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Présenté Par :

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-THÈME-

Experimental study of hydraulic fracturing fluid effect on proppant permeability

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Dedication

*Almighty **Allah** thank you for always being with me,*

In the name of love of obedience and respect, I am dedicating this thesis to two beloved people who have meant and continue to mean so much to me. Although they are no longer of this world, their memories continue to regulate my life. Uncle **KADER** & aunt **DJAHIDA**, may god have mercy on you.

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Dedication

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Abstract:

During hydraulic fracturing treatment, huge quantities of gel and Proppant are pumped into the formation. The fracture dimensionless conductivity (FCD) is a key parameter to optimize the hydraulic fracturing, to estimate the productivity index (PI) and the Folds of Increase (FOI). However, these parameters are affected by the closure pressure and gel residues which decrease the fracture conductivity. In this work some laboratory tests were proposed for gel viscosity measurement under bottom-hole conditions where the parameters temperature and fracturing fluid were investigated. A huge drop in the fracturing fluid viscosity was observed, varied between 74% to 77%, at a varied temperature of 85°C and 110ºC. The results show that the gel was not broken, taking into consideration that the Hassi Messaoud reservoirs are under-pressurized which leads to a low retained fracture permeability that will affect the FCD and, as results, the PI due to the insufficient energy that needed for a better cleanup of the fracture.

Keywords: Hydraulic fracturing, FCD, cleanup, Proppant conductivity, Viscosity.

Résumé :

Pendant le traitement de fracturation hydraulique, d'énormes quantités de gel et de Proppant sont pompés dans la formation. La conductivité adimensionnelle de la fracture (FCD) est un paramètre clé pour optimiser la fracturation hydraulique, pour estimer l'indice de productivité (IP) et Folds of Increase (FOI). Cependant, ces paramètres sont affectés par la pression de fermeture et les résidus de gel qui diminuent la conductivité de la fracture. Dans ce travail, des essais en laboratoire ont été proposés pour la mesure de la viscosité du gel dans des conditions de fond où les paramètres de température et de liquide de fracturation ont été étudiés. Une diminution importante de la viscosité du fluide de fracturation a été observée, variant entre 74 % et 77 %, à une température variable de 85 °C et 110 °C. Les résultats montrent que le gel n'a pas été brisé, en tenant compte du fait que les réservoirs de Hassi Messaoud sont sous-pressurisé qui mène à une faible perméabilité retenue de la fracture qui affectera le FCD et, par conséquent, l'IP en raison de l'énergie insuffisante qui nécessaire pour un meilleur nettoyage de la fracture.

Mots-clés : Fracturation hydraulique, FCD, nettoyage, Conductivité proppant, Viscosité.

ملخص:

أثناء علاج التكسير الهيدروليكي، يتم ضخ كميات هائلة من السوائل و المواد الداعمة داخل المكمن. يعتبرعامل النفاذية (FCD) مفتاحا رئيسيا لتحسين التكسير الهيدروليكي، لتقدير مؤشر الإنتاجية (PI) وثنايا الزيادة .(FOI) ومع ذلك، تتأثر هذه العوامل بضغط الطبقات الجيولوجية و السائل المتبقي في الطبقة التي تقلل من النفاذية. في هذا العمل، تم اقتراح بعض الاختبارات المخبرية لقياس لزوجة السائل في ظل ظروف الثقب السفلي حيث تم فحص درجة حرارة وسائل التكسير. لوحظ انخفاض كبير في لزوجة سائل التكسير، وتراوحت بين 74٪ إلى 77٪، عند درجة حرارة مختلفة تبلغ 85 درجة مئوية و 110 درجة مئوية .تظهر النتائج أن السائل لم يتم كسره، مع الأخذ في الاعتبار أن آبار حاسي مسعود تعاني من نقص الضغط مما يؤدي إلى إنخفاض عامل النفاذية والتي ستؤثر على FCD، وكنتائج، على IP بسبب عدم كفاية الطاقة اللازمة لتنظيف الكسر بشكل أفضل.

الكلمات الرئيسية: التكسير الهيدروليكي، FCD، التنظيف، التوصيل، اللزوجة.

List of abbreviations

API: American Petroleum Institute.

$CaCO_3$: Calcium Carbonates.

$BaSO_4$: Barium Sulphates.

NaCl: Sodium Chloride.

L_f: Fracture Length.

W_f: Fracture Width.

H_f: Fracture Height.

FCD: Fracture Conductivity Dimensionless.

KGD: Kristianovich-Geertsma-de Klerk.

PKN: Perkins-Kern-Nordgren.

r_f: Fracture Radius.

ISIP: Instantaneous Shut-In Pressure.

VES: Visco Elastic Surfactant.

KCl: Potassium Chloride.

pH: Potential Hydrogen.

K: Consistency Index.

n: Shear Rate.

API RP: American Petroleum Institute Recommended Practices.

Kf: Permeability of the fracture.

K: Formation permeability.

FOI: Folds of Increase.

SPE: Society of Petroleum Engineers.

HPG: HydroxyPropyl Guar.

SEM: Scanning Electron Microscope.

Rms: Root Mean Square.

BA: Boric Acid.

NAOH: Sodium Hydroxide.

Zr-KG: Zirconium Crosslinker Gum Karaya.

EM: Elastic Contact Model.

EPM: Elastic-Plastic contact model.

MG-3: Medium Granite.

FS-3: Fine Sandstone.

MS-3: Medium Sandstone.

RSD: Relative Standard Deviation.

BJSP : Byron Jackson Service aux puits.

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Chapter I: Hydraulic fracturing fundamentals

Chapter III: Experimental study on hydraulic fracturing fluid effect on proppant permeability.

General Introduction

The natural exploitation of an oilfield is to bring the hydrocarbons to the surface under favorable conditions, by its natural depletion. Once this energy decrease, this leads to a reduction in permeability and productivity of the well. for which the reserves in place are significant, new recovery techniques have been revealed in order to improve the potential as well as the characteristics of the wells.

Among the most frequently used techniques, the stimulation which open up new channels in the rock for the oil and gas to flow through. their main objective is to increase the productivity of a well, bypassing the damage near the wellbore by creating high conductivity path in the formation.

Three stimulation treatments are commonly used: explosives to break up the rock, injection of acid to partially dissolve the rock, and hydraulic fracturing to split the rock and prop it open with proppants, The treatment with hydraulic fracturing is applied generally in low permeability reservoirs of origin or in the heavily damaged formations where the production is still low, so the primary goal is to increase the productivity by creating a highly conductive flow path of the reservoir, which will have a permeability substantially greater than that of the matrix for the first case and go over the damage in the second case.

Hydraulic fracturing consists to inject a viscous fluid with high pressure to crack the reservoir rock, and it is often accompanied by solid (propping agents) to keep the fracture open so that the fluid can flow more easily between the reservoir and the well.

The conductivity of the proppant pack is one of the parameters the bottom conditions (viscosity, temperature, stress, fluid, etc.) influence this parameter. How do these factors affect conductivity? How can this parameter be improved?

The aim of this work is to study the factors affecting the conductivity of the proppant pack in the laboratory by simulating the reservoir conditions and studying the viscosity. A field application consisting of a well was presented. This final brief consists of two parts:

- The theoretical part contains two chapters:

- The first chapter provides general hydraulic fracturing fundamentals.
- The second chapter provides a presentation on the gel viscosity with a focus on API tests and a literature review of previous experiments.

➢ The practical part is dedicated to the realization of the experiments of viscosity measurement of Proppant Pack in the laboratory by simulating the conditions of reservoir and application at wellsite.

I. Chapter I. Hydraulic fracturing fundamentals

I.1. Introduction

Formation damage has become a well-known problem in the oil and gas industry, the main reason that many oil, gas, and water injection wells have low productivity or injectivity. Caused by many factors (Scales, swelling clays, water block ….) and may occur from drilling to any time during the life of a well, which requires a matrix treatment by stimulation.

Reservoir stimulation is one of the main activities of the reservoir and production engineering in the petroleum and related industries, it plays a vital role in oil and gas production, considered as a general term describing a variety of operations (mechanical or chemical treatment) performed on a reservoir to restore or to improve the flow capacity to the well. it can take a number of methods, depending on the mechanism by which initial productivity was reduced and on commercial and operational factors for each well. but the objective in every case is to improve the productivity (flow rate) of the well.

Hydraulic fracturing is one of stimulation methods, which consist to inject a viscous fluid into the fracture at high pressure to create a high conductivity path and increase well productivity from the reservoir to the wellbore by: **Acid fracturing, or Propped fracture.**

I.2. History of hydraulic fracturing

In the 1940s, Floyd Farris of Stanolind Oil proposed that fracturing a rock formation through hydraulic pressure might increase well productivity.

Figure I. 1: Kelpper No.1 First Hydraulic Fracturing Operations (1947). [1]

This was followed in 1947 by the first hydraulic fracturing treatment where was pumped on a gas well operated by Pan American Petroleum Corp. in the Hugoton field. Kelpper Well No. 1, located in Grant County, Kansas, was a low-productivity well, even though it had been acidized. The well was chosen for the first hydraulic fracture stimulation treatment so that hydraulic fracturing could be compared directly with acidizing. **[1]** Since that first treatment in 1947, hydraulic fracturing has become a common treatment for stimulating the productivity of oil and gas wells.

I.3. Formation damage

Formation damage occurs almost in every field operation. It is an adverse and complicated phenomenon caused by particle invasion, formation fines migration, chemical precipitation, organic deposition, and pore deformation or collapse. The production performance of a well is strongly affected by the magnitude of damage in the near-wellbore formations. Searching for methods to reduce the cost of formation damage is of continuing interest to the petroleum industry. **[2]**

Formation damage near wellbore can be determined by well testing techniques. However, these techniques can only provide the skin factor as an overall measure of formation damage, but they do not reveal any insight into the temporal and spatial development and causes of the damage for the assessment and control of formation damage. **[3]**

$$S = \frac{k - k_a}{k_a} \ln \frac{r_a}{r_w} \qquad I.\ 1$$

K: Reservoir permeability — ra: Damaged radius

Ka: Damaged permeability — rw: Well radius

Below are the main types of formation damage:

I.3.1. Scale Deposits

Scales are inorganic (mineral) deposits typically in the wellbore and in the perforation, caused by changes in thermodynamic conditions (Pressure & temperature), and formation of incompatible waters mixed (injected and formation water), for example ($CaCO_3$, $BaSO_4$, Silica scale, NaCl….). **[4]**

Figure I. 2: Calcium carbonates (CaCO3) scale [4].

I.3.2. Organic Deposits

I.3.2.1. Asphaltenes

Organic materials consisting of aromatic ring containing nitrogen, oxygen and sulfur molecules, it occurs during production because of decrease in pressure and temperature. **[4]**

Figure I. 3: An example of an asphaltenes [4].

I.3.2.2. Paraffins

Paraffins are normal straight chain alkanes; carbon chain length associated with formation of solid, paraffins deposits have a minimum of 16 carbon atoms per molecule, it occurs during production when fluid temperature goes below cloud point. **[4]**

Figure I. 4: An example of a paraffins [4].

I.3.3. Emulsion

Emulsions are combinations of two or more immiscible fluids. It comes from fluids used in well operation mixed with reservoir fluids (for example oil or brine). Divided into two types: Direct emulsion (Water-outside) and Inverse emulsion (Oil-outside). **[5]**

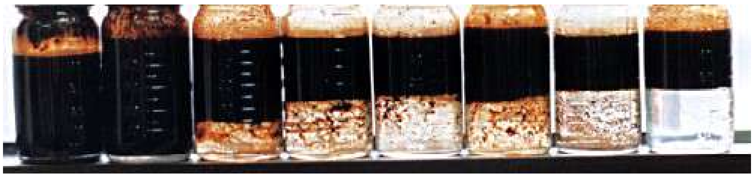

Figure I. 5: Emulsions with Crude Oil and Completion Fluids [5].

I.3.4. Water Block

Water block is a reduction in effective or relative permeability to oil due to increased water saturation in the near wellbore region, characterized by an abnormally high water-cut. **[6]**

I.3.5. Wettability Changes

Wettability change occurs when rocks that are normally wet with water become wet with oil, it may be a result of using surfactant (surface active materials) in drilling fluid, workover fluid or any treating fluids. **[6]**

I.3.6. Swelling Clays

Swelling clays is an inherent problem in sandstone that contains water-sensitive clays. When a fresh-water filtrate invades the reservoir rock, it will cause the clay and thus reduce or totally block the throat area. Carbonate formations are seldom clay-bearing, when clays are present, they are incorporated in the matrix. The most common swelling clays are smectite and pyrite. **[7]**

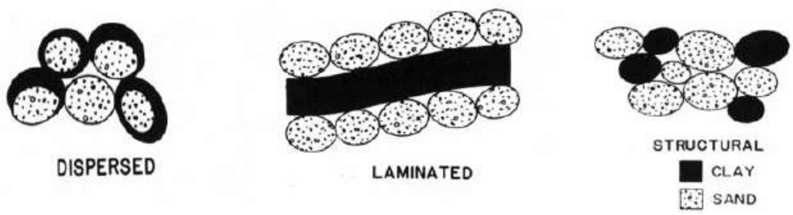

Figure I. 6: Clays forms [7].

I.3.7. Fines Migration

Fine migration is the movement of formation particles in the produced fluids. These particles can bridge across pore throats, reducing flow capacity and well productivity. Kaolinite and illite are a most common migrating clay. **[7]**

Figure I. 7: Kaolinite and illite (fine migration) [7].

I.3.8. Bacteria

The formation can also be damaged by the colony of bacteria and their precipitated products, blocking the pore channels. Bacterial formation damage can occur both with and without oxygen present. Bacterial agents into the formation during drilling and the subsequent generation of slimes which reduce permeability. **[5]**

Figure I. 8: Oilfield microbial bacteria [5].

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I.4. Objectives of hydraulic fracturing

In general, hydraulic fracture treatments are used to increase the productivity index of a producing well or the injectivity index of an injection well. The productivity or the injectivity index defines the rate at which oil or gas can be produced or injected at a given pressure differential between the reservoir and the wellbore. **[8]**

$$IP = \frac{Q}{P_r - P_w} \quad \textit{I. 2}$$

IP: Productivity index Q: Flow rate

P_r: Reservoir pressure P_w: Wellbore pressure

There are many objectives for hydraulic fracturing, which can:

- Increase the flow rate of oil and/or gas from low-permeability reservoirs.
- Increase the flow rate of oil and/or gas from wells that have been damaged.
- Connect the natural fractures and/or cleats in a formation to the wellbore.
- Decrease the pressure drop around the well to minimize sand production.
- Enhance gravel-packing sand placement.
- Decrease the pressure drop around the well to minimize problems with asphaltene and/or paraffin deposition.
- Increase the area of drainage or the amount of formation in contact with the wellbore.
- Connect the full vertical extent of a reservoir to a slanted or horizontal well.

I.5. Rock mechanics

Rock mechanics is a vital decision-making tool for insuring economic benefits in all phases of petroleum reservoir development. Petroleum Rock Mechanics introduces the fundamentals of solid mechanics and applies them to oil and gas. Mechanical behavior of elastic materials is modeled by three main independent constants; Young's modulus and Poisson's ratio and in-situ stresses. An accurate measurement of both constants is necessary in most engineering applications. **[9]**

I.5.1. Young modulus

When a body's motion is constrained in space while a force is applied to it a deformation will occur. Young´s modulus is defined as a measurement of stress over the stain or only as a slope of a line on a stress versus strain plot. **[10]**

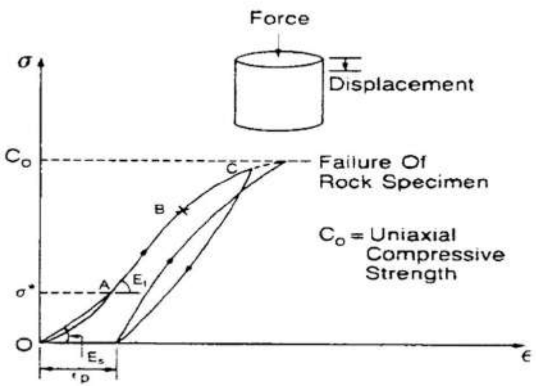

Figure I. 9: Graph of stress and deformation (Young Modulus) [10].

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In hydraulic fracturing it can also be referred to as the amount of pressure needed to deform the rock. Young´s modulus measures rock stiffness, and greater it is, harder the rock.

I.5.2. Poisson's ratio

Poisson´s ratio measures how much a material will deform in a direction perpendicular to the direction of the applied force. It is another measure of rock strength that is crucial rock property related to closure stress. **[9]**

$$v = -\frac{\varepsilon_2}{\varepsilon_1} \qquad \textbf{\textit{I. 3}}$$

$$\varepsilon_1 = \frac{(L_1 - L_2)}{L_1} \qquad \textbf{\textit{I. 4}}$$

$$\varepsilon_2 = \frac{(D_1 - D_2)}{D_1} \qquad \textbf{\textit{I. 5}}$$

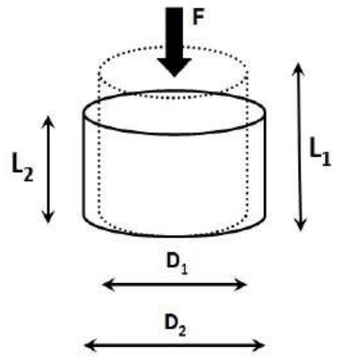

Figure I. 10: Poisson's ratio formula [9].

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The typical values of the dimensionless Poisson´s ratio is in the range between 0.1 and 0.45, The core sample is the best way to measure Poisson´s ratio even though the sonic log is also used.

I.5.3. The main stresses of massive rocks

There are three principal stresses that characterize in-situ stress. They are the stresses within the formation, which serve as a load on the formation and are oriented perpendicular to each other. They impose the size and orientation of a fracture, In-situ stresses the collective forces activating on the rock while the rock is in place below the earth's surface. **[9]** it is the most important parameter controlling hydraulic fracture parameters which affects the following parameters:

- ✓ Orientation
- ✓ Width and height of the fracture
- ✓ Pressure of Treatment
- ✓ Crash of the proppant and embedment

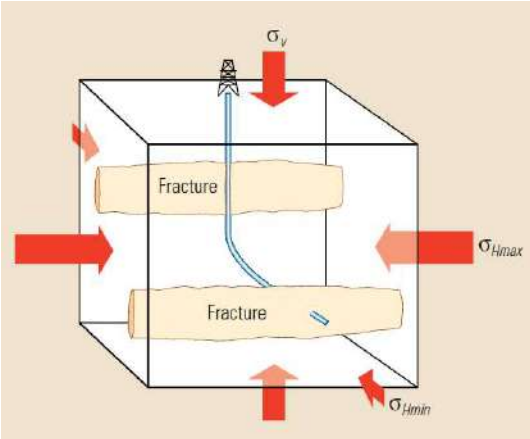

Figure I. 11: In-situ stresses and hydraulic fracture propagation [6].

Three unequal mutually perpendicular stresses:

- **Vertical (overburden), s_v:** Stress parallel to wellbore axis due to overburden load.

- **Horizontal stresses:** Perpendicular to the overburden stress at the right angles of each other. **(Maximum horizontal stress, s_1, Least horizontal stress s_2). [6]**

I.6. Fracture geometry

Having a detailed knowledge of the distribution of petrophysical properties is vital to pinpoint the initiation of hydraulic fractures, and to figure out the progression of fracture geometry configuration. **[5]** Description of a fracture:

- Length ($2X_f$ or L_F)
- Width (W_f)
- Height of fracture (H_f)
- Fracture conductivity FCD

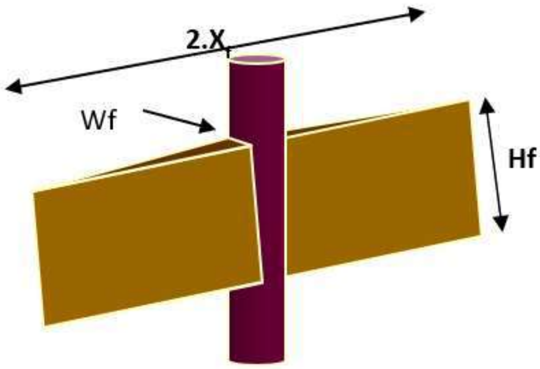

Figure I. 12: Schematic of a fracture geometry [5].

I.7. Fracturing modelling

Prediction of fracture geometry is central issue in engineering design and evaluation **[5],** Models determine fracture geometry by relating to variables:

- Rock properties
- Fluid properties
- Fluid volume pumped
- Stress data

2D Fracture Propagation Model

I.7.1. KGD: Kristianovich-Geertsma-de Klerk

The KGD model assumes a fixed fracture height and width is proportional to fracture length **(**XL < h).

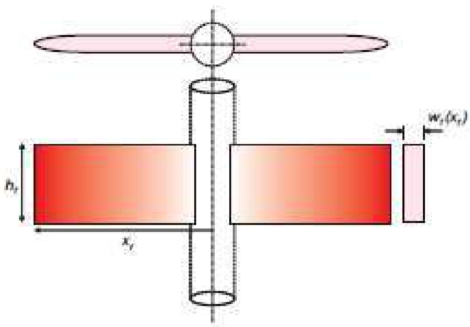

Figure I. 13: KGD fracture geometry [9].

Also, it is assumed that width is constant in the vertical direction and rock stiffness is only considered in horizontal plane. **Figure I. 13** show the fracture geometry in the KGD model. **[9]**

I.7.2. PKN: Perkins-Kern-Nordgren

Like the previous model, height is again assumed to be constant. However, unlike the previous one, the width is proportional to fracture height (XL > h). **[9]**

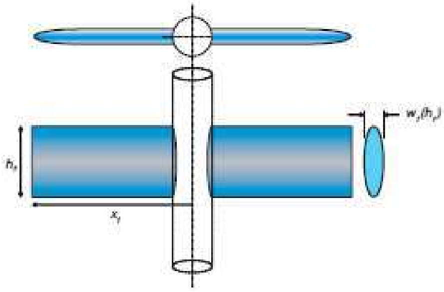

Figure I. 14:PKN fracture geometry [9].

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Also, here we have an elliptical cross-section in a vertical direction. The PKN model assumes a fracture height that is much smaller than the fracture length (opposite of KGD model) which is shown in **Figure I. 14.**

I.7.3. Radial

There are various radial models that have been developed, but in all of them it is assumed that the height of fracture (hf) is directly related to fracture length (xf) **(**XL = h/2). It is used in shallow formations where overburden stress is equal to minimum horizontal stress. **[9]**

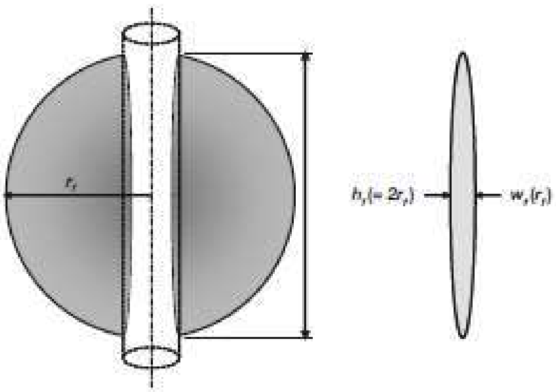

Figure I. 15: Radial fracture geometry [9].

In this model, a fluid pressure within the fracture and the injection rate are assumed to be constant. Also, the fracture width (wf) is proportional to fracture radius (rf) as shown in **Figure I. 15.**

I.8. Hydraulic fracturing procedures

I.8.1. Calibration test

The calibration test is Pump-in/Decline test depending on the operator, service company or injected volume. It is designed to be as close as possible to the actual fracking treatment, but without using any proppant. Thus, should be pumped with the treatment fluid, at the rate expected for the main treatment, and it should have enough volume to contact all the formations, it will provide data on rock mechanical properties, fracture geometry and fluid leak off, which are crucial for conducting the main treatment. **[11]**

First, the well needs to be filled with water, with special care to remove any remaining gas and air. Then, a typical Minifrac sequence follows as shown in **Figure I. 16:**

1. A surface pump establishes a constant injection rate during which pressure on formation rises.

2. After some time, formation breakdown pressure is reached, indicating that a hydraulic fracture is being propagated into the formation.

3. Injection of treatment fluid continues, and wellhead pressure is stabilized or changes slightly.

4. After reaching desired volume, surface injection is stopped, which results in instantaneous shut-in pressure (ISIP).

5. The pressure decline is then monitored for signs of fracture closure pressure.

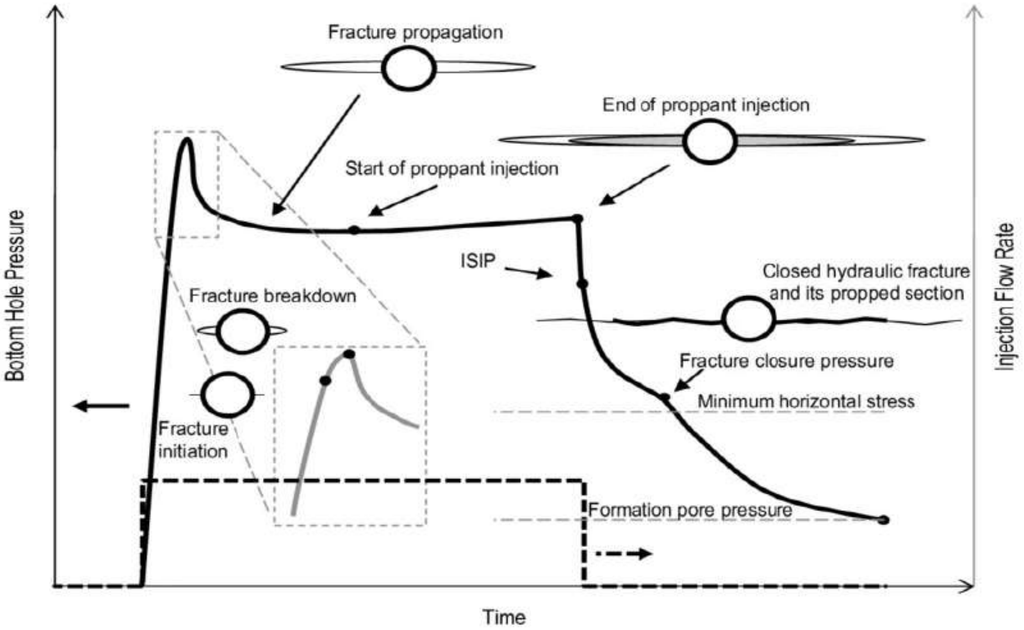

Figure I. 16: Idealized schematic of fracture pressure variation during a MiniFrac test [11].

MiniFrac is a small fracture treatment, without proppant, pumped into a well to determine:

- Fracture breakdown pressure
- Fracture extension pressure
- Fluid loss coefficient
- Frac fluid efficiency
- Fracture closure time

I.8.2. MainFrac

I.8.2.1. Pre-Pad

It is the first fluid pumped into a well during a fracture treatment, which is used to fill the casing and tubing, test the system for pressure, and break down the formation cool the tubulars and the formation. **[12]**

I.8.2.2. Pad

In order to initiate fracture creation, a fluid stage is known as the pad (which is a combination of only water and chemicals) is pumped first. The pad will create fracture length, height and width before going with the proppant stage. It is strongly believed that if not enough pad volume is pumped, then when the proppant reaches the fracture tip, the fractures will be filled and a sand-off (screen-out) will occur. Nevertheless, if too much pad volume is pumped, after pumping the proppant, a vast unpropped region will remain. **[9]**

Figure I. 17: A crosslinked gel (PAD) [5].

I.8.2.3. Slurry

When the pad volume is pumped, the proppant stage starts. In this stage a combination of water, chemicals and proppant (slurry) is pumped downhole. Depending on the fluid system used for fracturing, the primary mechanism for placing proppant in the formations is either pump rate or viscosity of the fluid. Either way, the proppant stage starts with small concentrations of proppant and gradually increases to higher ones. **[9]**

Figure I. 18: A Propped gel (Slurry) [9].

I.8.2.4. Flush

After pumping the designed proppant stage, the proppant is cut, and the well is flushed. The purpose of flushing is to clear the inside of tubing of sand and to move/flush all the remaining proppant into the formation. For flushing only water and chemicals are used. The casing grade, weight, and bottom perforation depth are needed to calculate the desired flush volume. **[9]**

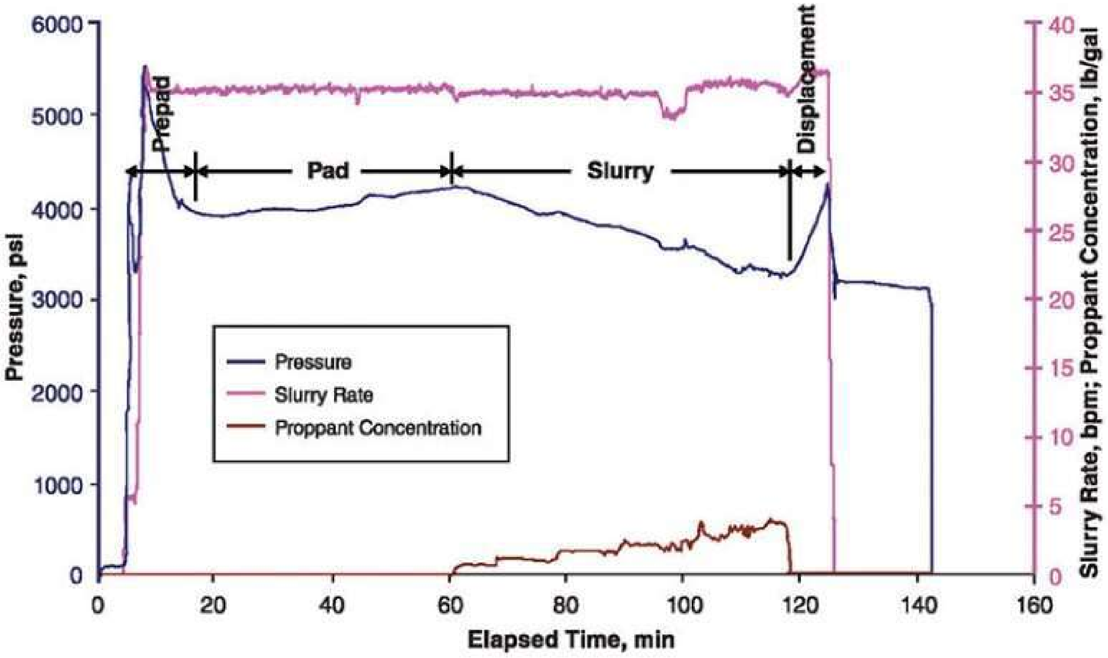

Figure I. 19: A typical fracturing chart illustrates the steps to hydraulically fracture a well [13].

I.9. Fracturing fluids

Fracturing fluids are different-based fluids with a small number of additives or chemicals (generally less than 1% volume of the fracturing fluid) that are used to treat the subsurface formation to stimulate the flow of oil or gas. **[13]**

The fracturing fluid is composed of 99.5% of water and sand, the remaining 0.5% is made up of additives.

I.9.1. The Objectives

The functions of Fracturing fluid are:

- Initiate and propagate the fracture
- Developpe fracture width
- Transport proppant throughout the length of the fracture

The fracturing fluid will be chosen according to several criteria such as: availability, security. **[14]**

I.9.2. Characterizations of fracturing fluids

1. Compatible with formation rock and formation fluids to avoid formation damage
2. Adequate viscosity Required to transport proppant
3. Good fluid loss control: low leak off rate
4. Easy to recover during flowback
5. low friction pressure drop to reduce the surface pressure treatment
6. Stable at Reservoir condition
7. Safe and easy to prepare and make and break
8. Economical / low cost
9. Non-toxic **[15]**

I.9.3. Types of Fracturing fluids

- Oil-base Fluids
- Water base fluids
- VES: Visco Elastic Surfactant
- Foam based fluids **[16]**

I.10. Proppant

Propping agents are required to « prop open » a created fracture to increase flow capacity. **[18]**

I.10.1. Ideal Properties of proppant

- High strength
- Corrosion resistant
- Low specific gravity
- Readily available at low cost

I.10.2. Types of proppant

- Sand
- Resin Coated
- Ceramic

I.10.3. Proppant Size

- 12/20
- 16/30
- 20/40
- 30/50
- 40/70

Figure I. 20: Different fracturing proppant size [18].

I.11. Additives

Fluid additives are materials used to produce a specific effect independent of the fluid type. **[17]**

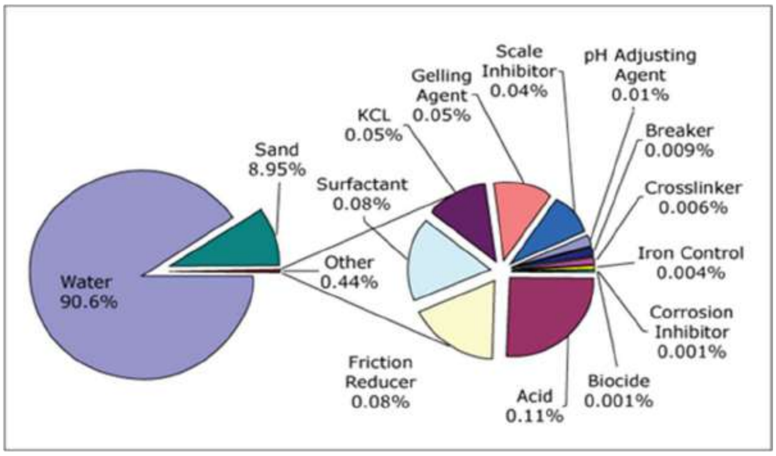

Figure I. 21: Volumetric composition of a fracturing fluids [17].

The additives are represented in the below table with their functions:

Table I. 1: Additives functions [17].

Additive	**Function**
Clay stabilizer (KCl…)	Avoid clay swelling
Surfactant	Lower surface tension

Gelling Agent	Help carry proppants into the fracture
Scale inhibitor	Avoid scales
Crosslinker	Increase viscosity
Corrosion inhibitor	Avoid tools corrosion
Acid	Dissolve minerals
Biocide	Kill bacteria
Breaker	Reduce fluid viscosity
Buffer	Control the pH
Friction reducer	Reduce the frictions
Iron controller	Prevent Iron dissolving in Acid

I.12. Hydraulic fracturing equipment

Hydraulic fracturing is a stimulation method which consist to inject a viscous fluid with proppant into the formation using different equipment. **[14]**

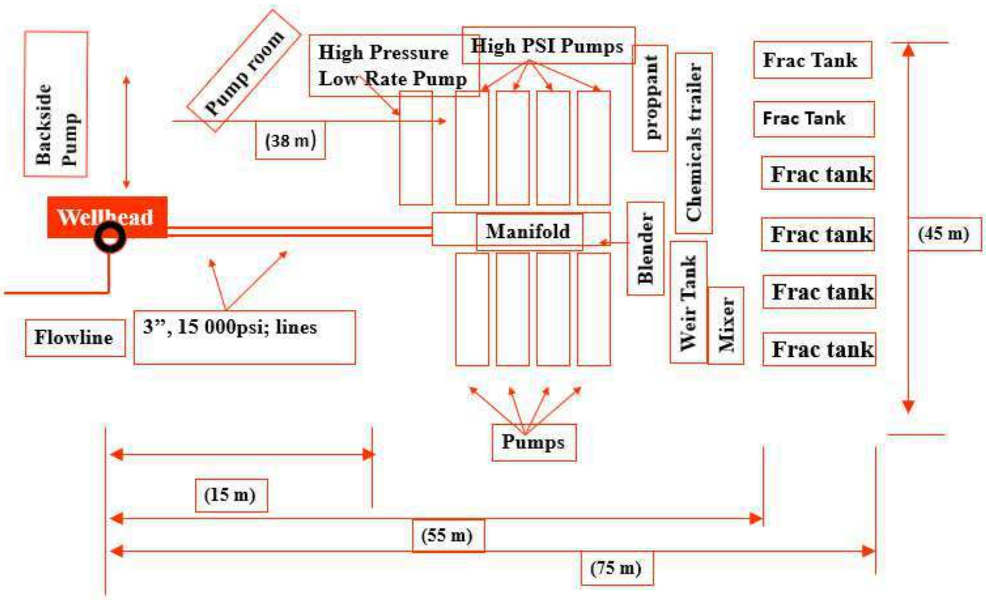

Figure I. 22: Frac equipment placement planning [14].

I.12.1. Frac tanks

A frac tank is a large capacity steel tank that can store water during the hydraulic fracturing operation.

Figure I. 23: Frac tanks.

I.12.2. Hydration unit

The Hydration Unit is a truck, trailer ore skid mounted unit for the purpose of mixing fracturing fluids with chemicals, Large flowrate with high quality fluid: self-developed mixer and mixing system can mix the gel powder and water, concentrated solution and water efficiently.

Figure I. 24: Hydration unit.

I.12.3. Blender

Manual, semiautomatic and fully automatic process control of proppant, liquid and dry additives from the Control Vehicle.

Figure I. 25: Blender.

I.12.4. Proppant transport

The proppant transport is a track to store the different proppant size at the well site

Figure I. 26: Proppant transport.

I.12.5. Manifolds

A frac manifold is an arrangement of flow fittings and valves installed downstream of the fracturing pump output header and upstream of each frac tree being served.

Figure I. 27: Frac manifold.

I.12.6. Pumps

Frac pumps are reciprocating positive-displacement pumps that contain a fluid end and a power end. It endures all types of stress including harsh fluids and high-pressure activity. The purpose of a frac pump is to push sand-laden fluid into a well bore's perforation, which enables you to fracture a formation.

Figure I. 28: Frac pump.

I.12.7. Control unit

These control unit as "**mobile control rooms**", monitoring important equipment such as fracturing fluid blenders, chemical vans, pump engines, and various others. Collecting and monitoring process data from this equipment allows operators in the data van to control functions throughout all stages of the fracking process.

Figure I. 29: Control unit [14].

I.12.8. Backside Pump

This pump is used for balancing the annular and tubing pressures to prevent tubing burst and collapse.

Figure I. 30: Backside pump.

I.13. Conclusion

Hydraulic fracturing has a very important procedures, and their objective is to bypass restriction damage, including tests. MiniFrac is the principle one which gives the important rock and fracture properties to choose the compatible formation fluids, after performing the MiniFrac test, getting a new data which allow to reset the design and execute the main job. proppant selection and design are the key to successful stimulation treatments, which need a planning of equipment desired to run the job correctly.

Fracking is essential for the production of natural gas and oil from shale formations, and with advances in fracking technology, it is becoming easier and more accessible to access natural gas. **[19]**

II. Chapter II. Parameters affecting the proppant conductivity

II.1. Introduction

The fluid viscosity is the major fluid related parameter for fracture design. However, how much viscosity needed is often overestimated. Excessive viscosity increases costs, raises treating pressure which may cause undesired height growth, and can reduce fracture conductivity since many of the chemicals used to increase viscosity leave residue which damages the proppant permeability.

When fracturing, viscosity plays a major role in providing sufficient fracture width to insure proppant entrance into the fracture, carrying the proppant from the wellbore to the fracture tip, generating a desired net pressure to control height growth and providing fluid loss control. The fluid used to generate the desired viscosity must be safe to handle, non-damaging to the fracture conductivity and to the reservoir permeability, easy to mix, and able to control fluid loss. This is a very demanding list of requirements that has been recognized since the beginning of Hydraulic fracturing. **[13]**

II.2. Fracturing Fluid Rheology

Fracturing fluids are complex, non-Newtonian fluids, which their properties are very difficult to quantify and affected by shear rate, shear history, minor additive concentrations, proppant types, temperature, mix water chemistry, age of chemicals, and many other factors.

To design a successful hydraulic fracturing treatment employing crosslinked gels, accurate measurements of the rheologic properties of these fluids are required. Rheologic characterization of borate crosslinked gels turned out to be difficult with a rotational viscometer. In a laboratory apparatus, field pumping condition and fluid flow down tubing or casing and in the fracture could be simulated (Shah et al., 1988). The effects of the pH and temperature of the fluid and the type and concentration of the gelling agent on the rheologic properties of fluids have been measured.

These parameters have significant effect on the final viscosity of the gel in the fracture. Providing correlations to estimate friction pressures in field size tubulars will be developed from laboratory test data. In conjunction with field calibrations, these correlations can aid in accurate prediction of the friction pressure of borate crosslinked fluids. **[13]**

Fracturing fluid rheology data are usually determined under laminar flow conditions in a rotational concentric cylinder viscometer. Reported in terms of the power law parameters n and k. K is dependent on the flow geometry for concentric cylinder devices and is referred to as the viscometer consistency index K. for a power law fluid the shear rate depends on the value of n in addition to the flow rate and conduit dimension. A fracturing fluid will have considerably different value of μ_a. Depending on the shear that is exerted on the fluid.

$$\tau = K \quad and \quad \mu_a = K \times \gamma^{(n-1)} \qquad \textbf{II.1}$$

Where K is the consistency index in lbf^n/ft^2 or $kPa\text{-}s^n$ and n is the flow behavior index (dimensionless). **[21]**

II.2.1. Fracturing Fluid Viscosity

Viscosity is a measure of how much a fluid resists deformation as a result of an applied force or pressure. It is a measure of how "thick" the fluid is.

Viscosity, μ, is the fluid property that defines how much shear stress is produce by shear rate. Is called viscosity. The greater the viscosity the greater the resistance of a fluid to shear agitation.

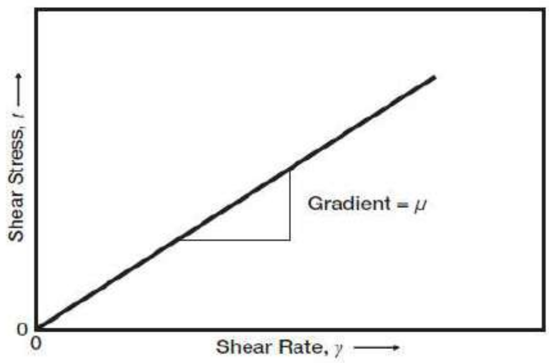

Figure II. 1: Relation between shear rate and shear stress for a fluid [15].

The fluid that is used to pump down the well to accomplish the high pressure frack is mixed with proppant on the surface before going to the high-pressure pumping system. The fluid has to be able to hold the proppant in solution until it gets to the perforations down hole in the well where it goes out into the formation. Proppants form a thin layer between the fracture faces to keep the fractures open at the end of the fracturing process. Without proppants, the fractures will close after the pumping of fracturing fluids under high pressure is ceased, resulting in minimal or no gain of hydrocarbon productivity. Usually, viscous hydraulic fracturing fluids are required to ensure proper proppant transport and the even distribution of proppant along the fractures. **[15]**

The need for a precise value of viscosity is also over engineered. This can be seen from the basic equations where treating pressure, and thus fracture width. Therefore, getting the viscosity of the fluid/proppant mix to the right point is critical to ensure that the important function of fracturing fluid to carry and transport proppants into the fracture is achieved.

Fracturing fluids have predominantly non- Newtonian behavior. This means that the apparent viscosity of the fluid is dependent on the shear that the fluid is experiencing at a specific point. **[21]**

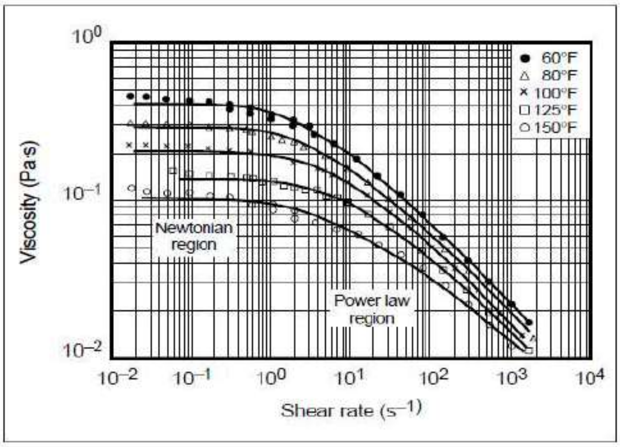

Figure II. 2: The apparent viscosity of a simple Fracturing fluid over a wide range of shear [15].

II.2.2. Shear stress & Shear rate

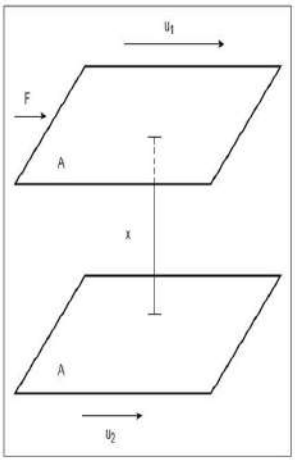

Figure II. 3: A plan to define a shear rate and shear stress by velocity [21].

II.2.2.1. Shear Rate, γ

In fluid mechanics, shear rate is a measure of how fast a fluid is flowing past a fixed surface. Shear rate can be thought of as a measure of how much agitation a fluid is receiving. **[21]**

$$\gamma = \frac{du}{dx} = \frac{u_{1-} u_2}{x} \qquad \text{II.2}$$

Causes of Shear Rate are:

- Spinning centrifugal pump
- Flow through a pipe
- Model 35 viscometer test
- Jet mixer
- Tank agitators

II.2.2.2. Shear Stress, τ

Shear stress is the resistance the fluid produces to an applied shear rate. For instance, it requires more force (or pressure) to pump water at 20 bpm than at 10 bpm.

$$\tau = \frac{F}{A} \qquad \text{II.3}$$

Viscosity is only very rarely a constant value, as it can change dramatically with temperature, applied shear stress and fluid composition. it is defined as the relationship between shear stress and shear rate. **[21]**

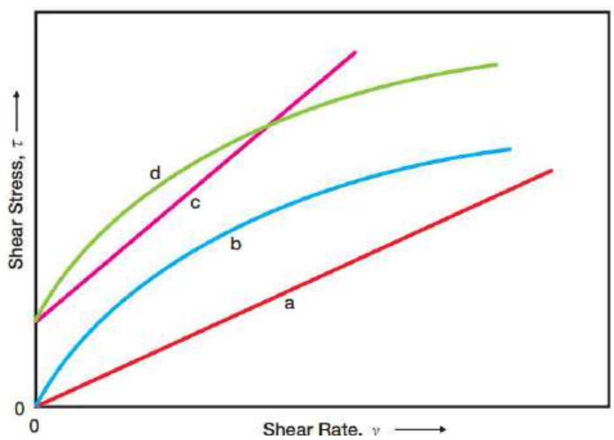

Figure II. 4: The relationship between shear rate and shear stress for a-Newtonian fluid, b-power law fluid (shear thinning), c-Binghalm plastic fluid and d-Herschel Buckley fluid [21].

Figure II. 4 Change in apparent viscosity for a power as can been seen, for a shear-thinning power law fluid, the apparent viscosity of the fluid (the slope of the two lines) decreases as the shear rate increases. At shear rate γ1, the slope of line 1, µ1, (and hence the apparent viscosity) is greater than the slope of line 2 at the greater shear rate γ2. Hence the fluid is said to be shear thinning. In practice, it is the apparent viscosity that is usually measured. The model 35 viscometer is set up so that at 300 rpm (with an R1 rotor, B1 bob and spring factor = 1), the apparatus reads apparent viscosity directly with no additional calculations required.

II.2.3. Rheology models

Figure II. 5 shows the models that are used by the oil industry and these are: **[44]**

II.2.3.1. Newtonian Fluid

The Newtonian fluid has a linear relation between shear rate and shear stress, and fluid viscosity is the slope of the shear rate versus shear rate data.

II.2.3.2. Bingham Plastic

The Bingham Plastic differs from a Newtonian fluid in that a non-zero shear stress called the Plastic Yield Value is required to initiate fluid flow. The slope of the shear rate/shear stress data is labeled plastic viscosity and this model is routinely used for cements and many drilling muds.

II.2.3.3. Power Law Fluid

This is the most common fluid model used for current fracturing fluids, and for this rheological model the shear stress/shear rate data give a linear relation on log-log scales. labeled the Consistency Index and is denoted by K'. For real fluids K' and n' change with temperature and time with K' generally decreasing and n' tending toward unity.

II.2.3.4. Herschel Bulkley

The Herschel–Bulkley model can be used to describe the rheological behavior of certain non-Newtonian fluids. When fitting to experimental data, its parameters need to be determined and this is a non-linear problem. The conventional approach is to solve the resulting normal equations numerically.

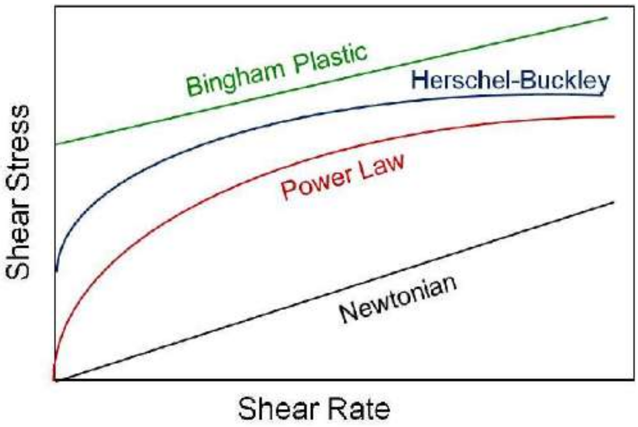

Figure II. 5: Rheology Models [44].

II.3. API RP 39 Viscosity

API RP 39 is a recommended Practices on Measuring the Viscous Properties of a Cross-Linked Water-Based Fracturing Fluid, it was created first with the 60th Edition on 1966, then second edition in January 1983, and the final edition in May 1998. **[22]**

These recommended practices were prepared by the API Subcommittee on Fracturing Fluid Rheology. These practices and procedures were compiled on the basis of several years of comparative testing, debate, discussion, and continued cross-linked fracturing fluid research in the industry concerning the factors that affect cross-linked fracture fluid behavior. The recommended practices contained are specifically for mixing and testing cross-linked water-based fracturing fluids. Recommended practices are given for two situations:

II.3.1. Laboratory Testing

Specified procedures for comparative testing and for cross-linked fracturing fluid research and development, where the work is conducted in a research laboratory. Data developed for use in hydraulic fracture propagation simulators should be measured using the recommended procedures for laboratory testing.

II.3.2. Field Testing

Also developed procedures for testing cross-linked water-based fracture fluids in the field. These procedures were developed to allow personnel to perform quality control of the base polymer solutions, and determination of cross-linked gel properties in field applications to verify the quality of treatment fluids before and during actual fracture treatments. The procedures have been developed only for quality control purposes.

This recommended practice is based on the knowledge and experience of petroleum refiners, valve manufacturers, and others, and its objective is to describe practices that will result in a purchaser's receipt of valves, which consistently meet API valve specifications. Any modifications, deletions, and amplifications necessary for individual users should be made by supplementing this recommended practice rather than by rewriting it. **[22]**

II.4. Viscosity Measurement

The standard method for measuring the viscosity of a fluid is to agitate it at a known shear rate, and then see how much force is produced on a fixed surface, positioned close to the source of agitation, with a thin layer of the test fluid between them. For a fixed rate of shear, the greater the force on the fixed surface, the greater the viscosity of the fluid.

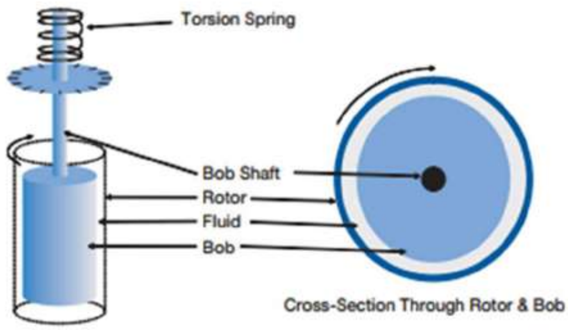

Figure II. 6: Diagrammatic illustration of the rotor and bob configuration used to measure viscosity [21].

Viscosity-measuring device. The device consists of a fixed solid cylinder (or “bob”) surrounded by a hollow cylinder, which is positioned concentrically to the bob. The cylinder (also referred to as the rotor) spins around the bob such that a fluid positioned between the rotor and the bob will produce a drag effect on the bob. The greater the viscosity of the fluid, the greater the drag force on the bob. The bob is connected, via a shaft, to a torsion spring and a measuring device. As the fluid produces drag on the bob/shaft assembly, it is allowed to deflect against the torsion spring, so that the greater the drag force, the more the shaft and bob assembly will deflect. The deflection is measured and displayed as viscosity. Because some fluids have viscosity that is not constant and will vary with shear rate, most viscometers allow the rotational speed of the rotor (and hence the shear rate) to be varied.

Viscometers based on this rotor and bob method are available in various configurations, including fully computer-controlled versions capable of testing fluids at high temperatures and high pressures. **[21]**

II.5. Factors affecting the proppant conductivity

The fracture conductivity is the product of propped fracture width and the permeability of the propping agent.

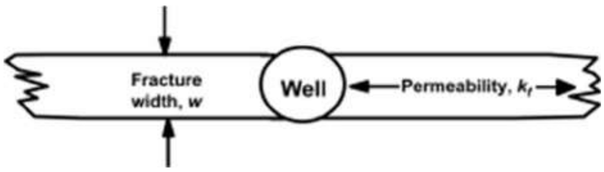

Figure II. 7: Definition of fracture conductivity [21].

as **Figure II. 7** illustrates the conductivity of the fracture will be reduced during the life of the well because of:

II.5.1. Increasing stress on the propping agents

The surface stresses are more uniform on well-rounded, spherical particles, they are capable of carrying higher loadings than a less-rounded particle.

II.5.2. Proppant crushing

At failure, most proppants crush to form particulates of some smaller size, but also must characterize proppants and their potential application by using such tests.

II.5.3. Proppant embedment into the formation

Proppants are used to maintain fracture width and enhance conductivity. If the formation is too soft, excessive proppant embedment may detrimentally reduce conductivity.

II.5.4. Damage resulting from gel residue

Traditional borate crosslink fluid system maintains good proppant suspension capacity, high resistance for shear stress and temperature. However, this type of fracturing fluid system can cause significant skin damage and decrease well productivity. Borate crosslinked fracturing fluids can damage both the formation and permeability of proppant pack. Insoluble gels residual of crosslinked fluids has been proven to have a regained conductivity of 10-12% less compared that without crosslinkers. However, the increase of breaker concentration can increase the regained conductivity. The negative effect of increase of breaker concentration can decrease proppant carrying capacity since crosslinker will be degraded faster. **[21]**

II.6. Effect of fracturing fluid on proppant conductivity FCD

Dimensionless fracture conductivity (F_{cd}) is defined as fracture conductivity, $k_f w$ (md-ft), divided by reservoir permeability (k) multiplied by the fracture half-length, x_f (ft). It provides a means of optimizing the amount of conductivity in a fracture for varying permeability and fracture length. **[20]**

$$Fcd = \frac{Kf \times Wf}{K \times Xf} \quad \textbf{II.4}$$

Kf: Permeability of the fracture.

K: Formation permeability.

Wf : Fracture Width.

Xf : Productive fracture length.

Conductivity varies with different proppants, and with proppant stress of the formation as seen in **Figure II. 8**. If F_{cd} calculated is very low, investigate increasing the concentration or using higher strength proppant, which would increase the F_{cd}. Conversely, if F_{cd} is very high, a weaker (cheaper) proppant might be investigated to see the effect on FOI.

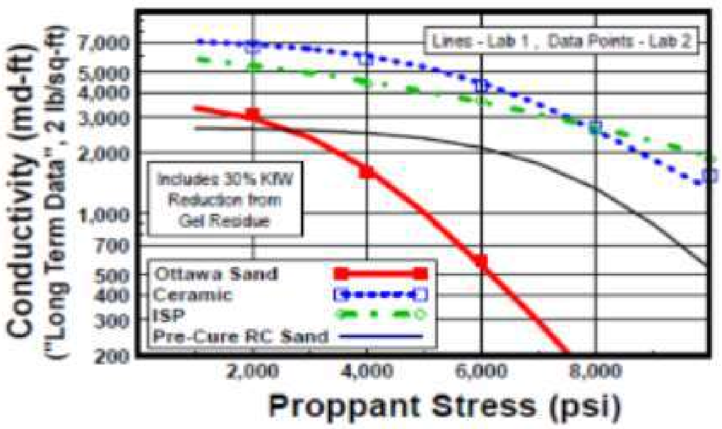

Figure II. 8: The Relationship between conductivity and proppant stress [21].

II.7. Literature review about the viscosity effect on proppant conductivity

In 1970 Richard Sinclair studied the new viscous fluid system and its application. He concluded with:

- Fluid mixtures containing highly viscous oil can be pumped at fracturing rates with tubular friction losses less than that obtained with water because of annular water ring lubrication and because of the slippage layer in the water-in-oil dispersion.
- Tubular friction losses can be predicted for pipe of any size. This prediction is based on reported data and on an analytical flow model of the new system. **[23]**

In 1973, C. E. Cooke introduced the conductivity of multilayer fracture proppant to determine the efficiency of fracturing treatment. The conductivity was affected by two factors. **[24]**

- First is the tank environment (of hot brine can reduce the permeability of brittle proppants under stress.
- The second is the deviation of Darcy flow, or turbulence.

In 1986, Pascal investigates a short communication about the effects of the non-Newtonian behavior of the fracturing fluids in the hydraulic fracturing mechanism, in which the fracturing fluid is of power law and of pseudo-plastic type. **[25]**

The results obtained demonstrate the theoretical evidence to support the field and laboratory observations showing that the rheological behavior on the mechanism of propagation of a vertical fracture is significant. These relevant results indicate that larger fracture lengths may be generated in formations of relative high permeability by using certain non-Newtonian fluids where the fluid losses in these formations may be minimized, and shows that the optimal policy of selecting the rheological properties of the fracturing fluid expressed in terms of formation properties is required.

Then In 1993, S.N. Shah from Halliburton had published an SPE paper researching the flow behavior of concentrated suspensions or slurries prepared with non-Newtonian carrier fluids. This aims to present experimental results obtained by pumping various hydraulic fracturing slurries into a fracture model and gathering data on differential pressure vs. flow rate. Several concentrations of hydroxypropyl guar (HPG), a wide range of proppant concentrations, and three test temperatures were studied. some correlations for predicting the relative slurry viscosity for these HPG fluids. **[26]**

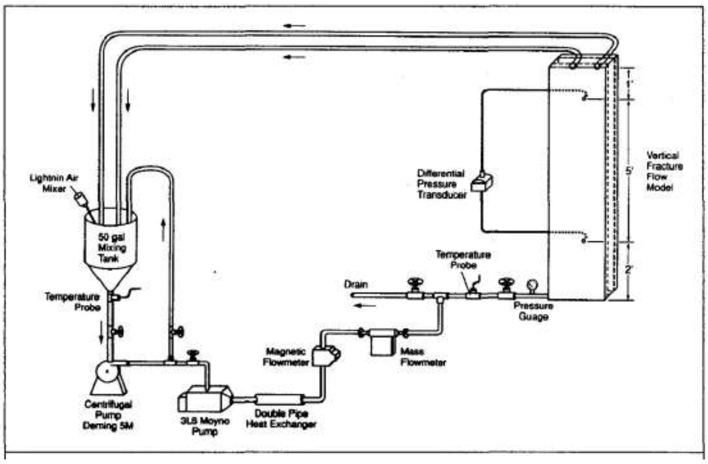

Figure II. 9: Schematic of the experimental setup of vertical-fracture-flow model [26].

- Higher viscosity increases or relative viscosities are seen at lower gelling-agent concentration, lower fracture shear rate, higher solids concentration, and higher test temperature. All relative viscosities, however, were lower than those predicted for Newtonian fluids.

In 2007 Jerrod Adam Core showed us that Crosslinked fluid testing is a necessary step in developing a responsible plan of action for performing a fracture treatment. While the oil and gas industry does have a developed standard for measuring the viscous properties of crosslinked fluids on a rotational viscometer, this standard covers only the basic operation of the viscometer. There are a number of factors left open for interpretation and company preference when establishing a crosslinked test procedure and request. Operators and service companies must work together to establish definitive guidelines for each set of fluid tests, including test temperature, start/stop of fluid stability time, fluid viscosity requirement, test shear rate, and a clear preference for the fluid optimization path. If either the service company or the operator fails in their responsibility to develop and agree upon concise testing guidelines, then they have missed an opportunity to save time and money. **[27]**

June 2010, Sarah Kassis from Oklahoma examined the effects of fracture roughness, offset, proppant and effective stress on fracture permeability of Barnett Shale samples, and the proppant fractured and embedded in the shale at higher pressures. he measured the permeability of fractured rock, Pressure dependence of permeability of these fractured surfaces does obey the Walsh permeability models. SEM (Scanning Electron Microscope) observations of surfaces and proppant suggest a new approach to proppant design. **[28]**

- rms (root mean square) asperity height, ascertained through optical profilometry, is directly proportional to permeability.
- Permeabilities using sand tended to be higher than the ceramic.

February 2012, O. Awoleke from Texas A&M university undertake a systematic investigation of the interactive effects of the key parameters that affect the final conductivity of a propped fracture, including flow back rate, proppant loading, polymer loading in the fracture fluid, the presence or absence of breaker, closure stress, and reservoir temperature with three principles (**Hierarchical ordering, Effect sparsity, Effect heredity principle). [29]**

Figure II. 10: Experimental setup showing conductivity cell with heating jacket and pressure transducers [26].

The results show that:

- Closure stress, increased polymer loading and the absence of breaker have a deleterious effect on fracture conductivity.
- Using high strength proppant, high conductivities can be obtained at low proppant concentrations due to the existence of channels and void spaces in the proppant pack.

In 2014 Nick Ohanian studied the rheology of guar borate fracturing fluid with synthesis methods, prepared two solutions (water, potassium chloride salt, BA (boric acid), NAOH (sodium hydroxide)), solution A contains HPG (hydroxypropyl guar), and solution B contains a polymer powder, both solutions were placed on a roller mixer for 24 hours, He determined that:

- the shear viscosity of the fluid decreases with an increase in shear rate known as a property called shear thinning. This phenomenon was anticipated due to the crosslinked nature.
- In the lower range of shear rates, solution A had a larger viscosity, but also had a larger amount of variability in values. in accordance with the Cross Model, which displays Newtonian behavior would be applicable to solution B due to its Newtonian-like behavior in the lower range of the shear rate. **[30]**

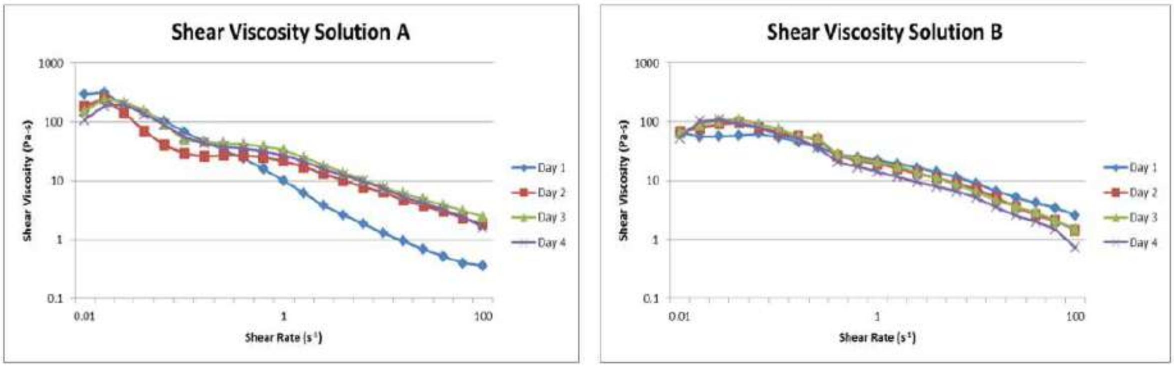

Figure II. 11: Shear Viscosity vs. Shear Rate for both solutions [30].

In 2015 N. Esmaeilirad a, S. White a, C. Terry b, A. Prior c and K. Carlson demonstrate that produced water can be used as a supplemental water source for hydraulic fracturing but when using gel-based polymers, a good understanding of the ionic interactions is required. **[31]**

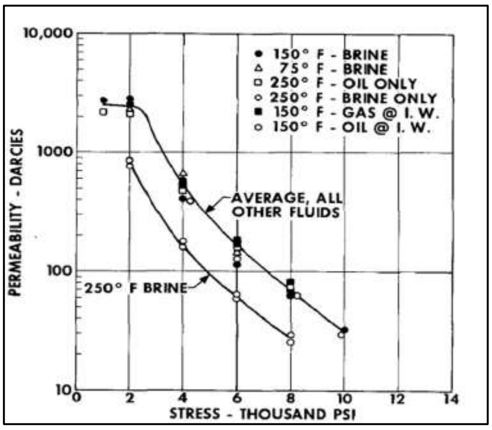

Figure II. 12: Effect of stress, fluid and temperature on sand permeability 8/12 [31].

In 2016, Xiaojin Zheng studied how to effectively evaluate the fracture conductivity in channel fracturing, which is a new technique in the oil and gas industry, with two distinct conductive media within the fracture (proppant pillar and free conduit), using the expression of fracture opening on the basis of Hertz contact theory and geometry of proppant embedment, then evaluating the key parameters controlling the fracture conductivity and permeability in channel fracturing, the research was on the rectangular area surrounded by dashed lines in **Figure II. 13**. The results provided a way to calculate the fracture conductivity in channel fracturing are:

- Fracture conductivity in channel fracturing changes with proppant pack distribution density.
- Proppant pack with regular contour is good for fluid flowing. **[32]**

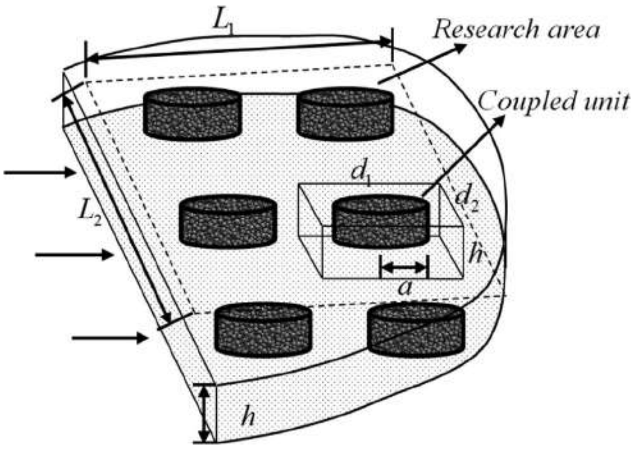

Figure II. 13: Proppant distribution within the fracture [32].

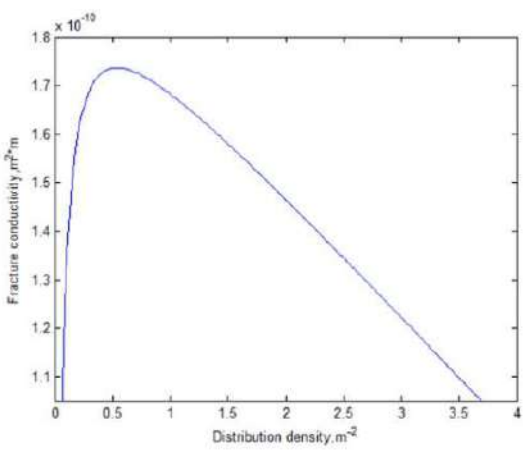

Figure II. 14: Correlation between distribution density and fracture conductivity [32].

September 2018, Geetanjali Chauhan and al analyze the frac fluid characteristics such as rheological (reduce of a proppant permeability) and breaking (the presence of large insoluble residues), using a novel crosslinked gel (Zr gum karaya) with oxidative breaker ammonium per sulfate under simulated pressure and high temperature, also which was has been synthesized as alternate guar based fracturing application. **[33]**

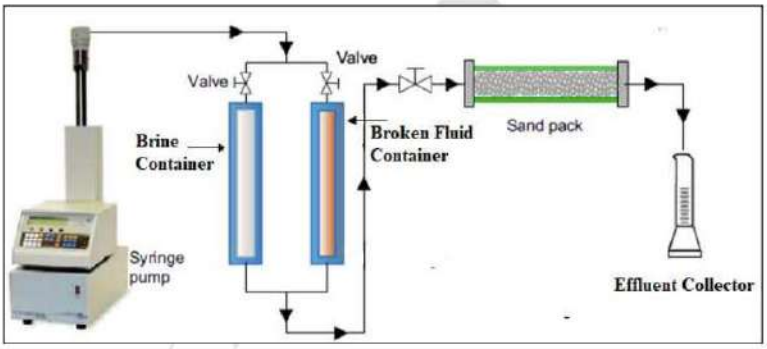

Figure II. 15: Schematic diagram of experimental set up for sand pack flooding study [32].

Figure II. 16: Karaya Guar Zr Crosslinked gel used [32].

- The Zr-KG crosslinked gel exhibits stability up to 150 °C due to formation of covalent bonding.
- FE-SEM (scanning electron microscopy) images revealed smooth, dense structure of Zr-KG gels.
- Exhibits comparable rheological characteristics with Guar.
- Critical overlap concentration (C*) and critical gel concentration (C**) and gel region was determined by the capillary viscometric technique.

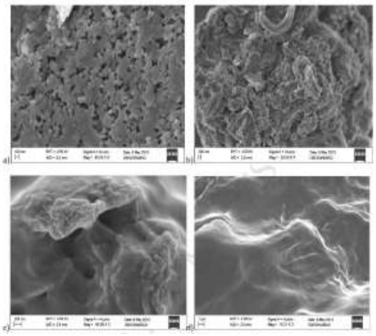

Figure II. 17: FE-SEM images for linear karaya gel (a & b), Zr-crosslinked karaya Gel (c & d) [32].

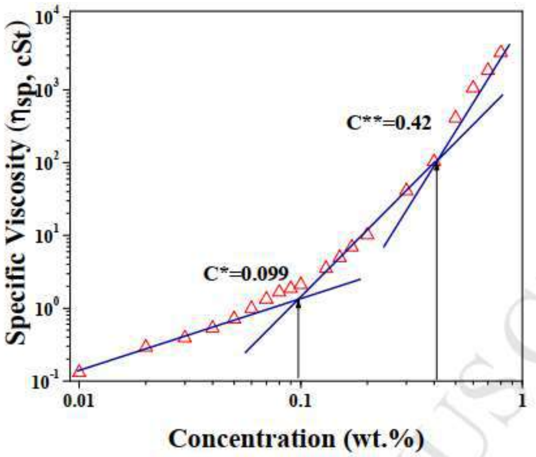

Figure II. 18: Determination of C and C** for Gum Karaya [33].*

Jiaxiang Xu (2019) investigated the effect of proppants sphericity on the fracture conductivity in tight oil reservoir, considering the change of the proppant embedment and fracture width under different closure pressures by the solid mechanics, and simulating the pressure and velocity of the fluid during the fracture deformation by Lattice-Boltzmann method.

In order to verify the accuracy of this simulating model, fracture conductivity tests were conducted on the experimental equipment named ZCJ-200, and the simulation results were compared with the experimental data. **[34]**

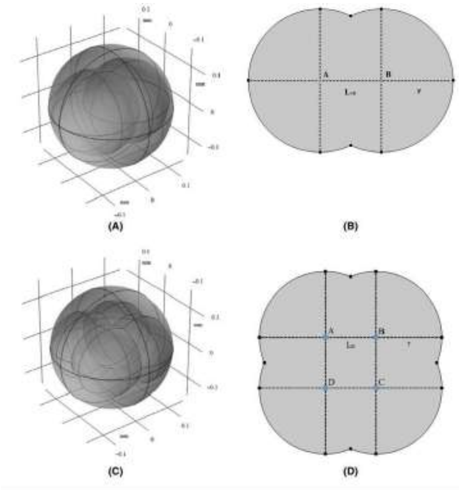

Figure II. 19: Geometry structure of non-spherical proppants [33].

A) 3D graph of cylindrical proppant and its circumscribed sphere. B) cross-section of cylindrical proppant. C) 3D graph of planar proppant and its circumscribed sphere. D) cross- section of planar proppant.

Regarding the results the fracture permeability and conductivity decrease with the decrease in the rock's Young's modulus, proppant size, and sphericity, and their stress sensitivity increases with the decrease in the rock's Young's modulus and the increase in the proppant size. Then increasing fracture width can improve fracture conductivity more significantly than increasing fracture permeability. The permeability and conductivity of the fractures filled cylindrical proppants are higher than that of the fractures filled with planar proppants.

M. Wrobel and al (2020), analyzed the hydraulic fracture driven by a non-Newtonian shear thinning fluid, describing the fluid viscosity by the four parameters truncated power law model, with a variation in a rheological model parameter, he investigated spatial and temporal evolution of fluid flow with three shear rate variants with an interrelation between rheological properties of the fluid and the flow regime inside the crack and the resulting fracture geometry, resulting that the rheological properties of fracturing fluids affect crucially the process of hydraulic fracture not only by the limiting values of viscosity, but also by the range of fluid shear rates over which variation of viscosity occurs. **[35]**

In 2021, Bo Li and al prepared a series of natural and synthetic rock fractures with apertures falling in the typical engineering range, with realistic surfaces and with mean apertures typical for the effective medium regime, To demonstrate the importance of plastic deformation, they considered simulations with EM (Elastic contact model) and EPM (Elastic-Plastic contact model) to compare the closure behavior observed in normal loading experiments on three rock fractures (MG-3(medium granite), FS-3(fine sandstone),and MS-3 (medium sandstone)).and they derived the simple relationship in the effective medium regime, using the elastic modulus of the rock matrix (mechanical aperture, and the relative standard deviation (RSD) of it), At the end they established a new and relatively simple relationship (Equation 2) help to estimate the fracture stiffness from the permeability or fracture permeability from stiffness, depending on which quantity is observable in the field. **[36]**

Ali Seyfeddine G (2021), Conducted an experimental simulation with a Self-made confinement cell to determine the effect of different parameters on the fracture conductivity under various bottom-hole conditions where different variables were used: effect of Proppant type, guar gel concentration, crosslinker, temperature, breaker concentration and closure pressure at extended time. **[37]**

He described that the unachieved planed fracture geometry parameters and low retained fracture conductivity due to gel damage from high polymer loading and the time taken between the closure and cleanup operation, which is a commonly observed phenomenon In Hassi Messaoud field, due to the unavailability of Coiled Tubing units. And the results were:

- An important drop in fracture conductivity was observed varied between 10 and 80% under stresses at interval of 2000 psi and 8000 psi, gel concentration up to 200 lb/1000 gal at extended time and temperature.
- Using less guar concentration is a key parameter to avoid additional damage to the fracture permeability.
- Reducing the time between stimulation and cleanup operations in Hassi Messaoud filed is a key parameter to minimize the proppant pack permeability impairment.
- Choosing the type of proppants according to the closing pressure is a must which condition the success of the fracturing treatment.
- Increasing the breaker concentration will reduce the severity of proppant pack damage caused by concentrated polymers.

Figure II. 20: Installation schematic of the permeability measurement of proppant [37].

This year 2022, Kangwu Feng and al conducted a large- scale three- dimensional physical simulation experimental study of hydraulic fracturing, with high temperature of oil sand reservoir under different intermediate principal stress conditions state, and monitored the water pressure change at various points inside the box during the hydraulic fracturing by laying pressure sensors. the results showed that:

- The effect of shear fractures on permeability is greater than that of tensile fractures.
- The fractures generated by hydraulic fracturing cause high- pressure fluid to flow into them, resulting in significant changes in fluid pressure inside the oil sands. **[38]**

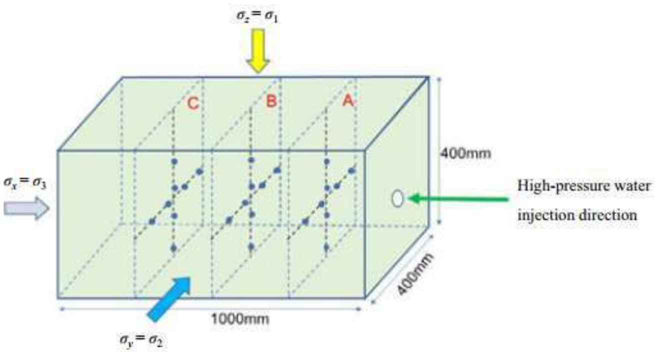

Figure II. 21: Three-dimensional view of the pressure sensor position [33].

II.8. Conclusion

The significant damage caused to the proppant pack by residues left after incomplete breaking of fracturing fluids, pushed researchers to develop their studies about the effect of different parameters on the proppant conductivity.

The surfactants increase viscosity in the absence of a crosslinker, the gel breaking performance of the guar fracturing fluid is affected by the amount of the gel breaker and the temperature. The undesirable viscosity reduction at high temperature, which cannot effectively reduce the median particle size of the gel breaker.

The damage of the conductivity caused by the crush and embedding of the proppant showed that the potential rock/fluid reaction between the gel breaking fluid and the formation has a certain influence on the proppant embedding. **[20]**

III. Chapter III. Experimental study on hydraulic fracturing fluid effect on proppant permeability

III.1. Introduction

Borate cross-linkers improve the fluid's ability to carry proppant and create viscosity for wider fracture geometry. Which can damage both the formation and permeability of proppant pack. Insoluble gels residual of crosslinked fluids has been proven to have a regained conductivity of 10-12% less compared that without crosslinkers. **[39]**

The fracturing fluid residues may have a series of effects on the reservoir flow deliverability due to physical blockage of flow pathway, in addition to the damage of permeability, the initial insoluble residue causes damage to the proppant pack left after incomplete breaking of fracturing fluids. **[40]**

III.2. Problematic description

Fracture conductivity and fracture length are two factors that determine the success of a fracturing treatment, which is affected by many variables such as type of polymer, proppant type, production rate, temperature, reservoir stress, etc. which translates to lower well productivity and potentially compromise the economic success of the well. **[42]**

In addition to the residue made during the preparation, up to 6–10% by weight insoluble residue is expected from guar. gel residue considered as a factor which hinder fracture conductivity from unbroken polymer and decreases effective fracture length which is the part of a propped fracture that cleans up and contributes to gas production. **[41]**

The breakers also generate additional residues. Experiments using enzyme breakers have shown that giving too much time to the cleanup causes more residues to be present. These breaker-generated residues also reduce the conductivity of the proppant pack. It takes a couple of hours to a few days for precipitates to develop. **[42]**

This phenomenon is well known in Hassi Messaoud field, the unbroken gel leaves some residues which will be retained inside the fracture which damage the fracture conductivity, and the delay of coiled tubing for cleanup, that what unachieved the fracturing stimulation. below resumed of 10 wells fractured in Hassi Messaoud, between 2018-2020, the period between the fracturing treatment and the cleanup operation, the production rate before and after the treatment are regrouped as well. **[34]**

Table III. 1: Data of 10 wells fractured in Hassi Messaoud between 2018 and 2020 [37].

Well	Fracturing treatment Date	Gel concentration (lb/1000 gal)	Clean up date	Period between fracturingand cleanup (Day)	Pre-frac production rate (m^3/h)	Post-frac production rate (m^3/h)
Well 1	21-Mar-20	35	22-Mar-20	1	Closed	0.00
Well 2	30-Mar-20	35	31-Mar-20	1	Closed	0.50
Well 3	2-Apr-20	35	2-Apr-20	0	Closed	2.48
Well 4	30-Jun-20	35	1-Jul-20	1	Closed	0.63
Well 5	11-Jul-20	35	12-Jul-20	1	Closed	2.45
Well 6	11-Jan-19	35	13-Jan-19	2	Closed	2.15
Well 7	15-Jan-19	35	18-Jan-19	3	Closed	1.86
Well 8	5-Feb-19	35	7-Feb-19	2	Closed	2.00
Well 9	7-Sep-19	35	8-Sep-19	1	0.60	1.74
Well 10	8-Aug-18	35	9-Aug-18	1	Closed	0.00

III.3. Objective

This research had four main objectives:

1. Conduct a series of experiment with existing equipment inside the laboratory to obtain experimental data for ascertaining the effects of gel residue with required polymer concentration on fracture conductivity.
2. Identify the effect of breaker on fracture conductivity.
3. Identify the effect of gel residue on fracture conductivity.
4. Studied the Viscosity effect on broken gel.

By achieving the above objectives, this research was able to predict more accurately the conductivity of a hydraulic fracture in a well drilled formations based on experimental work using dynamic fracture conductivity testing equipment.

Additionally, this study provides better understanding of factors affecting fracture conductivity, which aids in the future design of fracturing treatments and future prediction of well performance.

III.4. Methodology

III.4.1. Products & Materials

III.4.1.1. Proppant Size

Carbo Ceramics has provided proppant with 30-50 mesh size. 30-50 mesh size proppant is common in Hassi Messaoud, Algeria. Since we will not study the effect of proppant size, 30-50 mesh proppant is appropriate to achieve the objective of this study.

Figure III. 1: Proppant types.

III.4.1.2. Fracturing Fluid Composition and Conditioning

A simple fracturing fluid composition is selected and provided by a service company for this experiment. This fracturing fluid was selected due to its similarity to the actual fracturing job operations. Gel concentrated polymer is used as a base gel for this experiment. All experiments are conducted at 85°C & 110°C. The composition of the fracturing fluids used for the series of experiment is shown in Table below:

Table III. 2: Fracturing Fluid Recipes.

Additives	Concentration
Buffer	6 Gpt
Enzyme Breaker	1 Gpt
Clay stabilizer	1 Gpt
Non-emulsifier	1 Gpt
Bactericide	0.05 Gpt

Concentrated Liquid Gel	8.75 Gpt
Crosslinker	6 Gpt

The components for the selected fracturing fluid are as follows:

III.4.1.2.1. Concentrated gel

Crosslinker is a gel is used to form a viscous base fracturing gel fluid.

Figure III. 2: Concentrated gel.

III.4.1.2.2. pH Buffer

The pH Buffer is a liquid weak acid and liquid carbonate are used to control pH which is important for polymer hydration rate and crosslinking rate.

Figure III. 3: pH Buffer.

III.4.1.2.3. Breaker Enzyme

The purpose of breaker is to reduce the viscosity of the polymer solution and provide rapid fluid clean up. An enzyme breaker is used in this experiment.

Figure III. 4: Breaker Enzyme.

III.4.1.2.4. Breaker encapsulated

Another type of breaker (encapsulated) is used to activate breaker because of the low temperature environment.

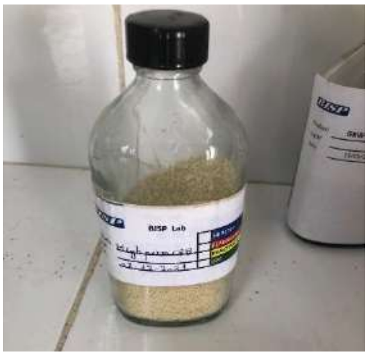

Figure III. 5: Breaker encapsulated.

III.4.1.2.5. Crosslinker

The crosslinker is used to increase gel viscosity and give better proppant transport capability, borate crosslinker is used for this experiment.

Figure III. 6: Crosslinker.

III.4.1.3. Materials

III.4.1.3.1. Viscosimeter Fann 35A:

The viscosimeters are measuring instruments for determining the resistance and viscosity of different liquids. Viscometers are mainly used for laboratory applications. But they are also necessary for process control to help regulate these processes.

Figure III. 7: Viscosimeter Fann 35A.

III.4.1.3.2. Rheometer Brookfield:

Rheometer is an instrument used to measure gel rheology parameters (power law parameters).

Figure III. 8: Rheometer Brookfield.

III.4.1.3.3. Batch mixer:

The batcher mixer is a device who carefully measures and adds ingredients to a small mixture to create a useful, large-scale batch of materials to work with.

Figure III. 9: Batch mixer.

III.4.1.3.4. pH Meter:

pH meter is a portable device used to measure pH and conductivity. It also allows the temperature to be measured simultaneously.

Figure III. 10: pH-Meter.

III.4.1.3.5. Oil bath:

An oil bath is a type of heated bath used in a laboratory, most commonly used to heat up chemical reactions.

Figure III. 11: Oil-Bath.

III.4.2. Preparation procedures

The tests have been done in the BJSP fracturing laboratory with all the chemicals that have been used in the real fracturing jobs in the field. Below is the general mixing procedure:

1. Make sure that water tank is clean.
2. Start preparing the linear gel and add the polymer (concentrated) by mixing 1 L water with 8,75 cc concentrated in the 35^{th} system (high depth), and 7,5 cc from concentrated in the 30^{th} system (low depth).

3. Mix base gel for 20 minutes to allow the gel adequate hydration time;
4. Measure viscosity of the linear gel by the viscosimeter Fann 35.
5. Measure density by measuring the weight of 10 cc from the sample and calculate it.
6. Dilute the enzyme breaker (1 cc in 33 cc water).
7. Add the clay stabilizer
8. Add the surfactant
9. Slowly add 1,5 cc pH Buffer until the mixing fluid reaches a pH of 10.
10. Add the encapsulated breaker in the mixer put the linear gel inside the mixer and when add the crosslinker start counting time by a chronometer for almost 10 seconds.

III.4.2.1. Breaking Time

Breaking time was determined as a factor of gel shut-in time. After putting the sample in the oil-bath with ° C, found that the gel was broken after 40 minutes.

III.4.2.2. Temperature

Temperature will affect gel breaking performance. In this series of experiments, 85°C & 110°C has been selected as sample temperature.

III.4.2.3. Polymer Concentration

The purpose of using polymer is to provide fracture width and transport proppant. Guar polymer was used as it is the most commonly used gelling agent. The purpose of using polymer is to transport proppant from the surface to the fracture tip. **[43]** The concentration varies from 3 to 4 lb/gal as this is a common gel concentration in the real fracturing job.

After preparing the linear and crosslinked gel, using the viscosimeter to measure the gel viscosity as below:

1. Measure the linear gel viscosity;

Figure III. 12: Measuring the viscosity of linear gel with Fann 35A.

2. Check the viscosimeter if it is recently calibrated;
3. Prepare and clean the viscosimeter in order to be ready to measure the viscosity;

Figure III. 13: Measuring the viscosity of crosslinked gel with the rheometer.

4. Fill the cell with the crosslinked gel in order to be measured;

Figure III. 14: Viscosimeter cell with crosslinked gel.

5. Place and fix it in the viscosimeter.

Figure III. 15: Viscosimeter spindle.

III.5. Results & Discussions

Figure III. 16 shows diagrammatically how enzymes work, and **Figure III. 17** the degradation of the molecular weight of HPG with time as it is digested by Hemicellulase. **[45]**

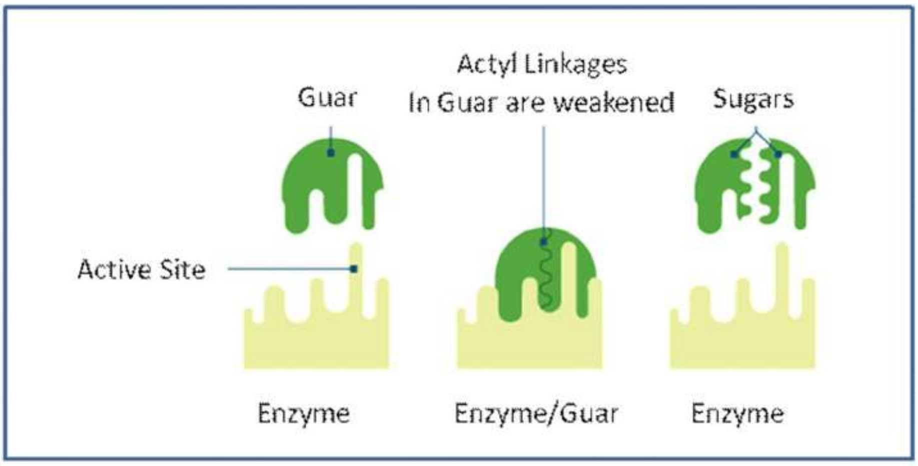

Figure III. 16: Schematic Degradation of Guar by Hemicellulase Enzymes mechanism [46].

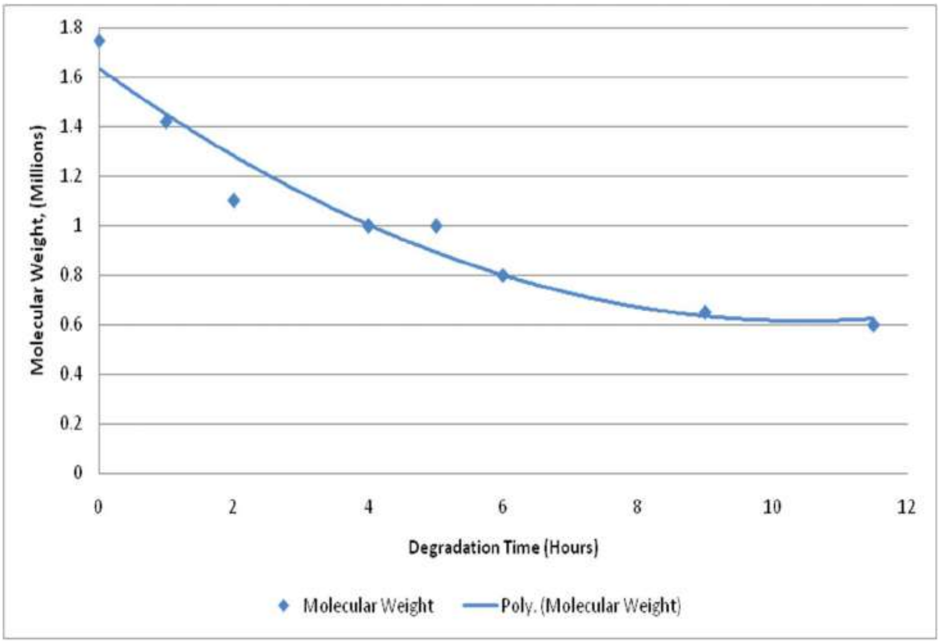

Figure III. 17: Diagram of Degradation of Guar by Hemicellulase Enzymes [46].

For enzymes, the most effective approach to engineer a structural dismantling of a guar polymer is to concentrate the attack upon the beta-1,4 linkage and alpha-1,6 linkage. Successful cleavage of these linkages will reduce the polymer to simple monosaccharide sugars which are completely soluble in water. Many different existing enzymes are specific for only guar polymer, but do not effectively reduce the polymer to simple sugars or reduce molecular weight. The enzyme must be not only polymer-specific to match up with the polymer, but also additionally, it must be polymer linkage-specific to attack the appropriate linkages to affect the desired degradation. As noted above, the most effective pathway would be the cleavage of the beta-1,4 linkages between the mannose units prior to cleavage of the alpha-1,6 linkages between the galactose and the mannose unit as shown in **Figure III. 18**, which can be considered as the highest efficiency breaking mechanism of enzyme breakers. **[46]**

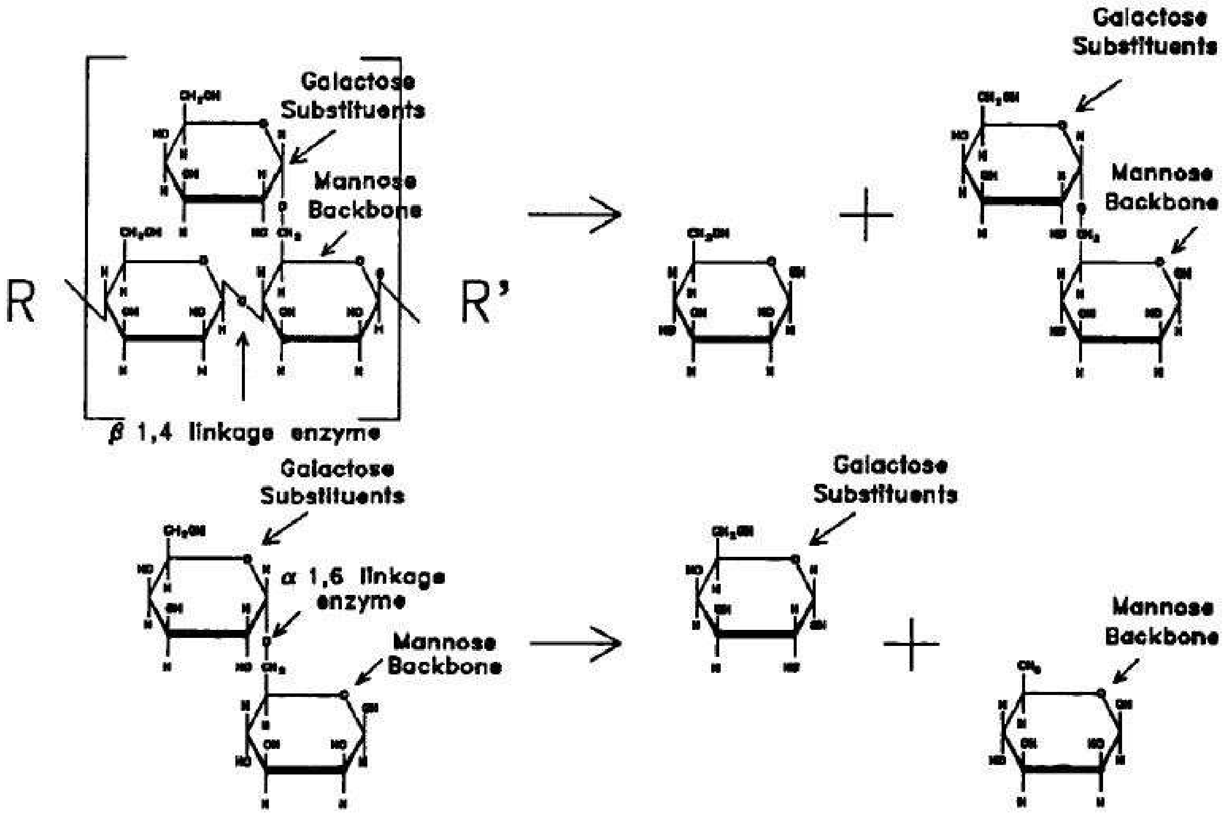

Figure III. 18: Guar Enzymatic Degradation Mechanism [47].

Figure III. 21 represents viscosity of fracturing fluid and temperature as function of time. A concentration of 35 lb/1000 gal guar based fracturing fluid crosslinked with borate was used to measure the viscosity at 110°C with enzyme breaker.

After preparing the fluid sample the viscosity was measured by applying a shear of 100 s^{-1} ramping it to 150 each 15 min to check the reversibility of the fracturing fluid.

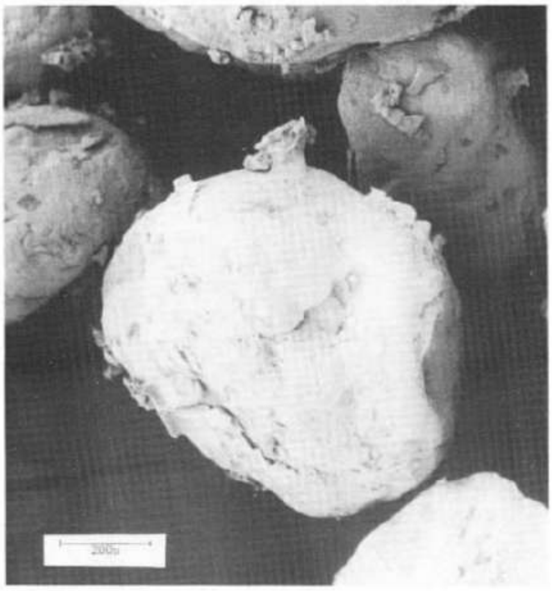

Figure III. 19: Sand grains covered with dried fracturing fluid residue [47].

Figure III. 19 shows dried sand grains after fracturing fluid containing guar and fluid-loss additives was degraded in the pore spaces. **[47]**

Notice the layer of dried residue that is loosened from the grain at the top of the photograph.

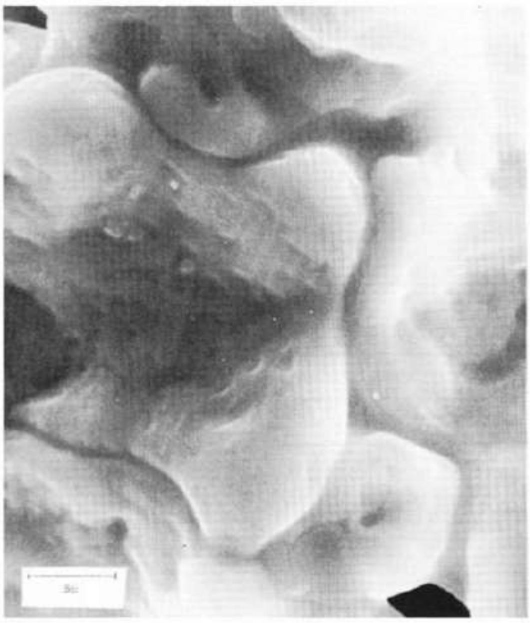

Figure III. 20: Guar polymer residue [47].

Figure III. 20 shows an area of residue, magnified 2,000 times, that contained fluid-loss additive and polymer debris.

The residue present in the pore spaces of the fracture will reduce the permeability of the proppant. Tests indicated that this reduction will be long term; the residue will not be displaced from the fracture by production and will degrade slowly. Only a small amount of guar residue could be displaced from a simulated fracture at extremely high-pressure gradients. **[47]**

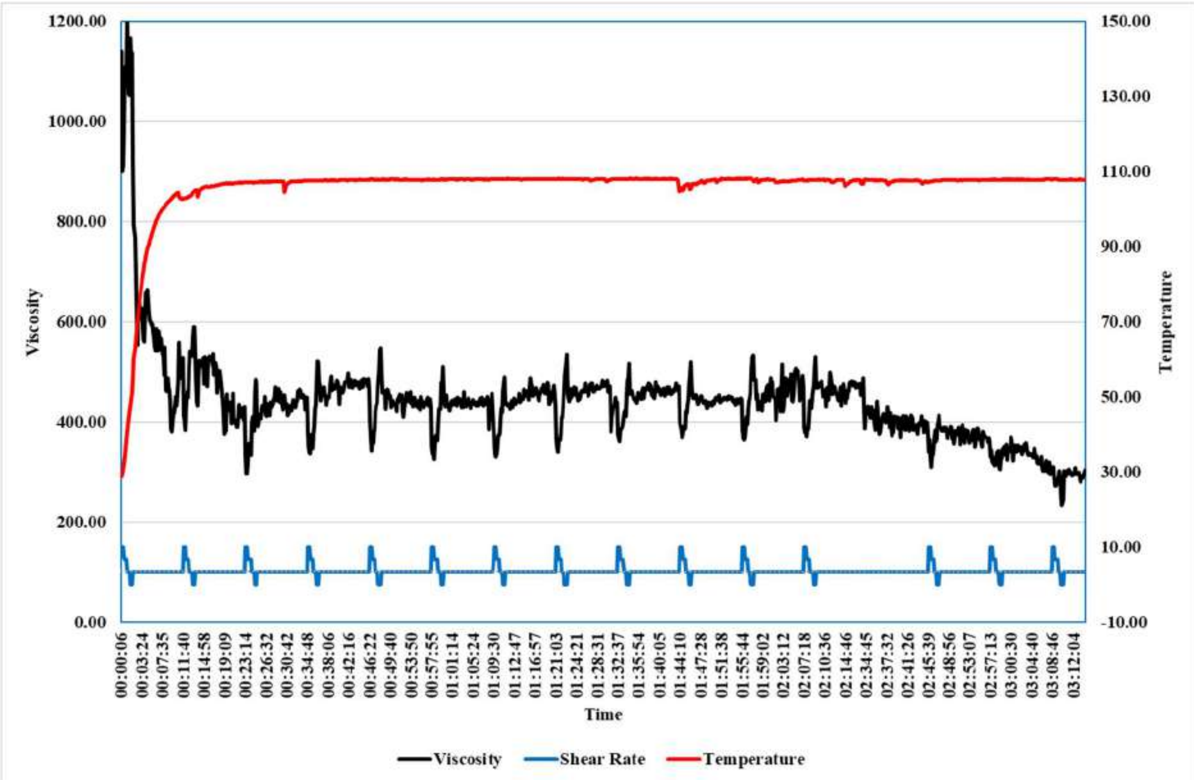

Figure III. 21: Viscosity chart at 110°C.

When starting the test, the viscosity of the fluid was very high exceeding 1000 cP after that it stabilized between 400 and 500 cP. When applying high shear, the fracturing fluid was showing a good reversibility and viscosity healing.

However even though after 3 hours the gel did not break showing a viscosity around 300 cP which make it hard for the gel to flowback outside the fracture after the fracturing treatment.

Taking in consideration that pressure gradients in most regions in Hassi Messaoud field are under 0.45 psi/ft (underpressurized reservoir), this will lead to a low fracture retained permeability which will affect the Fcd and as result the IP because more driving energy is needed in this case for better fractur cleanup which is not the case in Hassi Messaoud field.

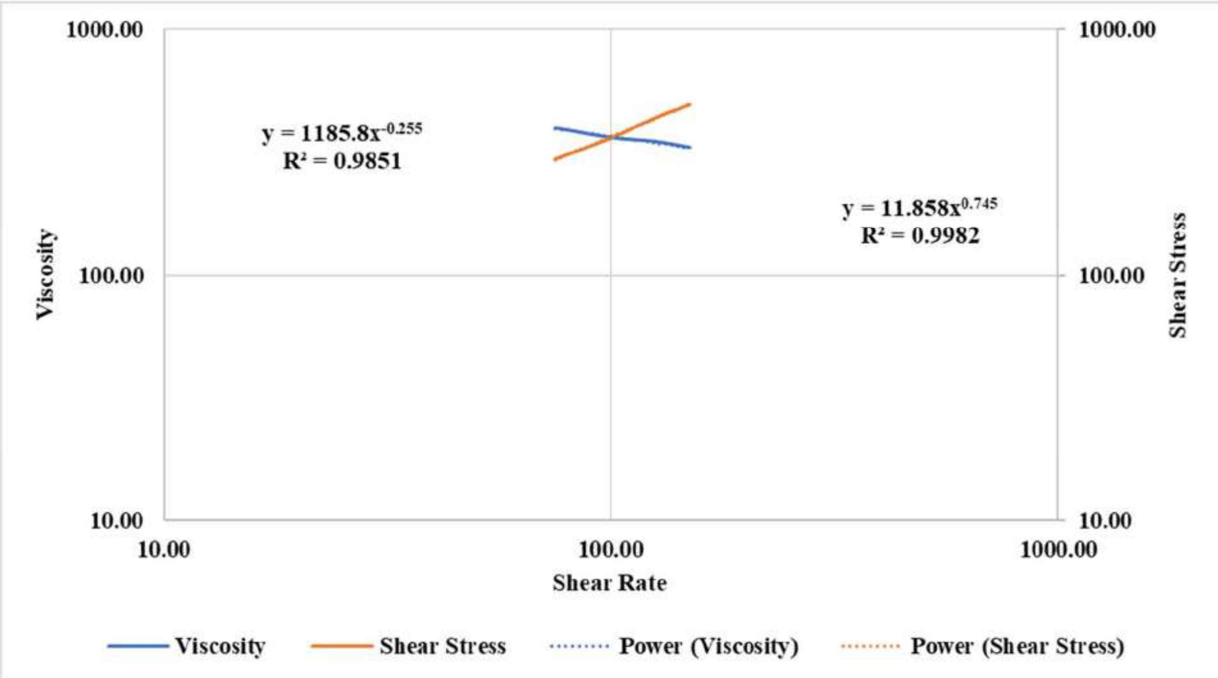

Figure III. 22: Log of viscosity and shear stress as function of log of shear rate.

Figure III. 22 Log of viscosity and shear stress as function of log of shear rate at the end of the previous breaker test (**Figure III. 16**), the equations of the log-log chart for viscosity and shear stress show that the fluid behavior is still in the power law model. From the chart the following equations have been concluded:

$$\tau = 11.858\gamma^{0.745} \quad \text{III.1}$$

$$\mu = 11.858\gamma^{-0.255} \quad \text{III.2}$$

From the chart and equations, the behavior index is n= 0.745, which means that the fluid did not totally break. This phenomenon will result in serious cleanup problem, this is explained by the high superficial tension of the unbroken gel which make it hard for the it to be removed. Thus, the fracture conductivity impairment will be severe which will affect negatively the IP and as result will affect the FOI.

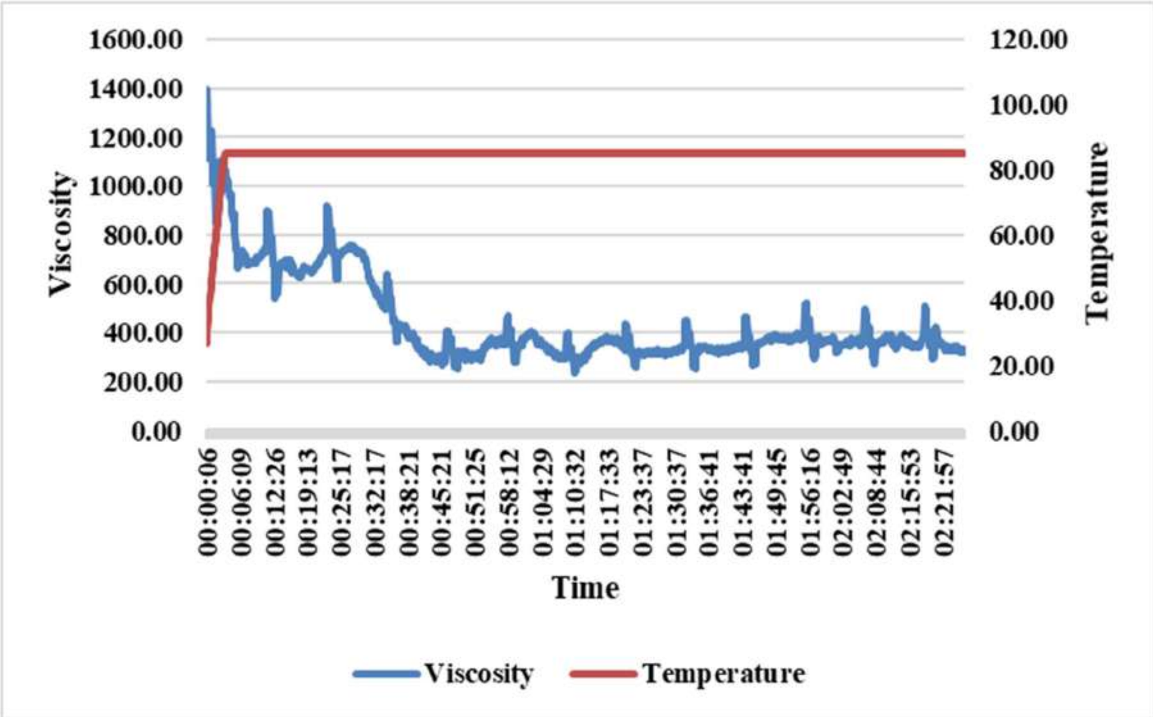

Figure III. 23: Viscosity chart at 85°C.

Figure III. 23 represents viscosity of fracturing fluid and temperature as function of time. A concentration of 35 lb/1000 gal guar based fracturing fluid crosslinked with borate was used to measure the viscosity at 85°C with enzyme breaker.

When starting the test, the viscosity was very high more than 1000 cP after that it stabilized between 200 and 400 cP.

However even though after 2 two hours, the gel did not break showing a viscosity around 300 cP, which make it hard for the gel to flowback outside the fracture to the surface after the fracturing treatment.

Taking in consideration that pressure gradients in most regions in Hassi Messaoud field are under 0.45 psi/ft (underpressurized reservoir), this will lead to a low fracture retained permeability which will affect the Fcd and as result the IP because more driving energy is needed in this case for better fracture cleanup which is not the case in Hassi Messaoud field.

To highlight the Effect of gel residues on proppant conductivity, this operation starts by adding the amount of Slurry (gel + proppant) into the cell and then closing it and tightening it. Then the piston is placed on top of the press after applying pressure to the containment cell. Each time the closing pressure 6000 psi and the gel concentration 50Lb/1000gal are changed.

Figure III. 24: Applying pressure to the containment cell.

After the compression of the proppant, the cell is kept in an oven at 120 Co (Hassi Messaoud deposit temperature) for a determined time.

Figure III. 25: cell inside the oven at 120 °C.

III.5.1. Results of gel residues on proppant conductivity

The mechanism of gel degradation is explained by the process by which the oxidant works. They release free radicals that act on the oxidizable bonds which are susceptible. Free radicals are charged ions with unpaired electrons and are highly reactive because of the natural tendency to form electron pair bonds, and can generate free radicals by stabilizing the thermal or catalytic activation of oxidizing species. (TjonJoePin, 1996).

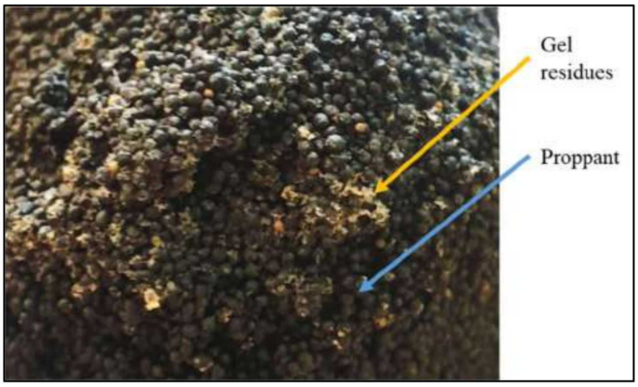

Figure III. 26: Gel residues after 24 h under 6000 psi at 120 °C with 5 lb/1000 gal breaker concentration.

III.6. Conclusion

In this study, a series of experiments have been performed to study the damage to fracture conductivity caused by gel residue remaining in the fracture. Fracture conductivity tests were conducted at known additives concentrations. **[44]**

Figure III. 17 Highlighting the degradation of the molecular weight of HPG with time as it is digested by Hemicellulase, then as result of viscosity tests the fracturing fluid was not broken for more than 2 hours with different temperature, thus defining that the fluid has a high viscosity with 300 cP which means that still have a non-Newtonian behavior ($n < 1$).

General conclusion

The conductivity of the proppant pack is one of the essential parameters that determine the success of hydraulic fracturing, this parameter has already been the subject of several studies which have led to the highlighting of the importance of the fracturing fluid rheology and his ability to transport proppant to the fracture and flowback when the proppant take place and maintain the fracture open.

Additionally, the experimental studies carried out in this research project have shown the effect of fracturing fluid on the proppant conductivity as well as the viscosity and temperature on the Folds of Increase (FOI) and Fracture Conductivity Dimensionless (FCD).

The damage of the proppant conductivity caused mechanically by the crush of the proppant showed influence on the proppant embedding that the potential rock/fluid reaction between the gel breaking fluid and the formation, that which pushed researchers to develop their studies about the effect of different parameters on the proppant conductivity.

In the laboratory of BJSP, with the tests carried out to measure the fracture fluid viscosity and its behavior through the fracture, also the effect on the proppant conductivity by simulating the reservoir conditions with different temperatures once with 85°C than 110°C using the oil bath to increase the sample temperature, the viscosity obtained was 300 cP after almost two hours with a behavior index less than 1 which determine that the fluid keeps a Non-Newtonian behavior in the power law system, that which led the result to a unbroken fluid.

Due to the speed of the measurements and the simplicity of the manipulations, the results of the tests have proven its efficiency and has made it possible to display an accuracy of the measurements as well as a robustness of the data.

Finally, the recorded results of the experiments performed in the laboratory were used to define the breaking time according to the fluid behavior. A 74% decrease in viscosity breaker test was observed at 110°C and 77% reduction of viscosity at 85°C, with the same concentration, which confirm that the fluid was not yet totally broken.

Recommendations

- Perform breaker type selection through preliminary performance tests using in the laboratory before the job with appropriate concentration, taking in consideration the limited pumping time.
- Choose the type of breaker according to the reservoir conditions.
- Reduce the time between the fracturing operation and the cleanup due to gel residue precipitation.
- Use the viscoelastic surfactant (VES)-based fluids that are viscous under shear but leave minimal to no residues.

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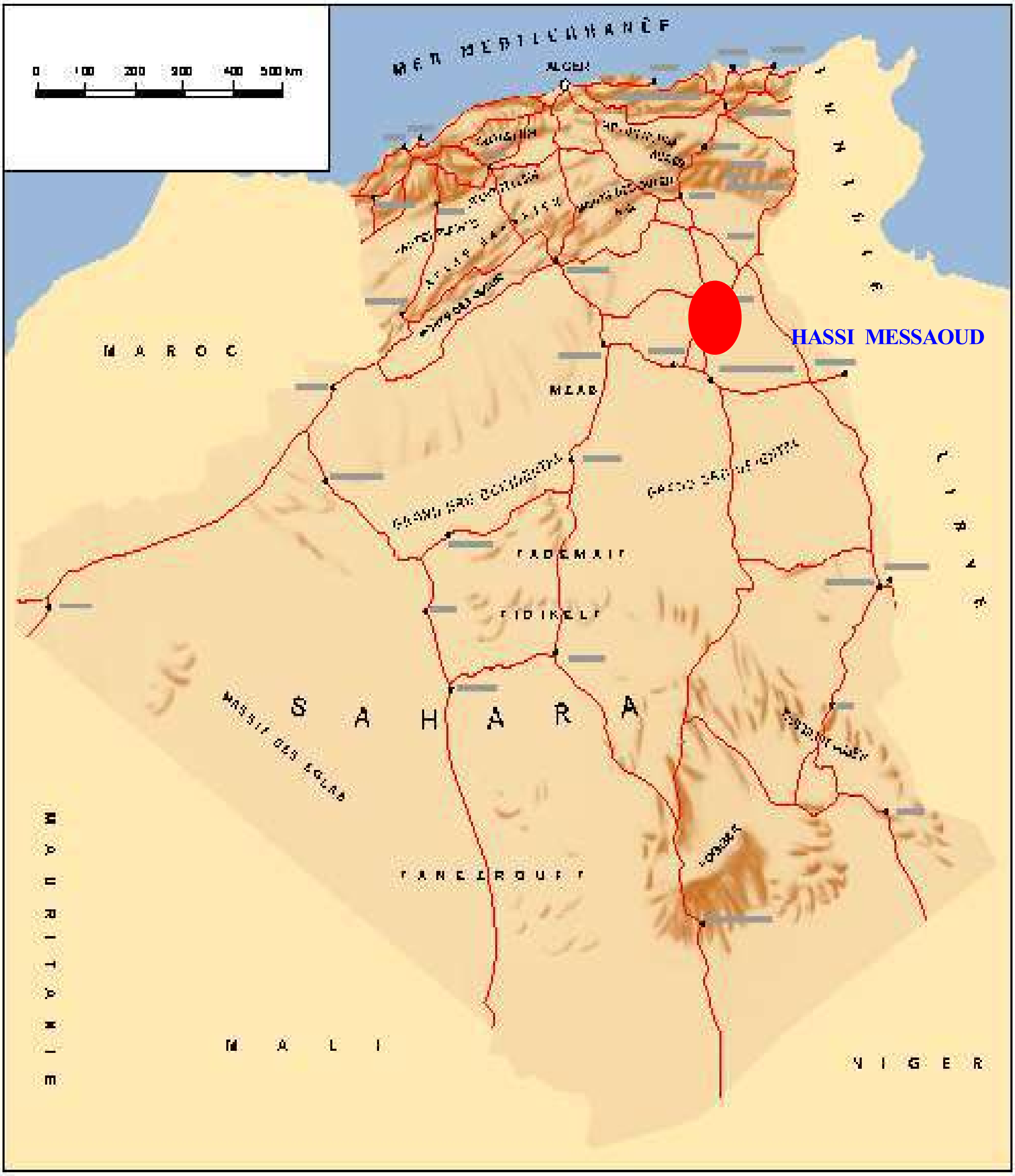
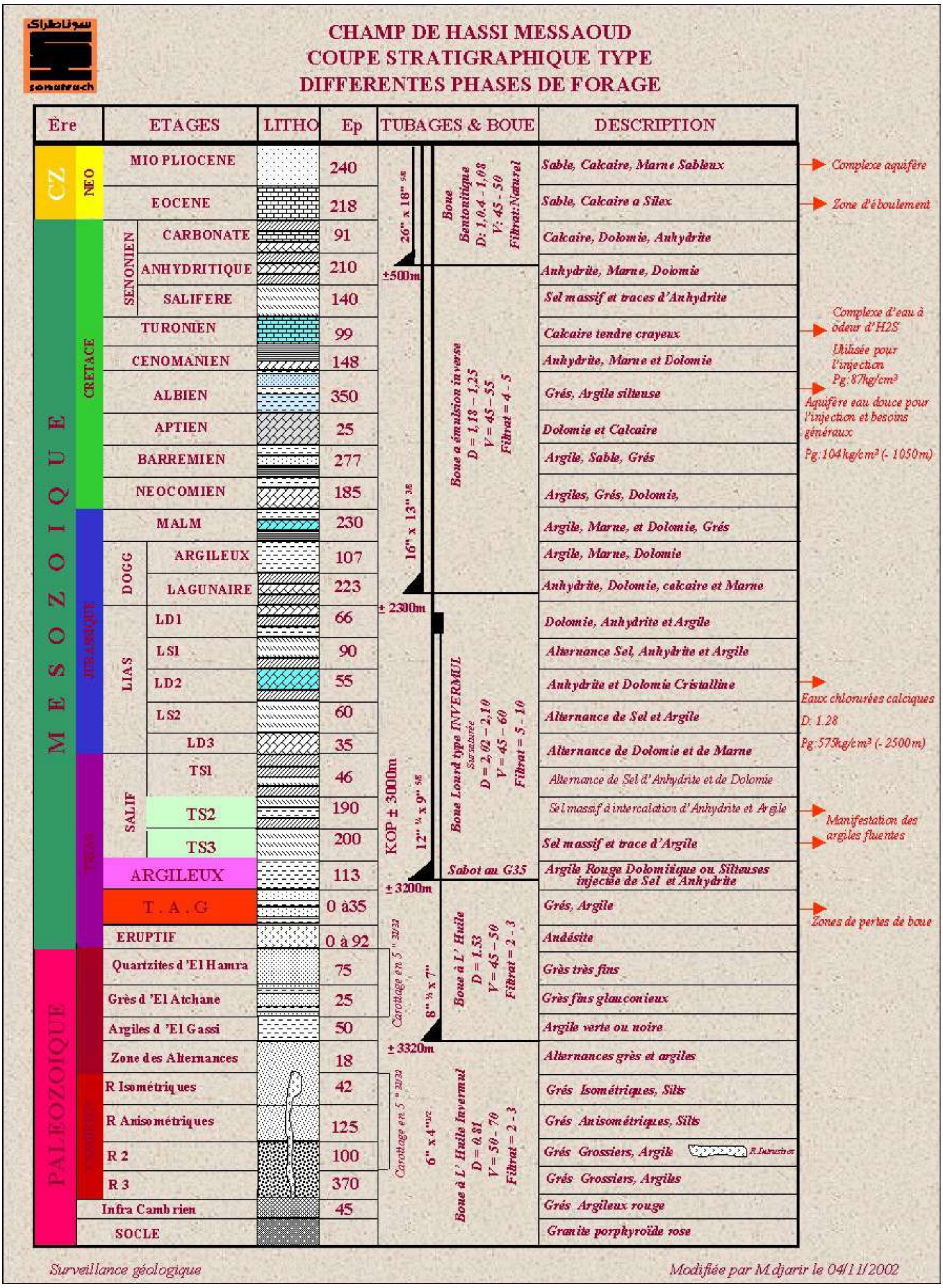
Appendix



Appendix A: Ggeographical situation of the Hassi Messaoud field.



Appendix B: Stratigraphic carte & different drilling phases of the Hassi Messaoud field.