drilled and there exists a significant difference between the near well bore stress and the restraining pressure provided by the drilling fluid density. When a hole is drilled in an area of high tectonic stresses the rock around the well bore will collapse into the well bore as represented in **Fig.II.4** [46].

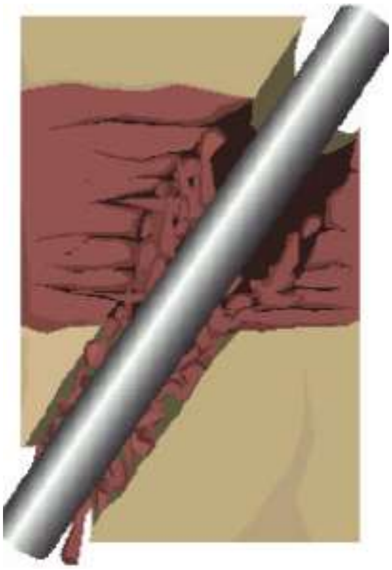

Fig.II.4: Tectonically Stressed Shales *[46].*

II.3.2. Formation Damage

Formation damage occurs when the permeability of a producing formation decreases, limiting the outflow of hydrocarbons. This problem can arise during different phases of oil and gas recovery, including drilling, production, hydraulic fracturing, and workover operations. Fines migration and clay swelling are the primary reasons for this damage, resulting in reduced permeability [47], Authigenic clay minerals can contribute to formation damage as **Table.II.1** shows.

Table.II.1: Description and typical problems caused by the Authigenic Clay Minerals *[48] [49].*

Mineral	Chemical Composition	Morphology	Surface area (m2/gm)	Major reservoir Problems
Kaolinite	$Al_4[Si_4O_{10}](OH)_8$	Stacked plate or sheets	20	Breaks apart, migrates and concentrates at the pore throat causing severe plugging and loss of permeability.

Chlorite	(Mg, Al., Fe)12[(Si, Al)8O20] (OH)16	Plates, honeycomb, cabbage-head rosette or fan.	100	Extremely sensitive to acid and oxygenated waters. Will precipitate gelatinous. Fe (OH)3 which will not pass through pore throats.
Illite	(K1-1,5Al4[Si7-6,5Al11,5O20] (OH)4)	Irregular with elongated spines or granules	100	Plugs pore throats with other migrating fines. Leaching of potassium ions will change it to expandable clay
Smectite	(1/2Ca, Na)0,7(Al, Mg, Fe)4[(Si.Al)8O20]•nH2O	Irregular, wavy, wrinkled sheets, webby or honeycomb	700	Water sensitive, 100% expandable. Causes loss of micro porosity and permeability
Mixed Layer	Illite- Smectite and Chlorite-Smectite	Filamentous morphology	100-700	Breaks apart in clumps and bridges across pores reducing permeability.

II.3.2.1. Hydration (Swelling)

Hydration (swelling) and dispersion are related phenomena that depend on the amount and type of clays present in shale. Surface hydration is considered less significant and causes only slight expansion due to the addition of a few water molecules to the clay surfaces as shown in **Fig.II.5**. Hydrogen bonding holds water molecules to the oxygen atoms, forming a quasi-crystalline structure between unit layers, which increases the c-spacing [50].

II.3.2.2. Osmotic Hydration

Osmotic swelling of clays occurs when the concentration of cations between clay layers is higher than the surrounding water, leading to water being drawn into the layers and causing expansion. This creates a larger volume increase compared to surface hydration as mentioned in **Fig.II.5**, but only a few clays can swell in this manner. Clays with low valence exchangeable cations tend to swell more than those with high valences due to the stronger adsorption of high valence cations [50].

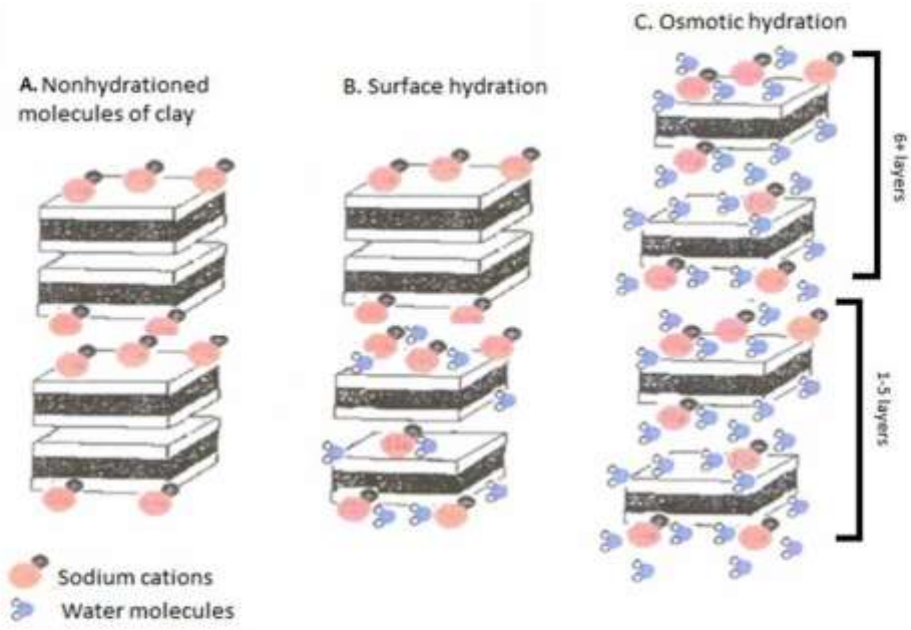

Fig.II.5: Clay Hydration process *[51]*.

II.3.2.3. Dispersion Clays

Dispersion is the rapid disintegration of the shale surface caused by reduced bonds between clay particles due to water adsorption and increased pore pressure. This can weaken the shale and lead to borehole failure. Montmorillonites are dispersible and hydratable, while illites are non-swelling but have a high dispersion tendency. However, if illites come from smectite transformation, they may cause borehole closure due to swelling [44].

II.3.3. During Cementing Operation

Clay minerals can cause significant problems during cementing operations by altering the properties of cement slurries and leading to poor bonding between the cement sheath and the formation as shown in **Fig.II.6.** The various inhibition techniques used to mitigate these problems, including the use of KCl, polymer-based inhibitors, nano-clay inhibitors, surfactants, and other chemical inhibitors [52].

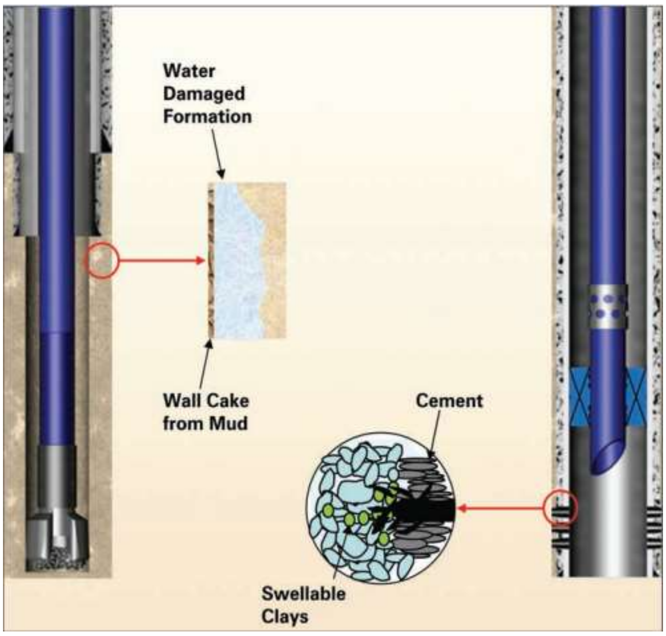

Fig.II.6: Formation damage during cementing operations *[52].*

II.3.4. During Workover Operation

Clay-related problems are common during workover and completion operations, leading to reduced productivity and increased costs. Common issues include clay swelling, migration, formation damage, instability, and cuttings disposal as shown in **Fig.II.7** Solutions include chemical treatments, proper fluid management, and best practices during drilling and completion [52].

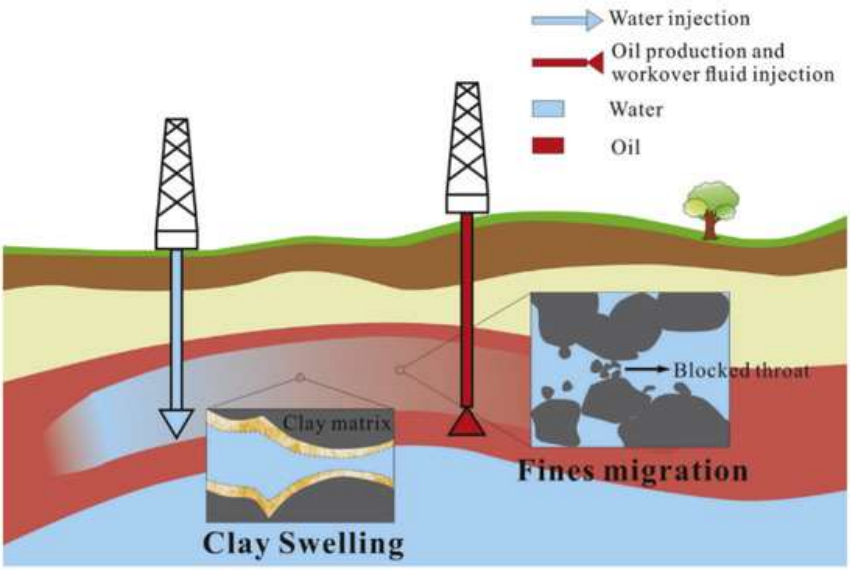

Fig.II.7: Permeability alterations caused by swelling of clay and migration of fines near the wellbore region after rock–fluid interaction *[66]*.

II.3.5. During Well Stimulation Operation

Clay minerals may cause a reduction in hydraulic fracture conductivity, proppant flowback, water blocking and clay swelling, in response to changes in fluid composition, pH, temperature, and pressure, can lead to significant problems in hydraulic fracturing, In addition, other factors such as, mineral dissolution, precipitation, fines migration, and wettability alteration can also impact hydraulic fracturing operations as shown in **Fig.II.8**, several inhibitions are used :

1. Use of water-based fluids with high salinity to prevent clay swelling and dispersion,
2. Addition of potassium chloride to water-based fluids to inhibit clay hydration and swelling,
3. Use of surfactants to modify the wettability of the rock surface and prevent clay swelling and dispersion,
4. Addition of nanoparticles, such as silica and clay particles, to the fracturing fluid to reinforce the proppant pack and prevent clay migration [53].

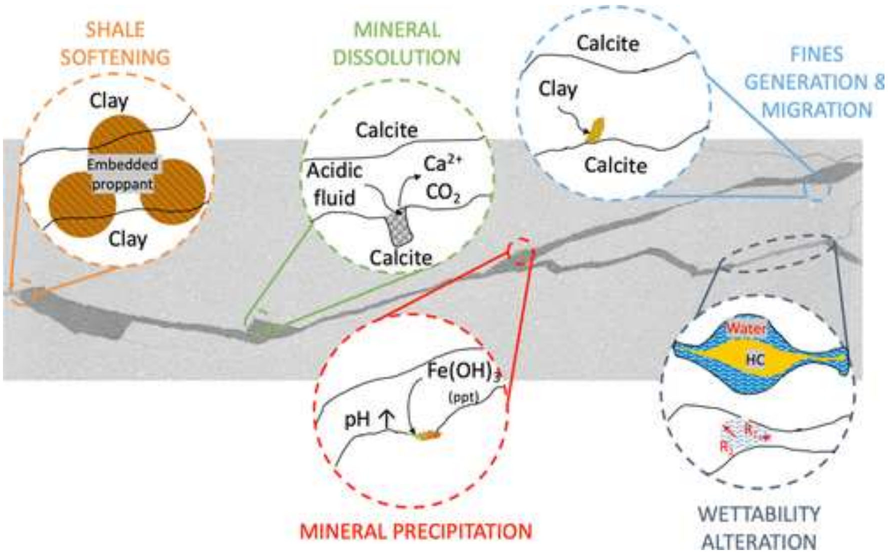

Fig.II.8: Hydraulic fracturing problems of unconventional hydrocarbon resources *[53]*.

II.3.6. During the Process of Production

The presence of clay minerals in the production fluids can affect the production rate and the quality of the produced hydrocarbons by:

a. ***Plugging of the Formation:*** Clay minerals can accumulate in the formation and cause plugging, which reduces the permeability of the formation and inhibits the flow of hydrocarbons.

b. ***Reduced Flow Rate:*** The presence of clay minerals in the production fluids can increase the viscosity and reduce the flow rate of the fluids.

c. *Corrosion:* lead to increased corrosion rates of the production equipment and facilities. This is because clay minerals can contain minerals that are corrosive to the metal surfaces of the equipment, leading to degradation and potential failure [52].

II.4. Methods of Inhibitions Used in Algeria

Applying chemical inhibitors and/or increasing mud weight may be two possible remedies on such problems, although they do not appear to be the complete solution. Another possibility in regards to mitigating clay related instability is to seal the formation against the invasion of drilling mud/fluid injecting. This can be done by controlling pressure, temperature and filtration properties of water-based muds.

II.4.1. Mud Treatment

There are three main mud treatment used in Algeria which are OBM, WBM and HPWBM.

II.4.1.1. Oil Based Muds (OBMs)

Oil Based Muds (OBMs) are often used to partially or fully stabilize reactive shale formations during drilling. The stability of shales during drilling with an OBM is linked to polarity and capillary effects. The emulsified water in an OBM may still migrate into shale due to osmosis if the salinity levels are not equal, and an appropriate density must be selected for mechanical stability. However, OBMs have limited applications due to high costs, poor biodegradability, and environmental constraints [50].

II.4.1.2. Water Based Muds (WBMs)

Three approaches are generally taken to mitigate for the instability problems posed by the interactions between WBMs and clays. They include:

A) Ionic inhibition, B) Encapsulation and C) Physical plugging

These treatments may be used independently or in combination with others, depending upon the amount and nature of the clays within the shale. The treated WBM may not be as efficient as an OBM, but may have some applications in mitigating shale instability. When any of the above treatments are considered, caution must be taken to have a low-solid and non-dispersed fluid [54].

II.4.1.3. High Performance Water-Based Mud (HPWBM)

It is a type of drilling fluid used in oil and gas exploration and production. It is designed to have enhanced rheological and filtration properties, as well as better stability and compatibility with the formation being drilled as it is depicted in **Fig.II.9**.

HPWBM typically includes additives such as polymers, surfactants, and viscosifiers to improve its performance, and may also contain salts like potassium chloride to inhibit shale hydration. HPWBM is considered to be more environmentally friendly than oil-based muds and can be employed in a wider range of drilling conditions [55].

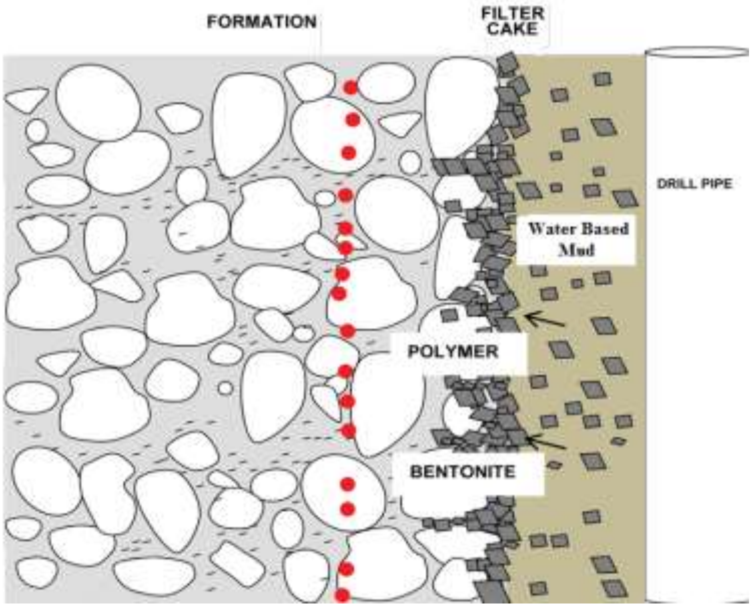

Fig.II.9: Schematic of filtration control by HPWBM *[68]*.

II.4.2. Additives

There have been many shale inhibitors proposed in the past decades, many of which were not totally successful either because of complicated nature of clays or their cost and environmental issues. Many of these inhibitors, especially the polymer, have also revealed functionality/integrity issues under different pressure, temperature and pH conditions.

II.4.2.1. Potassium Chloride (KCl)

Traditionally, salts are used to reduce the hydration of clays by the exchange of cations. Potassium chloride is one of the earliest chemicals used as an inhibitor of water sensitive clays in Algeria. In WBMs, potassium cations of KCl can effectively saturate the surface of clay and mitigate against the swelling and dispersive tendencies.

It prevents further hydration and swelling of the clay particles by bonding with the anions on their surface. However, high concentrations of KCl are needed for efficient inhibition, which can have negative impacts on the environment and wireline logging measurements due to the high concentration of chloride ions that remain in the mud solution [56].

II.4.2.2. Calcium Chloride ($CaCl_2$) and Formates

The mechanisms through which $CaCl_2$ based muds stabilizes clay include:

a. **Osmotic Dehydration:** a process where elevated levels of $CaCl_2$ salt in drilling fluid create an osmotic force that dehydrates shale and partially offsets the hydraulic invasion of filtrate into the shale. This can help prevent issues such as cuttings and wellbore instability caused by pressure overbalance.
b. **Membrane Building**: The osmotic process mentioned above is not totally effective, i.e., the membrane system acts as a 'leaky membrane' allowing solutes/ions to pass from the drilling fluid to the clay and vice versa. The osmotic process is amplified by increasing the membrane efficiency. This is achieved by the use of glycols in the mud which attaches to clay surfaces and restricts the free transport of solutes.
c. **Ion Exchange:** Additional help in preventing destabilization of clay-rich clay is offered through inhibition of swelling clays by Ca^{2+} ions. These ions may displace mono-valent ions on clay surfaces and thereby reduces the swelling stress/pressure acting between clay platelets.
d. **Encapsulation:** Further inhibition is offered by the use of encapsulation polymers in $CaCl_2$ based water-based muds. These polymers have a specific affinity for clay surfaces, and can be adsorbed by them. This adsorption aids in preventing dispersion into the colloidal suspension [57].

II.4.2.3. Organic Amines

Amines are effective inhibitors and can be as efficient as KCl. Organic amines are classified into monocationic, oligocationic, and polycationic categories. Monocationic amines have limited temperature stability, while oligocationic amines have a unique molecular structure that allows cations to bind the clay platelets together, resulting in extensive clay stabilization. Polyethoxylated diamines, polyether amines and polyethylene amine salts, are examples of oligocationic amines. Polycationic amines have limited effectiveness and can increase the viscosity and toxicity of muds [58].

II.4.2.4. PHPA/Amine Combination

Partially hydrolysed polyacrylamide (PHPA) polymer is introduced as a polymeric swelling inhibitor to improve clay stability. PHPA is a water-soluble anionic synthetic polymer and is known as a mechanical inhibitor due to its high molecular weight, which can physically block the capillary network on the clay surface as shown in **Fig.II.10** [59].

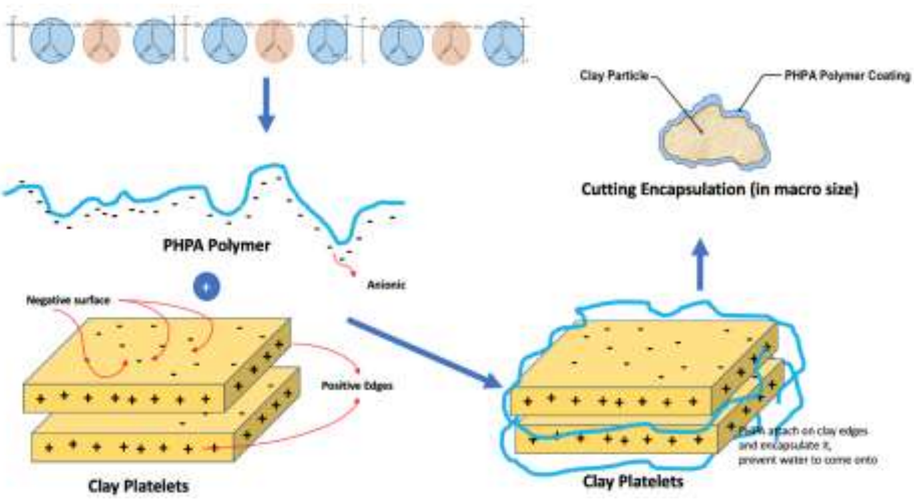

Fig.II.10: Encapsulation Mechanism of PHPA *[67]*.

II.4.2.5. Salt/Polymer (PHPA)

Salt/polymer drilling fluids were introduced in the 1970s and were a major improvement in shale stabilization. Their main stabilization mechanisms are:

- Inhibition through ion exchange where the swelling pressure between the platelets is reduced, decreasing the dispersion tendency,
- Inhibition through encapsulation where high molecular weight polymers such as PHPA.

These additives are inexpensive, easy to maintain, and environmentally friendly. However, they do not counteract filtration and pressure invasion, which can lead to borehole instability if the mud is left in the open-hole for a long time [50].

II.5. Conclusion

Clay problems can be a significant challenge for well productivity in many regions, including Algeria. Different inhibition methods, such as chemical inhibitors like potassium chloride, polyacrylamide (PHPA) polymer, and mechanical inhibitors like drilling muds with low filtrate and high viscosity, can be used to control clay swelling and mitigate formation damage. The selection of the appropriate method depends on the specific operation and formation conditions. Additionally, laboratory testing and analysis can be conducted to optimize the inhibition treatment design and ensure optimal well performance.

Chapter 3

Implementation and Findings Materials, Methods, Results, and Discussion

III.1 Introduction

Exploration and production operators highly prioritize the identification of clay beds within sedimentary sequences. These layers can serve as source rocks for hydrocarbons and act as effective cap rocks. However, the presence of clay in reservoir formations can introduce significant challenges and adversely affect hydrocarbon recovery. This study focuses on investigating migration and swelling phenomena in the Ouabed reservoirs, which are known for their complex clay mineralogy.

III.2. General Geological Framework of El Ouabed

III.2.1. Geographical location

Algeria is divided into two major tectonic units separated by the South Atlas Fault:

Northern Domain: This region is characterized by Alpine mountain chains of Tertiary age, resulting from the Alpine orogeny.

Southern Saharan Platform: This domain is relatively more stable and consists of a Precambrian basement upon which thick sedimentary series have been deposited in structurally formed basins, primarily during the Paleozoic era.

In this study, the specific area of interest covers the Sillon Benoud basin which is located in the northwest part of the Saharan platform (towards the western Saharan Atlas), in a NE-SW direction as shown in **Fig.III.1**. It covers an area of 23,980.62 km², and is situated between 00°30' - 02°40' east longitude and 32°30' - 33°40' north latitude. It spans across the wilayas (provinces) of El Bayadh, Béchar, Laghouat to the south, and Nâama to the north. The most important localities in the vicinity are Tadjrouna (in Laghouat province) and Brezina (in El Bayadh province) [60].

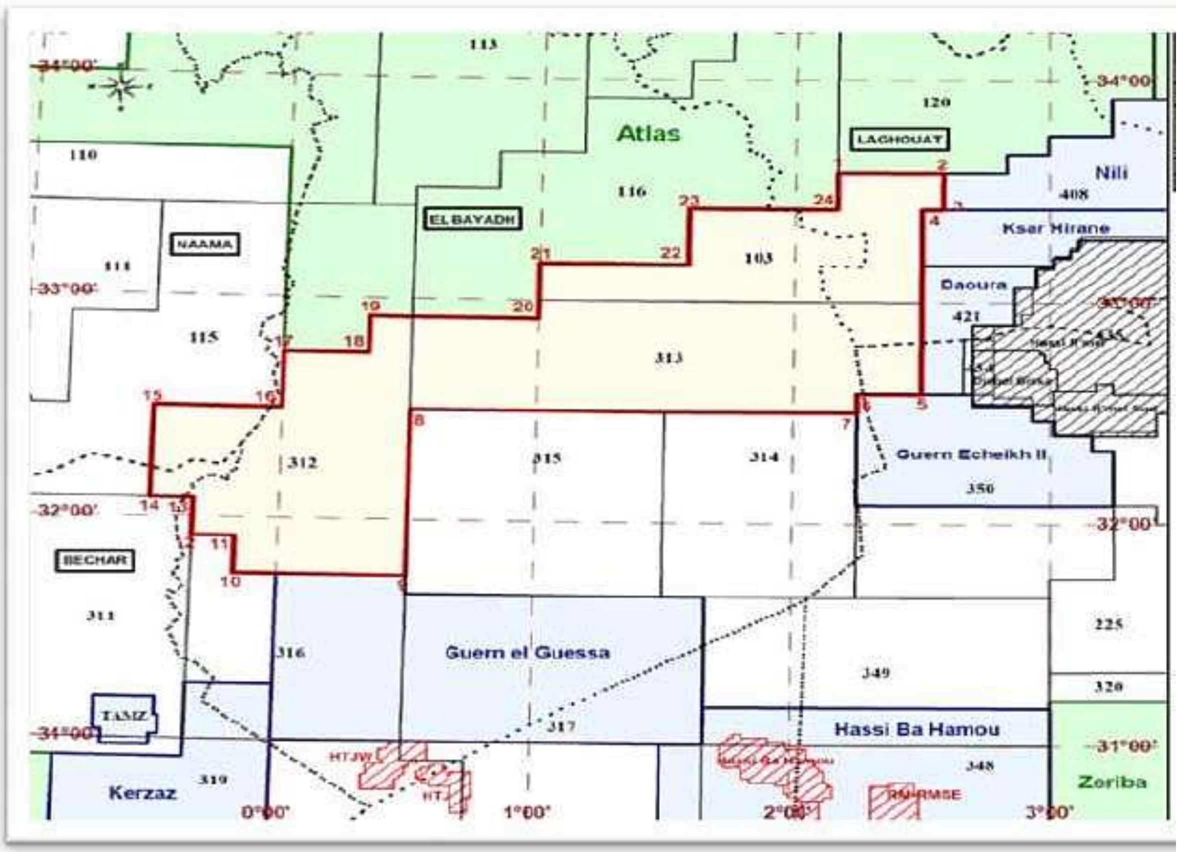

Fig.III.1: The geographical location of the El Ouabed research area *[70]*.

III.2.2. Stratigraphy of El Ouabed

The sedimentary cover in the Benoud trough is essentially composed of Paleozoic age formations, well preserved in the northeast and southwest parts, affected by the intra-Viséan unconformity. The entire Paleozoic is overlain in angular unconformity by the Mesozoic-Cenozoic, more developed on the northern band of the trough, Thus, the Paleozoic stratigraphic succession of this region can be summarized as follows (**Fig.III.2**):

- **Paleozoic**

A/ Devonian

- **Emsian: 2689m to 3018m**

Clay: Gray to greenish-gray, light gray, reddish-brown, soft to indurated, silty, with traces of white to greenish-white silt, slightly dolomitic, and intervals of white to gray-white, microcrystalline, sandy, friable to moderately hard limestone.

Anhydrite: White, powdery.

Sandstone: White to gray-white, fine to very fine, siliceous, moderately consolidated to friable, rarely pyritic, hard, locally light gray, very fine to fine, sub-angular to sub-rounded, silico-argillaceous, friable to moderately hard, with fine intervals of light gray clay, soft to indurated, silty.

- **Siegenian: 3018m to 3272m**

Sandstone: White, clayey, very fine to fine, friable, locally light gray, very fine to fine, rounded to sub-rounded, siliceous, silico-argillaceous, hard, carbonate-rich at the base, moderately hard to well-consolidated.

Clay: Gray to light gray, dark gray, blackish, soft to indurated, micaceous, silty, with intercalations of white to gray, light gray, very fine to fine, rounded to sub-rounded, silico-argillaceous, hard sandstone.

- **Gedinnean: 3272m-3321m**

White to brown to dark gray sandstone, transitioning to siltstone, very fine to fine, silico-argillaceous, moderately consolidated to friable, sub-angular to sub-rounded, with intervals of gray to light gray, soft to indurated, silty clay. Gray to light gray, reddish-brown clay with intervals of soft white limestone.

B/ Silurian: 3321m to 3489m

Gray to light gray to reddish-brown clay, silty, soft, slightly carbonate-rich, with intervals of white to off-white, soft, clayey limestone. Siltstone to very fine to fine white sandstone, occasionally blackish, clay-carbonate, moderately hard. Gray clay, indurated, silty, carbonate-rich, finely micaceous, traces of limestone.

C/ Ordovician: 3489m to 3540m

Sandstone: White to gray-white, very fine, clayey, moderately consolidated to well-consolidated, pyritic. Presence of rounded to sub-rounded quartz grains.

Clay: Gray to light gray, gray-brown, occasionally green, soft to indurated, locally dark gray, pasty, soft to indurated, micaceous, silty to highly silty.

Silt: Gray-white to dark gray [60].

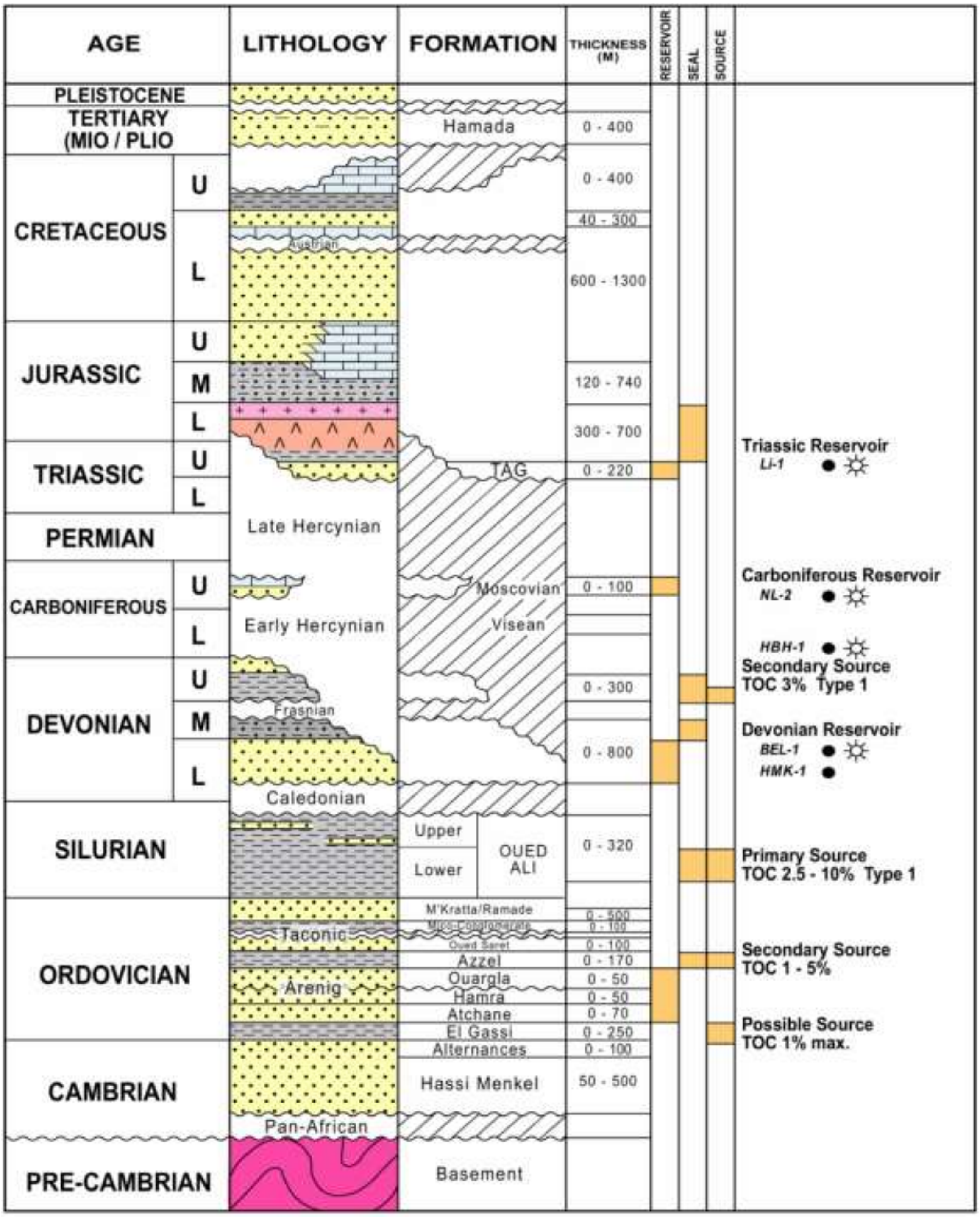

Fig.III.2: Lithostratigraphic column of the study area *[60]*.

III.2.3. Reservoir Rock

The Lower Devonian reservoirs consist of the Emsian, Siegenian, and Gedinnean sandstones, intersected by wells A, B, and C. These reservoirs have shown good porosities (over 13%) but low permeabilities (<0.1mD). This can be explained by the very fine sediment grain size (influenced by depositional environments), the presence of a high percentage of clay, and significant siliceous and carbonate cementation filling the intergranular connectivity space [61].

III.2.4. Cap Rock

The potential reservoirs in the region can be capped by the Saliferous levels of the Triassic [61].

III.2.5. Source Rock

The Benoud Trench holds certain petroleum potential. The Silurian formation represents the most interesting source rock in the region. It has a thickness ranging from 100 to 400 meters. Total Organic Carbon (COT) values range from 3.95 to 13%. Analyses conducted on cuttings from well B revealed COT values ranging from 0.4 to 7.06%, with an average of 3.97%. Maximum pyrolysis temperatures, ranging from 443 to 460°C, indicate that the Silurian source rock is in the late oil to wet gas/condensate phase [61].

III.2.6. Description of Selected Wells

The primary objective of drilling Wells A, B, and C was to explore the Lower Devonian formations, including the Emsian, Siegenian, Gedinnean, and the Ordovician formation.

However, the drilling process faced obstacles such as irregular structural variations, mud losses, casing failures, stuck pipe incidents, and wellbore instability. These challenges hindered the progress of drilling operations.

Furthermore, the reservoir encountered complications due to the presence of clay, which led to a reduction in permeability and porosity. The clay particles exhibited swelling and migration behavior, blocking the pore throats and impeding fluid flow within the reservoir [61].

***Well A*:** which specifically targeted the Lower Devonian formations and utilized Oil-Based Mud (OBM) as the drilling fluid, did not demonstrate significant potential for commercial oil accumulation. In contrast, the M'Kratta Formation displayed promising signs of petroleum interest, featuring a 4-meter net pay zone. However, the presence of a substantial volume of clay within the formation posed a significant limitation on permeability. Due to these factors, it was decided to permanently abandon well A as represented in **Fig.III.3**.

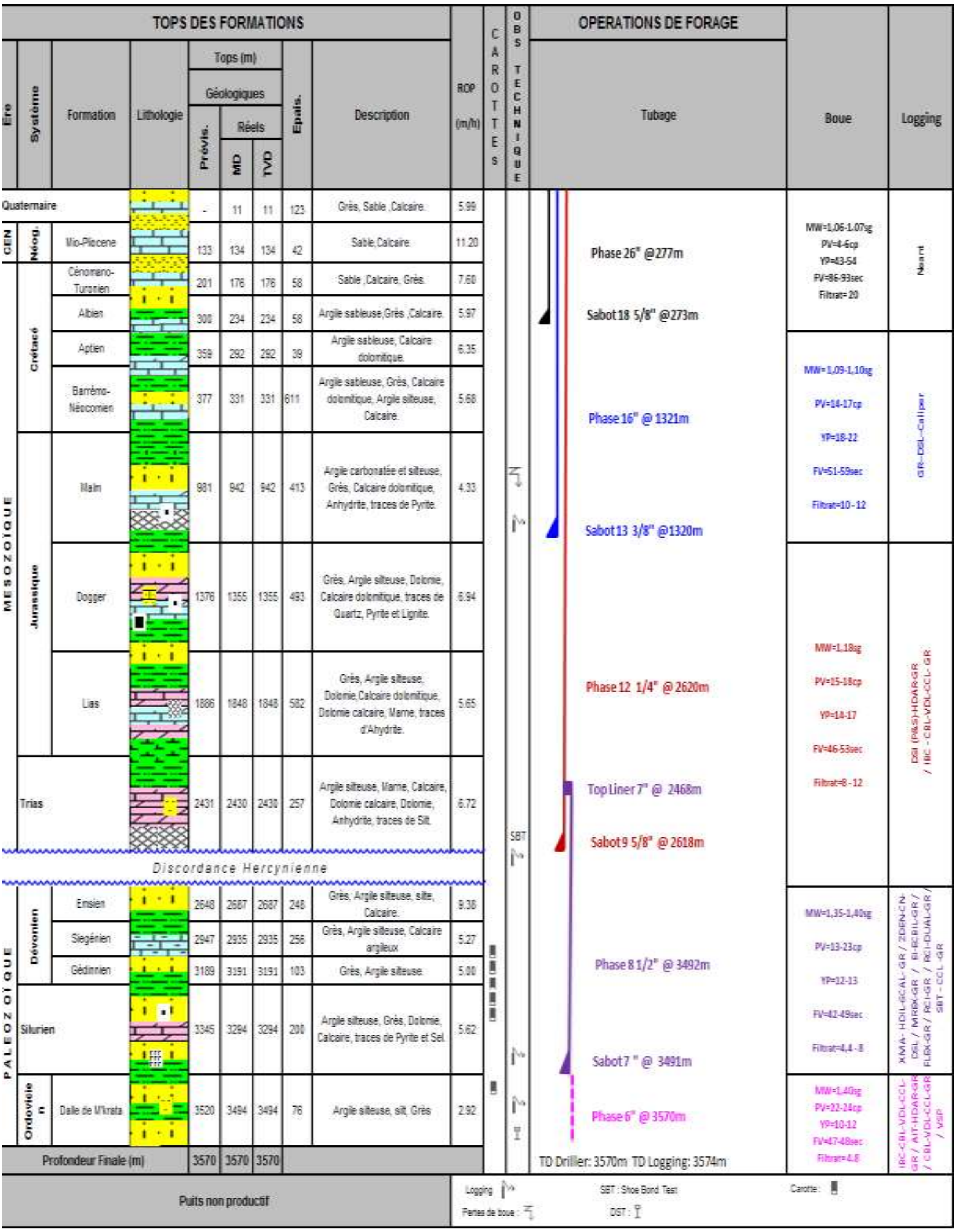

Fig.III.3: Technical Data Sheet of Well A *[61]*.

Well B: focusing on the exploration of the Lower Devonian formations, proved to be productive as represented in **Fig.III.4,** yielding approximately 2.2 cubic meters. In this case, the drilling fluid used was KCL polymer when reaching the reservoir target. However, the reservoirs within the Lower

Devonian formations exhibited mediocre permeability and porosity characteristics due to the presence of clay. This clay content posed limitations on the efficient flow of hydrocarbons.

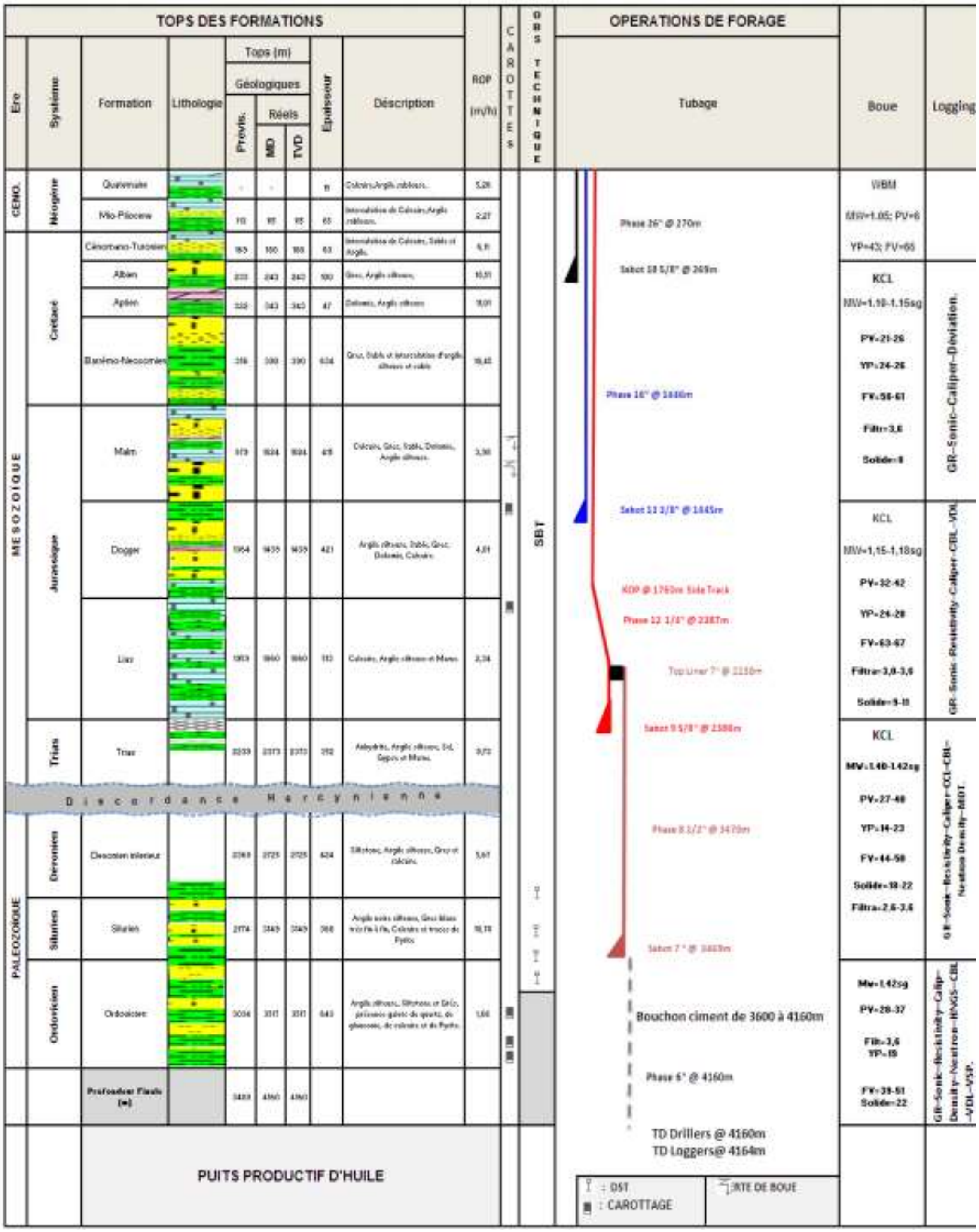

Fig.III.4: Technical Data Sheet of Well B *[61]*.

Well C: successfully achieved its objectives and exhibited productivity as represented in **Fig.III.5**. This well utilized a Water-Based Mud (WBM) with KCL polymer as the drilling fluid.

Petrophysical analyses of core samples from different intervals indicated positive and favorable permeability and porosity characteristics in the Gedinnean and Ordovician reservoirs.

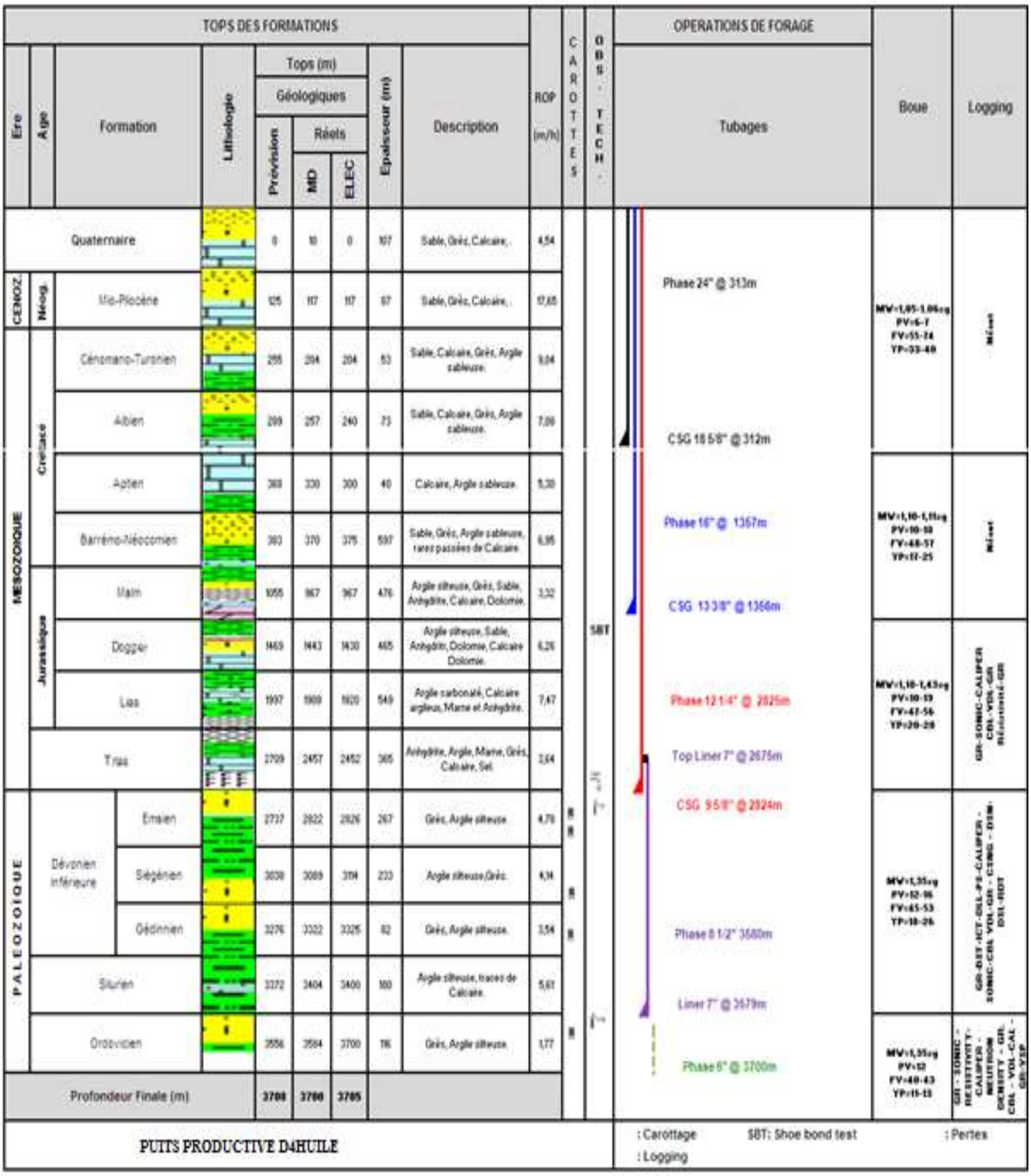

Fig.III.5: Technical Data Sheet of Well C *[61]*.

III.3. Problematic

It has been proven that clay's problem such as swelling and migration affect significantly the permeability and thus the productivity index. The Gedinnean reservoir in El Ouabed perimeter in Algeria shows the presence of a high rate of clay with different types.

During drilling and production of Well A, B and C located in Bloc 313 within the El Ouabed perimeter, a lot of problems have been encountered which had a negative impact on the recovery process. Despite the use of oil-based mud (OBM) in Well A, it has been abandoned because of its non-productivity. On the other hand, Wells B and C, which were drilled with water-based mud (WBM) containing KCl polymer, are producing, but their properties are not optimal.

In this study an investigation has been conducted to explain the impact of clay migration and swelling on oil recovery. Therefore, the following questions need to be answered:

- How does clay swelling and migration affect the permeability and porosity of Gedinnean reservoir?
- What are the advantages and disadvantages of various inhibition techniques used to mitigate clay-related formation damage?

III.4. Objectives and Research

The present work aims to:

- To identify clay minerals in the EL Ouabed reservoir through a combination of indirect methods, such as interpreting results from the FLEX tool and cross-plot data analysis, as well as direct methods, including X-ray diffraction (XRD) and hyperspectral camera analysis,
- To conduct micro-model experiments to investigate the main mechanisms of clay mineral behavior that influence the permeability and the porosity of Gedinnean reservoirs in the Sillon Benoud basin,
- To assess the effects of different inhibition techniques on reservoir properties, particularly focusing on the way they influence clay-related formation damage and alter reservoir characteristics.

By achieving these objectives, the study promotes the comprehension of clay minerals in the reservoir, their impact on reservoir performance, and the effectiveness of various inhibition methods in mitigating formation damage.

III.5. Materials, Equipment and Methodology

In this study, multiple techniques are used to identify the types of clays existed in the reservoir and to identify their effects on productivity. Indirect methods were utilized such as FLEX tool and gamma ray logging tool; and direct methods such as X-ray Diffraction (XRD) and hyper spectral camera, others are mentioned in the annex section.

Additional tests have performed in the laboratory using an experimental model developed by **GUENAOUI et al., 2021**, to study the influence of clay minerals on reservoirs and their properties.

III.5.1. FLEX Tool Logs

The Formation Lithology Explorer (FLEX) is an advanced spectroscopy tool that is used as a first method to identify the types of clay present in geological formations, specifically in the El Ouabed wells. It employs gamma ray spectrometry induced by neutron interactions with the formation's elements.

The FLEX tool consists of a pulsed neutron generator source emitting 100 million neutrons per second at 14 MeV. It utilizes a Bismuth Germanate Oxygen (BGO) crystal detector enclosed in a boron-coated sleeve as shown in **Fig.III.6**, enabling operation at temperatures up to 177°C. With a diameter of 4.87 inches.

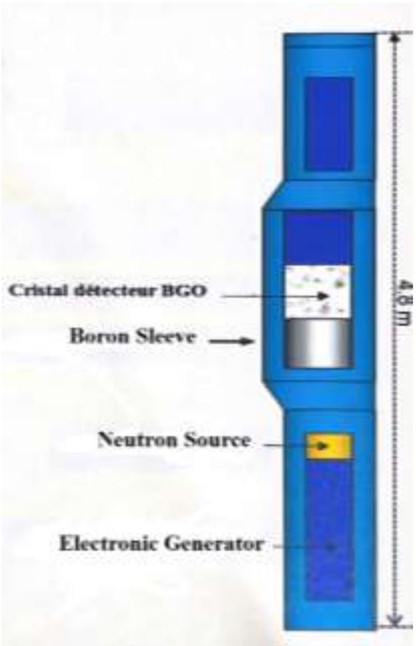

Fig.III.6: Description of the FLEX tool *[61]*.

These neutrons interact in two ways depending on time: inelastic interaction and thermal neutron capture. It is used to determine lithology and mineralogy in complex reservoirs by "**Rock view**" software and to identify types of clay [61].

III.5.2. Natural Gamma Ray Spectroscopy (SGR)

Once the FLEX tool has identified the presence of clay in the reservoir of the El Ouabed wells, SGR can be employed to further identify and characterize the specific type of clay present.

SGR is a technique used to measure the natural gamma radiation emitted by various radioactive isotopes present in geological formations, the gamma rays emitted by radioactive elements, such as potassium-40 (K-40) which indicate the presence of clay minerals as shown in **Fig.III.7**, uranium-238 (U-238), and thorium-232 (Th-232), have specific energy signatures [61].

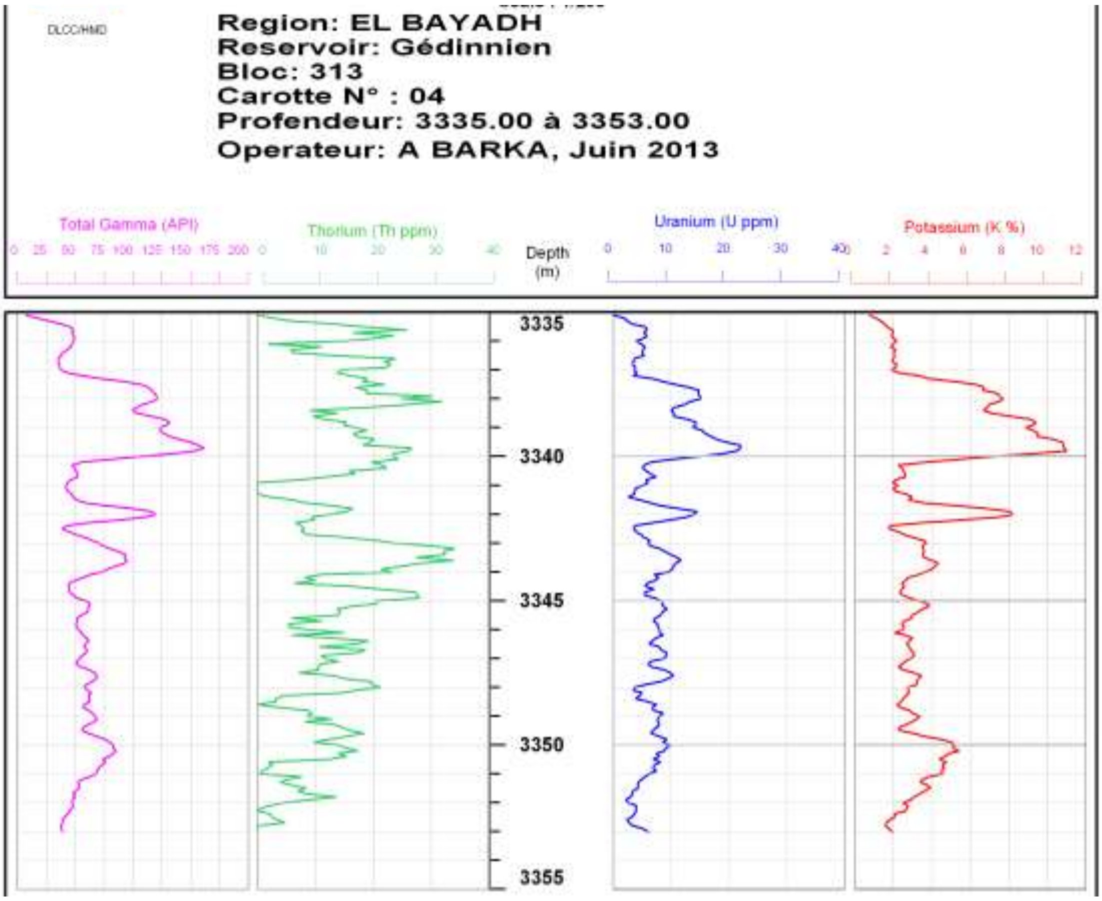

Fig.III.7: The logs of Natural Gamma Ray Spectrometry for well B of El Ouabed *[61]*.

By analyzing the energy spectrum of gamma rays detected, the concentrations of these radioactive isotopes can be determined.

The presence of radioactive elements in geological formations is often directly related to mineralogy or lithology. The presence of Uranium, for example, serves as an indicator of the presence of organic matter.

III.5.2.1. SLB Techlog, Version 2015.3 Software

Techlog software developed by SLB was used to interpret the data contained in the Natural Gamma Ray Spectroscopy logs of wells A, B and C for identifying the types of clay in the reservoirs in El Ouabed. Techlog has a modular structure, allowing the utilization of various processing applications commonly referred to as "modules."

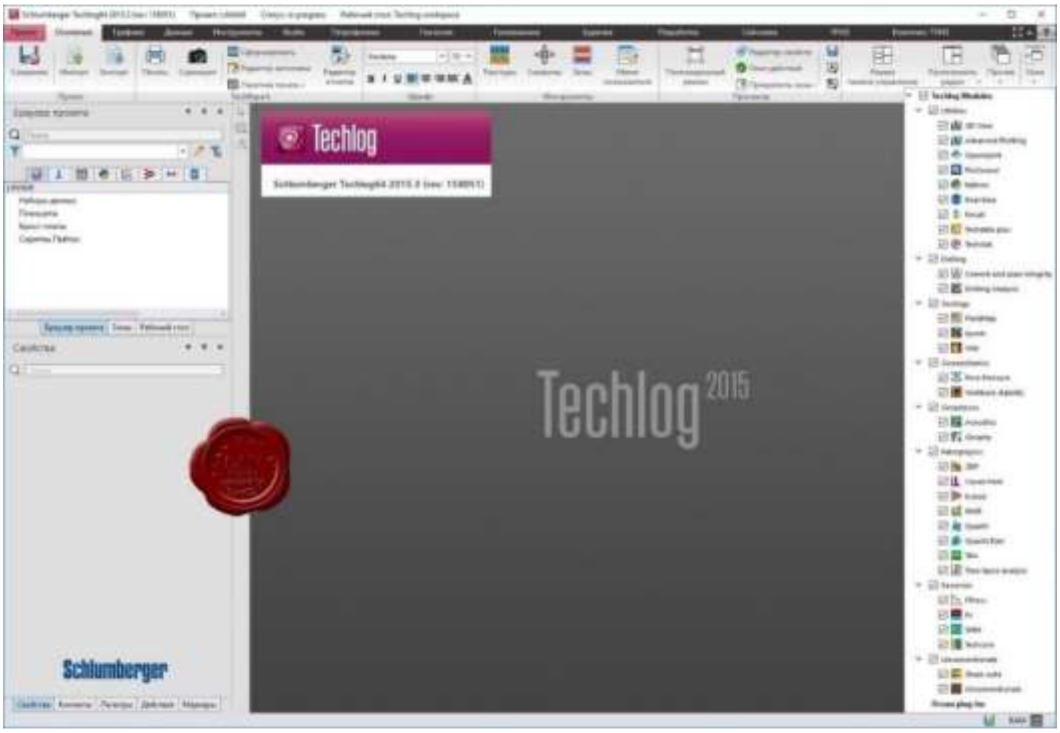

Fig.III.8: Techlog 2015.3 software interface *[61]*.

These modules are interconnected, forming a processing chain where the output data of one module becomes the input for the next module as shown in **Fig.III.8**. The software's database serves as a repository for all the interpreted well results [61].

III.5.3. X-Ray Diffraction

X-ray diffraction (XRD) was used as a highly convenient method rather than the previous mentioned methods for identifying the type of clay present in Gedinnean reservoirs. The technique can provide information about the mineralogy, crystal structure, and properties of clay minerals.

Fig.III.9 : The X-Ray Diffraction's model.

When X-rays are directed at a crystalline material, they interact with the atoms in the crystal lattice and produce a diffraction pattern that provides information about the arrangement of atoms in the crystal lattice. The diffraction pattern is obtained by measuring the intensity and angle of the diffracted X-rays using a XRD diffractometer as shown in **Fig.III.9** [62].

III.5.3.1. Principle of X-ray Diffraction

X-rays pass through a sample; the diffracted beams provide information about the arrangement of atoms in the crystal lattice as shown in **Fig.III.10**.

When X-rays interact with the atoms, they cause vibrations and emit new X-rays in all directions. These emitted X-rays interfere with each other, forming an interference pattern that depends on the crystal lattice's arrangement and the angle of the X-rays. The detector records this pattern, resulting in a diffraction pattern [62].

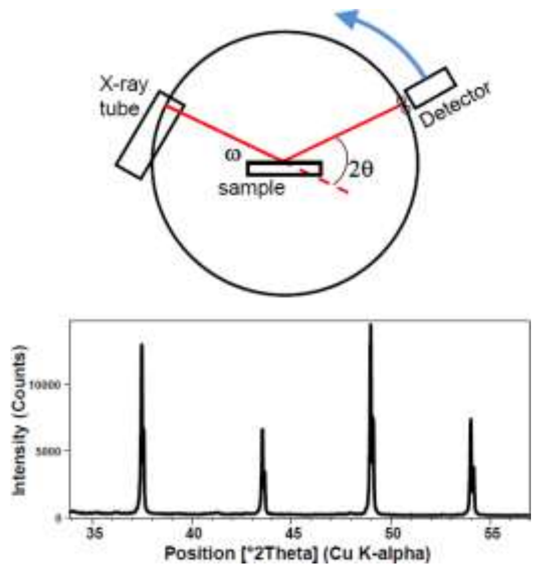

Fig.III.10: XRD Diffraction's method *[71]*.

Bragg's Law is a fundamental principle in XRD that mathematically describes the relationship between the wavelength of the X-ray beam, the distance between adjacent crystal planes (d), and the angle of incidence (θ) and diffraction. According to Bragg's Law:

$$n.\lambda = 2d.sin\theta \qquad III.1$$

Where n is an integer, λ is the wavelength of the X-ray beam, and sinθ is the angle of diffraction as **Fig.III.11** shows [62].

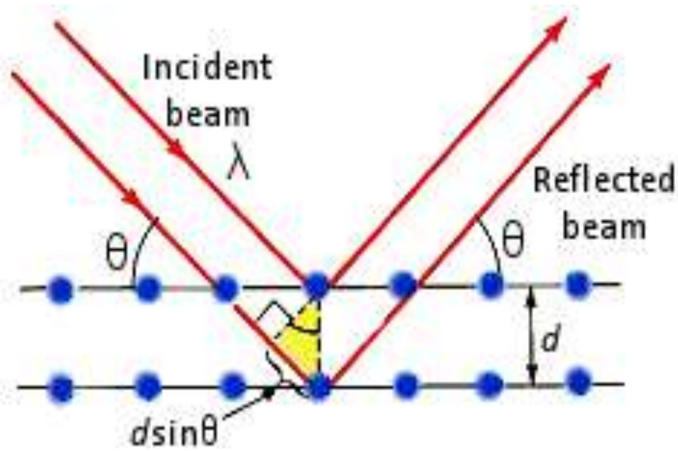

Fig.III.11: Bragg's Law Principle [62].

III.5.3.2. X Ray Diffraction's Software

Specialized software packages, including HighScore Plus and Match, are used in this research for analyzing and interpreting X-ray diffraction (XRD) data. These software applications play a crucial role in identifying the dominant clay minerals present in the reservoir.

They perform data analysis and graphing, and gain insights into the crystal structure of the materials under investigation, other software packages like PowderX and FullProf are also available and can be utilized.

III.5.3.3. Operating Method

The operating method of XRD typically involves the following steps:

Sample Preparation: The sample from wells A and B is prepared by grinding it into a fine powder to ensure a homogeneous and representative sample as shown in **Fig.III.12**.

Fig.III.12: Core Samples from Wells A and B for XRD Analysis.

Instrument Setup: The XRD instrument is calibrated and set up according to the specific requirements of the analysis. This includes adjusting the X-ray source, detector position, and other instrument parameters.

Sample Loading: The prepared sample is loaded onto a sample holder as shown in **Fig.III.13**, and securely mounted in the instrument.

Fig.III.13 : Core Holder with Well A Core Samples for XRD Analysis.

Data Collection: The XRD instrument generates a focused beam of X-rays that is directed onto the clay sample. The X-rays interact with the crystal lattice of the clay minerals, resulting in diffraction patterns.

Data Analysis: The obtained diffraction pattern is processed using specialized software's which are High Score Plus and Match to identify and quantify the clay minerals present in the sample. This involves comparing the diffraction pattern with known reference patterns from a mineral database.

III.5.4. The Hyperspectral Cam

The hyperspectral camera SpecCam 4 which is a more precise method and a new technology that was used to exactly determine and confirm the types of clays present in the reservoir. This method uses real-time infrared (IR) spectroscopic imaging to identify and generate semi-quantitative mineralogy from the surface of cores and rock cuttings as shown in **Fig.III.14** [63].

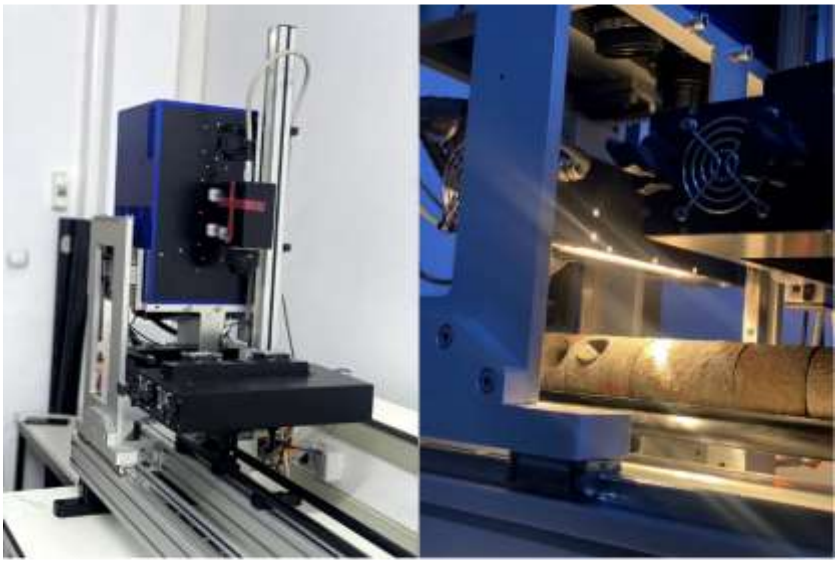

Fig.III.14: The hyperspectral camera SpecCam 4 Imaging Technology.

III.5.4.1. Principle Measurement

It used Very Near Infrared (VNIR) and Short-Wave Infrared (SWIR) reflectance spectroscopy measures the vibrational bonds of molecules and their overtones, which are considered absorptions in the reflected light (**Fig.III.15)**.

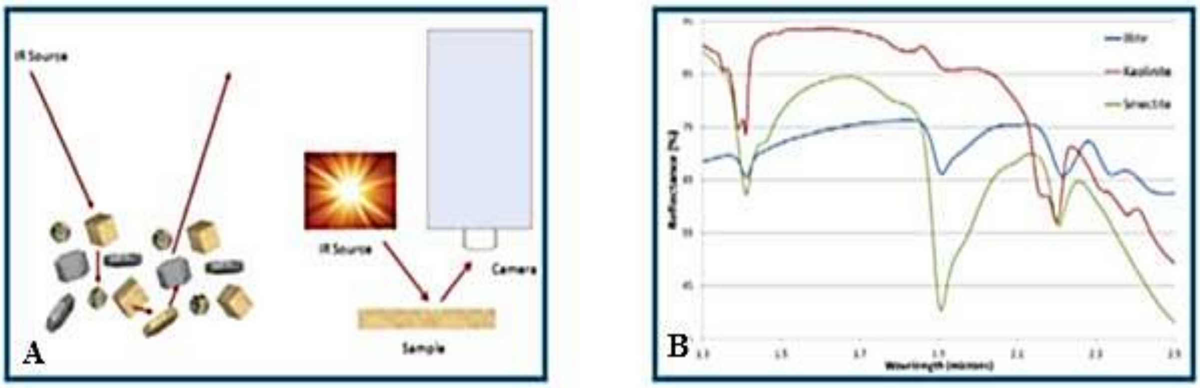

Fig.III.15: A. Reflectance Spectroscopy Light Pathway. **B.** Example Mineral Spectra *[63]*.

Both crystalline and amorphous minerals (including hydrocarbons) can be measured. The exact positions and shapes of the absorptions provide important information about precise composition, crystallinity, and, most importantly, quantity.

Hyperspectral VNIR/SWIR technology generates nearly continuous data on the surface of core samples, plugs, and whole or slabbed cores. Each pixel of a VNIR and SWIR hyperspectral image contains an infrared spectrum ranging from 400 nm to 2500 nm, which is analyzed using specialized interpretation software to identify, quantify, and map specific mineral types, mineral chemistry, mineral alteration zones, fluids, solid hydrocarbons, and contaminants (**Fig.III.16**) [63].

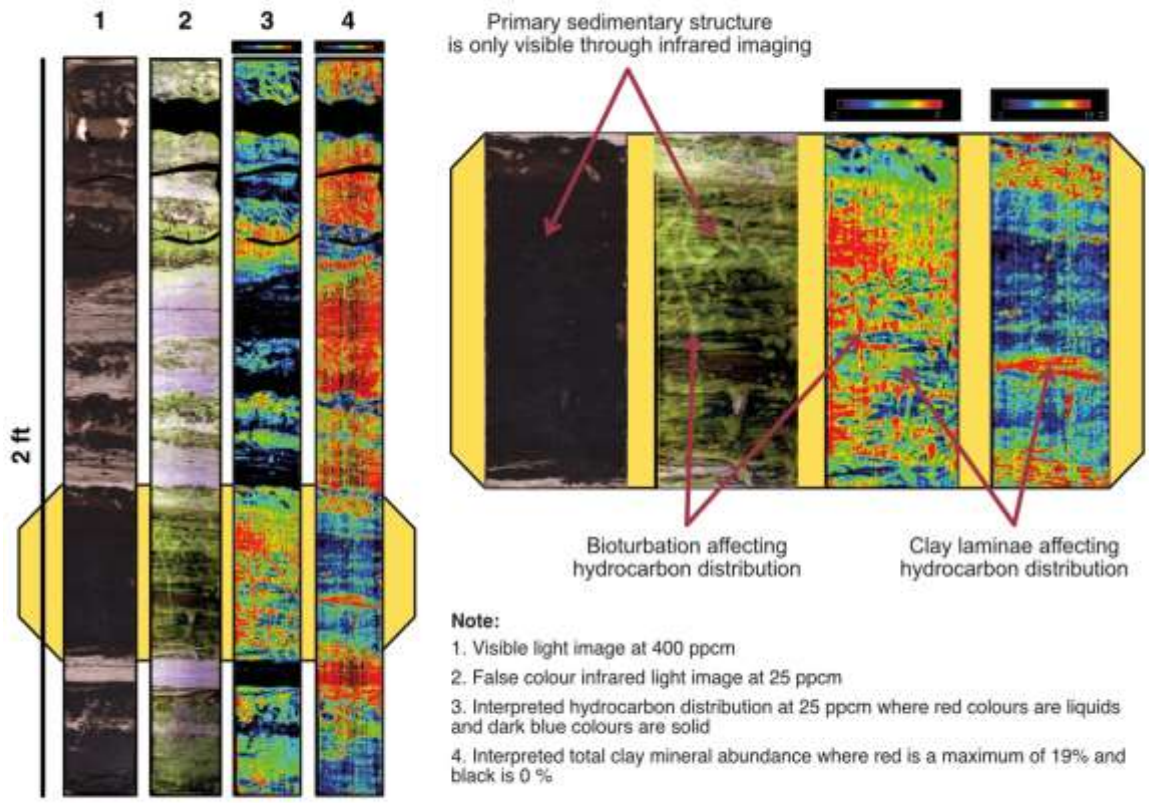

Fig.III.16: Example SWIR dataset from SpecCam 4 VNIR and SWIR Hyperspectral Spectrometer from an oil sand *[63]*.

Subsequent mineral maps and mineral composition logs created from this data will allow geoscientists to confidently determine the interrelationship between mineralogy and lithology through physical and chemical characteristics, thus improving lithological description and stratigraphic correlation of geological formations.

A list of minerals of interest to the oil and gas industry that can be interpreted from SpecCam 4 data is presented in **Table.III.1**.

This is not an exhaustive list but provides an impression of the range of minerals identifiable through infrared spectroscopy [63].

Table.III.1: Summary of Minerals Identified using SpecCam 4 [63].

Clay/Phyllosilicate Group	**Amphiboles**
• Mica polytypes incl glauconite	• Tremolite
• Smectite polytypes	• Actinolite
• Kaolin polymorphs	**Zeolite Group**
• Chlorite polytypes	• Laumontite
• Illites	• Natrolite
Sulphate Group	• Chabazite
• Gypsum	**Ferric Oxides Group**
• Basanite	• Linonite
• Epsomite	• Haematite
• Na and K alunites	• Goethite
• Jarosite	• Ferrihydrite
Carbonate Group	**Others**
• Calcite	• Brucite
• Dolomite	• Serpentine group
• Fe-dolomite	• Sphalerite
• Ankerite	• Opaline silica
• Magnesite	• Diopside
• Siderite	• Grossulargarnet
Various OH bearing silicates	• Forsterite
• Epidote	• Antigorite
• Zoisite	**Hydrocarbons**
• Clinozoisite	• Kerogen
• Tourmaline	• Bitumen
• Topaz	• Liquidoil

III.5.4.2. Interpretation Software

The SpecCam 4 spectrometer is purchased with an annual interpretation software package, which includes the assistance of an infrared spectroscopist. The software comes with two mineral databases that are used to interpret the spectrometer's reflectance data and convert it into mineral classification and semi-quantification results to produce mineral maps **Fig.III.16** and mineral composition logs [63].

III.5.4.3. Operating Method

Sample preparation: 1-meter core samples were selected from the Gedinnean reservoir layer in wells A and B based on geological descriptions from the master log and TVD data. As the following: From 3306 m to 3307 m for well A - From 3120 m to 3121 m for well B.

The core samples were obtained from the shed of DLCC in HMD and cleaned and then transferred to the Hyperspectral camera for scanning as shown in **Fig.III.17**.

Fig.III.17: Core Samples for Hyperspectral Analysis: Well A and Well B.

Instrument setup: The hyper spectral instrument is calibrated by the adjustment of the resolution and dimensions of the two cameras VNIR/SWIR, also the lighting and the position of the laser (**Fig.III.18**).

The sample loading: The prepared sample is loaded in a sample holder which can move with programmed steps of 3 mm.

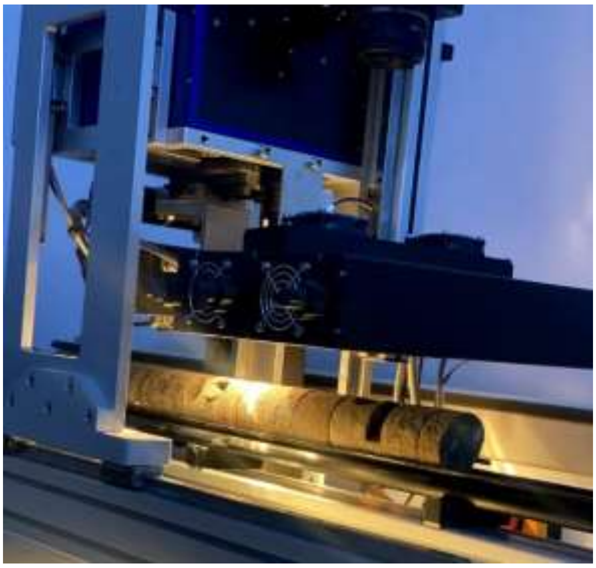

Fig.III.18: Hyperspectral Analysis of Core Sample from Well A.

Data collection and analysis: The hyper spectral used the IR which shines on the sample and received by the VNIR/SWR sensors and resulting in specific graphs and mineral maps using a specific software which work with two mineral databases that are used to interpret the reflectance data, and give the position and the percentage of various minerals, as well as the presence of hydrocarbons

III.5.5. Swelling Index Test

A swelling index test was conducted to study the performance of the well A reservoir. Which is a simple standard test used to measure the swelling tendency of clays. To perform these tests, a 15 g sample of dry and finely ground of reservoir core was added to fresh water in a 100 ml cylinder, as shown in **Fig.III.19**.

Fig.III.19: Swelling index Test.

The sample was then covered and protected from disturbances for a period of 16–24 h. After that the increase in the mixture's volume was measured as an indicator of the swelling.

III.5.6. Micromodel Tests

The permeability confinement cell developed by **GUENAOUI et al., 2021** was used to determine the effect of clay on permeability of El Ouabed reservoirs. It is composed of three main parts: the cylinder, the piston, and the plug.

Fig.III.20: Piston components of the installation (Plug, cylinder, piston) *[64]*.

The cylinder serves as the main body and provides space for the core sample, allowing stress application as represented in **Fig.III.21**. The piston, made of inox steel, acts as a barrier between the proppant and the fluid, ensuring a proper seal and it has a diameter of 4 cm, a length of 15 cm, inlet and an outlet of 2 millimeters as shown in **Fig.III.22.** The plug, located at the base of the cylinder, securely closes the cell to prevent fluid leakage as represented in **Fig.III.23** [64].

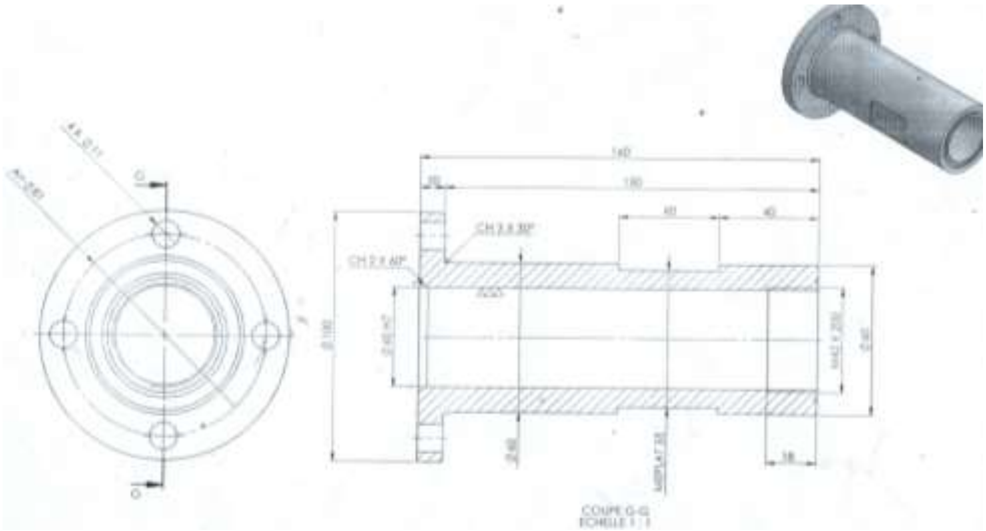

Fig.III.21: Cylinder of Piston for proppant permeability measurement [64].

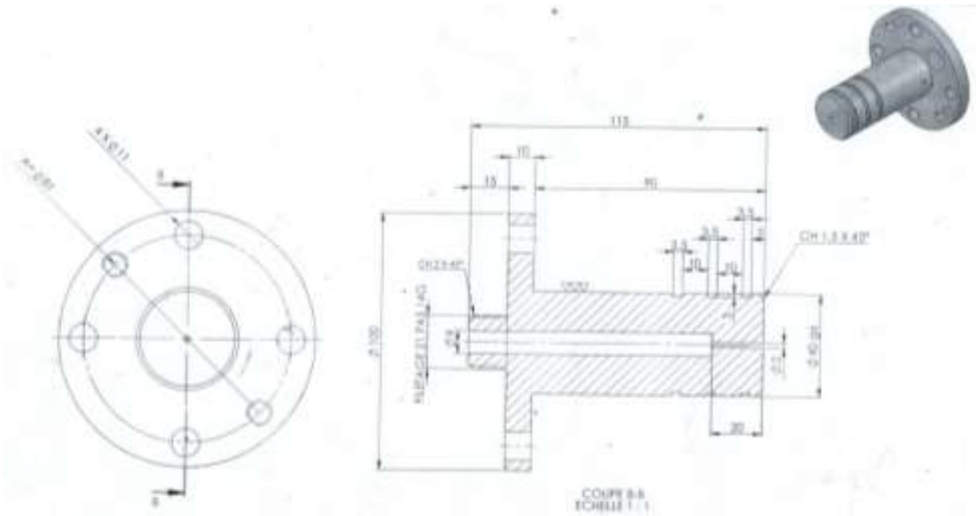

Fig.III.22: Piston for proppant permeability measurement *[64]*.

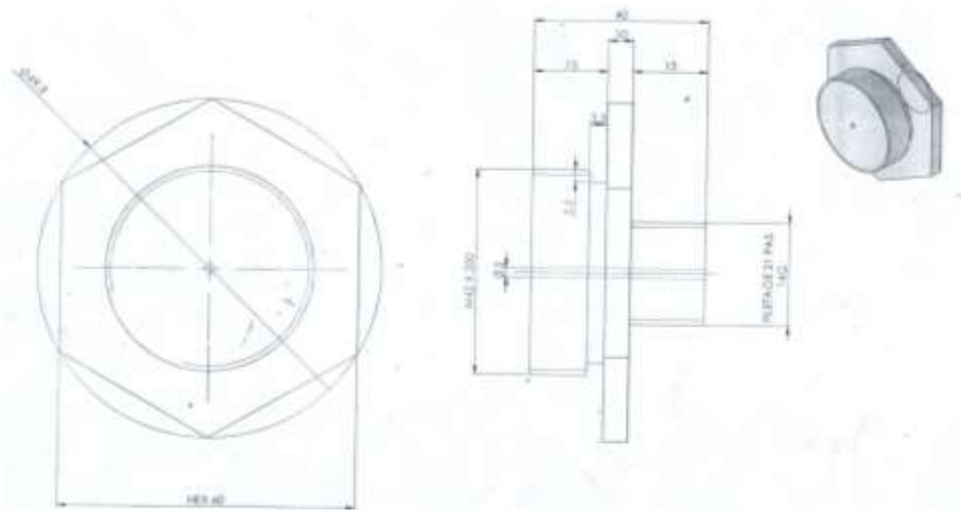

Fig.III.23: Plug of Piston for proppant permeability measurement [64].

The inlet and outlet of the cell have dimensions of 2 millimeters each to facilitate controlled fluid flow.

The installation includes pipes, valves, a pump, and manometers to control fluid flow, apply stress, and monitor pressure as shown in **Fig.III.24**. An injection pump was used to measure the permeability of the sample. The installation is designed to generate data for calculating the permeability of Gedinnean reservoirs.

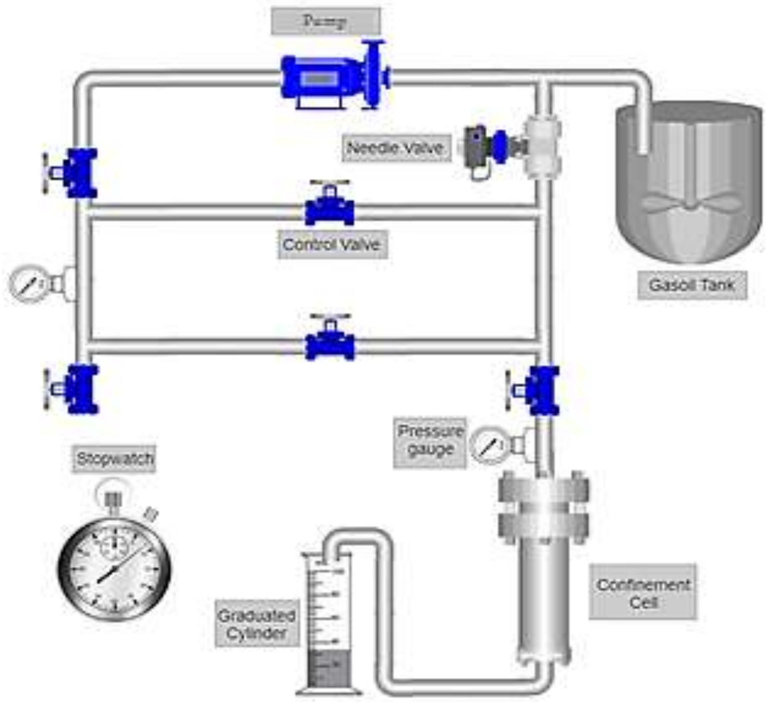

Fig.III.24: Installation schematic of the permeability measurement [64].

III.5.6.1. Operating Method

The operating method of the permeability confinement under a reservoir pressure of 6,000 psi (HP) using a containment cell and a reservoir temperature of 110°C (HT) through the use of an oven as shown in **Fig.III.25**,involves the following steps:

Fig.III.25: **A**. the containment cell - **B**. the oven.

Preparation of Sample: A fine ground sample, that is used in XRD analysis from well A, is obtained using a ceramic grinder. Additionally, a proppant of 20/40 bauxite as shown in **Fig.III.26**, along with KCl ,$CaCl_2$ solutions and distilled water are prepared to be used for the experiments.

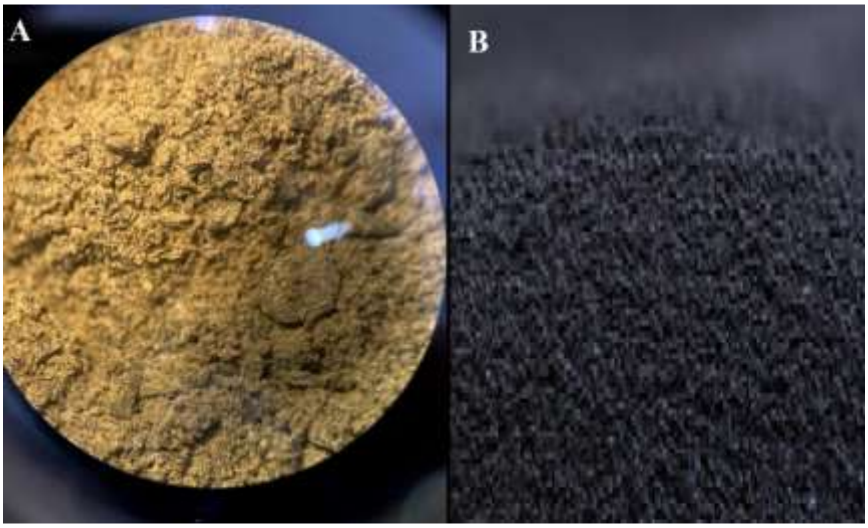

Fig.III.26: A. size of cutting from well A - **B.** 20/40 HSP Proppant used.

First Experimental Run: In the first run of the experiment, the cell set up and the necessary equipment is prepared, as depicted in **Fig.III.27**. The cylinder is filled with a mixture comprising 90% proppant and 10% cuttings. After injecting distilled water into the cell, the permeability of the sample is measured based on the Darcy's law:

$$\boldsymbol{Q} = (\boldsymbol{K} * \boldsymbol{A} * \Delta \boldsymbol{P})/\boldsymbol{L} \qquad \textbf{III.2}$$

Where: Q: is the flow rate of the fluid, K is the permeability of sample, A: is the cross-sectional area of the piston, ΔP: is the pressure difference, and L: is the length of the piston.

Second Experimental Run: In the second run, the mixture of 90% proppant and 10% cutting of sample is used again, but this time, KCl is injected. And the permeability is then measured.

Fig.III.27: Installation schematic of the permeability measurement of reservoirs samples.

Third Experimental Run: In the third run of the experiment, a beaker containing 25 g of cuttings is saturated with 2.5 g of $CaCl_2$. The mixture is stirred and kept at room temperature (25°C) for 48 hours. After that, the mixture is dried in an oven at 105°C until a constant weight is achieved as shown in **Fig.III.28**. Once the sample is prepared, the cylinder is filled with the prepared mixture. Subsequently, an oil-based mud (OBM) is injected into the cylinder, and then the permeability is measured.

Additionally, the permeability of the proppant is also recorded.

Fig.III.28: Cutting Saturation with $CaCl_2$.

III.6. Results and Discussion

III.6.1. FLEX Tool Result

The initial phase begins with the results obtained from the FLEX tool, the graphical representation from well A combines the geochemical data from the Spectralog tool (K, Th, U) as represented in **Fig.III.7**,and the measurements from the FLEX tool (Si, Mg, Al, S, C, Cl) which indicates that:

The Gedinnean Formation (3195-3312) consists mainly of sandstone and is composed of non-clay constituents such as quartz and calcite, as well as clay minerals including illite, smectite, and kaolinite as represented in **Fig.III.29**. Quartz is the dominant component of the formation, accounting for 52% of the rock and making it more brittle.

Clay minerals make up 37% of the formation, with illite being the most abundant mineral at an average value of 30%, followed by smectite (6%) and kaolinite (1%). Pyrite content is less than 0.1%.

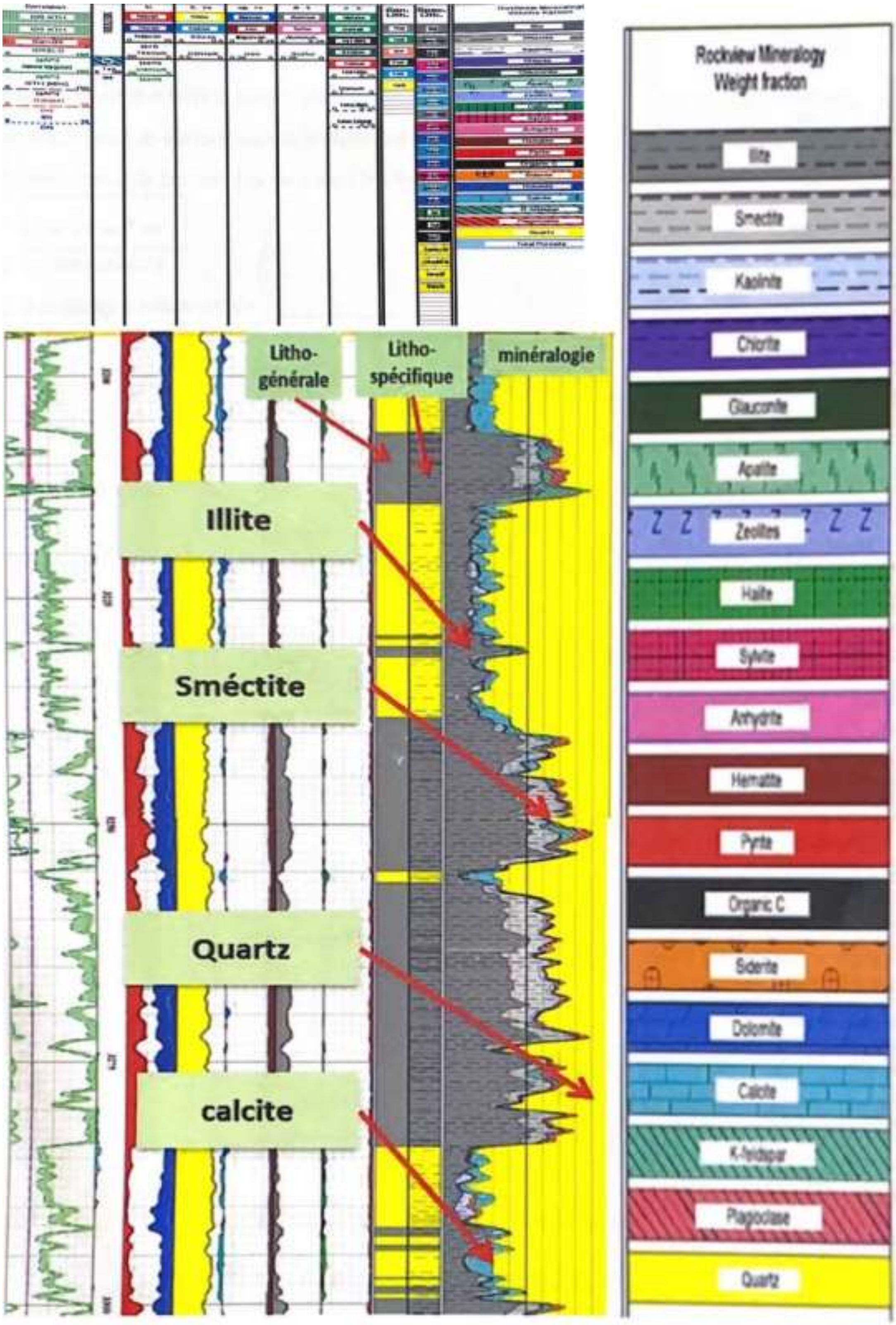

Fig.III.29: The mineralogical composition of the Gedinnean *[61]*.

III.6.2. Cross Plot Th/K

To further confirm and enhance the understanding of the reservoir mineralogy, special chart analyses were performed using SLB's Techlog 2015.3 software. The cross plots for wells A, B, and C in this study are presented along with their interpretations as follows:

III.6.2.1. Cross Plot (Th/K) for A Well

The cross plot of Thorium (Th) versus Potassium (K) for Well A in the Gedinnean reservoir reveals the abacuses representing different clay types. The points on the plot indicate a strong tendency towards the area corresponding to 100% kaolinite, as well as a percentage of montmorillonite. Furthermore, there are points located between the lines representing the boundaries of illite and montmorillonite as **Fig.III.30** indicates.

Based on these observations, it can be concluded that the primary clay mineral present in the reservoir is kaolinite. Additionally, there are occurrences of mixed-layer illite-montmorillonite observed.

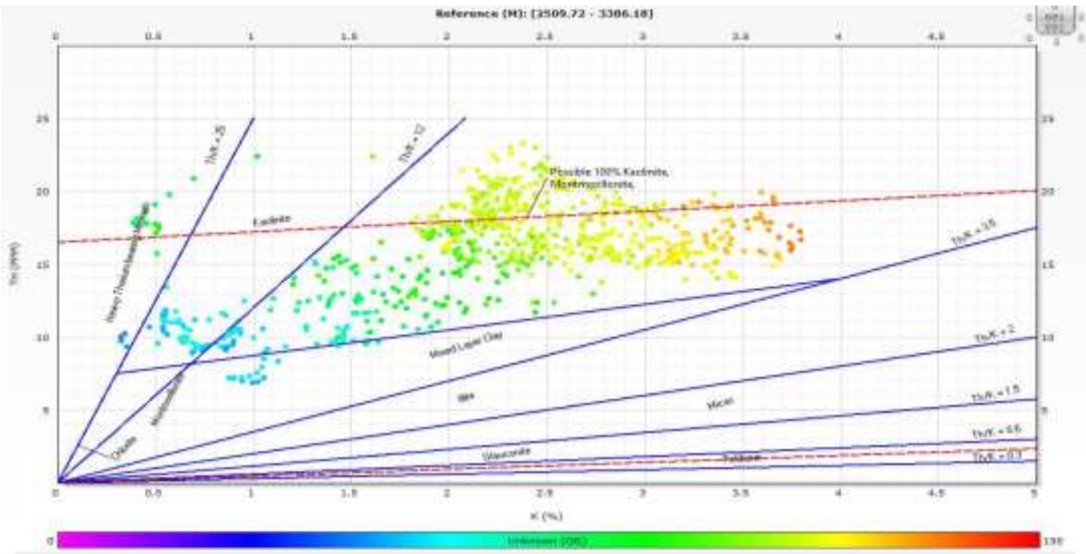

Fig.III.30: SLB CP Th/K chart displaying the clay composition of the Gedinnean at the well level (A).

III.6.2.2. Cross Plot (POTA vs Photoelectric Factor) for A Well

The cross plot of Potassium (POTA) versus Photoelectric factor for Well A in the Gedinnean reservoir displays the bar limits for each clay type. The points on the plot indicate a predominant tendency towards the area representing montmorillonite and illite, with some additional points tending towards the area of glauconite as represented in **Fig.III.31**.

Based on these observations, it can be concluded that the primary clay mineral present in the reservoir is mixed-layer illite-montmorillonite. Additionally, there is a percentage of glauconite observed

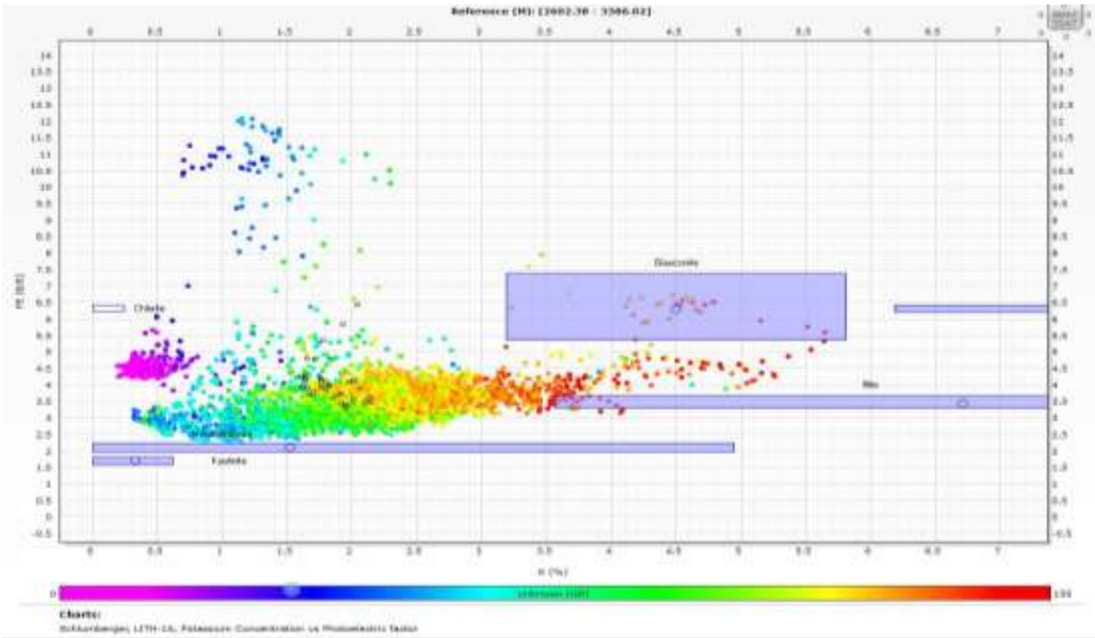

Fig.III.31: SLB CP chart for the identification of clay minerals in the Gedinnean at the well level (A) by cross-plotting Pe and K.

III.6.2.3. Cross Plot (Th/K) for B Well

The cross plot of Thorium (Th) versus Potassium (K) for Well B in the Gedinnean reservoir reveals the abacuses representing different clay types. The points on the plot indicate a strong tendency towards the area corresponding to montmorillonite, Furthermore, there are points located between the lines representing the boundaries of illite and montmorillonite as shown in **Fig.III.32**.

Based on these observations, it can be concluded that the primary clay mineral present in the reservoir is montmorillonite. However, there are also intervals that exhibit a combination of montmorillonite and illite, indicating the presence of mixed-layer clays.

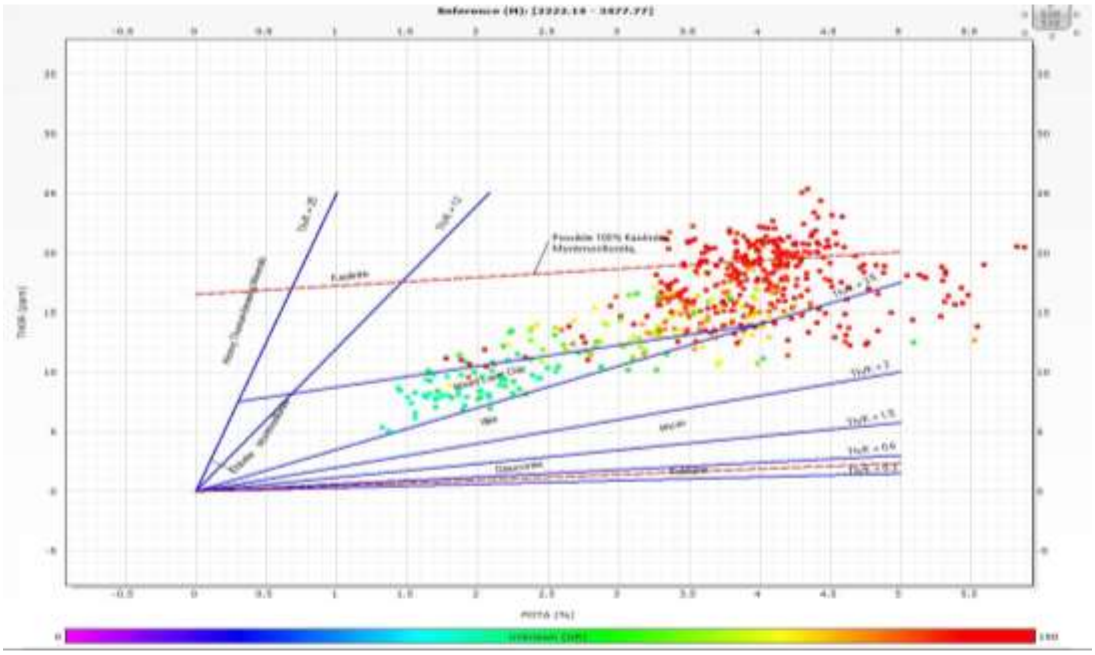

Fig.III.32: Schlumberger CP Th/K chart displaying the clay composition of the Gedinnean at the well level (B).

III.6.2.4. Cross Plot (Th/K) for C Well

The cross plot of Thorium (Th) versus Potassium (K) for Well B in the Gedinnean reservoir reveals the abacuses representing different clay types. The points on the plot indicate a strong tendency towards the area corresponding to montmorillonite and illite as shown in **Fig.III.33**.

Based on these observations, it can be concluded that the primary clay mineral present in the reservoir is mixed-layer illite-montmorillonite.

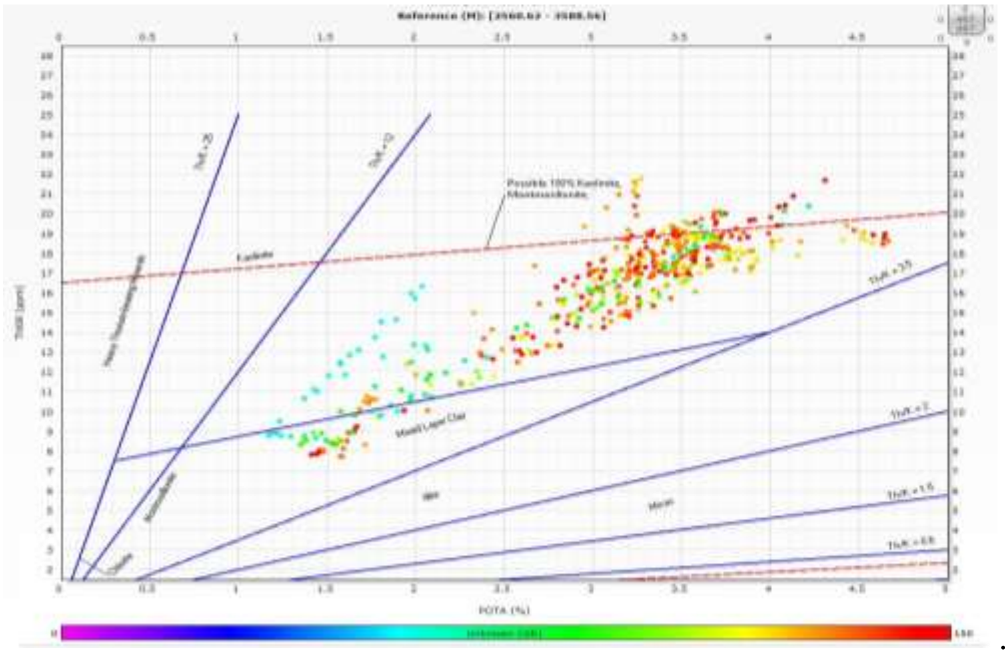

Fig.III.33: SLB CP Th/K chart displaying the clay composition of the Gedinnean at the well level (C).

However, in Bloc 313 of El Ouabed, the cross plots of wells A, B, and C indicate that the dominant clay minerals in this area are montmorillonite, illite, and kaolinite. Where Montmorillonite, a smectite clay mineral, suggests the potential of swelling in the reservoir due to its expandable properties. Illite, a non-expandable clay mineral, indicates diagenetic alteration and a mature sedimentary environment. Kaolinite, formed through weathering processes, suggests the potential of migration can impact reservoir properties such as porosity and permeability.

III.6.3. XRD Results

Indeed, it is important to note that the results obtained from logging measurements may not provide an exact view of the reservoir mineralogy. Therefore, the use of X-Ray Diffraction (XRD) analysis becomes crucial in this stage of the study so based on result obtained:

The X-Ray powder diffraction (XRPD) analyses of the sample from the Gedinnean reservoir in Well A where the intensity is plotted against the 2-theta angle revealed the presence of kaolinite ($Al_4(OH)_8(Si_4O_{10})$) as the main mineral. The kaolinite mineral is identified by the highest intensity peak observed at a d-spacing of 5,48032Å (**Fig.III.34**). additionally, pyrophyllite (d-spacing = 6.37366 Å) was also detected in the sample.

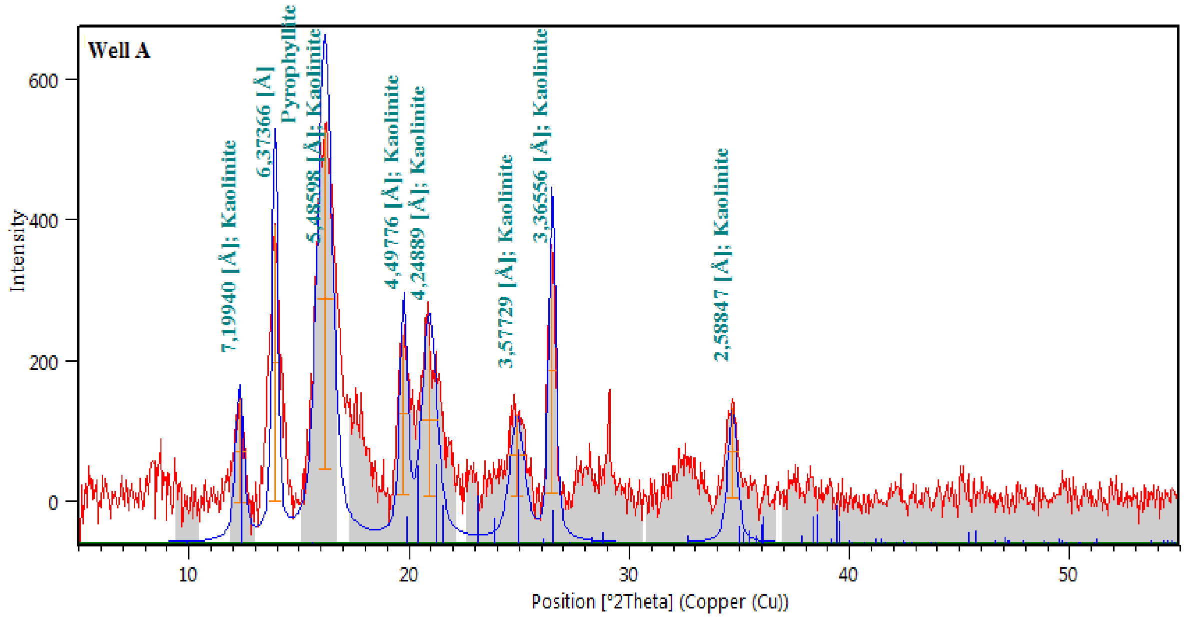

Fig.III.34: XRD patterns of Gedinnean samples from well A.

The X-ray powder diffraction (XRPD) analyses of the sample from the Gedinnean reservoir in Well B where the intensity is plotted against the 2-theta angle, revealed the presence of kaolinite ($Al_4(OH)_8(Si_4O_{10})$) as the main mineral. The kaolinite mineral is identified by the highest intensity peak observed at a d-spacing of 3.36585 Å (**Fig.III.35**).

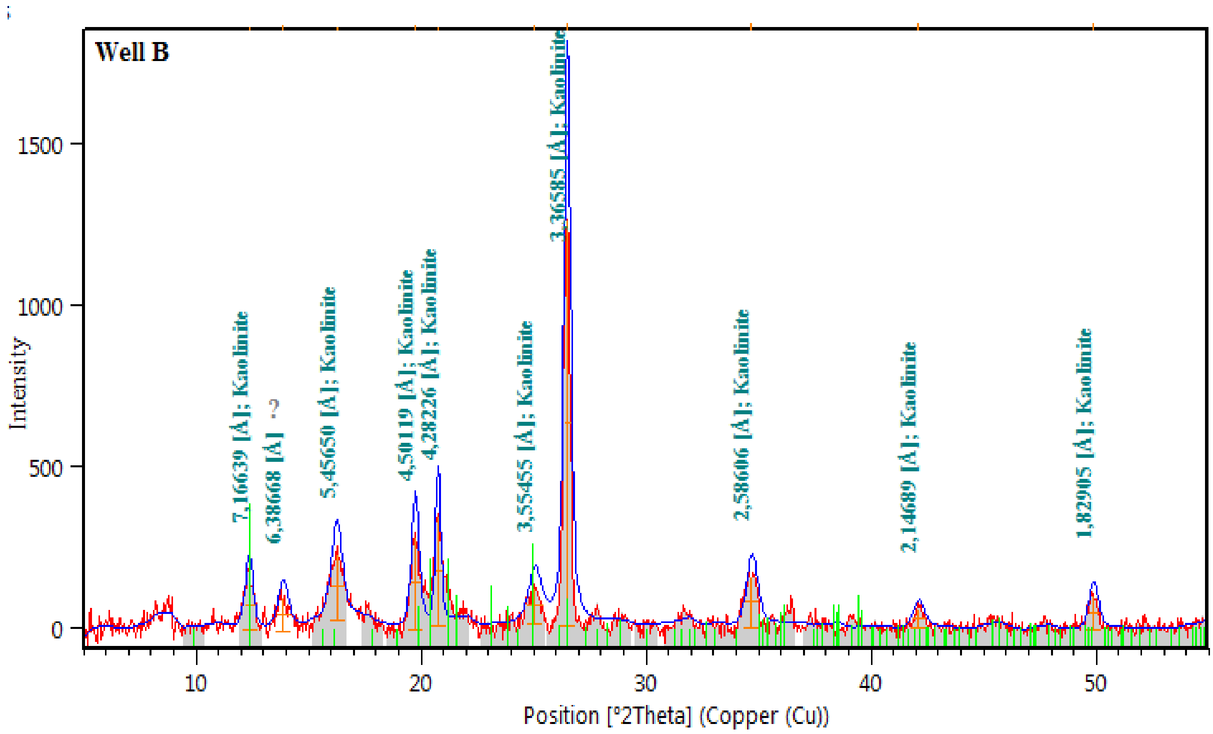

Fig.III.35 : XRD patterns of Gedinnean samples from well B.

Based on the results, there is indeed a discrepancy between the XRD analysis indicating the presence of kaolinite and the results from the FLEX tool and cross plot suggesting the presence of montmorillonite.

However, it is important to note that this interpretation is semi-quantitative. To obtain more accurate results and identify the specific mineral peaks, a series of three runs is recommended. The first run involves separating the clay phase into particles that are smaller than 2 microns in size. for better resolution. The second run focuses on selecting the appropriate homogeneous clay type for comparison. Lastly, the third run incorporates the use of a solvent (ethanol) to enhance mineral separation.

By following this approach, a more comprehensive understanding of the clay composition can be obtained.

III.6.4. Hyperspectral Results

Due to the challenges encountered in accurately determining the type of clay minerals by XRD analysis in which clay minerals pose problems in the production of the three wells, the inclusion of an alternative direct method such as hyperspectral analysis becomes highly significant at this stage so based on the result:

The bar chart illustrates the clay mineral percentages versus depth for the Gedinnean reservoir core from Well A within the 1-meter depth range (3306 to 3307m). The analysis reveals that kaolinite is the predominant clay mineral, comprising a significant proportion of 35% as shown in **Fig.III.36**. Furthermore, both illite and chlorite demonstrate noticeable percentages in the core 20% and 15% respectively.

However, the presence of smectite is found to be negligible or potentially absent. The points cloud further supports the dominance of kaolinite and its association with mica, along with traces of illite. With no sign of smectite or chlorite is observed within this core sample.

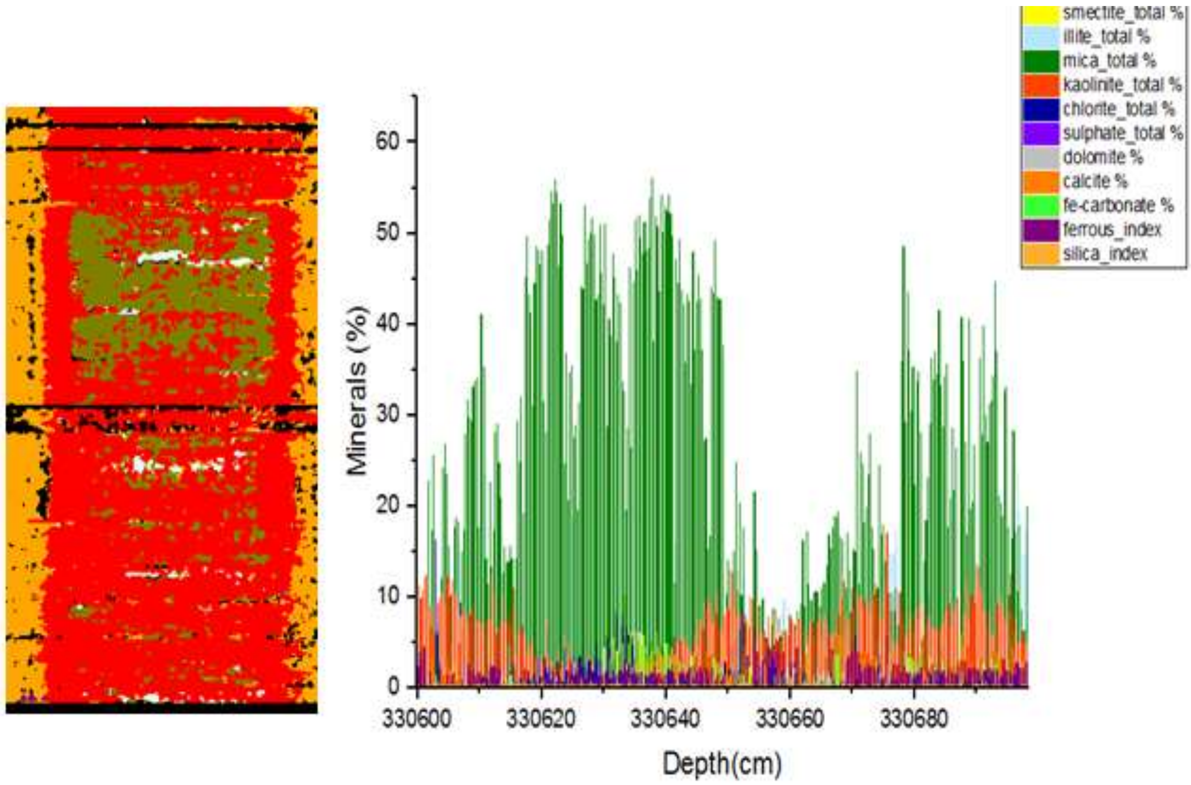

Fig.III.36: Mineral Composition Analysis of Gedinnean Core Sample from Well (A): Percentage Distribution.

The bar chart illustrates the clay mineral percentages versus depth for a 1-meter core interval (3120 to 3121m) from Well B in the El Ouabed region. The analysis reveals a significant percentage of kaolinite (40%), indicating its prominent presence within the core as shown in **Fig.III.37**. In contrast, the percentages of illite and chlorite are relatively lower, Notably, there is no observable sign of smectite within this particular core.

Additionally, the points cloud visualization confirms the dominance of kaolinite and mica in the core, there are minor traces of illite present, but no indications of smectite or chlorite in this particular core interval.

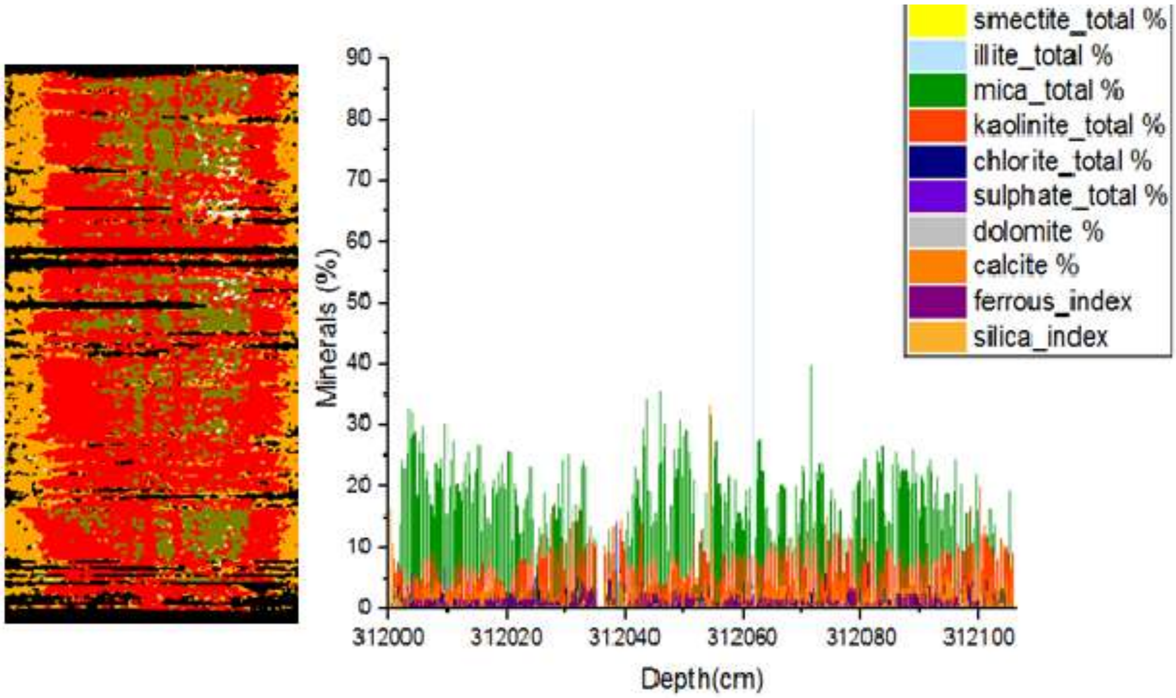

Fig.III.37: Mineral Composition Analysis of Gedinnean Core Sample from Well (B): Percentage Distribution.

III.6.5. Result from the Experimental Tests

III.6.5.1. Swelling Index Test Result

In the initial experiment, the swelling index was measured by monitoring the volume increase of the cuttings after 24 hours. This experiment served as a reference to confirm the absence of swelling clay in the cutting sample from well A.

Fig.III.38: Swelling Index Test after 24h.

The results, as shown in **Fig.III.38**, indicated no significant increase in volume, suggesting that swelling is not affecting the permeability and is not the main mechanism influencing the productivity of well A.

III.6.5.2. Micromodel Test Results

After confirming the presence of kaolinite and illite through the previous mineralogical testing, it has been identified that the migration of these clay minerals is the main factor affecting reservoir permeability of the A, B and C wells. Consequently, the study now aims to investigate the impact of water-based mud (WBM), potassium chloride (KCl), and oil-based mud (OBM) with the presence of calcium chloride ($CaCl_2$), on the permeability of this reservoir.

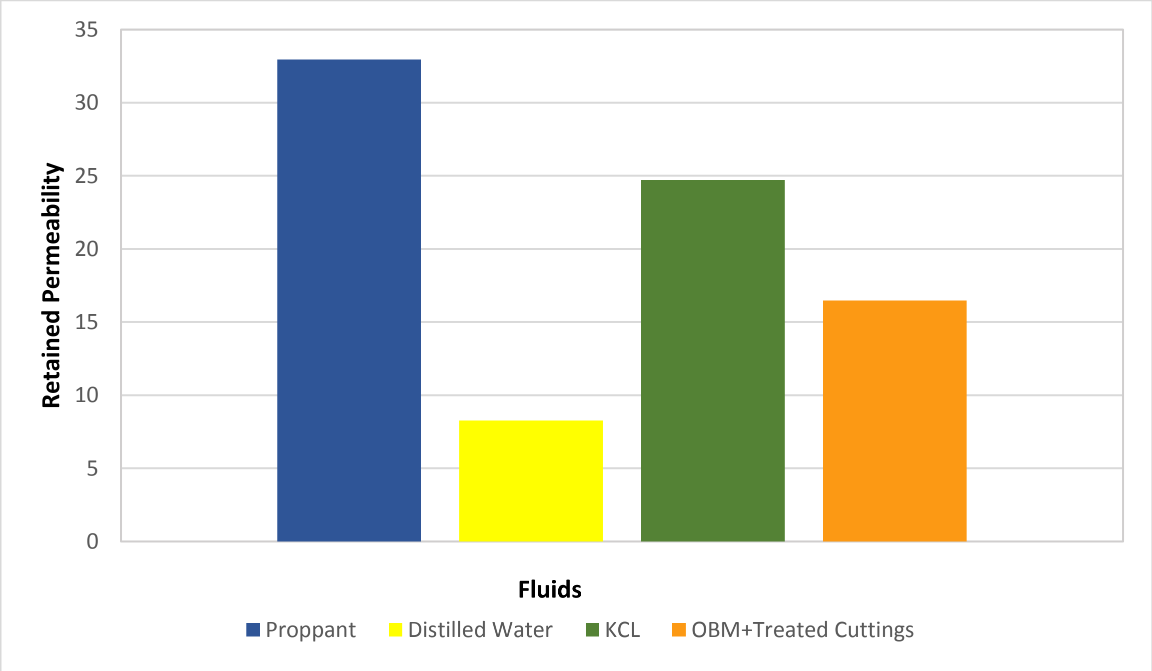

Fig.III.39: Results of Micromodel Tests for three Experimental Runs.

Results from the first Run

Based on the graph representing retained permeability versus the use of distilled water on the cuttings along with proppant packs for the first experimental run, the results indicate a decrease in permeability percentage over time compared to using of proppant alone as shown in **Fig.III.39**. This decrease in permeability can be attributed to the migration and/or swelling of clay minerals, which restrict the flow of fluids. Consequently, the movement of water becomes limited, resulting in decreased permeability.

However, depending on the result of the swelling index test which excludes the presence of clay swelling, so the decrease of the permeability can be explain by the migration of kaolinite and illite in the reservoir.

Results from the second Run

Based on the graph representing retained permeability versus the use of KCl on the cuttings along with proppant packs for the second run of the experiment, the reduction in permeability observed on the graph was less significant compared to the first run as shown in **Fig.III.39**. This finding suggests that KCl has a partial control over clay migration.

The inhibitory effect of potassium (K^+) can be attributed primarily to its small solvated ion radius. And that what happened in the well B and C of El Ouabed when the use of WBM with KCl control clay, resulting in favorable production.

Results from the third Run

Based on the graph representing retained permeability versus the use of OBM plus the treated cuttings, the restricted permeability, even with the presence of $CaCl_2$ as an effective clay inhibitor can be explained by the presence of organophilic clay as shown in **Fig.III.39**. The wettability of the clay has been reversed by the presence of calcium-associated surfactants. These surfactants, specifically the calcium-based ones, have selectively adsorbed onto the clay minerals following the Paneth-Fajans rule, which states that only atoms that are part of the clay structure are preferentially adsorbed.

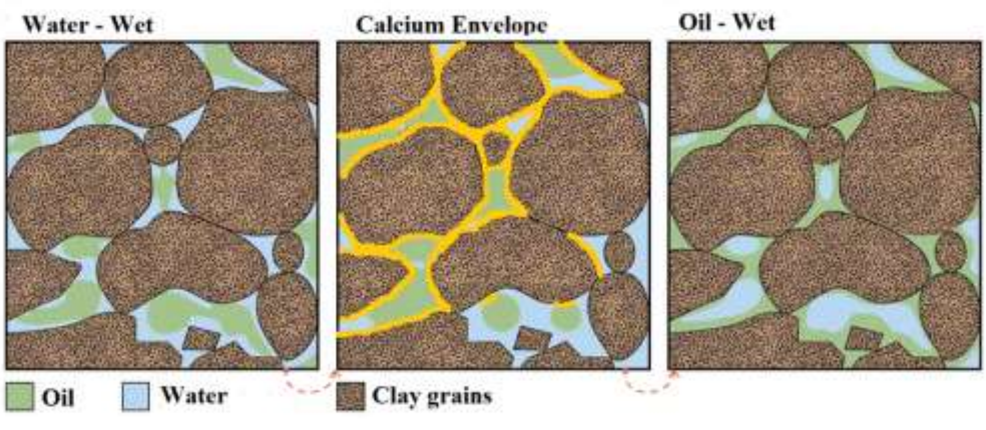

Fig.III.40: Impact of Calcium Envelope on the Inverse Wettability of Clay Minerals.

The calcium ions from the surfactants encapsulate the clay minerals and convert their charge to a positive state. This leads to a change in the wettability and behavior of the clay as represented in **Fig.III.40**, resulting in reduced oil production and preferential water production. This phenomenon can explain the abandonment of well A in the El Ouabed reservoir where the OBM was used as clay inhibition.

Based on the experimental results of the micromodel experiment, it is evident that the migration of kaolinite and illite plays a significant role in influencing the production of the El Ouabed wells. When fluid is present, these clay minerals have a tendency to migrate and block the pore throats, impeding the flow of fluids through the reservoir as depicted in **Fig.III.41**.

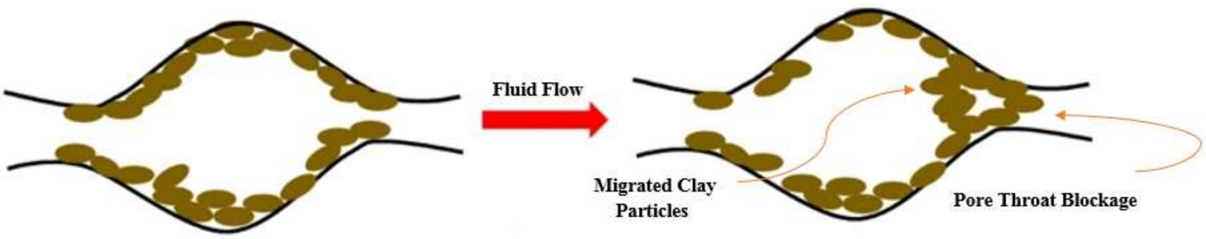

Fig.III.41: Clay Particles Migration.

Furthermore, when the drilling fluid contains calcium ions, these ions can interact with surfactants to form calcium surfactants. This interaction can cause a reversal of clay wettability from hydrophilic to hydrophobic. This change in wettability can lead to the adsorption of oil onto the clay surfaces, potentially reducing the amount of oil that can be produced from the reservoir.

These findings highlight the importance of understanding and managing clay migration in reservoirs to optimize production.

III.7. Conclusion

This research investigates the issues related to clay presence in El Ouabed reservoirs. The primary objective is to analyze the clay type within the reservoir and gain a comprehensive understanding of the associated challenges. Through direct and indirect analysis, the dominant clay minerals, kaolinite and illite, were successfully identified. Experimental tests confirmed the migration of these clay minerals, leading to pore throat blockage and reduced permeability.

Furthermore, the use of OBM as an inhibition technique was found to have adverse effects on reservoir properties and introduce additional complexities in reservoir behavior.

GENERAL CONCLUSION

This study addresses the current reservoir issues encountered during the production phase in the Gedinnean reservoir. Several problems have been observed which affected the productivity. The investigation of the factors causing these problems led to the study of the reservoir's mineralogy.

The mineralogical analysis of the El Ouabed reservoir employed a combination of indirect and direct techniques, including the FLEX tool and Techlog software, X-ray diffraction (XRD), and hyperspectral camera analysis. These techniques were used to identify and analyze the clay minerals present in the reservoir.

The results of the analysis confirmed the presence of different types of clay minerals. The FLEX tool results revealed the presence of montmorillonite, along with illite and kaolinite. The cross-plot analysis further confirmed the presence of a mixed layer of montmorillonite-illite.

Providing additional evidence of the main clay types in the reservoir. XRD analysis was used which identified kaolinite as the predominant clay mineral. However, due to inconsistencies between the logging interpretation and XRD results, the hyperspectral camera analysis was employed as a more precise technique which confirmed the presence of kaolinite and illite.

Overall, the mineralogical analysis of the El Ouabed reservoir indicated the presence of non-swelling clay minerals, with kaolinite and illite being the predominant types.

These clay minerals are known to exhibit migration tendencies. To analyze the reservoir behavior in the presence of fluids like WBM, KCL, and OBM, Experimental tests were carried out under high-pressure (HP) and high-temperature (HT) conditions. The results clearly demonstrated the migration of kaolinite and illite within the reservoir and their impact on reducing the permeability.

Furthermore, the effects of OBM as an inhibition technique was examined. It was determined that OBM inversely affects the wettability of clay minerals because of presence of calcium ions. These ions encapsulate the clay minerals causing their charge to become positive. This alteration in charge leads to changes in the wettability and behavior of the clay minerals.

Despite the use of OBM, the migration of kaolinite and illite can still occur, resulting in the blockage of pore throats and a subsequent reduction in permeability.

By addressing these findings and emphasizing the importance of direct analysis, this study contributes to a better understanding of the Gedinnean reservoir behavior in El Ouabed and provides valuable insights for mitigating clay-related issues.

RECOMMANDATIONS

The findings indicate that the Gedinnean reservoir presents challenges, with oil-based mud (OBM) negatively impacting oil recovery while water-based mud (WBM) with potassium chloride (KCl) is more efficient. Therefore, these findings should be considered when drilling similar reservoirs.

The use of logging interpretation alone is insufficient to accurately determine the types of clay minerals present in the reservoir and to identify the main challenges associated with each clay type (migration or/and swelling). Therefore, it is crucial to employ additional analysis techniques to precisely identify the dominant clay mineral types. The use of hyperspectral camera as a new technique is highly recommended as it provides a precise identification of the dominant clay mineral types.

The use of oil-based mud (OBM) requires careful control of the formation to prevent the risk of clay wettability inversion.

The utilization of water-based mud (WBM) with well-defined characteristics offers several advantages in reducing the risk of migration and/or swelling. WBM is regarded more environmentally friendly compared to oil-based mud (OBM) and its availability. So, the use of High-Performance Water-Based Mud (HPWBM), which incorporates polymers like polyacrylamide, is highly recommended.

The swelling and migration studies apparatus is highly recommended both in laboratories and in oil rigs due to its simplicity and effectiveness.

BIBLIOGRAPHY

[1] P. P. b. M. G. a. S. A. c. Abdolhamid Sameni a, "Effect of nanoparticles on clay swelling and migration," Egyptian Journal of Petroleum, Vols. Volume 24, Issue 4, pp. Pages 429-437, December 2015,.

[2] J. T. B. v. O. E. Friedheim, "Drilling Faster with Water-Based Muds. AADEHouston – Annual Forum – Improvements in Drilling Fluid Technology. Houston (TX)," March 30–31,1999.

[3] E. van Oort, "On the physical and chemical stability of shales. J. Petr. Sci. Eng. 38,," p. 213–235., 2003.

[4] Shlumberger, PPC WS SFE MMM Section 18-Clay Stabilization V1_9_4319881_01, 27 Dec 2014.

[5] N. BARKA, L'élimination des colorants de synthèse par adsorption sur un phosphate naturel et par dégradation supporté photocatalytique sur TiO2. (Thèse de doctorat), 2008..

[6] K. Cylia, Influence de la nature du sable sur les caractéristiques physiques et mécaniques d'une argile (Mémoire de fin d'études), 2020/2021.

[7] C. Anouar, Etude des caractéristiques mécaniques d'un argile naturelle expansive (mémoire de master), 2015/2016 .

[8] B. A. HAKIM, Initiation à une étude géotechnique et analyse minéralogique des argiles oxfordiennes de la région (Tiaret mémoire de master), 2016.

[9] A. Benchabane, Etude du comportement rhéologique de mélanges argiles-polymères: Effets de l'ajout de polymères Thesis for: phD, Janaury 2006.

[10] L. A, Etude des performances dans un système mixte tensio-actif polymère dans les fluides de forage Aspect stabilité des argiles et endommagement des réservoirs, 2009.

[11] V. O. H, An introduction to clay colloid chemistry, Inter science New York, 1963.

[12] S. Nanomaterials:, Preparation, Properties, and Functional Applications Chunhui Zhou, Weihua Yu, in Nanomaterials from Clay Minerals,, 2019.

[13] E. T. A., Ion exchange in geosynthetic clay liner Geotechnical fabrics report, Paul,USA, 1997.

[14] P. F., LUCKHAM U, and SYLVIA ROSSI, The colloidal and rheological properties of bentonite suspensions », Advances in Colloid and Interface Science, 1999.

[15] O. M'BODJ, Plastic and elastic properties of the systems interstratified clay–water–electrolyte–xanthan, Journal of Colloid and Interface Science, 2004.

[16] F. K, Amélioration des propriétés rhéologiques Des fluides de forage à base de bio-polymères : « Application aux puits horizontaux », 2007.

[17] COMPARONL, Étude expérimentale des propriétés électriques et diélectriques des matériaux argileux consolidés, 2005.

[18] A. e. m. a. p. p.-c. p. A. E. HACHMI, Université Abdelmalek Essaadi - Master fondamentale Chimie, 2013.

[19] W. J, Influence des solutions aqueuses sur le comportement mécanique des roches argileuses, 2005.

[20] N. Nicole Liewig, Mehrnaz Katouzian-Safadi and Celso de Sousa Figueired, Clays and Health Properties and Therapeutic Uses Michel Rautureau.

[21] G. Pédro, Les minéraux argileuxdans dans Pédologie (2 - Constituants et propriétés du sol), Masson, Paris: Duchaufour Ph. et Southier B. , 994.

[22] H. Viallis-Terrisse, Interaction des Silicates de Calcium Hydratés, principaux constituants du ciment, avec les chlorures d'alcalins. Analogie avec les argiles.," Thèse de doctorat de l'Université de Bourgogne, 2000.

[23] Merrien-Soukatchoff, D. Amitrano and J.P.Piguet, Elément de géotechnique département sciences de la terre et environnement, Ecole des mines de Nancy, mai 2005.

[24] Vincent Robitaille and Denis Tremblay, Mécanique des sols (théorie et pratique).

[25] R. J. Hunter, Foundations of Colloid Science, Vol I, Clarendon Press, Oxford, 1986.

[26] "Clay Mineralogy and the Colloid Chemistry of Drilling Fluids, " Oil Well Drilling Fluids, Chapter 4, 140-183.

[27] K. Mohan, Krishna,, Vaidya,, Ravimadhav N,, Reed, and Marion G,, Water Sensitivity of Sandstones Containing Swelling and Non-Swelling Clays Colloids and Surfaces A: Physicochemical and Enginee, Amsterdam: Elsevier Science Publishers, 1993.

[28] R. ,. F. H. Aidya, Fines Migration and Formation Damage: Influence of pH and Ion Exchange, SPE Production Engineering, November 1992.

[29] M. Sharma, Y. M. and L. Handy, Release and Deposition of Clays in Sandstones," SPE 13562, presented at the International Symposium on Oilfield Chemistry, Phoenix, April 9-11, 1985.

[30] N. Mungan, Permeability Reduction Through Changes in pH and Salinity, Journal of Petroleum Technology, December, 1965.

[31] W. Olive, A.F. Chleborad, C.W. Frahme, and Julius Schlocker, , Swelling Clays Map Of The Conterminous United States, 1989.

[32] T. Al-Bazali, A critical investigation of diffuse double layer changes in clay electrolyte systems at high temperatures, Journal of Geophysics and Engineering., ,August 2022.

[33] K. Mohan, Krishna and Fogler, Colloidally Induced Smectitic Fines Migration: Existence of Microquakes, AIChE Journa, March, 1997.

[34] C. Crowe, Laboratory Study Provides Guidelines for Selecting Clay Stabilizers," SPE 21556, presented at the Petroleum Society of CIM/Society of Petroleum Engineers International Technical Meeting, Alberta, Canada, , June 10-13, 1990.

[35] Nasr-El-Din, H.A., , Al-Mulhem,, A.A, and Lynn, J.D, Evaluation of Clay Stabilizers for a Sandstone Field in Central Saudi Arabia," SPA 39584, presented at the 1998 SPA International Symposium on Formation Damage Control, Lafayette, Louisiana, February 18-1998.

[36] M. G. Reed, Stabilization of Formation Clays with Hydroxy-Aluminum Solutions, JPT, 1972.

[37] C. Balaban, a, Emanuella Layne Ferreira Vidal and b, Maurício Rod, Design of experiments to evaluate clay swelling inhibition by different combinations of organic compounds and inorganic salts for application in water base drilling fluids, March 2015.

[38] J. W. T. J. G. Simpson, "Environmentally acceptable water-based mud can prevent shale hydration and maintain borehole stability.," Paper IADC/SPE 7496. IADC/SPE Drilling Conference, Dallas (TX), 15–18 February.1994.

[39] H. G. G. O. E. R. D. W. I. C. J. W. R. A. M. T. U. M. F. Darley, "Composition and Properties of Drilling and Completion Fluids, 5th Edition. Gulf Professional Publishing, Houston (TX).Silicatebaseddrilling fluids: competent, cost-effective and benign solutions to wellbore stability problems. Stabilizing boreholes.," SPE paper 35059. SPE/IADC Drilling Conference New Orleans, 1988,March 12–1999,1997,2000. .

[40] A. S. H. Gupta, "A novel procedure for screening drilling fluid compatibility.J. Can. Petr. Technol. 41 (5)," p. 39–43, 2002.

[41] M. D. A. A. H. A. A. Abdou, "Comparative study of using Water-Based mud containing Multiwall Carbon Nanotubes versus Oil-Based mud in HPHT fields," Egyptian Journal of Petroleum,, october 2015.

[42] M. P. P. N. A. Sharifipour, "Study of the effect of clay swelling on the oil recovery factor in porous media using a glass micromodel," Applied Clay Science, pp. 141, 125-131, 2017.

[43] Beihoffer, T.W., Dorrough, , D.S. and Schmidt, , The separation of electrolyte from rheological effects in studies of inhibition of shales with native moisture contents IADC/SPE Drilling Conference, Houston: SPE Paper, 2–5 October 1988.

[44] J. Fink, Petroleum Engineer's Guide to Oil Field Chemicals and Fluids, Elsevier,USA, 2011.

[45] I. Drašković, Analytical solution for stuck pipe problems based on worldwide company practices Master Thesis, June 2017.

[46] C. Bowes and Procter, R, Drillers Stuck Pipe Handbook. Ballater : Schlumberger, 1997.

[47] Karpiński and M. Szkodo, Clay Minerals–Mineralogy and Phenomenon of Clay Swelling in Oil & Gas Industry, Adv. Mater. Sci., vol. 15, no. 1,, 2015.

[48] F. Civan, Chapter 10 – Single-phase formation damage by fines migration and clay swelling," in Reservoir Formation Damage, Gulf Professional Publishing,, 2007.

[49] A. M. Ezzat, Completion Fluids Design Criteria and Current Technology Weaknesses, Lafayette, Louisiana,USA: SPE Formation Damage Control Symposium, 22-23 February 1990.

[50] A. Patel, Stamatakis, E., Young, S. and Friedeim, J, Advances in inhibitive water-based drilling fluids-can they replace oil-based muds? SPE Paper 106476, Houston, Texas,: SPE International Symposium on Oilfield Chemistry, 28 February–2 March 2007.

[51] S. Wysocki, Magdalena Gaczo and Marta Wysocka, Drilling mud with addition of new hydration inhibitor for clay rocks, 2018.

[52] B. Dehghanpour, M. Fassihi, and M. Dusseault, , Clay Swelling and Its Impact on Oil Recovery: A Review, Journal of Petroleum Science and Engineering, 2011.

[53] Hasan Javed Khan, Eleanor Spielman-Sun, and Adam D. Jew,, A Critical Review of the Physicochemical Impacts of Water Chemistry on Shale in Hydraulic Fracturing Systems, 2021.

[54] Anderson, R. L., Ratcliffe, , I. Greenwell, H. C. and Williams, Clay swelling — A challenge in the oilfield. Earth-Sci Rev, 98 (3-4), 201-216. doi:10.1016/j.earscirev, 2010.

[55] SPE-194626-MS, Integration of 1D Geomechanics Modeling and High-Performance Water-Based Mud HPWBM System Design Sankhajit Saha, Baker Hughes, a GE company , 9 11 April 2019.

[56] Y. Qu, Xiaoqing Lai, , LaifangZou, and Yi'nao Su. , "Polyoxyalkyleneamine as shale inhibitor in water-based drilling fluids," Appl Clay Sci, 44 (3–4):265-268., 2009. [Online]. Available: http://dx.doi.org/10.1016/j.clay.2009.03.003..

[57] C. R., Darley H. C. H., and Gray, G. R. , Composition and Properties of Drilling and Completion Fluids, Elsevier, UK: 6th edition, 2011.

[58] X. Guerrero, Guerrero, M., and Warren, B., , Use of amine/PHPA system to drill high reactive shales in the Orito field in Colombia, Cancun, Mexico: SPE Paper 104010 First International Oil Conference and Exhibition, 31 August–2 September 2006.

[59] M. Khodja, Canselier, , J.P., , Bergaya, , Fourar, and K. Khodja,, Shale problems and water-based drilling fluid optimization in the Hassi Messaoud Algerian oil field, Appl. Clay. Sci. 49, 383-393., 2010.

[60] K. D. EDDAIF Fatma Zohra, "Apport de la méthode gravimétrique à l'étude structurale du Sillon de Benoud Nord-Ouest Algérienne," mémoire de fin d'études, pp. 5-15, 2018/2019.

[61] o. F. 2. 2. t. From, File from the SONATRACH Exploration Department, well log service (tarining periode), March ,2023.

[62] G. &. C. KGaA, "Weinheim 100th Anniversary of the Discovery of X-ray Diffraction's report Copyright: Wiley-VCH Verlag," June 8th, 2012.

[63] catalog from DLCC (Direction Laboratoire Carothèque Centrale) Hassi Messaoud, departement Gamma-Ray (training periode), March 2023.

[64] G. A. Seyfeddine, "Experimental simulation of proppant permeability in hydraulic fracturing at extended time under bottom-hole conditions ,," 09 November 2021 .

[65] M. Pervukhina, Gurevich, B., Golodoniuc, P. and Dewhurst, D. N, Parameterization of elastic stress sensitivity in shales, Geophysics,, 2011.

[66] Y. Yang, Li, Y., Yao, J., Zhang, K., Iglauer, S. and Luquot,, Wang, Z. Formation damage evaluation of a sandstone reservoir via pore-scale X-ray computed tomography analysis, [Google Scholar] [CrossRef], 2019.

[67] MI Handbook and Baker Mud School.

[68] R. Collins, Drilling Fluids: It's About the Chemistry, November 14, 2014 .

[69] S. Devereux, Practical Well Planning & Drilling Manual, First Edition, 510 p, 1998.

[70] O. A. K. IGHEROUSSENE Siham, "Evolution du potentiel pétrolier et caractérisation des réservoirs du Lias dans le sillon de Benoud (passage vers l'Atlas Saharien occidental)," mémoire de fin d'études, 2018/2019.

[71] D. Banerjee, "https://www.iitk.ac.in/che/pdf/resources/XRD-reading-material.pdf," Department of Chemical Engineering IIT Kanpur. [Online].

ANNEXE

ANNEXE

1- Description and characteristics of the hyper spectral cam utilized

This table describe the hyper spectral cam device and its performance

Tab 1: characteristics of the hyper spectral cam [63].

GEOTEK SENSOR TECHNOLOGY	PERFORMANCE STATISTICS	DATA OUTPUT	ADVANTAGE
VNIR/SWIR Hyperspectral Spectrometer (Section 1.1.2)	• Standard resolution: 20 ppcm x 0.33 ppcm over a core width of 72 mm • Spectral range 400 nm at 2500 nm • Résolution spectrale : 2 nm • Standard speed resolution: 15 minutes by m • Proprietary software for deliver semi-quantitative mineral	• RAW ENVI format reflectance data • Individual mineral card for each kernel section in JPG format	• Mineralogy by ASCII scan line table • Améliorer la corrélation puits à puits grâce à la minéralogie • False Color infrared images like JPG • Semi-quantified mineralogy of clayey and carbonate species • Images illustrating the spatial distribution of mineral resources abundance • Images showing location and composition of hydrocarbons (solid vs liquid) • Tabulated mineralogy 3 mm apart

2- Infrared spectroscopy [61]

Is a technique used to study the interaction of infrared radiation, it involves measuring and analyzing the absorption, transmission, and reflection of infrared light by a sample.

Infrared spectroscopy plays a vital role in clay studies by enabling mineral identification, structural analysis, quantitative measurements, and environmental investigations, based on their unique infrared absorption patterns. Each clay mineral has specific absorption bands associated with its structural components, allowing researchers to distinguish between different mineral types. Example of infrared analysis results are shown in **Fig 1**:

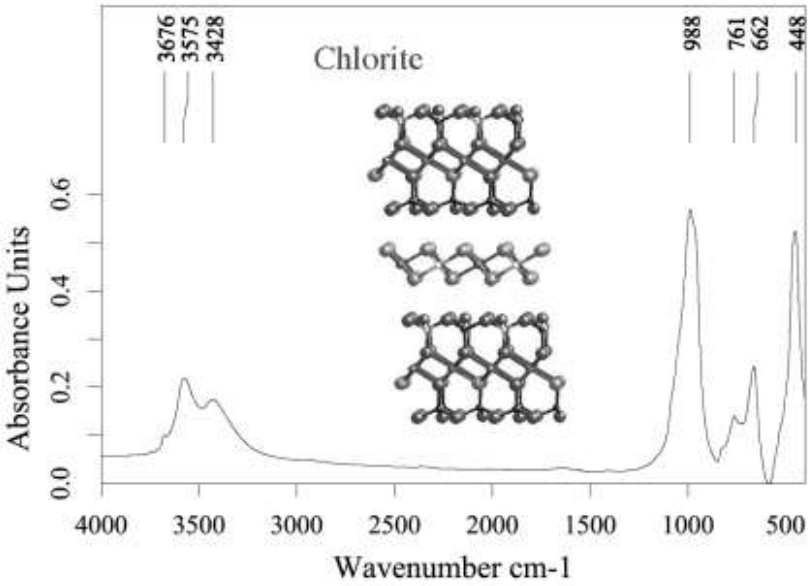

Fig 1: IR spectrum of clinochlore, Mg3AlSi3O10(OH)2 Mg3Al(OH)6, using 0.39 mg sample/150 mg (Google image).

3- Gamma Ray [63]

Gamma ray spectroscopy can help identify the presence of certain clay minerals in subsurface formations. Different clay minerals exhibit variations in their natural radioactivity due to the presence of specific radioactive elements such as potassium, uranium, and thorium. By measuring the gamma ray emissions from these elements, researchers can identify the types and relative abundance of clay minerals in a given geological formation.

There is two types of Gamma Ray Spectral model used for the measurement in DLCC Hassi Messaoud , the first type is fixed that can only be used in the laboratory as shown in **fig 2.**

Fig 2: Gamma Ray spectral fixed model

the second type is GT- 40S which is portable that can be used in both, the laboratory and the field, as shown in **fig 3**.

Fig 3: Gamma Ray spectral portable model

Fig. 4 and **fig.5** below show the results of gamma Ray for well C and well D, where the elevated levels of potassium observed in the reservoir of wells C and D of El Ouabed provide information about the presence of some clay minerals.

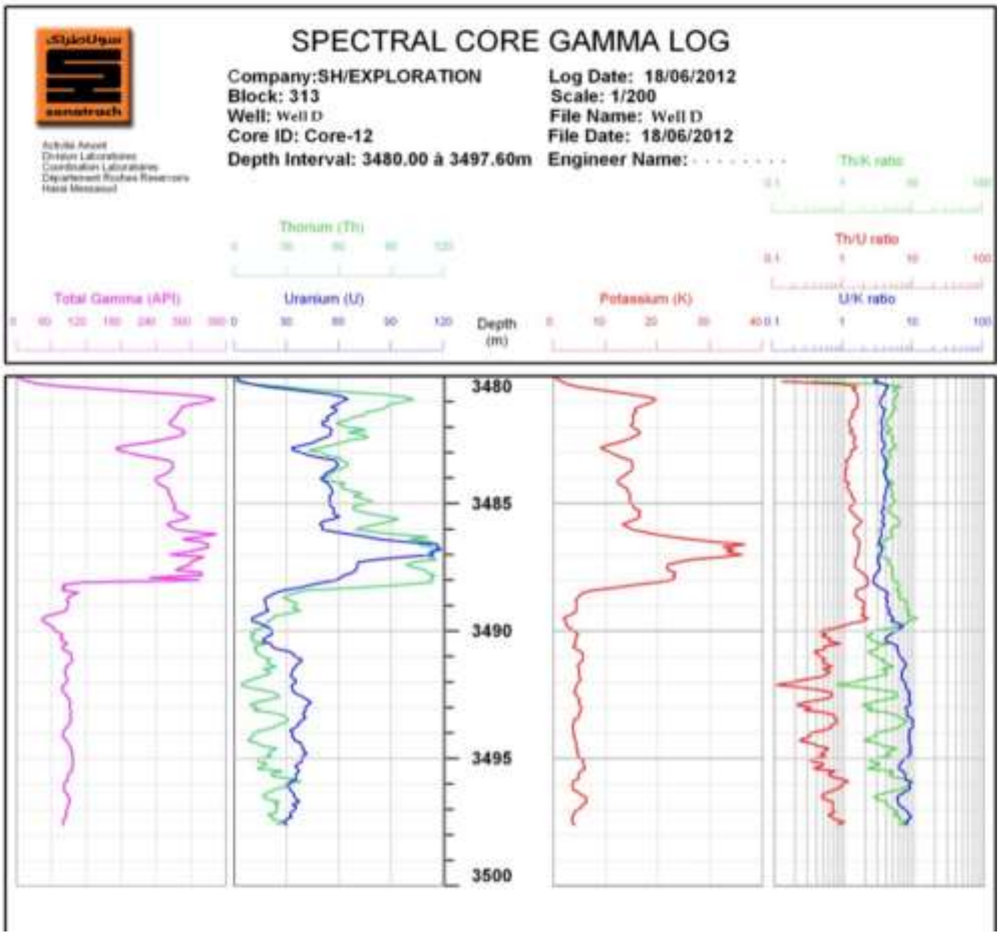

Fig 4: gamma ray results for well D [61]**.**

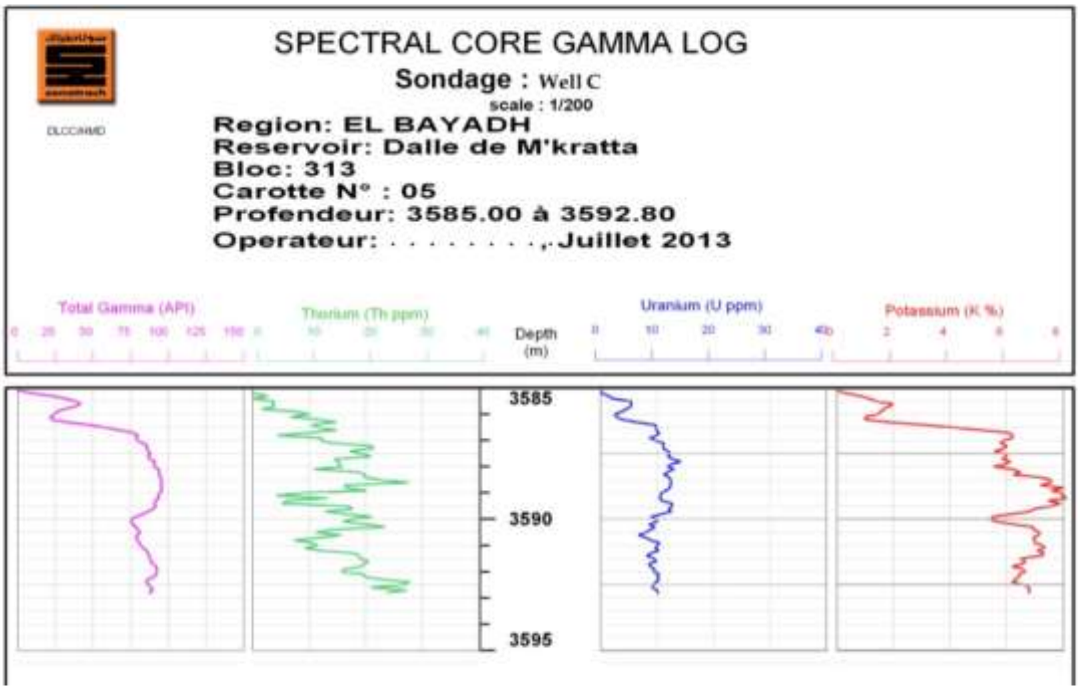

Fig 5: gamma ray results for well C [61]**.**

4- Multi-Sensor core logger (MSCL-S) [63]

To determine the elements contained in the sampling the Multi-Sensor Core Logger (MSCL-S) was used, which is recognized as a crucial step in many geological coring workflows, including those for paleoclimate, mineral exploration, geometallurgy, oil and gas, nuclear or geotechnical. The MSCL-S operates by automatically moving core samples past a series of sensors such as density and porosity detector, Ultraviolet camera scan, the XRF, Infrared camera, acoustic velocity logging as shown in **fig 6**.

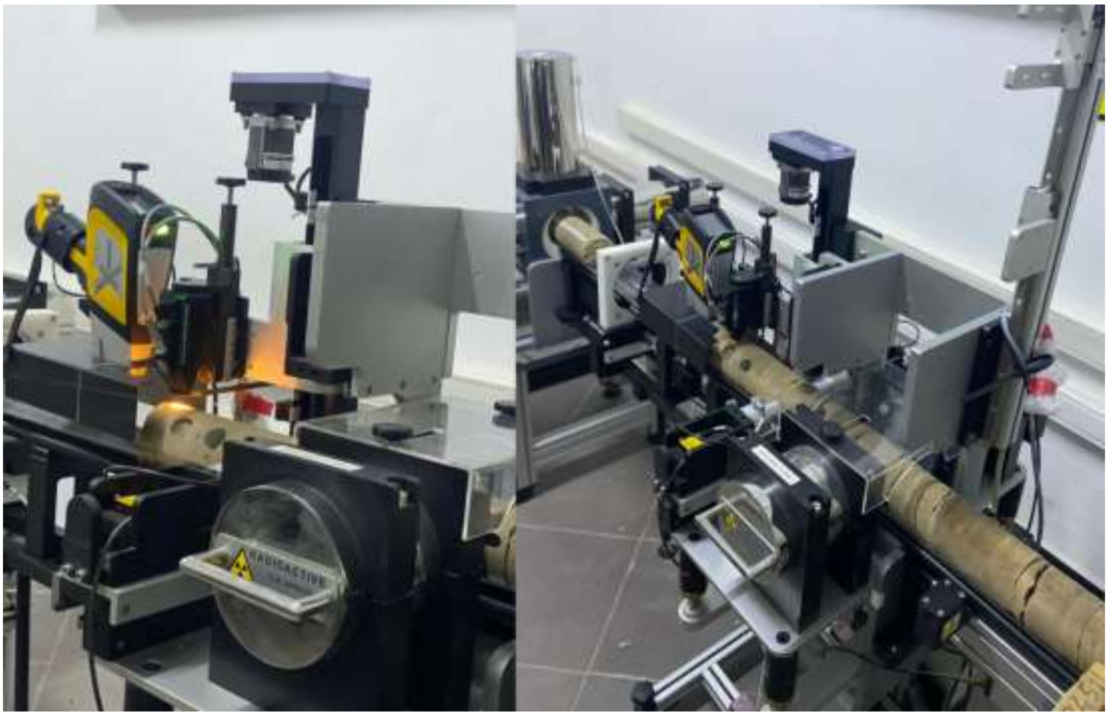

Fig 6: **Multi-Sensor core logger (MSCL-S)**