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Research article

Preliminary hydraulic fracturing campaign strategies for unconventional and tight reservoirs of UAE: Case studies and lessons learned

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Abstract: The challenges associated with applying hydraulic fracturing (HF) technology to tight carbonate reservoirs with very low clay content are substantial and demand a unique cost optimization strategy, especially in the context of low oil prices. This study discusses the challenges of applying HF technology to such reservoirs in the UAE. The work presents a comprehensive approach to assess and employ this technology, including a thorough study, a strategic roadmap, screening procedures, a fracturing workflow and strategy and an examination of the distinctive challenges and lessons learned from the process. The primary goal is to formulate a strategy that is applicable to tight and unconventional formations in the UAE, with a strong emphasis on cost optimization. Also, the evaluation methods of the fracturing technologies for these reservoirs were discussed, such as creating valid geomechanical properties to construct a Mechanical Earth Model (MEM) for successful execution and evaluating the reservoir quality. The results showed that conventional acidizing is not effective in stimulating the tight carbonate reservoirs, whereas acid-fracturing has successfully broken down the formation. It was also found that strategic planning, equipment availability, geomechanical studies and building an effective MEM are necessary for obtaining the optimum fracturing design and achieving successful development.

Keywords: hydraulic fracturing; strategic planning and management; reservoir geomechanics; exploration and appraisal strategies; oil and gas

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Acronyms: CT: Computer tomography; GR: Gamma ray; GC/MS: Gas chromatography/mass spectrometry; HCl: Hydrochloric acid; HF: Hydraulic fracture; LTT: Long term test; MEM: Mechanical earth model; NMR: Nuclear magnetic resonance; NPT: Non-productive time; PKN: Perkins-kern-Norgren fracture geometry model; SEM: Scanning electron microscopy; TBG/CSG: Tubing and casing; TOC: Total organic content; TVDss: Ture vertical depth-subsea; UFD: Unified fracture design

1. Introduction

The ever-growing daily energy demands have spurred the exploration of unconventional resources, including tight carbonates and source rocks, as crucial fuel sources. Over the past decade, unconventional reservoirs have garnered substantial global attention, particularly in North America and various locations, including the Middle East [1–11]. Thanks to technological advancements, it has become more economically feasible to develop and produce these reservoirs.

Since the inception of hydraulic fracturing (HF) technology [12,13], it has emerged as one of the most effective techniques for well stimulation and enhancing well productivity in the oil and gas industry [3,10,11,14–17]. HF is the process of initiation and propagation of a crack by pumping fluid at relatively high flow rates and pressures. These fractures can range in size from a few meters to hundreds of meters, and their cost is often a significant portion of the total development cost [18,19]. the geometry of HF can be predicted and controlled with reasonable accuracy if the in-situ stress field and the directions is known; however, for those wellbores that are not aligned with such a direction (deviated or horizontal wells), the hydraulic fracture geometry is usually more complex and more difficult to model. Therefore, numerical simulations are used to evaluate and predict the location, direction and extent of these fractures [18–20]. However, current fracture propagation simulation methods generate only limited propagation paths and cannot truly reflect the complexity of the propagation. Also, the predication of well performance after fracturing based on these studies are often inconsistent with actual field data [20].

HF plays a crucial role in increasing productivity from unconventional resources [1,21–24]. However, applying HF to tight carbonates and source rocks in UAE reservoirs poses unique challenges that demand precise design, planning, execution and cost optimization strategies.

The contribution of the work is to adapting HF and devising a workflow suitable for the unconventional formations found in the UAE [22,25]. It has been observed that the volume of hydrocarbon accumulation in the Middle Cretaceous Upper Wasia reservoirs ([26], Figure 1) is lower than the volumetric estimates of predicted oil-in-place [27]. This underscores the potential for generating ample volumes of oil from these reservoirs.

Most of the unconventional reservoirs are considered high risk due to huge uncertainties. That is why it needs special study before drilling, fracturing and production selection. Aim of these studies is to minimize the uncertainties and minimize the unwanted cost associated. Both major parameters could bring unconventional reservoir development to commercial project. The contribution of the work and the main objective is to make it successfully and avoid uncertainties.

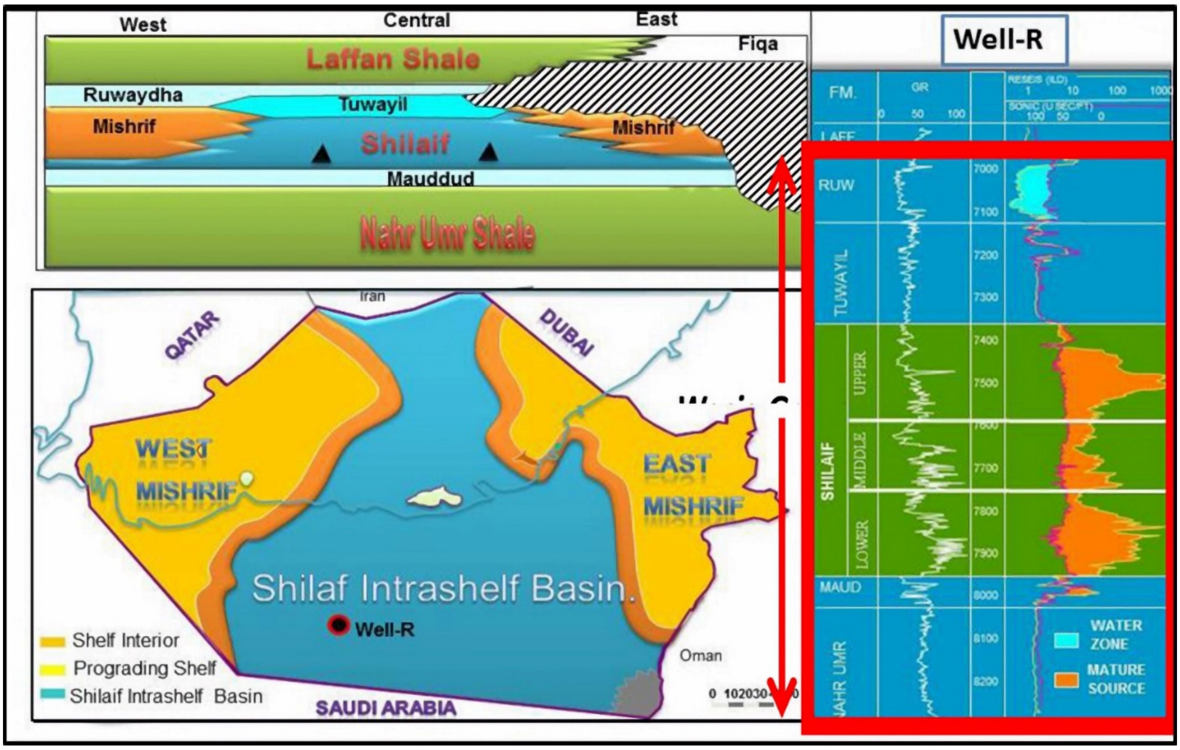


Figure 1. Paleo-geographic map, middle cretaceous stratigraphic successions and stratigraphic column of Wasia Group [26].

One of the major oil and gas companies conducted early trials in the UAE to assess the hydrocarbon potential of unconventional source rocks in Abu Dhabi. However, due to logistical issues, a complete fracturing and testing program was not executed. Instead, a redesigned program was performed, focusing solely on acid breakdown to demonstrate the feasibility of hydrocarbon production from such formations [28].

Subsequently, a new strategy was developed to explore tight oil and gas reservoirs utilizing a fit-for-purpose acid fracturing approach, executed through two exploration wells. A total of 51 appraisal and exploration reservoirs were examined, and a root-cause analysis was conducted to determine the factors contributing to matrix stimulation failure [29]. In many cases, the failure was due to the limitations in the fracturing technology. Matrix stimulation was found to be ineffective in reservoirs with permeability less than 4 millidarcy (mD) (Figure 2). However, the use of acid fracturing technology in three different case studies (tight oil, very tight oil, and extremely tight gas reservoirs) was found to be successful.

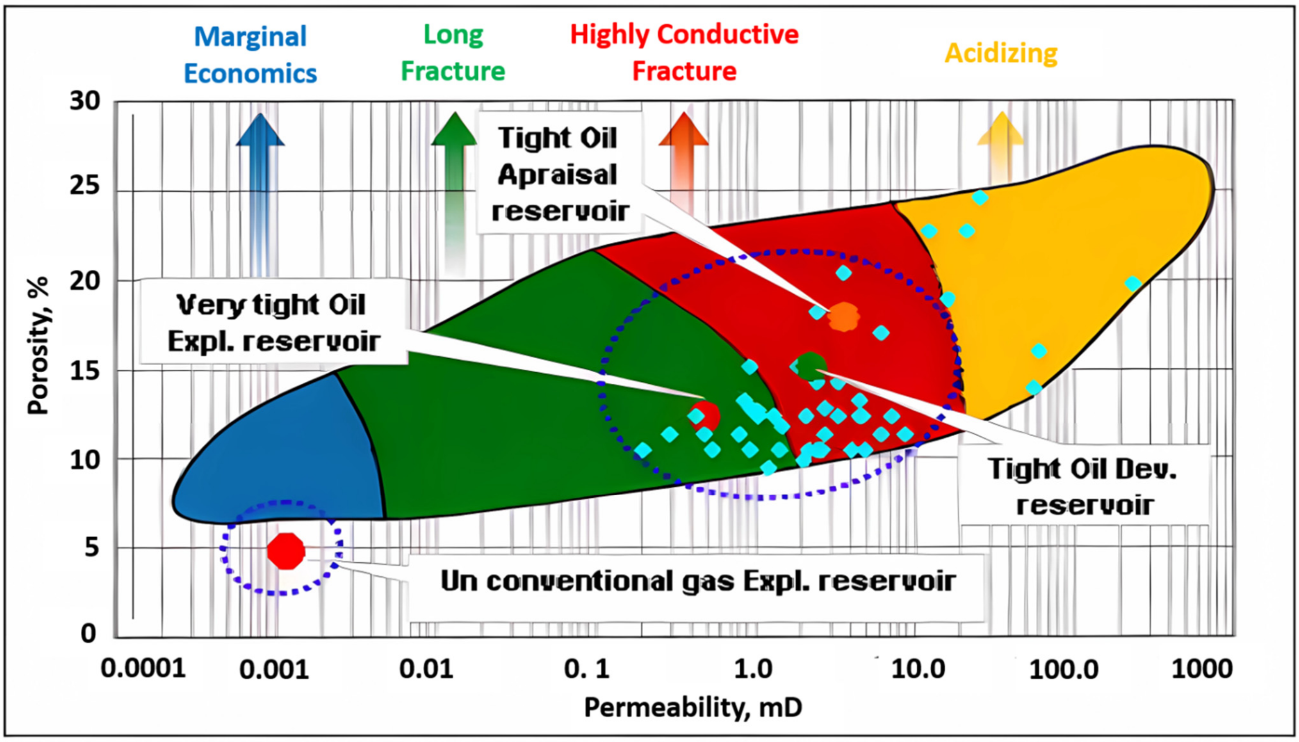


Figure 2. Porosity/permeability correlation chart.

This study was reassessed with the addition of two more acid-frac operations in tight reservoirs, further substantiating the concept before its application to unconventional reservoirs. The details of these five fracturing jobs, encompassing their design, execution, lessons learned and outcomes, are presented in this paper as case studies (Case 1 to Case 5). A strategy map was devised for the first campaign in unconventional reservoirs (Figure 3) by integrating the insights derived from the initial five fracturing operations. Various techniques, including conventional acid-frac, proppant frac and Surgi-Frac, were reviewed and assessed based on operational risks, reservoir quality, existing experience and operational costs [1,21].

We revealed the intricacies of the process due to several factors, such as limited resource availability, limited technological experience, restricted geomechanical studies and scarce data gathering opportunities. Furthermore, the operations carried higher risks and costs due to fluctuating oil and gas prices. Figure 4 depicts a flowchart illustrating the structure and workflow of this paper.

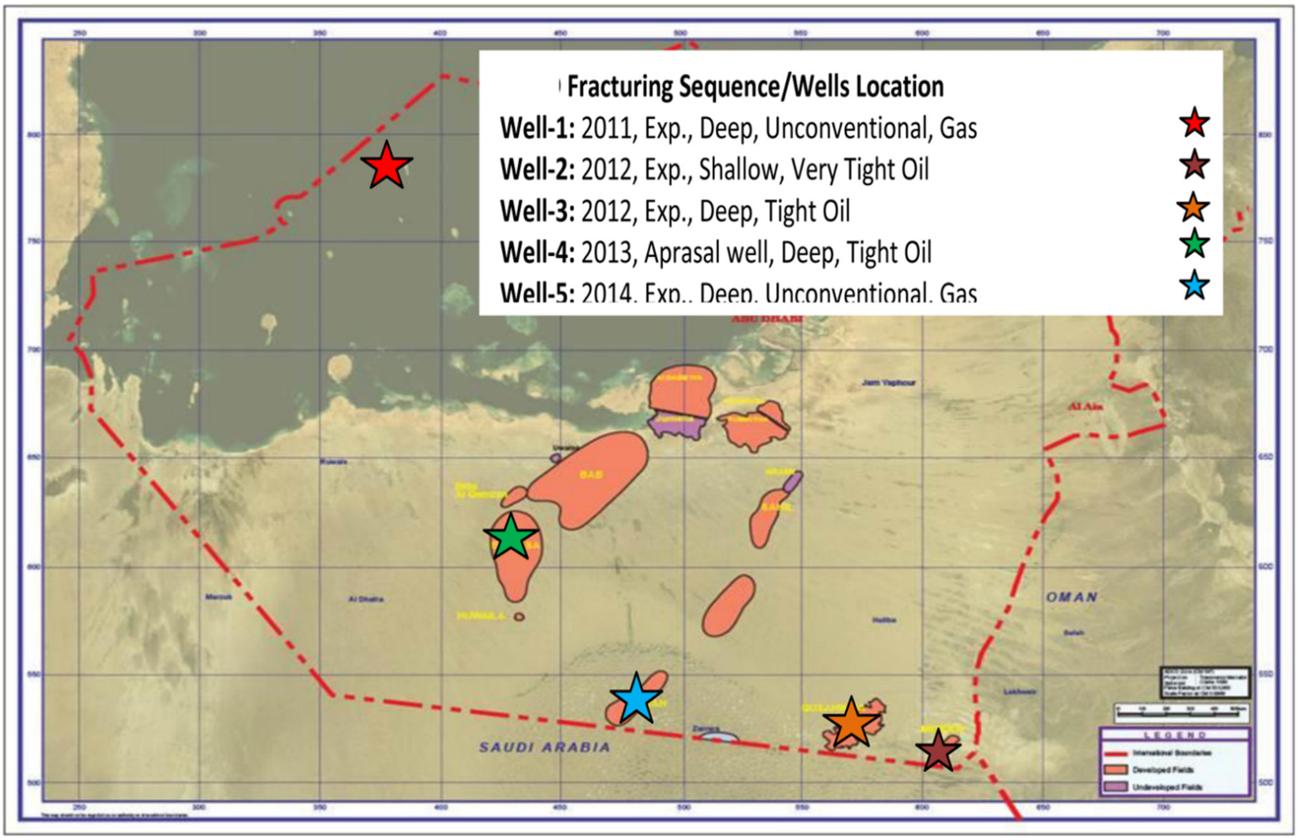


Figure 3. Fracturing sequence and well location map.

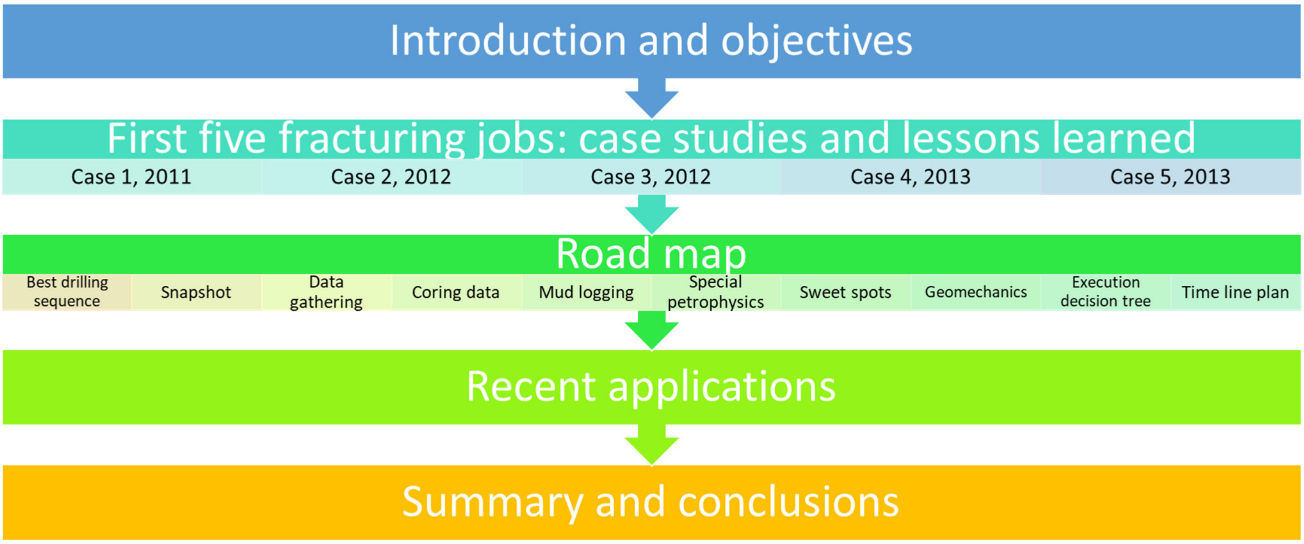


Figure 4. A flow chart illustrates the workflow of the paper.

2. First five fracturing jobs: Outcomes and lessons learned

The strategy for the Unconventional Reservoirs campaign-1 focuses on various fracturing techniques employed in unconventional resources, aiming to reduce both risk and cost while maximizing oil production. These fracturing techniques encompass conventional acid fracturing, surge-frac and proppant fracturing [30]. They were utilized to target a range of reservoir types, including those with near-wellbore damage, moderate to high permeability, shallow and deep formations, low-stress sandstone reservoirs and tight rock reservoirs.

2.1. Case 1, 2011

In the first case, an exploratory well was drilled in a deep, unconventional gas reservoir characterized by high-pressure and high-temperature conditions. The well's total measured depth reached 12,791 feet, and the reservoir exhibited a low porosity of 3% and very low permeability at 0.01 mD (Refer to Figure 5 for the open-hole logs). The well was completed using 3 ½" tubing and 7" casing, with a maximum allowable pressure of 8,500 psi.

Initially, a conventional acid stimulation attempt proved unsuccessful. Subsequently, a modified treatment employing hydrochloric acid (28% HCl) was carried out, leading to a successful breakdown of the reservoir and the initiation of gas flow (as evidenced by Figures 6 and 7). The success of this treatment was attributed to strategic planning and equipment availability, in conjunction with appropriate well-completion and geomechanical studies.

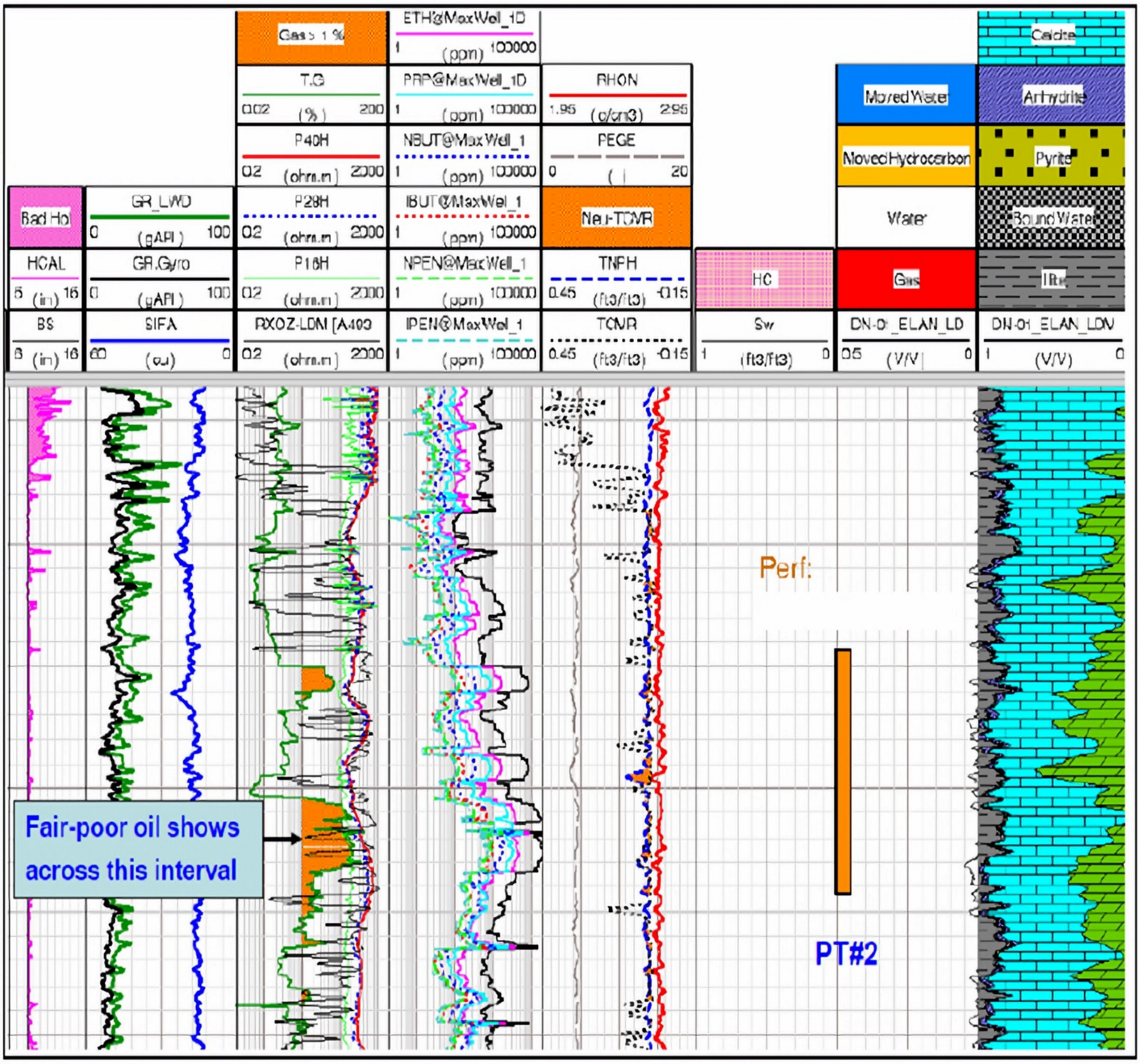


Figure 5. Case-1, open hole log interpretation.

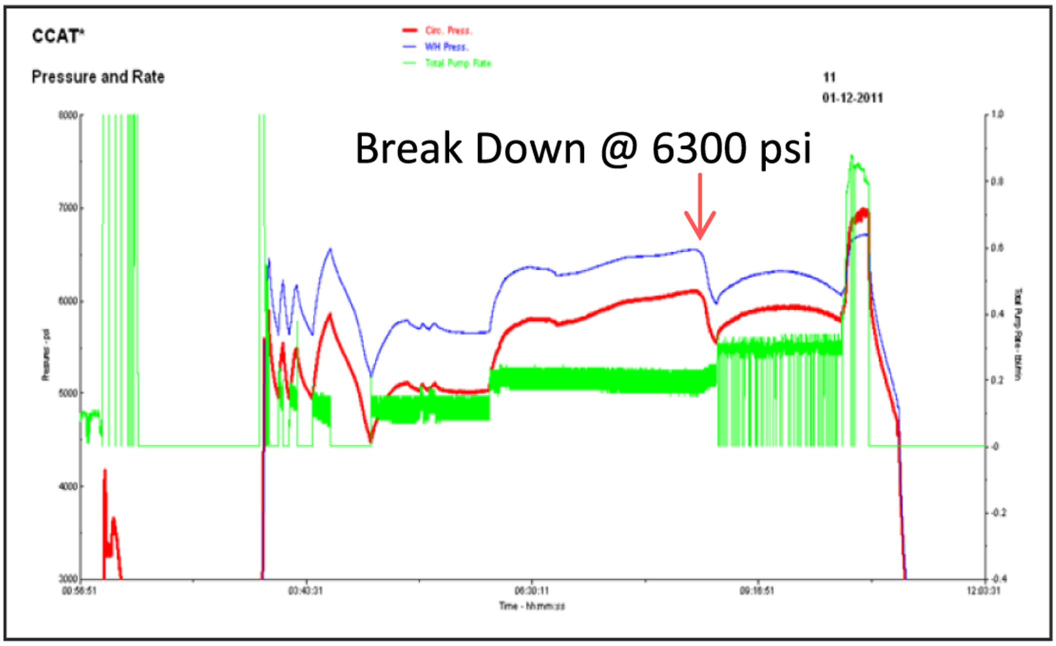


Figure 6. Case-1, successful break down (28% HCl, 6300 psi WHIP).

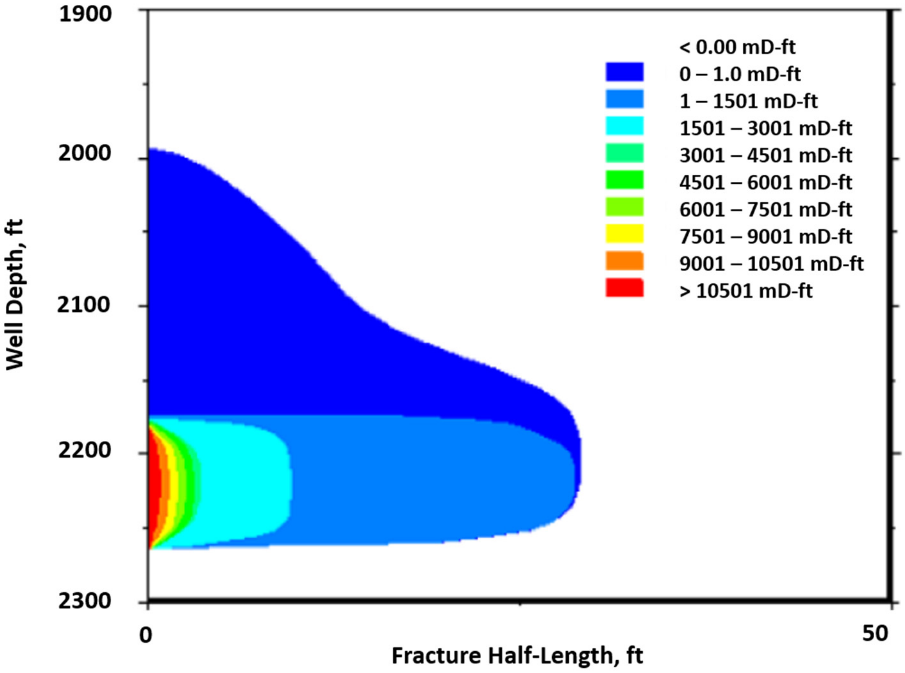


Figure 7: Case-1, Final fracture geometry.

2.2. Case 2, 2012

An exploratory well was drilled with a total measured depth of 3,552 feet in a tight formation that featured a shallow target within an oil reservoir. The reservoir exhibited a porosity of 15% and an anticipated permeability of 0.5 mD (Figure 8). The well was completed using 3 ½" tubing and 7" casing, and its maximum allowable pressure was set at 5,000 psi.

Cores were extracted from the well, revealing the presence of oil. However, while a Mechanical Earth Model (MEM) was constructed, no geomechanical analysis was performed on the well.

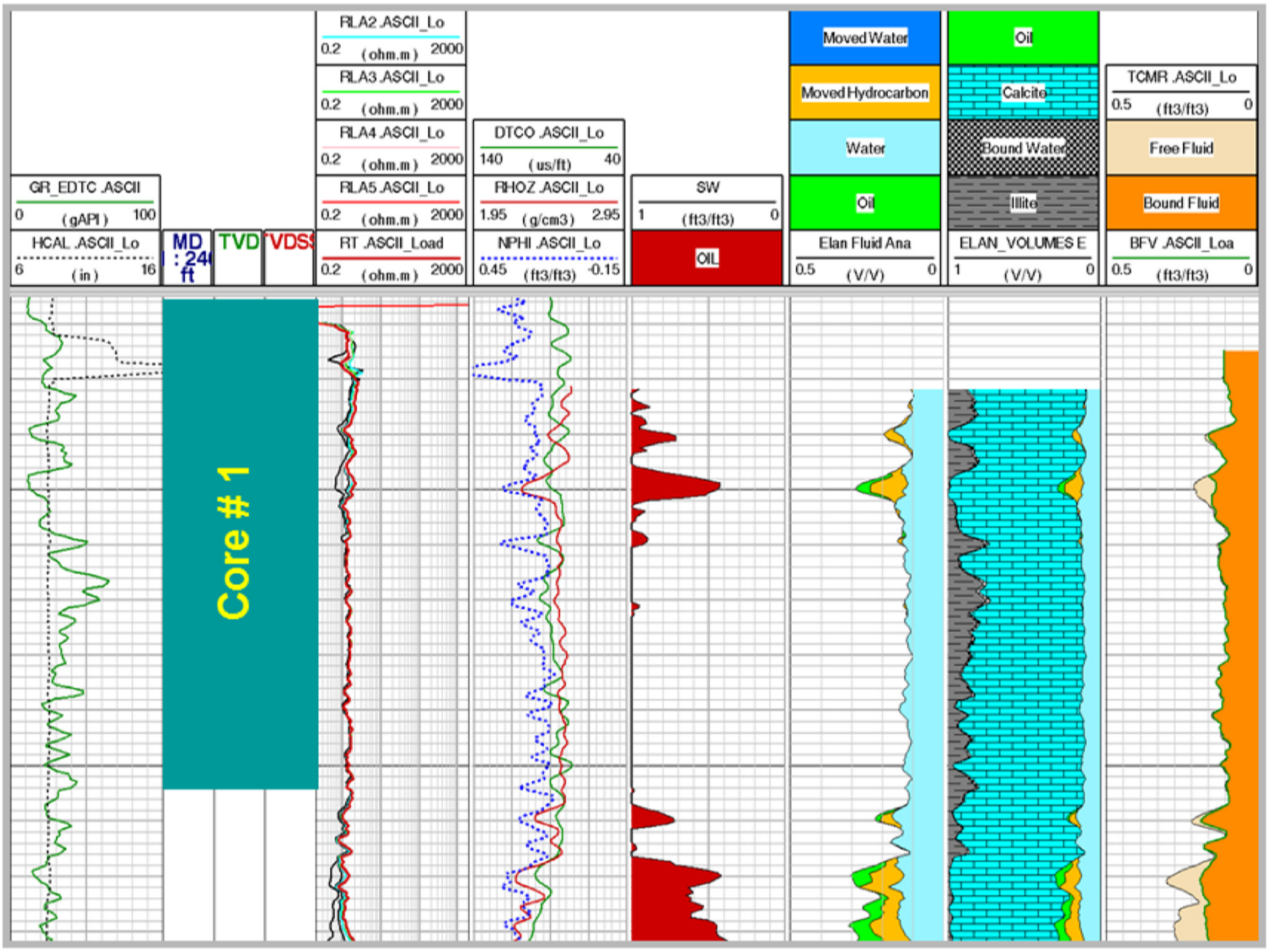


Figure 8. Case-2, open hole log interpretation.

A treatment was applied involving two conventional acid stimulation attempts, both of which proved unsuccessful. In response, a modification was made, and a small acid-fracturing operation was conducted using 200 barrels of 15% hydrochloric acid (HCl), (as depicted in Figure 9). This approach yielded some success, albeit with a limited fracture half length, (demonstrated in Figure 10). While the conventional acid stimulation trials failed, they led to the discovery of oil in this area for the first time, resulting in a production rate of 400 barrels of oil per day (BOPD). This experience offers several valuable lessons:

- Strategic planning and equipment availability play a crucial role in achieving a successful operation.
- The utilization of a MEM can enhance the potential for increased flow.
- Employing an acid-fracturing methodology can boost the chances of discovering oil at an optimal cost.
- Conducting a geomechanical study can assist in optimizing the fracture design for the development.

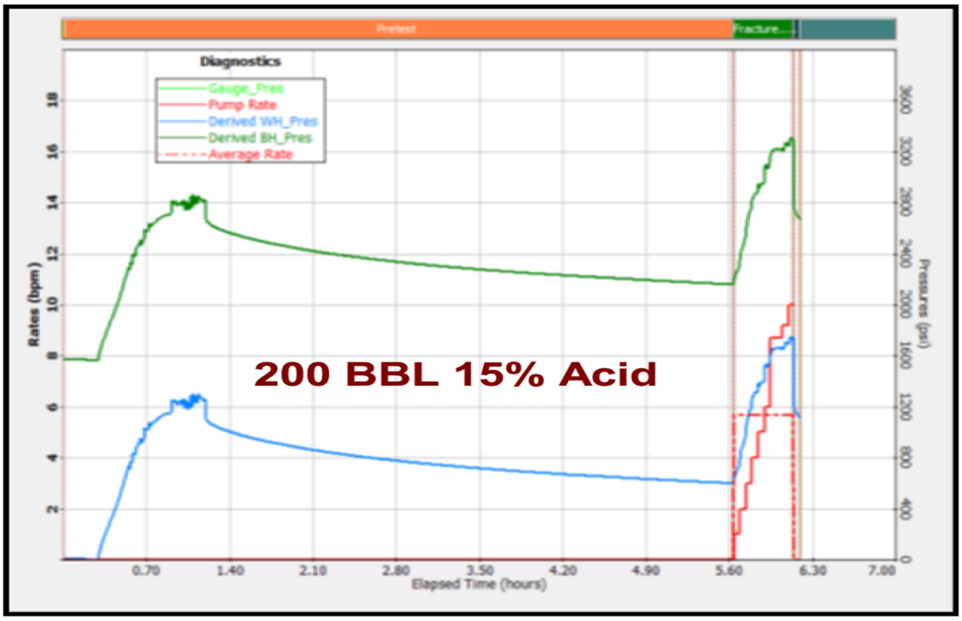


Figure 9. Case-2, successful acid-frac (15% HCl, 2800 psi WHIP).

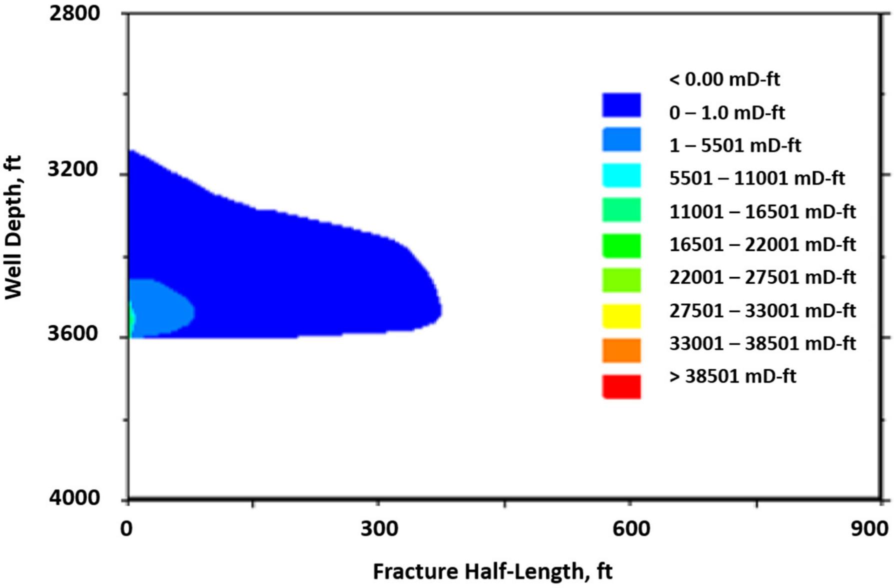


Figure 10. Case-2, final fracture geometry.

2.3. Case 3, 2012

This case involved an exploratory well in a tight formation with a deep target within an oil reservoir. The well had a total measured depth of 5,590 feet, and the reservoir exhibited a porosity of 18% and an expected permeability of 1 mD, (illustrated in Figure 11, which displays the analysis from the pre-job step rate test). The well was completed using 3 ½" tubing and 7" casing, with a maximum allowable pressure of 5,000 psi.

The initial plan encompassed a matrix stimulation, followed by a mini-frac and a primary frac job. Cores were extracted from the well, indicating the presence of oil. MEM was utilized; however, no geomechanical analysis was conducted on the well.

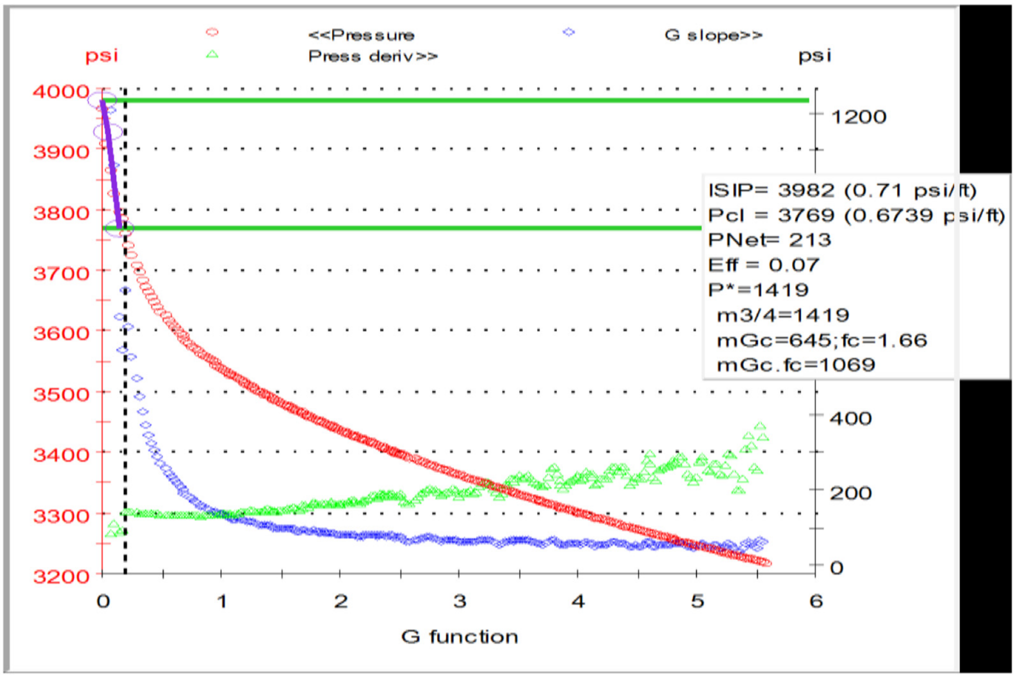


Figure 11. Case-3, decline curve analysis from the pre-job step rate test.

Conventional acid stimulation trials were initially employed but yielded low production flow rates. To optimize the frac-model, a mini-frac treatment was conducted, followed by an acid-frac treatment utilizing 250 barrels of 15% hydrochloric acid (HCl), (Figure 12). The acid-frac treatment turned out to be successful, with unexpected propagation geometry, (depicted in Figure 13). This endeavor led to the discovery of oil in the area, with a production rate of 350 barrels of oil per day (BOPD), affirming the presence of hydrocarbons.

Despite the success of the acid fracturing treatment, a few factors may have contributed to the production rate being lower than anticipated:

- Substantial fluid loss was observed during the injection and the primary job, which might have hindered the creation of a long conductive fracture.
- The use of low pump rates could have limited the ability to counteract high fluid loss.
- Poor stress contrast at the perforations may have caused the fracture to deviate from the target zone.
- Extensive perforated intervals may have struggled to maintain the fracture height.

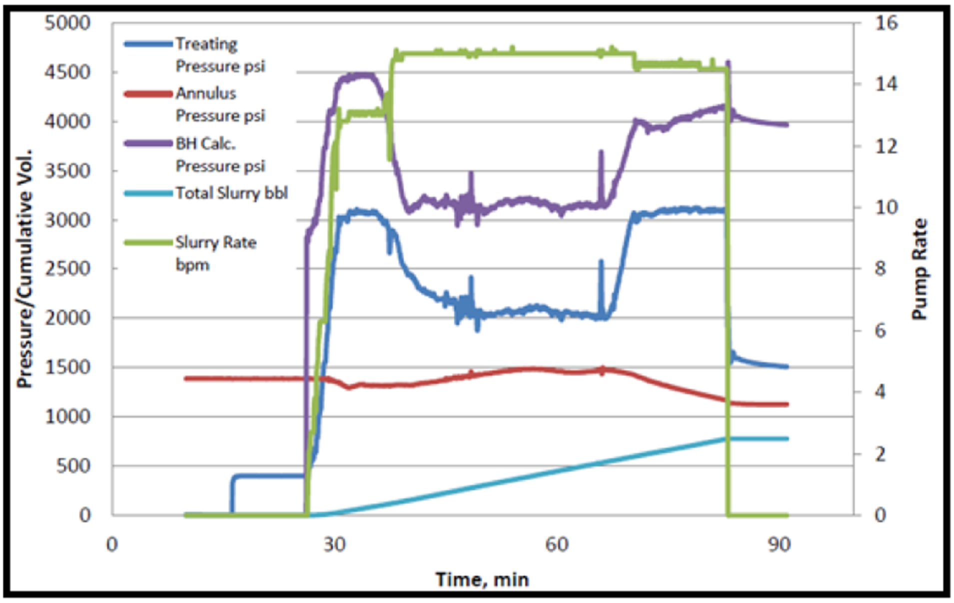


Figure 12. Case-3, pressure and rates for the main job (acid-frac).

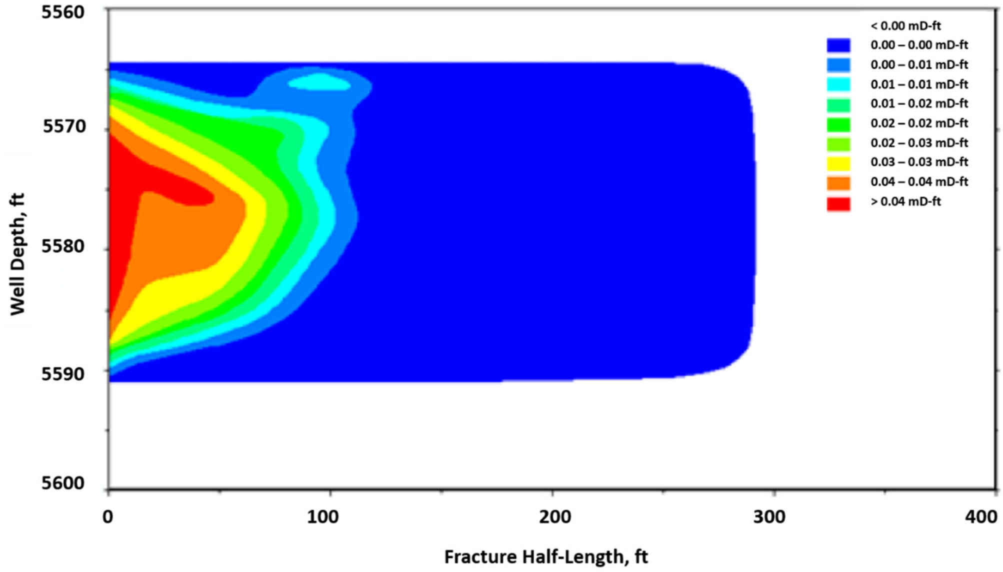


Figure 13. Case-3, final fracture geometry.

2.4. Case 4, 2013

An appraisal well was drilled to explore a deep formation within an oil reservoir characterized by moderate permeability and severe formation damage. The well reached a total measured depth of 11,200 feet, and the reservoir displayed a porosity of 20% with an anticipated permeability of 3 mD (Figure 14). The well completion used was 3 ½" tubing and 7" casing with a maximum allowable pressure of 5,000 psi.

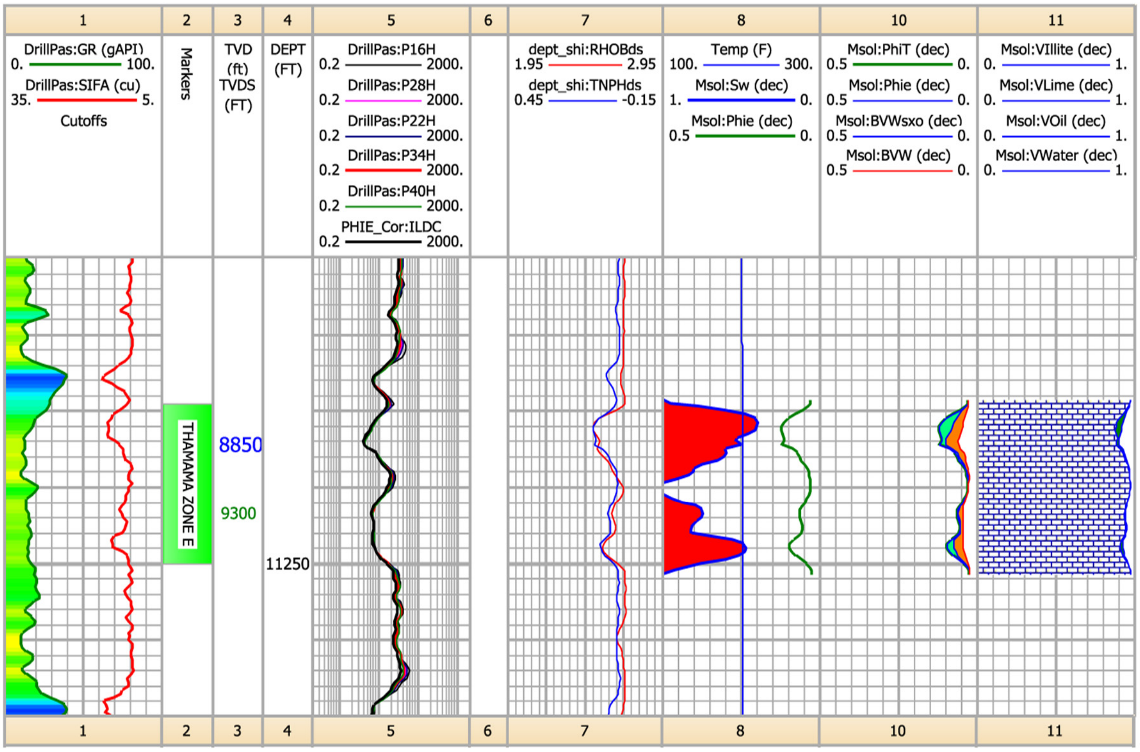


Figure 14. Case-4, open hole log Interpretation.

After conducting conventional acid stimulation trials, which were originally planned as the sole stimulation method, no oil flow was achieved. However, an unplanned acid-frac operation using 150 barrels of 28% hydrochloric acid (HCl) was carried out. This acid-frac treatment proved successful, resulting in a daily production rate of 1,000 barrels of oil per day (BOPD), (as shown in Figure 15). The success of this treatment suggested that the formation had severe damage, likely caused by the initial drilling process, which the conventional acid stimulation method had failed to adequately address.

The acid fracturing of this formation provided evidence of the severe formation damage stemming from the original borehole. In this case, the target for the Lower Treatment Top (LTT) was not achieved, possibly due to communication issues between the tubing and casing (TBG/CSG). Several potential causes for this could include equipment and technical staff shortages for the job, limited experience with acid-frac treatment, inadequate job planning, particularly concerning time management and possible operational confusion or a lack of clarity in the process.

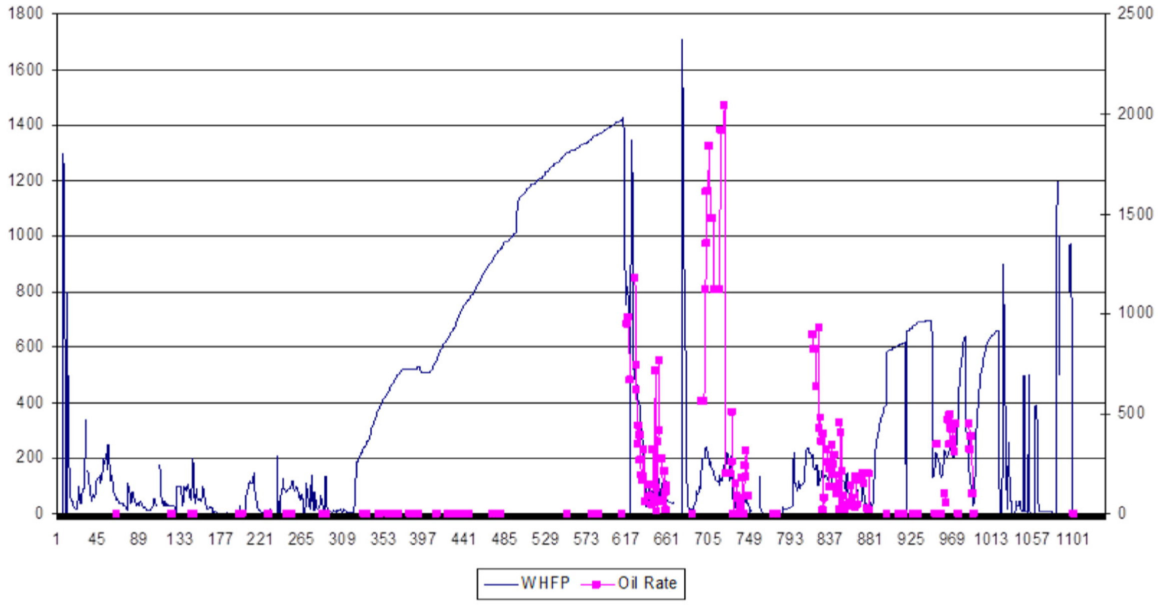


Figure 15. Case-4, well test results.

2.5. Case 5, 2013

An appraisal well was drilled in an unconventional deep gas reservoir characterized by low porosity (3–4%) and micro-permeability (0.002 mD), as illustrated in Figure 16. The completion of this well employed 3" tubing and 7" casing, with a maximum allowable pressure of 7,000 psi.

The initial plan was to conduct a production test using a 10-point Surgi-Frac stimulation technique. However, the Surgi-Frac stimulation was unsuccessful, and no flow rate was achieved, as seen in Figure 17. Several possible reasons for this failure include:

- Uncertainty regarding whether cuts were made in the casing during the hydra-jetting process.
- Challenges associated with controlling depth due to the use of computer tomography (CT), where only 4 points were cut with a 10–20 ft shift.
- Shallow rock penetration potentially results in limited fracture propagation.
- Limited injection pressure may have constrained injected volumes and reduced fracturing efficiency.

As an alternative approach, advanced techniques, such as deep perforation using Stim-Tube, were employed, and the well was re-stimulated (as depicted in Figure 18). This led to an increase in pressure and the successful flow of gas to the surface. Table 1 provides a summary of the five fracturing jobs (Case-1 to Case-5), including information on the design, execution, lessons learned and results.

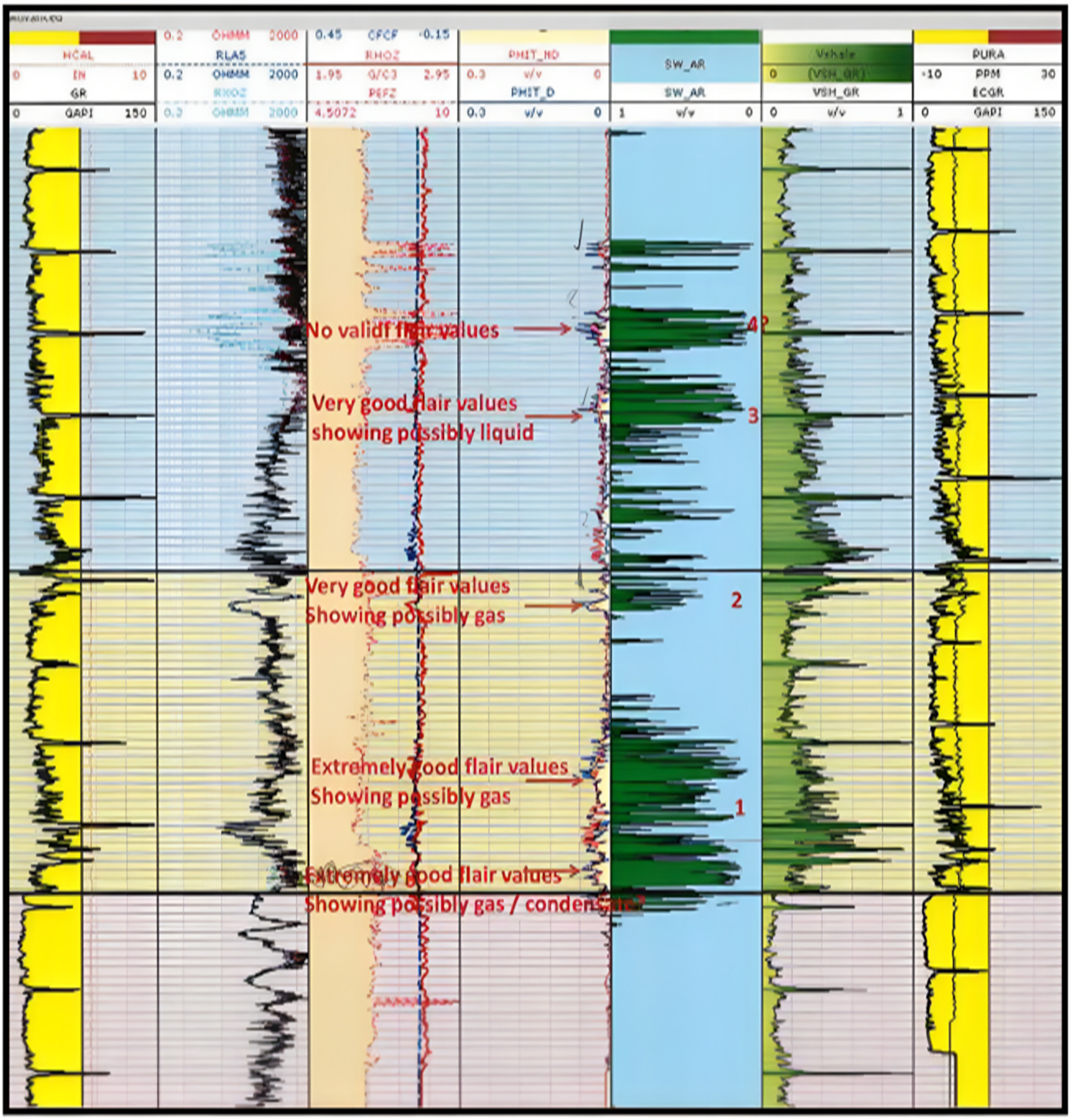


Figure 16. Case-5, open hole log interpretation.

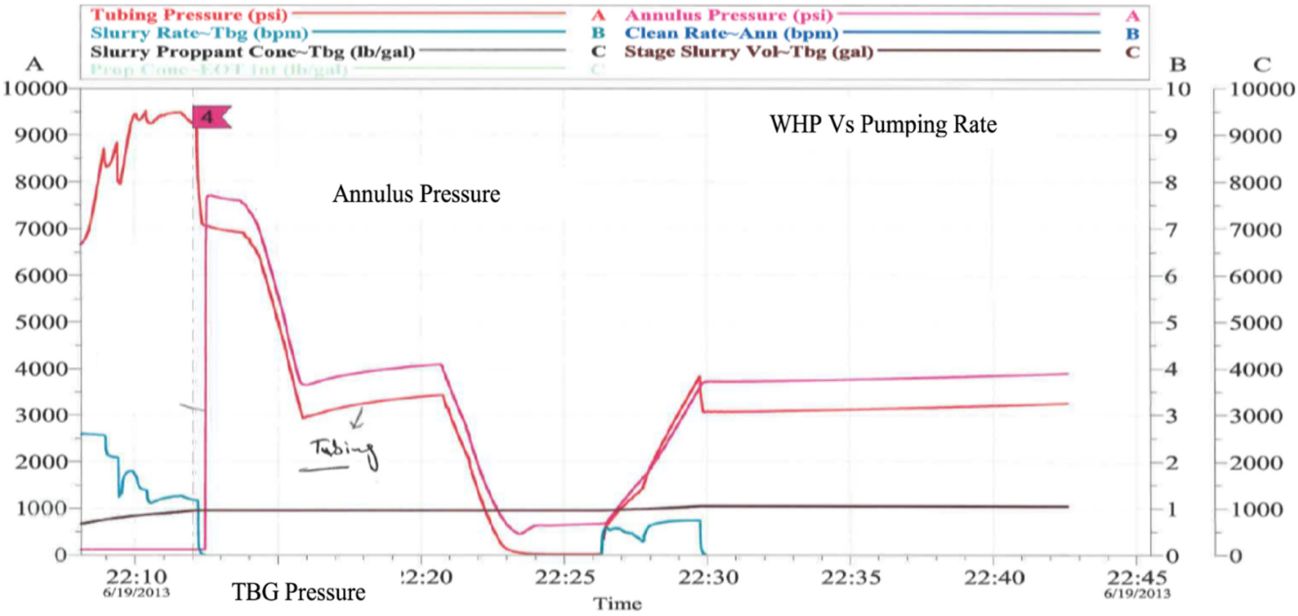


Figure 17. Case-5, treatment pressure.

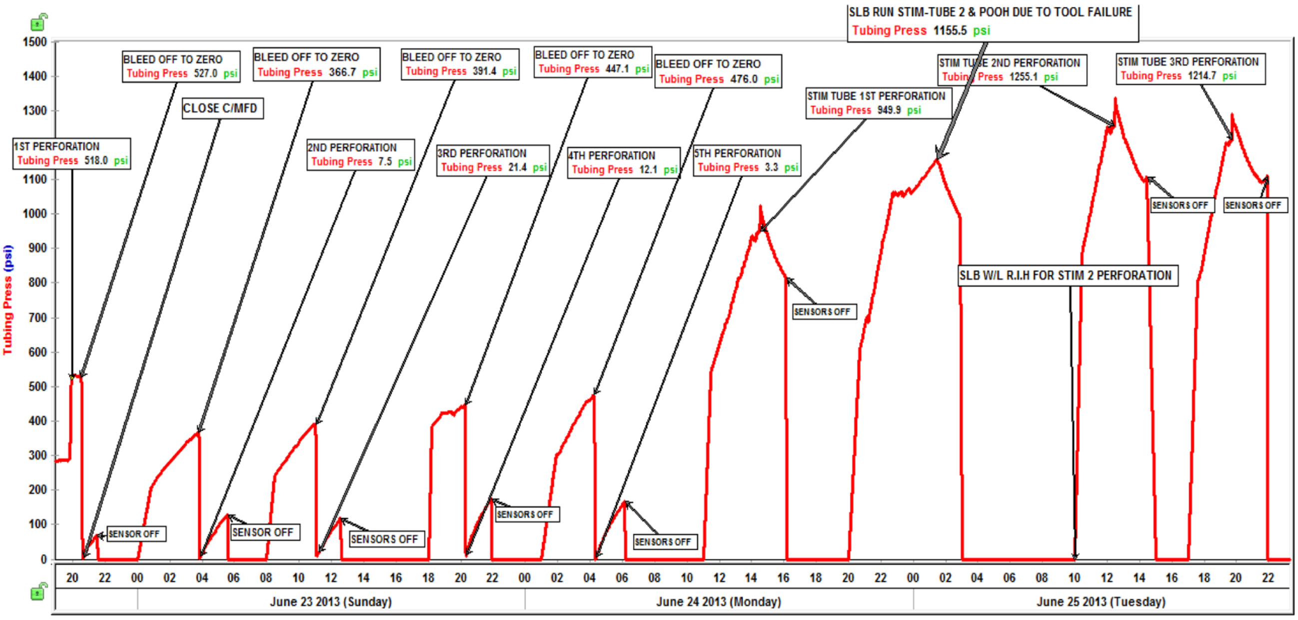


Figure 18. Case-5, perforation results.

Table 1. Summary of all of the five fracturing jobs (case-1 to case-5): Design, execution, lessons learned and results.

Case#	Case-1	Case-2	Case-3	Case-4	Case-5
Well type and reservoir data	Exploration well, 12,791 ft MD, HP/HT, 3% porosity, and 0.01 mD permeability	Exploration well, 3,550 ft MD,15% porosity, and 0.5 mD expected permeability	Exploration well, 5,590 ft MD,18% porosity, and 1 mD expected permeability	Appraisal well, 11,200 ft MD, 20% porosity, and 3 mD expected permeability	Appraisal well, 11,600 ft MD, 3–4% porosity, and 0.002 mD expected permeability
Completion data	3 ½ " TBG, 7" CSG, with 8,500 psi maximum allowable pressure	3 ½ " TBG, 7" CSG, with 5,000 psi maximum allowable pressure	3 ½ " TBG, 7" CSG, with 5,000 psi maximum allowable pressure	3 ½ " TBG, 7" CSG, with 5,000 psi maximum allowable pressure	3 ½ " TBG, 7" CSG, with 7,000 psi maximum allowable pressure
Plan	Production test for deep reservoirs with matrix stimulation	Production test with matrix stimulation	Production test with matrix stimulation then mini frac followed by main frac	Production test with matrix stimulation	Production test with 10 points of Surgi-Frac stimulation
Fluid type	Gas	Oil	Oil	Oil	Gas
Core	Not available and no geomechanical work was done	Available with oil shows, Mechanical Earth Model (MEM) was created, and no geomechanical work was done	Available with oil shows, MEM was created, and no geomechanical work was done	Not available and no geomechanical work was done	Not available and no geomechanical work was done
Applied treatments	Conventional acid stimulation trial was performed with no success	Two conventional acid stimulation trials were performed with no success	Conventional acid stimulation trials were performed with low flow rate results	Conventional acid stimulation trials were performed with no flow results	10 points of Surgi-Frac stimulation technique were performed
Mini frac treatments	---	---	Was performed to calibrate the frac model	---	---

Continued on next page

Case#	Case-1	Case-2	Case-3	Case-4	Case-5
Frac treatments	Break down with 28% HCl to confirm the fracturing possibility	Small acid-frac was performed with 200 bbls of 15% HCl	Acid-frac was performed with 250 bbls of 15% HCl	Un-planned, acid-frac was performed with 150 bbls of 28% HCl	Advanced deep perforation with Stim Tube were performed as an alternative action, then the well was re-stimulated
Acid-frac outcome	Successful break down of the formation	Successful acid-frac with limited frac half length	Successful acid-frac with unexpected geometry propagation	Successful acid-frac	Unsuccessful Surgi-Frac stimulation. Then, pressure was built up and gas started to flow to the surface
Test results	Gas discovery for the first time through the unconventional source rock	Oil discovery for the first time in this area (400 BOPD)	Oil discovery for the first time in this area (350 BOPD)	Oil flow rate (1000 BOPD)	Gas discovery for the first time in this area
Lessons learned	* Strategic planning and equipment availability plays the main cause of achieving a successful job * Suitable Completion and Geomechanical study (MEM) supports in achieving an enhanced potential flow	* Strategic planning and equipment availability plays the main cause of achieving a successful job * MEM supports in achieving an enhanced potential flow * acid-frac methodology enhances the possibility of discovering oil with optimum cost * Geomechanical study could help in obtaining the optimum frac design for the development phase	* Acid fracturing of this formation proved evidence of hydrocarbons	* Acid fracturing of this formation proved the evidence of severe formation damage due to the original hole effect	* Unsuccessful Surgi-Frac stimulation job

3. Road map

A strategy was developed based on the lessons learned from the five fracturing jobs conducted. This study played a crucial role in achieving the desired fracturing execution without disrupting the company's ongoing plans. Various techniques were reviewed and evaluated to align with the company's objectives, with a focus on operational risk, reservoir quality and the limited experience in the area as the primary targets, followed by operational costs. A roadmap was created, considering the following 10 key components.

3.1. The best way drilling sequence

One of the critical elements in oil drilling plans is the selection of the optimal well sequence to support the project and enhance the learning curve. While this may not always be the exact approach, most of the 10 wells in the plan are determined by the following considerations, as depicted in Figure 19:

- Drilling from shallow to deep targets, ranging from 4,000 to 9,600 feet.
- Initiating from the western area and progressing towards the east.
- Commencing with high-potential areas and moving to low-potential ones.
- Beginning with relatively straightforward drilling and then advancing to more complex wells, with fewer well design complications).

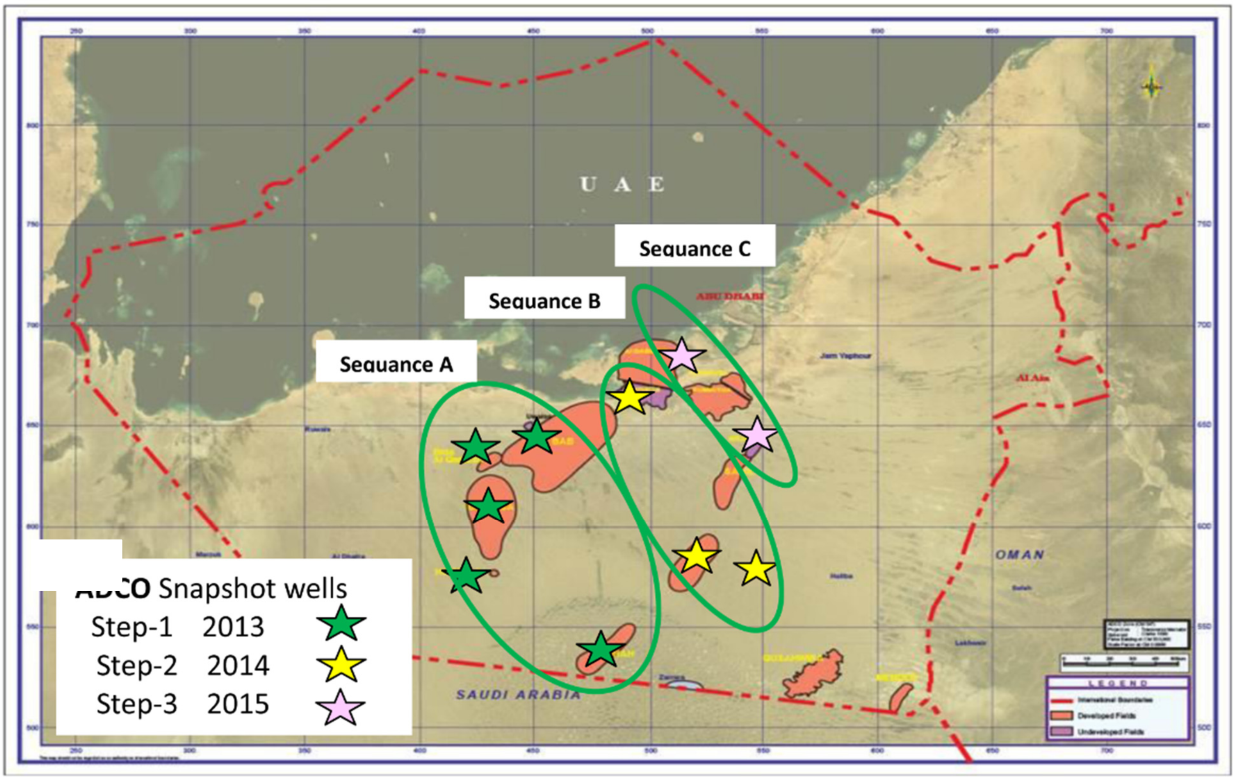


Figure 19. Well drilling sequence.

3.2. Snapshot concept

Unconventional reservoirs, like shale gas and tight oil, possess distinct characteristics that set them apart from traditional reservoirs. These distinctions include a low net present value and a fast-declining production profile, rendering them high-cost projects [2,4,8,31]. The exploration and appraisal of unconventional reservoirs are also typically more expensive due to the need for extensive data to identify the "sweet spot" for development and evaluate fracturing characteristics [32].

To mitigate costs, one strategy involves using existing development wells for "snapshot" activities, such as data collection or fracturing, is recommended. For instance, in a specific campaign, only one out of ten wells drilled was dedicated to fracturing, a decision based on data from an adjacent well. This approach resulted in an 80% cost savings compared to drilling dedicated wells, enabling the program to progress. Furthermore, the well was drilled at a shallower depth and lower cost, with its objectives aligned with other reservoir appraisal programs. Leveraging existing wells for snapshot activities can be an effective means to cut costs and support the appraisal of unconventional reservoirs.

3.3. Data gathering program

Unconventional resources necessitate different methods and technologies for their exploration, appraisal and development, often defying the application of traditional rules of thumb. Teams dealing with unconventional resources may need to embrace a more flexible and adaptive approach to successfully identify and develop these resources. The demarcation between appraisal and development phases might be less distinct, leading teams to concurrently manage acreage, explore, appraise and develop these resources to expedite commercial production.

The approach proposed by Burkholder et al. [33] offers a systematic method for evaluating and comparing appraisal strategies in resource plays, particularly unconventional reservoirs. This approach involves the formulation of an overarching field appraisal plan, identification of key uncertainties, and determination of the data required to make informed decisions regarding exploration and appraisal targets. Additionally, it entails pilot studies to ascertain optimal well spacing and completion configurations, which can provide a clear understanding of available appraisal options and the best course of action for informed decision-making.

Appraising conventional reservoirs has a well-established history of development, resulting in effective heuristics for reducing uncertainty and guiding development decisions. Typically, this is achieved through a combination of well data, seismic information, core tests, and geologic and reservoir modeling. However, achieving a comparable level of certainty in the appraisal of unconventional resources is often challenging. This challenge arises from the absence of a "Rosetta Stone" for translating appraisal information into reliable forecasts of development outcomes, as well as the ongoing complexities associated with developing unconventional resources, which frequently entails years of learning and optimization.

3.4. Strengthening knowledge based on the impact of case studies

Achieving success in the appraisal and development of unconventional plays necessitates a multi-disciplinary approach and close collaboration among various teams. Nonetheless, it is essential to have a single individual or group with the requisite knowledge and expertise to oversee all facets of the process [20]. In the pursuit of meeting future energy demands, the company has been actively exploring new technologies and scenarios aimed at optimizing project operation time and costs while enhancing the likelihood of success in the appraisal and development of these resources.

3.4.1. Extending coring

Extending Coring is also known as Long Barrel coring. This approach offers a cost-effective solution to fulfill the objectives of continuous coring across formations of interest. It achieves a reduction in the number of trips, rig time, and drilling costs by utilizing longer core barrels, typically ranging from 120 to 810 feet in length. The process of extended coring requires precise timing and planning.

A comparison between conventional and extended coring can be found in Table 2, highlighting the advantages of extended coring in terms of cost and time efficiency. This method can significantly save time and costs when compared to conventional techniques. The collective time and cost savings for 8 wells amount to 76 days and 4.15 million USD, respectively.

Table 2. Comparison between conventional and extended coring.

Case	Well	Hole size	Length	Conventional		New technology (extended)**		
				Runs	Days	Runs	Days	Days/Cost saving
Case 1	X-71	8 ½”	480	6	15	2	5	10 days/$0.08 MM
Case 2	X-71	6”	540	6	21	2	11	10 days/$0.50 MM
Case 3	X-30	8 ½”	420	5	13	1	6	7 days/0.45 MM
Case 4	X-30	8 ½”	780	9	26	2	8	18 days/$0.90 MM
Case 5	X-64	12 ¼”	186	2	4	2	4	Nil
Case 6	X-64	8 ½”	659	7	14	3	8	6 days/$0.30 MM
Case 7	X-03	8 ½”	480	6	18	3	6	12 days/$0.60 MM
Case 8	X-04	8 ½”	480	6	18	3	6	12 days/$0.60 MM
	Total		4025	47	130	18	54	76 days/$4.15 MM

**Extended Coring Saved total of 4,150,000 USD for Onshore Operation.

3.4.2. Wire line coring

An innovative technique employs a wireline-retrievable coring platform, enabling swift transitions between normal drilling mode (Quick-Drilling), pressure-coring (Quick-Capture Coring), and conventional coring (Quick-Coring) modes without the necessity of removing the drill string. This technique has successfully produced cores with a combined length of 338 feet and a remarkable recovery rate of 99% from the formation interval, ranging from x,251 to x,864 feet true vertical depth subsea (TVDss).

Table 3 outlines the drilling and coring configurations implemented, the drilled and cored intervals, and the corresponding core recoveries. This technique offers the advantages of seamless transitions between various coring modes, eliminating the need to pull out the drill string, and achieving high core recovery rates.

Table 3. Overview of the drilled and cored intervals.

Run #	Core#	Configuration	Depth in Ft	Depth out Ft	Cut Ft	Ree Ft
RIH with Quick-Drilling and Drill 10ft to Core Point (Core#1)						
1		Quick-Coring	x,241	x,251	10	
Retrieve Quick-Drilling Assembly, Drop 60ft Inner Core barrel						
2	1	Quick-Coring	x,251	x,295	44	44
3	2	Quick-Coring	x,295	x,325	30	30
Switch to Quick-Drilling and Drill 275ft to Next Core Point (Core#3)						
4		Quick-Drilling	x,325	x,600	275	
Wireline Retrieve Quick-Drilling Assembly, Drop 60ft Quick-Coring Inner Core barrel						
5	3	Quick-Coring	x,600	x,660	60	60
6	4	Quick-Coring	x,660	x,663	3	1
7	5	Quick-Drilling	x,663	x,723	60	60
RIH with Quick-Drilling and Drill few inches to clear any stump on bottom						
8		Quick-Drilling	x,723	x,723	0	
POOH Drill String to RIH with Quick-Capture Pressure Coring Barrel						
9	6	Quick-Capture Pressure Coring	x,723	x,723.7	9.7	8.8
Wireline Quick-Capture Pressure Coring Core and L/D QCAP Assembly, RIH with Quick-Coring Assembly						
10	7	Quick-Coring	x,733	x,793	60	60
11	8	Quick-Coring	x,793	x,853	60	60
12	9	Quick-Coring	x,853	x,864	11	11
Switch to Quick-Drilling and Drill 174ft to TD						
13		Quick-Drilling	x,864	x,038	174	
Retrieve Quick-Drilling Assembly, POOH Open-Ended						

3.5. Advanced mud logging concept

Geochemistry is the scientific study of the chemical composition of rocks, minerals, water, and samples of oil and gas. It aims to comprehend the underlying geological processes that have influenced these materials. By examining the chemical constituents of these samples, geochemists can gain valuable insights into the depositional environment, thermal history and fluid migration within the rocks. This information is instrumental in understanding the processes responsible for generating hydrocarbons, including source rock deposition, burial, generation, expulsion, entrapment and post-entrapment alterations [34]. Geochemistry also contributes to comprehending compositional changes that occur during production, which can enhance predictions of variations in oil and gas composition in the field.

Significant studies have been conducted on core and cuttings samples from wells within the Wasia Group to measure parameters like total organic content (TOC) and pyrolysis yield. Furthermore, a comprehensive fingerprinting analysis was performed using Gas Chromatography-Mass Spectrometry (GC-MS) on 80 oil samples and 50 source rock extracts. The acquisition of over 3,000 feet of core from the Wasia Group has facilitated a profound understanding of the play through an extensive geochemical evaluation program. The use of mud logging and advanced mud logging, in conjunction with petrophysical assessments, has proven to be exceptionally beneficial in ranking zones of interest for testing and predicting the hydrocarbon phase.

3.6. Intensive and special petrophysical data

Gathering petrophysical data plays a critical role in identifying unconventional reservoirs. Extensive wireline logging, coupled with routine and special core analyses, has been conducted in various wells. The primary objective is to delineate areas with high Total Organic Carbon (TOC), which are the primary targets in these formations. Additionally, logs and other studies, such as sonic log data, are used to calculate key geomechanical properties like Poisson's ratio and Young's modulus. The logs that are run and their primary objectives are as follows:

- High Resolution Lateralog: Utilized due to the high resistivity values in high-TOC reservoirs, this tool measures true resistivity (Rt), which is necessary for water saturation (Sw) calculations.
- Density-Neutron Tool: Primarily used to measure total porosity and for photoelectric lithology measurements.
- Spectral Gamma Ray (GR): Employed to differentiate natural GR into its major elements (Potassium, Thorium and Uranium) and accurately quantify organic matter-related GR (Uranium) and shale-related GR (Potassium and Thorium).
- Dielectric Tool: Assists in calculating high-resolution water-filled (SXO) porosity for hydrocarbon identification.
- Nuclear Magnetic Resonance (NMR): Aids in measuring accurate porosity values, determining porosity partitions, volumes of free and bound fluid, fluid type, SXO derived from capillary pressure curves, and rock type. NMR can also detect a porosity deficit, used to quantitatively assess the volumes of kerogen and bitumen-related materials.
- Advanced Cross Dipole Sonic: Used for seismic calibration, assessing reservoir anisotropy, and future geomechanical studies.
- High-Resolution Imaging: Supports dip picking, fault/fracture analyses, texture assessments and integration with core data.
- Advanced Elemental Spectroscopy: Identifies mineral volumes and directly computes TOC.

Two attempts were made to utilize advanced formation tester tools to obtain valid formation pressure data in these formations. However, due to the tight nature of the formations, as revealed by core results, all formation testing tools were excluded in the remaining campaign wells.

3.7. Defining sweet spots

Following the drilling of 10 wells and the application of comprehensive data gathering, an integration of advanced mud logging, specialized petrophysical data, and core analysis was carried out for each well. This process facilitated the identification and definition of zones of interest. Subsequently, all cases were thoroughly studied to select the sweet spots. Figure 20 provides examples of the logs that proved valuable in pinpointing the zones of interest and illustrates how they are integrated with mud logs and core analysis results.

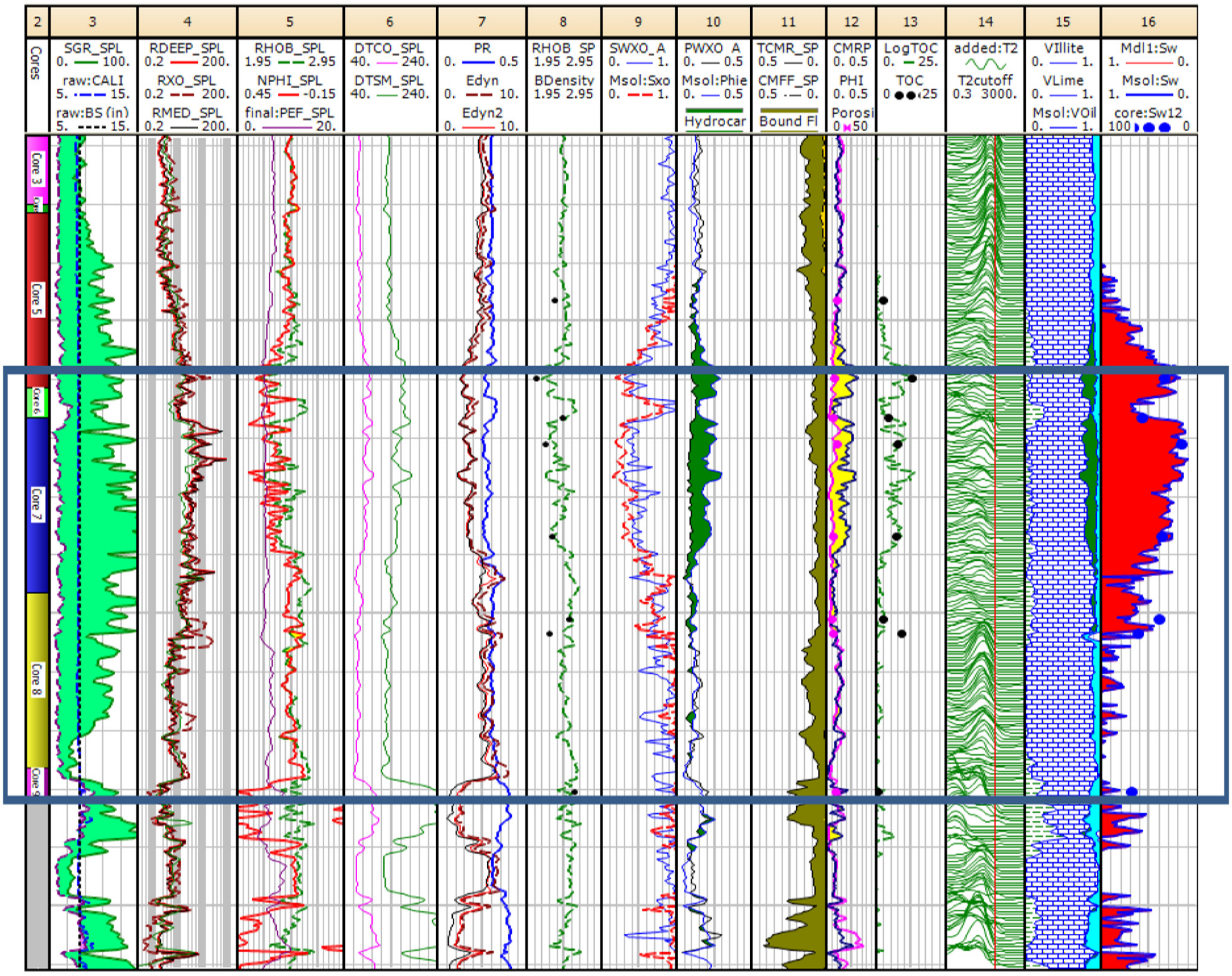


Figure 20. Petrophysical data integrated with mud logs and core analysis results.

3.8. Geomechanics for fracturing design of unconventional reservoirs

A workflow is discussed that integrates multidisciplinary data to develop an integrated approach model aimed at reducing exploration-drilling risk and optimizing reservoir appraisal in tight carbonates. The characterization of the reservoir and the construction of a robust HF model are accomplished through the use of core samples, wireline logs, CT scans, scanning electron microscopy (SEM) and thin sections.

The heterogeneous and anisotropic nature of the rocks in the Abu Dhabi tight carbonates plays a crucial role in determining the geometry and complexity of HF stimulation treatments. Solving the stress field perpendicular to a borehole requires the presence of material that has not failed and behaves in a linear elastic manner. This measurement also assumes that the borehole is uncased and anticipates that a failure will occur parallel to the hole axis in the direction of minimum stress. To create a pressure seal in an open hole, packers must be at a higher pressure than the injected fluid, which can potentially initiate failure unless pre-existing rock fractures are present in the test zone.

HF in the tight carbonate of the Lower Cretaceous formation in onshore Abu Dhabi is an essential stimulation technique for production enhancement, as depicted in Figure 21. However, the complexity of the fracture patterns arises due to the presence of planes of weakness, faults and natural fractures, which often lead to more intricate fracture patterns than the planar geometry assumed in the models discussed above. To optimize the HF process, it is crucial to comprehend the interaction between the induced fractures and the pre-existing fractures, faults and planes of weakness.

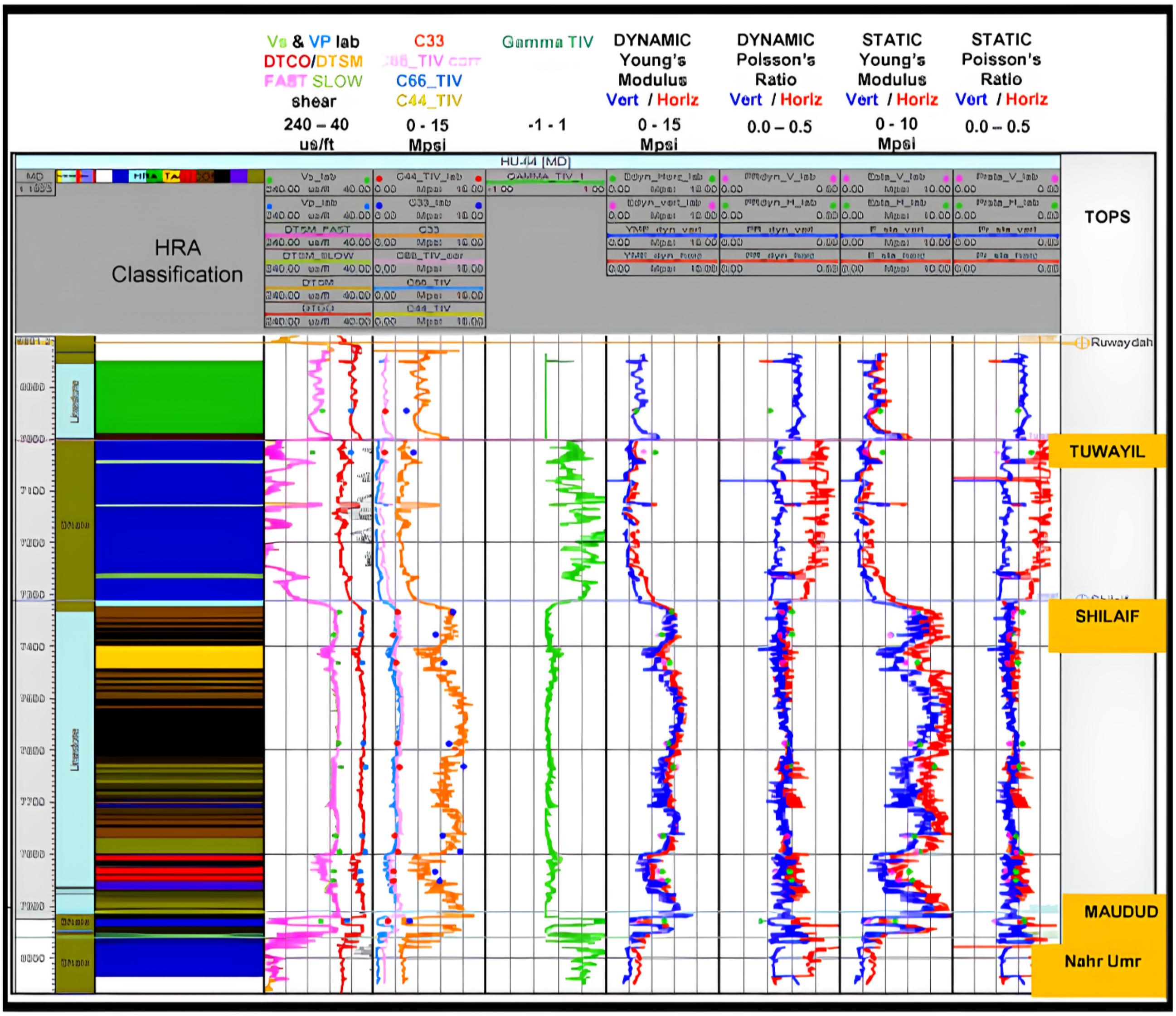


Figure 21. Anisotropic elastic properties of Well-A. Lab-measured dynamic Young's modulus and Poisson's ratio from vertical and horizontal plugs were used to calibrate the calculated dynamic anisotropic elastic properties.

A geomechanical model has been developed to simulate the interaction between HF and natural fractures, allowing for an assessment of how geomechanics impacts potential productivity in these naturally fractured formations. Three distinct cases were examined to observe the effects of natural fracture geometry, fracturing treatment and the mechanical properties of the sealed fractures, as the majority of the carbonates in Abu Dhabi are sealed.

Leveraging image data and geomechanical modeling, a one-dimensional (1D) high-resolution geomechanical model was constructed and calibrated. This model generates a stress profile essential for fracture design. The fracture geometry can be influenced to some extent by adjusting pumping rates, fluid viscosity and proppant loading. The degree to which a reservoir forms complex fracture networks, breaks into fresh rock, or creates simple bi-wing fractures depends on the design of the stimulation treatment. The creation of a complex fracture network is influenced by factors such as the rheology of the stimulation fluid, rock properties and the presence and orientation of preexisting planes of weakness that act within the stress state of the reservoir. In the Wasia Group, the success of HF is dependent on the mechanical properties of the rock and the dip and orientation of preexisting planes of weakness in the rock under the current stress state.

The developed geomechanical model was employed to analyze and predict the potential performance and risks of HF. It involved identifying stress barriers, determining fracture geometry attributes, assessing near-well tortuosity and evaluating the level of stress anisotropy. The model's attributes align with actual fracturing data. Some of these attributes, like near-wellbore pressure drop and the overall ease or difficulty of placing a treatment, proved valuable for determining the location of perforations and stages as well as guiding the placement of the next lateral well. The model demonstrated that heterogeneity had a significant impact on the final geometry of HF, as depicted in Figure 22.

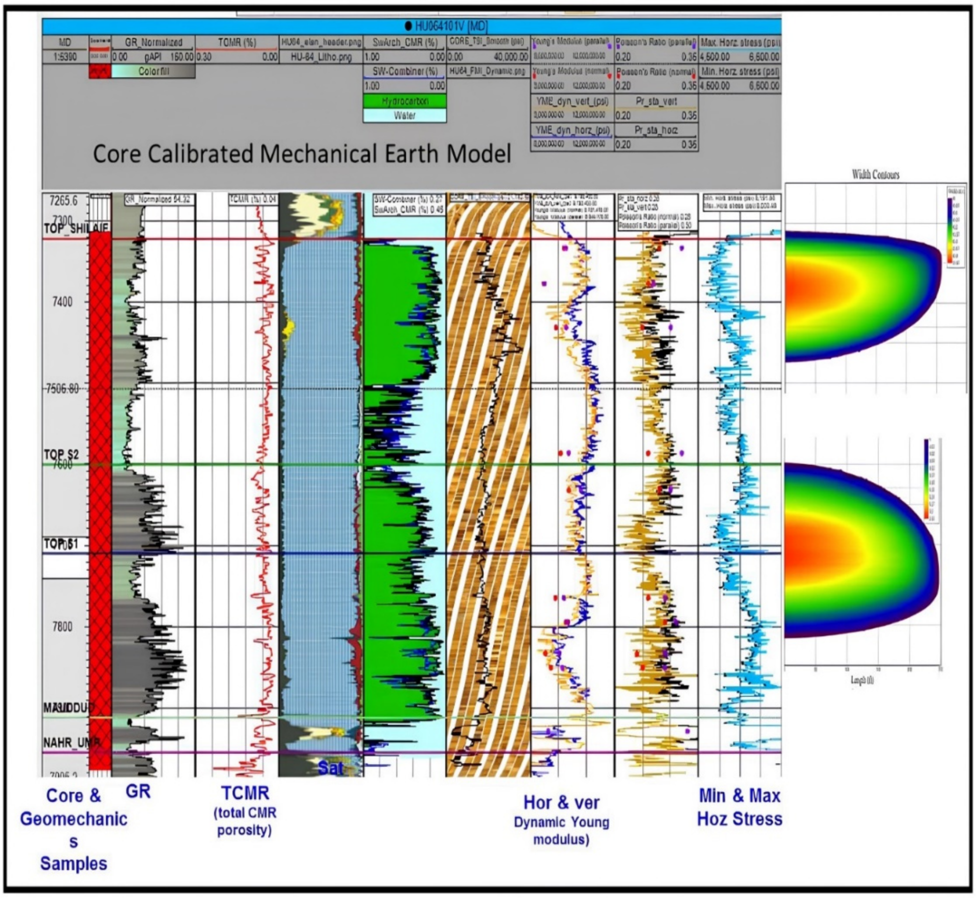


Figure 22. Anisotropic initial frac design of Well-A. Placing up to 75 klb proppant with ± 700 bbls of frac fluid across each stage Expected max pump rate of 25 bpm at max pressure of 5200 psi. Rig less testing to be performed, WHP limitation is 7500 psi for completion.

Anisotropic rock stresses can give rise to a tensile zone, resulting in fractures forming parallel to the borehole wall. This phenomenon can potentially compromise borehole sealing and introduce complexities into the analysis. In scenarios where the minimum stress is oriented perpendicular to the borehole, conventional packer systems may encounter limitations in loading the rock along the axis of the hole. This limitation arises from the mechanical linkage of the packers, and the initial fracture may tend to form parallel to the borehole.

3.9. Well-X fracturing excursion decision tree and time line plan

The aforementioned studies have led to the development of a workflow and a timeline plan for making decisions about fracturing excursions in oil and gas wells. The workflow is outlined in Figure 23, and the timeline plan is presented in Figure 24.

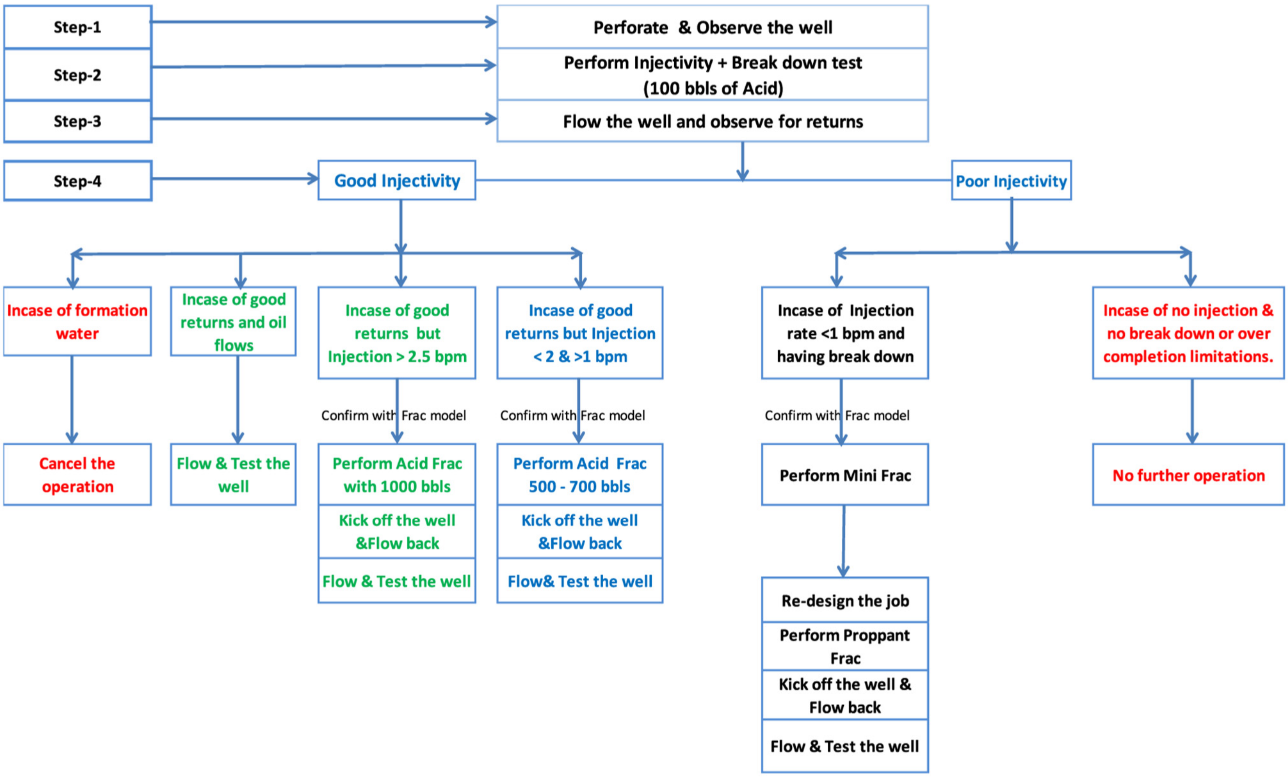
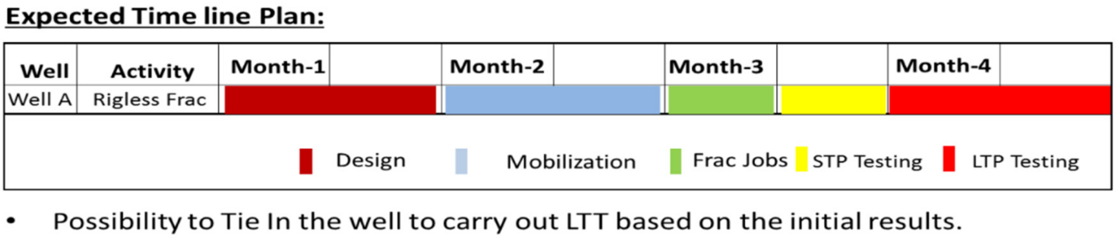


Figure 23. Fracturing excursion decision tree.



Expected Time line Plan:

Well	Activity	Month-1		Month-2		Month-3		Month-4	
Well A	Rigless Frac	🟥	🟥	🟦	🟦	🟩	🟨	🟥	🟥

🟥 Design 🟦 Mobilization 🟩 Frac Jobs 🟨 STP Testing 🟥 LTP Testing

- Possibility to Tie In the well to carry out LTT based on the initial results.

Figure 24. Fracturing design and excursion time line plan.

4. Recent applications

Edmonstone et al. [25] presented an ongoing project focused on implementing HF in low-permeability, thin, sour gas reservoirs. They outlined various challenges encountered during the project and offers best practices to overcome these challenges. Notably, they determined that the mechanical straddle packer was not the most effective isolation method for creating discrete fractures. Instead, they successfully achieved the predicted performance by employing a rig-less pinpoint acid fracturing approach.

Additionally, Al-Attar et al. [22] introduced a systematic design procedure for HF in tight petroleum-bearing reservoirs. This design process incorporates both the fracture geometry (PKN) model and the unified fracture design (UFD) methodology. Their findings indicate that the proper design and implementation of HF in tight gas reservoirs can lead to a significant improvement in productivity, resulting in a 15-fold increase and a gas recovery of 1.02 million MMscf over the initial 8 years of production, as illustrated in Figure 25.

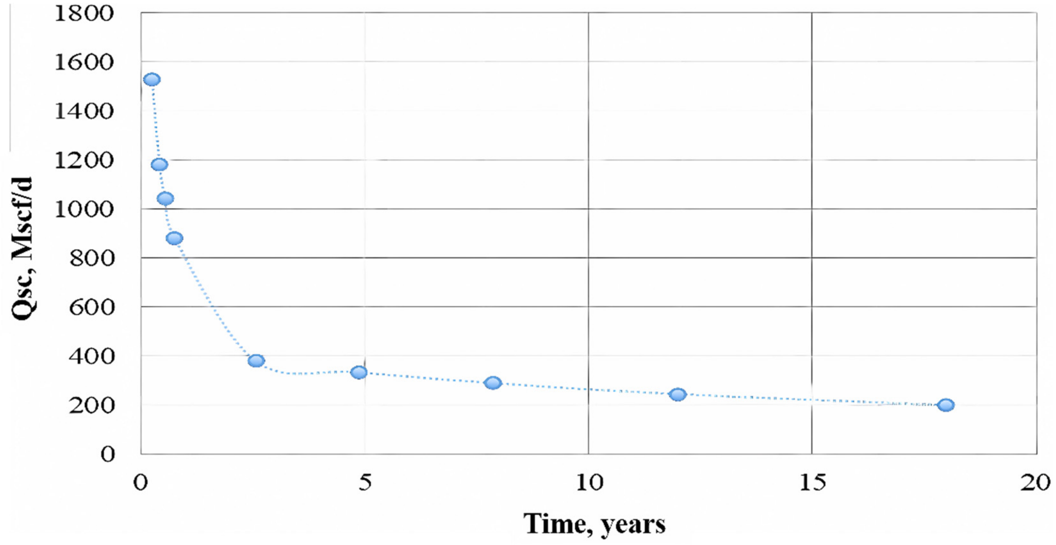


Figure 25: Post-fracturing predictions for the period of 8 years indicated improved productivity by 15-folds and increased gas recovery [22].

5. Summary and conclusions

This work discusses the plan, design and execution of the first five wells, emphasizing the successful application of acid fracturing technology in tight reservoirs, leading to the discovery of oil. Key lessons learned from these five fracturing jobs were captured and used to enhance the company's expertise. Furthermore, a creative roadmap was developed as a result.

We also present the acceptance of four technology applications—deep perforation, extended coring, wireline coring and side wall core—in Abu Dhabi, UAE, for the first time. A novel strategy for exploration, appraisal and development, taking economic considerations into account, was presented. The study successfully introduced an innovative fracture strategy and redeveloped matrix and acid fracturing stimulation strategies, contributing to cost optimization and maximizing data benefits.

One significant achievement of this study is the remarkable cost and time savings, along with minimized operation Non-Productive Time (NPT). These outcomes represent a valuable contribution to the field of oil and gas exploration and development in the UAE.

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Use of AI tools declaration

The authors declare that they have not used Artificial Intelligence (AI) tools in the creation of this article.

Conflict of interest

The authors declare no conflicts of interest.

Author contributions

Conceptualization, G.M.H., and O.M.; methodology, G.M.H., T.Y., and O.M.; investigation, G.M.H., and T.Y.; writing—original draft preparation, G.M.H., and T.Y.; writing—review and editing, G.M.H., T.Y., and O.M.; visualization, T.Y., and O.M.; supervision, O.M.; project administration, G.M.H.; funding acquisition, G.M.H. All authors have read and agreed to the published version of the manuscript.

References

1. King GE (2012) Hydraulic fracturing 101: What every representative, environmentalist, regulator, reporter, investor, university researcher, neighbor and engineer should know about estimating frac risk and improving frac performance in unconventional gas and oil wells. Paper SPE-152596-MS presented at the *SPE Hydraulic Fracturing Technology Conference*, The Woodlands, Texas, USA, 6–8. https://doi.org/10.2118/152596-MS
2. Soliman AM, Abdelfattah MH, Yassin MHA (2015) Unconventional reservoir: Definitions, types and Egypt's potential. Available from: https://www.researchgate.net/publication/283855761_Unconventional_Reservoir_Definitions_Types_and_Egypt%27s_Potential?channel=doi&linkId=5648e93008aef646e6d21190&showFulltext=true.
3. Mohamed MS, Meguid AA, Wang Q, et al. (2016) Lessons learned from hydraulic fracturing the first exploratory shale gas well in Egypt. Paper SPE-181870-MS presented at the *SPE Asia Pacific Hydraulic Fracturing Conference*, Beijing, China, 24–26. https://doi.org/10.2118/181870-MS
4. Sayed MA, Al-Muntasheri GA, Liang F, (2017) Development of shale reservoirs: Knowledge gained from developments in North America. *J Pet Sci Eng* 157: 164–186. https://doi.org/10.1016/j.petrol.2017.07.014

5. Ibrahim M, Salah M, (2017) Integration of pressure and rate transient analysis for transverse and longitudinal multistage fractured horizontal first unconventional gas well in Egypt. Paper SPE-187420-MS presented at the *SPE Annual Technical Conference and Exhibition*, San Antonio, Texas, USA, 9–11. https://doi.org/10.2118/187420-MS
6. Ibrahim M, Mahmoud O, Pieprzica C (2018) A new look at reserves estimation of unconventional gas reservoirs. Paper URTEC-2903130-MS presented at the *Unconventional Resources Technology Conference (URTeC)*, Houston, Texas, USA, 23–28. https://doi.org/10.15530/URTEC-2018-2903130
7. Salah M, Ibrahim M (2018) Unconventional reservoir development in Egypt's Western Desert: lessons learned from the first appraisal wells. Paper URTEC-2902739-MS presented at the *Unconventional Resources Technology Conference (URTeC)*, Houston, Texas, USA, 23–25. https://doi.org/10.15530/URTEC-2018-2902739
8. Mahmoud O, Ibrahim M, Pieprzica C, et al. (2018) EUR prediction for unconventional reservoirs: State of the art and field case. Paper SPE-191160-MS presented at the *SPE Trinidad and Tobago Section Energy Resources Conference*, Port of Spain, Trinidad and Tobago, 25–27. https://doi.org/10.2118/191160-MS
9. Ba Geri M, Ellafi A, Flori R, et al. (2019) New opportunities and challenges to discover and develop unconventional plays in the Middle East and North Africa: Critical review. Paper SPE-197271-MS presented at the *Abu Dhabi International Petroleum Exhibition and Conference*, Abu Dhabi, UAE, 11–14. https://doi.org/10.2118/197271-MS
10. Suboyin A, Rahman MM, Haroun M (2020) Hydraulic fracturing design considerations, water management challenges and insights for Middle Eastern shale gas reservoirs. *Energy Rep* 6: 745–760. https://doi.org/10.1016/j.egyr.2020.03.017
11. Al Mteiri S, Suboyin A, Rahman MM, et al. (2021) Hydraulic fracture propagation and analysis in heterogeneous Middle Eastern tight gas reservoirs: Influence of natural fractures and well placement. *ACS Omega* 6: 799–815. https://doi.org/10.1021/acsomega.0c05380
12. Holditch SA (1979) Factors affecting water blocking and gas flow from hydraulically fractured gas wells. *J Pet Technol* 31: 1515–1524. https://doi.org/10.2118/7561-PA
13. Gdanski R, Fulton D, Shen C (2009) Fracture-face-skin evolution during cleanup. *SPE Prod Oper* 24: 22–34. https://doi.org/10.2118/101083-PA
14. Salah M, Gabry MA, ElSebaee M, et al. (2016) Control of hydraulic fracture height growth above water zone by inducing artificial barrier in Western Desert, Egypt. Paper SPE-183040-MS presented at the *Abu Dhabi International Petroleum Exhibition & Conference*, Abu Dhabi, UAE, 7–10. https://doi.org/10.2118/183040-MS
15. Salah M, Bereak A, Gabry MA, et al. (2016) Microseismic monitoring improves hydraulic fracturing diagnostic and optimizes field development in Western Desert, Egypt. Paper OTC-26864-MS presented at the *Offshore Technology Conference*, Houston, Texas, USA, 2–5. https://doi.org/10.4043/26864-MS
16. Ibrahim AF, Assem A, Ibrahim M (2020) A novel workflow for water flowback RTA analysis to rank the shale quality and estimate fracture geometry. *J Nat Gas Sci Eng* 81: 103387. https://doi.org/10.1016/j.jngse.2020.103387

17. Ibrahim AF, Assem A, Ibrahim M, et al. (2020) Water flowback RTA analysis to estimate fracture geometry and rank the shale quality. Paper SPE-199158-MS presented at the *SPE Latin American and Caribbean Petroleum Engineering Conference*, Virtual, 27–31. https://doi.org/10.2118/199158-MS
18. Bunger AP, Zhang X, Jeffrey RG (2012) Parameters affecting the interaction among closely spaced hydraulic fractures. *SPE J* 17: 292–306. https://doi.org/10.2118/140426-PA
19. Carter BJ, Desroches J, Ingraffea AR, et al. (2000) Simulating Fully 3D hydraulic fracturing. In: Zaman M., Gioda G., Booker J., *Modeling in Geomechanics*, John Wiley and Sons, ISBN: 978-0-471-49218-4. Available from: https://www.abebooks.com/servlet/BookDetailsPL?bi=31325257142&searchurl=kn%3Dmodeling%2Bin%2Bgeomechanics%2B2000%26sortby%3D17&cm_sp=snippet-_-srp1-_-title1.
20. Wu Z, Cui C, Jia P, et al. (2022) Advances and challenges in hydraulic fracturing of tight reservoirs: A critical review. *Energy Geosci* 3: 427–435. https://doi.org/10.1016/j.engeos.2021.08.002
21. Britt L (2012) Fracture stimulation fundamentals. *J Nat Gas Sci Eng* 8: 34–51. https://doi.org/10.1016/j.jngse.2012.06.006
22. Al-Attar H, Alshadafan H, Al Kaabi M, et al. (2020) Integrated optimum design of hydraulic fracturing for tight hydrocarbon-bearing reservoirs. *J Pet Explor Prod Technol* 10: 3347–3361. https://doi.org/10.1007/s13202-020-00990-6
23. Maulianda B, Savitri CD, Prakasan A, et al. (2020) Recent comprehensive review for extended finite element method (XFEM) based on hydraulic fracturing models for unconventional hydrocarbon reservoirs. *J Pet Explor Prod Technol* 10: 3319–3331. https://doi.org/10.1007/s13202-020-00919-z
24. Li N, Chen F, Yu J, et al. (2021) Pre-acid system for improving the hydraulic fracturing effect in low-permeability tight gas reservoir. *J Pet Explor Prod Technol* 11: 1761–1780. https://doi.org/10.1007/s13202-021-01129-x
25. Edmonstone G, Martin AN, Turniyazov N, et al. (2020) Operational challenges of hydraulic fracturing of thin, low permeability and highly sour reservoirs in the UAE—A NOC Journey. Paper SPE-202834-MS presented at the *Abu Dhabi International Petroleum Exhibition & Conference*, Abu Dhabi, UAE, 9–12. https://doi.org/10.2118/202834-MS
26. Taher AK (2010) Unconventional oil exploration potential in early mature source rock kitchens. Paper SPE-137897-MS presented at the *Abu Dhabi International Petroleum Exhibition and Conference*, Abu Dhabi, UAE, 1–4. http://dx.doi.org/10.2118/137897-MS
27. Azzam IN, Taher AK (1993) Sequence stratigraphy and source rock potential of middle cretaceous (upper Wasia group) in West Abu Dhabi. Paper SPE-25577-MS presented at the *Middle East Oil Show*, Manama, Bahrain, 3–6. http://dx.doi.org/10.2118/25577-MS
28. Al Ameri F, Al-Kaabi M, Al Zarouni A, et al. (2012) First trial in the UAE for proving hydrocarbon productivity potential of unconventional source rocks in Abu Dhabi: a case study. Paper SPE-158196-MS presented at the *Abu Dhabi International Petroleum Conference and Exhibition*, Abu Dhabi, UAE, 11–14. http://dx.doi.org/10.2118/158196-MS
29. Hegazy GM, Salem AM, Shedid SA, et al. (2013) A new strategy to explore tight oil/gas reservoirs fit for purpose acid fracturing. Paper SPE-164778-MS presented at the *North Africa Technical Conference and Exhibition*, Cairo, Egypt, 15–17 April. http://dx.doi.org/10.2118/164778-MS

30. Chimmalgi VS, Al-Humoud J, Al-Sabea S, et al. (2013) Reactivating a tight carbonate reservoir in the Greater Burgan Field: Challenges, options and solutions. Paper SPE-164248-MS presented at the *SPE Middle East Oil and Gas Show and Conference*, Manama, Bahrain, 10–13 March. http://dx.doi.org/10.2118/164248-MS
31. Asadi MB, Zendehboudi S (2019) Evaluation of productivity index in unconventional reservoir systems: An extended Distributed Volumetric Sources method. *J Nat Gas Sci Eng* 61: 1–17. https://doi.org/10.1016/j.jngse.2018.10.011
32. Sun F, Du S, Zhao YP (2022) Fluctuation of fracturing curves indicates in-situ brittleness and reservoir fracturing characteristics in unconventional energy exploitation. *Energy* 252: 124043. https://doi.org/10.1016/j.energy.2022.124043
33. Burkholder MK, Coopersmith EM, Schulze JH, (2012) Appraisal excellence in unconventional reservoirs. Paper SPE-162776-MS presented at the *SPE Canadian Unconventional Resources Conference*, Calgary, Alberta, Canada, 30 October–1 November. https://doi.org/10.2118/162776-MS
34. White WM (2020) Geochemistry. 2nd Ed., New Jersey: Wiley-Blackwell, ISBN 978-1-119-43805-2. Available from: https://www.abebooks.com/Geochemistry-White-William-M-Wiley-Blackwell/30753539132/bd.