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MINI-FALL OFF TESTS AS A COST-EFFECTIVE TOOL FOR RESERVOIR CHARACTERIZATION AND DST DECISION-MAKING IN DEEPWATER CONVENTIONAL RESERVOIRS

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ABSTRACT

This research introduces a methodology employing Mini-Fall Off injection tests to enhance reservoir characterization and inform Drill Stem Testing (DST) decision-making in deepwater conventional reservoirs. The methodology begins with log-driven permeability estimation, which is corrected using mobility data from Wire Formation Tester (WFT) point results. Despite these corrections, uncertainties persisted regarding the dominant permeability, which is crucial for ensuring the minimum required deliverability for DST.

To address these uncertainties and flow assurance challenges, the Mini-Fall Off injection test was employed to estimate permeability within the target flow zone unit of the conventional reservoir. This approach allowed for precise permeability assessment in specific zones, thereby enhancing the overall understanding of reservoir quality and well deliverability. The Mini-Fall Off test provided critical Value of Information (VOI) by revealing that the well deliverability did not meet the minimum required flow rates for DST, leading to the cancellation of DST and substantial cost savings.

The application of Mini-Fall Off tests demonstrates a significant advancement in reservoir assessment strategies, offering a cost-effective and efficient alternative to traditional methods. By integrating log-driven permeability data with WFT-derived mobility data and employing the Mini-Fall Off test, the methodology provides a comprehensive framework for reducing uncertainties and optimizing resource allocation in the oil and gas industry.

Furthermore, this technique underscores the importance of VOI in data acquisition and decision-making processes throughout the asset lifecycle, from exploration to development. The results of this study highlight the potential for Mini-Fall Off tests to become a standard practice in reservoir characterization, particularly in deepwater conventional reservoirs where cost and efficiency are paramount.

This work presents a novel, cost-effective approach to obtaining accurate reservoir characterization, thereby demonstrating its potential to optimize operational efficiency and resource management in the oil and gas sector.

Keywords: reservoir characterization, value of information, DST test, Mini-Fall Off test, West Africa offshore basin

INTRODUCTION

Reservoir characterization is a method to understand and describe the variations in the reservoir rock and fluid properties along the production period of the oil field. Typically, it's based on the amount of data available to describe the characteristics of the reservoir using the obtained data. Gaining a clearer understanding of reservoir rock and fluid properties, as well as the geometry of the reservoir rock, requires ongoing efforts in data acquisition and refining interpretation methods. The characterization of reservoir rock is normally depending on the understanding and interpretations of geological and petrophysical obtained data such as the distribution of reservoir properties [2], [19], [20], [21].

Transient well testing is one of the primary sources of data for describing reservoir properties, significantly improving the understanding of geological models and better defining reservoir characteristics and boundaries [3], [4], [17]. This method has experienced notable advancements in recent years, with substantial improvements in pressure gauge accuracy and resolution, alongside enhancements in analytical approaches and dynamic modelling. These developments have collectively led to more precise and reliable reservoir characterization techniques.

Well potential evaluation is key to reservoir development which can be estimated from petrophysical logs, mobility from wireline formation tester, or measured directly from drill stem tests, production well tests, or through extended well testing. At the early stages of the field discovery, direct measurements are costly, so operators prefer to estimate the permeability and benchmark it before it comes to the confirmation of Minimum Economic Field Size (MEFS). So economic limitations dictate the data acquisition strategy especially for deep water wells when the rig time costs too much, and the logistics become more difficult in the frontier area [16].

Well test outcomes offer multiple benefits during exploration activities, helping to determine the commercial viability of a discovery. Additionally, it provides valuable information for reservoir characterization, including predicting reservoir production performance, optimizing production, and identifying formation damage [11]. Ilfi [5] concluded that transient well testing is an excellent technique to be studied using simulated information from the reservoir dynamic model. The author stated that the response is known from pressure response at certain flow rate control either in the production or injection flow test. Kamal [6] stated that step-rate, falloff, interference, injectivity, and pulse tests are carried out over improved hydrocarbon recovery phases. Sometimes, those tests are applied over the life of the field, like the vertical permeability test and multilayer test.

The drawdown and build-up tests are used to estimate the reservoir permeability and to determine the impact of the drilling fluids and production operation on the original reservoir rock permeability close to the wellbore [8], [9]. Interference tests can be used to determine the directional permeability and reservoir storativity between adjacent wells. This test can be executed by measuring the pressure drop by producing a well and recorded at the nearby observational well [10]. Many other researchers proposed that the interference test must be used for complicated reservoir quality such as anisotropic and heterogeneous reservoirs [8], [15], [7], [18], [12]. Currently, the type curve matching method is applied to process interference test data [14], [8], [13], [9].

A Leak Off Test (LOT) is conducted to determine the strength or fracture pressure of an open hole formation, typically performed right below a newly set casing shoe. During the LOT, the well is closed and fluid is slowly injected into the formation to increase pressure at the target depth. At a certain pressure value, the injected fluid will flow into the wellbore, or "leak off," either through a permeable area in the formation or by creating space via fracturing the formation. The LOT results indicate the maximum drilling mud pressure required to safely drill this formation.

While this technique is used in unconventional reservoir rocks to enhance hydrocarbon recovery, LOTs are not typically conducted as a tool to understand reservoir characterization in conventional reservoir rocks [1].

This paper presented for the first time a real case study that used the Mini-Fall-Off Test as a unique tool to obtain reservoir rock parameters such as reservoir flow capacity as an alternative cheap option in the conventional reservoir.

This case study presents the Value of Information (VOI) in the context of Mini-Fall-Off testing, with the aim of positioning it as a viable alternative or contingency solution to traditional Drill Stem Testing (DST) in various scenarios. These scenarios include exploration wells in Deepwater environments where well flow may not be possible due to flow assurance issues such as high wax content, presence of CO2 or H2S, or in areas with strict water ban policies. The mini-drop test is essential for well testing to ensure commercial viability, especially in remote areas with logistical challenges. A comprehensive discussion is presented throughout the document, covering the background of the field, operational methodology, challenges encountered, data integration workflow, results of integrated studies, and Value of Information (VOI) associated with mini-drop testing.

Primarily, the Diagnostic Fracture Injection Test (DFIT) is utilized for the estimation of pore pressure, determination of stress, and identification of sweet spots particularly in scenarios where conventional wireline formation testers fail to acquire data [27], [28], [30]. Nonetheless, DFIT's secondary application in permeability estimation has garnered increasing attention in scholarly literature [25],[26]. A significant portion of published studies fails to comprehensively integrate this data. This paper endeavours to synthesize and employ data from various scales to achieve detailed reservoir characterization, thereby mitigating uncertainty and curtailing the substantial costs associated with data acquisition.

Data scale pertains to the spatial extent or depth evaluated in a particular analysis [24]. Petrophysical logs, generally reflecting less than one meter of the reservoir, are classified as small-scale data, whereas DST can encompass over 1000 meters, thus constituting large-scale data. Each type of permeability data retains its precision within its respective scale and is suitable for specific investigations [23]. Other data types, such as Deep Transient Testing (DTT) [22] and DFIT [33], [31] occupy intermediate positions but are still deemed large scale. Notably, the data scale of DFIT typically matches or surpasses that of Deep Transient Testing, signifying that DFIT results represent a greater rock volume of the reservoir compared to DTT.

A profound comprehension of data scale is fundamental for the precise analysis and interpretation in diverse geological and engineering applications. For instance, in reservoir characterization, small-scale data, like petrophysical logs, yield detailed information concerning the immediate vicinity of the wellbore, thereby capturing fine-scale features such as layering and lithological variations. Conversely, large-scale data, derived from DST or DFIT, elucidate the overall properties and dynamics of the reservoir across a substantially larger expanse. This facilitates the identification of broader trends and patterns that remain imperceptible in small-scale data.

Furthermore, the integration of multi-scale datasets can significantly enhance the reliability and comprehensiveness of reservoir models. By amalgamating the exactitude of small-scale data with the extensive reach of large-scale data, researchers and engineers gain a more holistic understanding of subsurface conditions. For example, in the realm of enhanced oil recovery, employing both small- and large-scale data enables more accurate predictions of well productivity prediction and utilizing the data in dynamic model upscaling and improve the model reliability through uncertainty reduction. Other tests such as wireline formation testers (WFT) has been in use for mimicking DST in homogeneous reservoirs, however the data scale of WFT tests are small and in heterogenous reservoir requires integration [32], [34].

SITE DESCRIPTION AND DATA OBSERVATIONS

The G-Field is located in the Offshore West Africa basin. The oil-bearing zone is a pre-salt reservoir 9000 feet below the seabed (mud-line). The field comprised two culminations which due to MEFS chasing the eastern culmination was chosen for drilling (Figure 1). So far two wells drilled, G1 and G2 wells. The G1 well was drilled with the objective of exploration discovery in the Eastern culmination and G2 was drilled in the Western culmination to prove the western fluid type and appraise the reservoir.

The G1 well was drilled in 2017 in a water depth of 2,808 m and encountered more than 200 ft of net hydrocarbon sand, in good quality sandstone. At the well location, the three Gas, oil, and water phases were observed from logs and pressure plot analysis (Figure 2).

As indicated in Figure 2, left track depicts the wireline formation tester with distinctive fluid contacts, together with petrophysical logs (GR, Resistivity, and Neutron Density/porosity) on the right track. The WFT contact is in full agreement with petrophysical logs. In the first well only mobility data and sidewall core data were used for planning the second appraisal well.

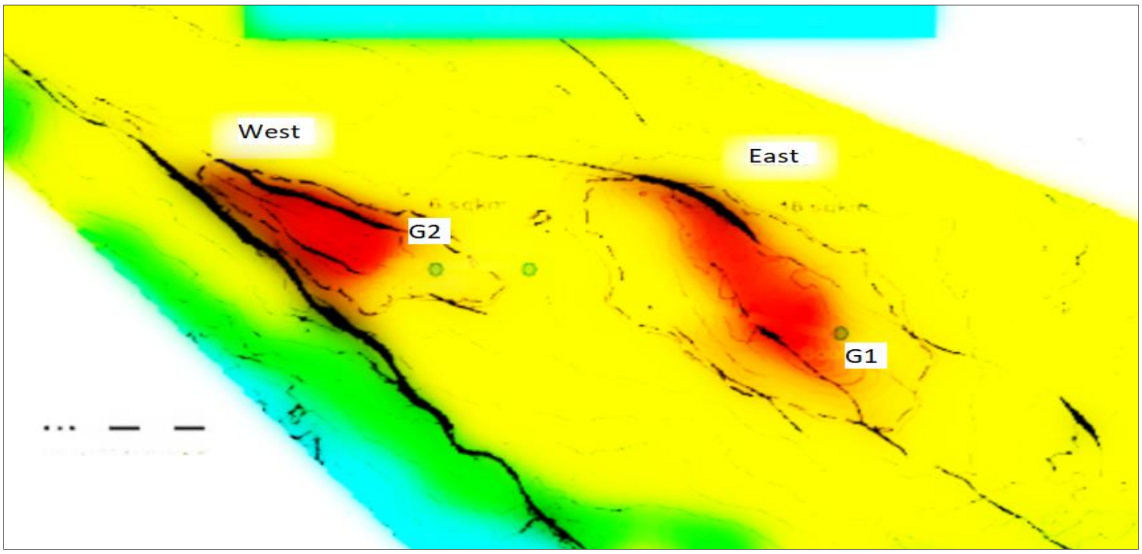

Figure 1*. G field structure outline indicating two culminations with drilled well location*

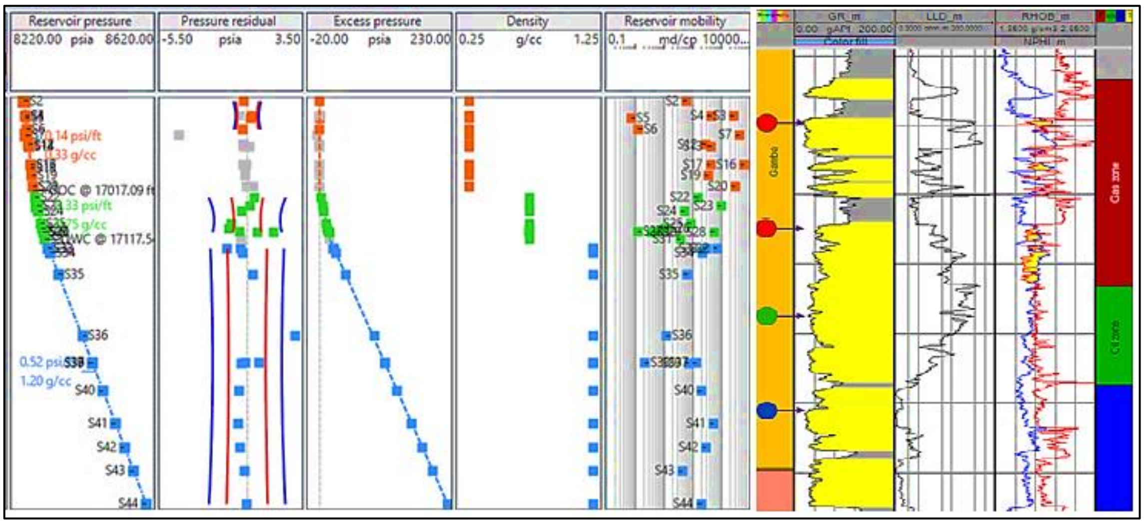

Figure 2*. G1 Well Findings: right track petrophysical logs, left track pressure pore pressure profile from wireline formation tester*

Drilling the second well turned out to be different reservoir characteristics. Drastic changes in reservoir lithology and quality were observed in the G2 well which was drilled recently (Figure 3). As indicated in the excess pressure track, the pressure difference in most of the oil zone perfectly matches with G1 well.

This confirms that two culminations (East with G1 well and West with G2 well) are hydraulically connected by showing the same pore pressure at the oil zone. Besides, both the reservoir in the eastern culmination and western culmination are saturated with a gas cap of same reservoir pressure. It's important to note that Figure 3 displays pressure data mainly. For mobility estimation, mud filtrate viscosity has been consistently used in both G1 and G2 wells.

There were few sampling stations in G1/G2 wells to collect oil and gas samples. These wireline formation tester data which were done through Modular Dynamic Tester (MDT) have been analysed to estimate the reservoir mobility. For these stations, reservoir fluid viscosity was used to calculate the permeability, as fluid is already cleaned through an elongated pump-out effort, and the in-situ fluid analyzer confirmed the reservoir fluid properties and fingerprint. Figure4 shows two MDT stations analysis which were done in the main zone of interest with higher reservoir quality called Zone Unit-A. As depicted in Figure 4, the spherical flow and radial flow are established. Therefore, vertical and horizontal permeability can be measured from these stations. The resulting flow capacity from both stations is in good agreement highlighting that the vertical flow communication is established despite drastic geological and lithological variation in the flow zone unit A.

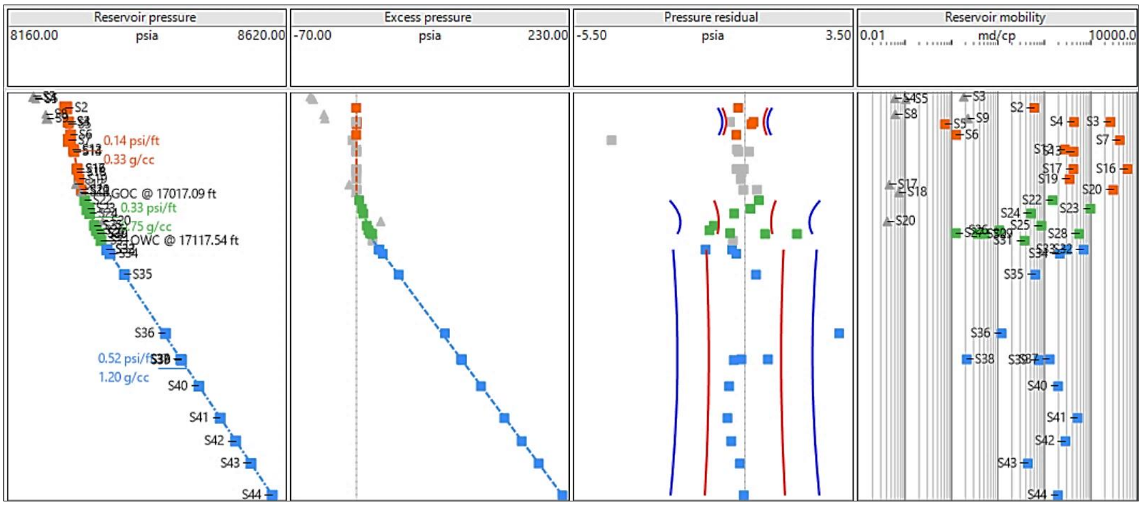

***Figure 3**. Pressure profile and mobility data for G1 and G2 wells. The Excess Pressure Track demonstrates a perfect match in the oil and gas sections, indicating the same hydraulic pressure system. The Reservoir Mobility Track shows significant permeability variation between the wells. Colorful points (red, green, blue) represent G1 data, while gray dots represent G2 data.*

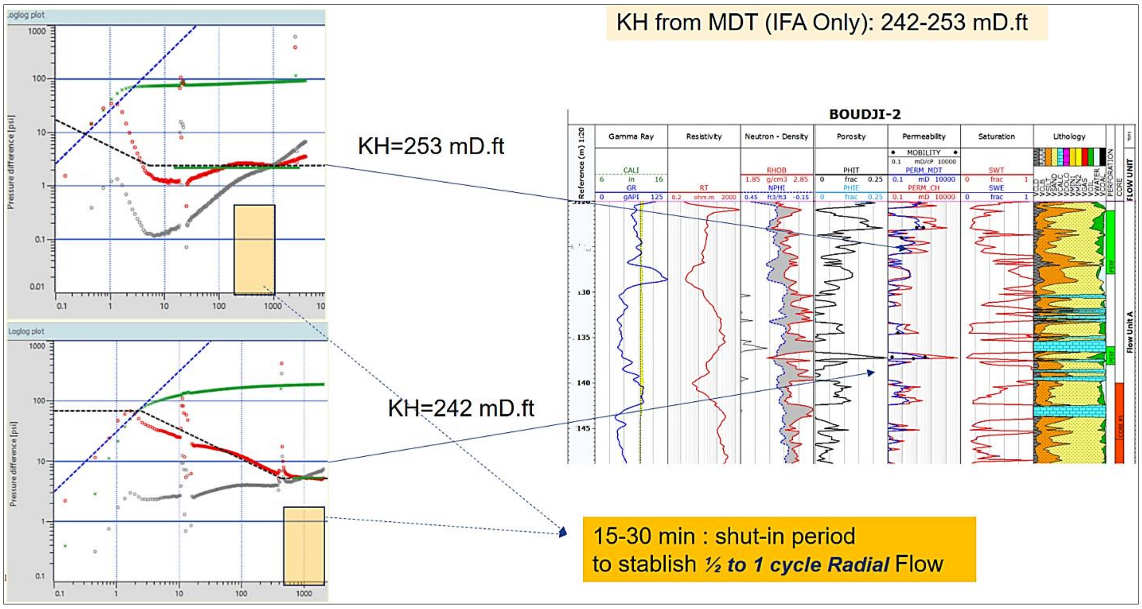

***Figure 4**. MDT analysis for two sampling stations for the G2 well at the main zone of interest*

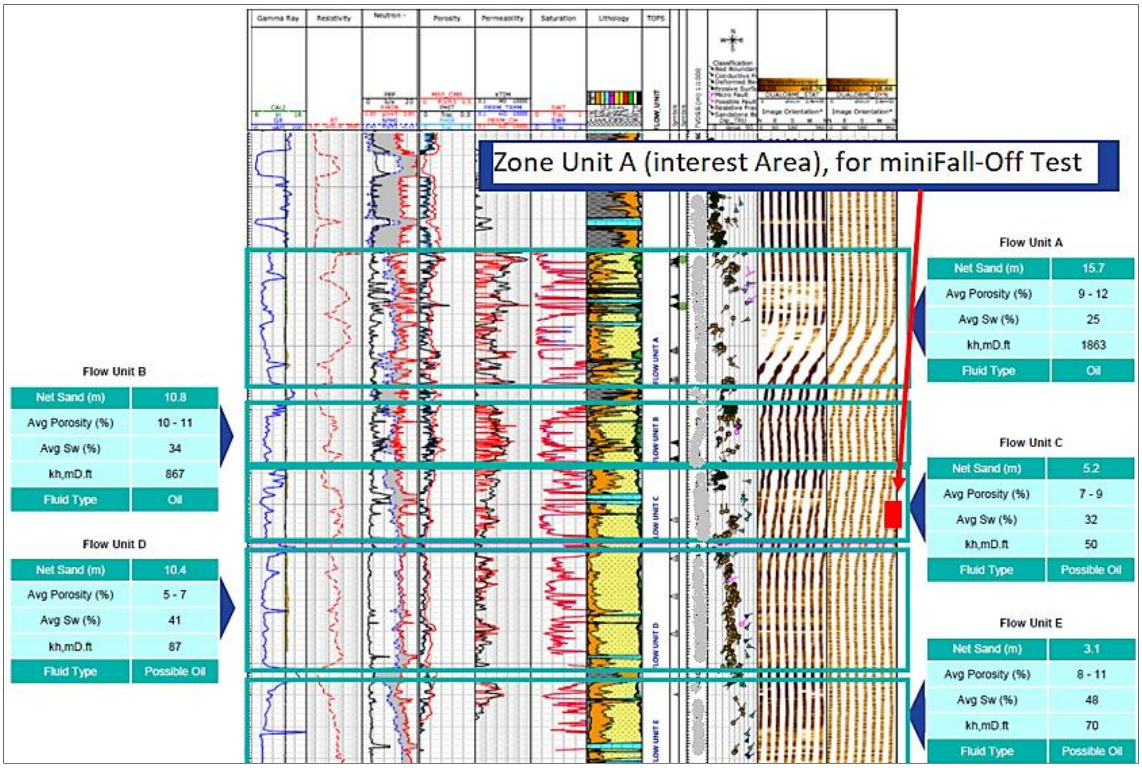

Figure 5. *Overall Well G2 logging results showing five flow zone units with shale barriers separating Zone Unit A*

WORKFLOW DESIGN

Mini-Fall Off test known as Diagnostic Fracture Injection Test (DFIT) is a process in which the fracturing fluid is pumped at a rate above the leak-off rate at high pressure (above fracturing gradient) to create the fracture in the formation. The goal of this pumping technique is to create a small, confined fracture. During pumping, the fracture propagates, and a portion of the fracturing fluid leaks off into the formation. After achieving formation fracture pressure, the pump is shut off. The pressure inside the fracture then begins declining, and as pumping ceases, the fracture closes. Since the fracture propagates during the pumping period, the mini-frac test could not be considered part of conventional well testing.

However, this pumping period is usually short (5-20 minutes) and pressure falls off after shut-in is used for testing. The pressure decline was first used by Nolte to estimate the leak-off coefficient, which describes the process of fracturing fluid leaking into the formation normal to the fracture face. The full pressure response is depicted in Figure 6 with all operational stages. After stopping the injection, the pressure falls off but up to some certain pressure fracture is still open, once it reaches the closure pressure, the fracture closes and then the fluid is leaking off into the reservoir. The period at which the fracture remains open is usually short compared to leak-off into the reservoir post closure.

The reservoir and fracture parameters are measures from post-closure analysis (Nolte 1988). As presented in Figure 7, the post-closure period consists of two flow regimes such as fracture linear flow followed by semi-radial flow in the reservoir. To analyzing the radial flow regime, Nolte derived the governing equation as per below:

$$p(t) - p_r \cong m_R F_R^2(t, t_c); \quad F_R \cong \frac{1}{4}\ln(1+\frac{X.t_c}{t-t_c}); \; X \cong \frac{16}{\pi^2} \cong 1.6 \tag{1}$$

Where t_c is the time-lapse from stopping injection to fracture closure point in minutes, P_r is the initial reservoir pressure in psi, and m_R is Horner slope. $p(t)$ is flowing pressure, in psi, F_R is a fracture set in radial shape, dimensionless, X is shape factor, dimensionless.

The Horner slope can be determined using a radial flow semi-log. By having the Horner slope, the reservoir transmissibility could be estimated using equation (2):

$$\frac{k.h}{\mu} = 251000 \left(\frac{V_i}{m_R t_c}\right) \tag{2}$$

In which parameters are as below:

k is reservoir permeability in mD

h is net pay thickness in fr

μ is fluid viscosity in cP

m_R is Horner slope

t_c is time-lapse from stopping injection to fracture in minutes and

Vi is injected volume in bbl.

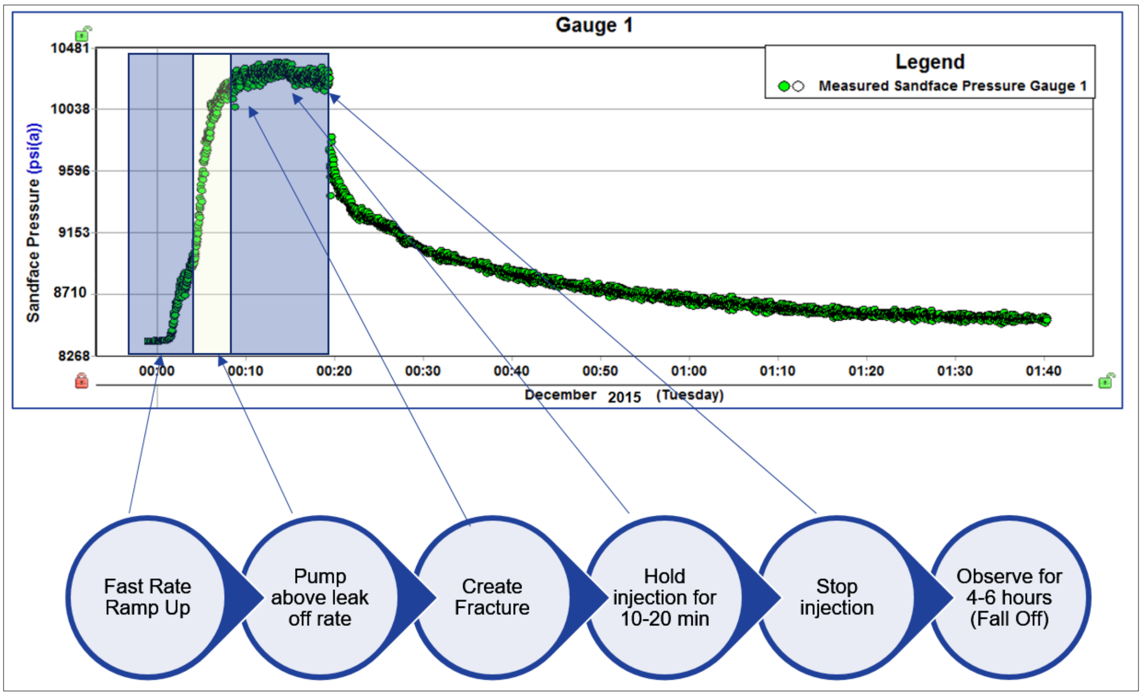

Figure 6. *Mini-fall-off injection test in G2 well.*

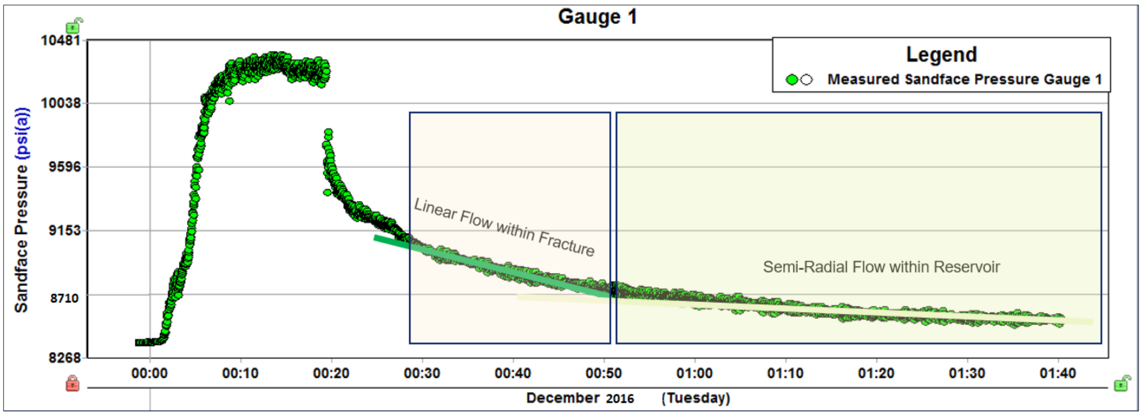

Figure 7. *Post-closure flow regimes, initially fracture linear flow followed by semi radial flow.*

DFIT OPERATION AND FRACTURE ANALYSIS

Using the provided leak-off test, the fracture gradient was estimated. It appears that only 2500 psi pressure at the surface, using brine, will be sufficient to fracture the reservoir. The leak-off rate was estimated using MDT mobility data. The spherical permeability was corrected according to the summarized workflow in Figure 8 for leak-off rate estimation. A geometric average of estimated horizontal permeability was used. Zone unit A is contained within shales as vertical fracture limits, so it was selected for the DFIT test. And out of 55 ft gross interval, only 30 ft (in two split intervals) were perforated prior to DFIT job as the interval was cased already.

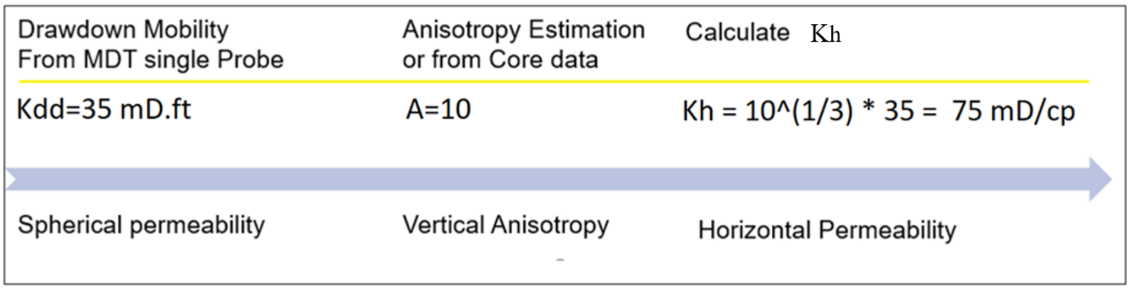

Figure 8. *Transforming spherical permeability to horizontal permeability (for isentropic system) with an example for zone unit A*

RESULTS AND DISCUSSIONS

The events chronology was driven by data criticality and value. Initially, a full suite log was run and permeability was derived from available correlations. Next, the MDT job was performed and mobility estimated. This mobility was used to upscale the permeability log to new MDT permeability (transformed to obtain horizontal permeability). Well potential was then estimated based on the latest upscaled permeability. Finally, MDT fluid sampling stations were analyzed (Figure 9) and these data were used to upscale log-driven permeability to a larger scale (deeper depth of investigation). The permeability transforms and cross-plot are illustrated in Figure 10.

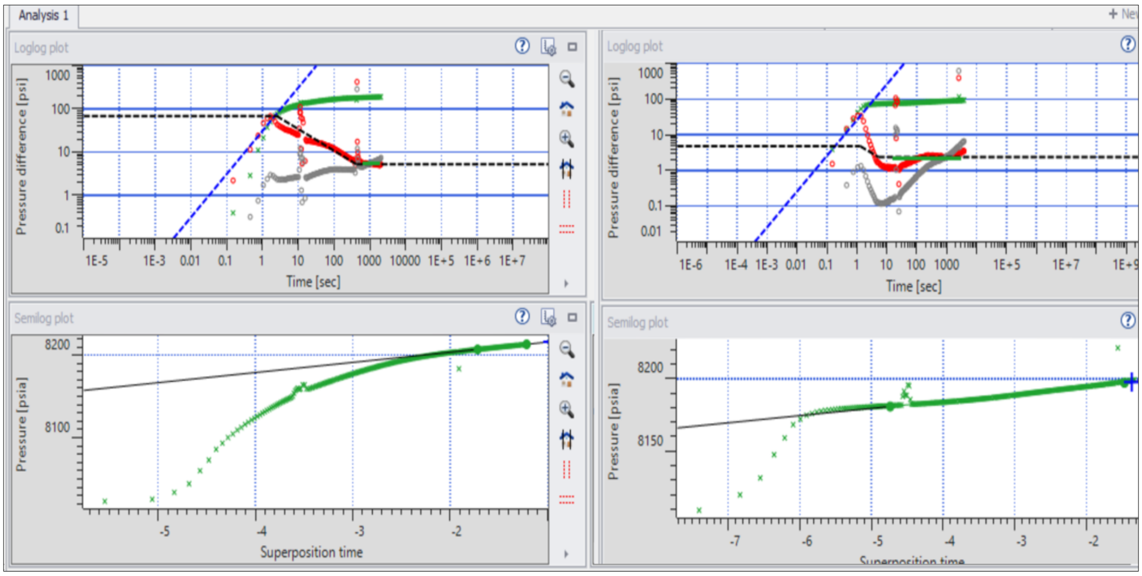

Figure 9. *MDT Fluid Stations Analysis demonstrates the establishment of spherical and radial flow with a depth of investigation exceeding 100 ft.*

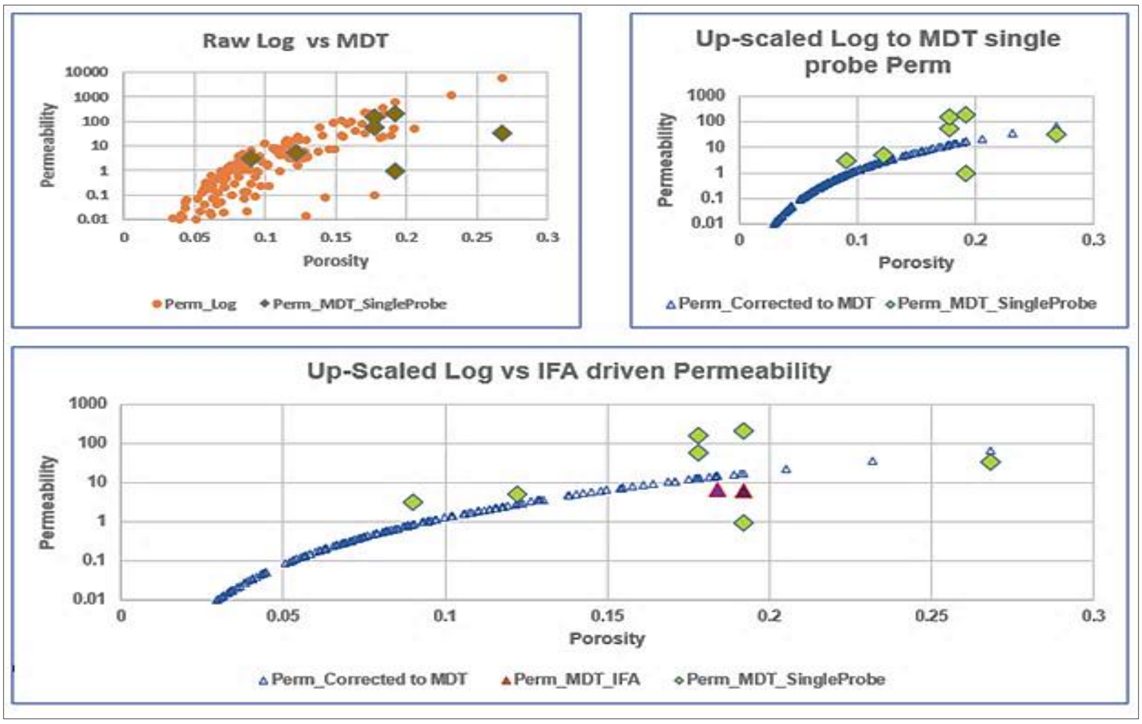

Figure 10. *Poro-perm cross-plot and upscaled permeability to log and MDT in well G2.*

Transient well modelling was used to assess the well's potential, utilizing the upscaled permeability from MDT data to evaluate flow assurance possibilities and severity. Figure 11 shows that the reservoir fluid has a low pour point temperature, below which even pour point depressants (PPD) won't allow a well with a low flow rate (650 bbl/d) to flow in the liquid phase. This indicates the minimum flow rate required for the well to flow.

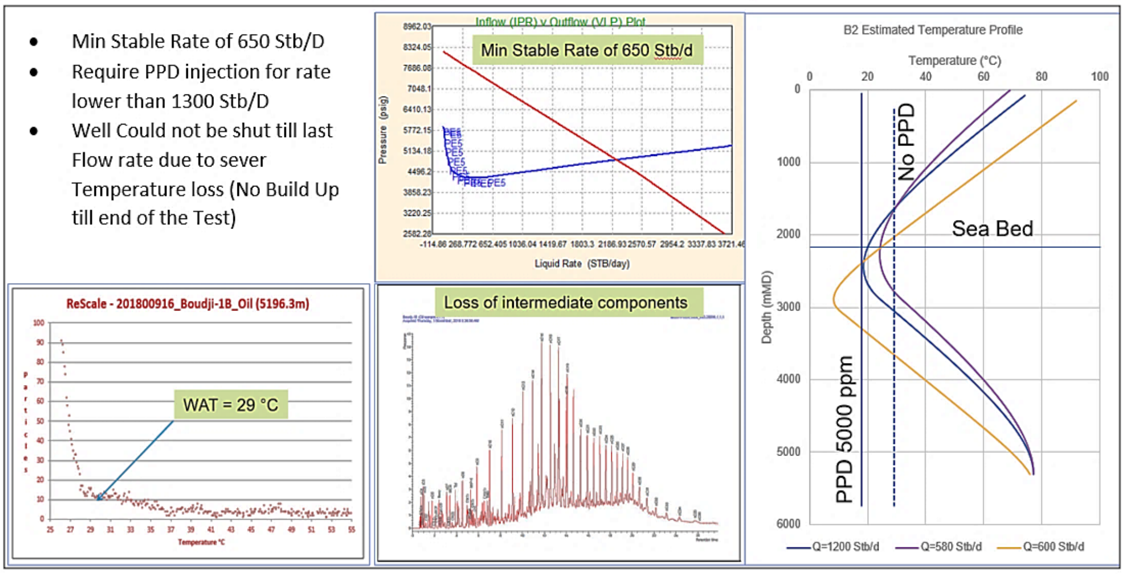

Figure 11. *Flow assurance studies result from the post on well G2 prior DFIT: Top middle: well model deliverability, Right: Estimated Temperature profile for different flow rates, Bottom Left: Wax Appearance Temperature, Bottom Middle: hydrocarbon degradation due to loss of intermediate components led to a waxy crude response*

The challenge of a wide permeability range prior to DST necessitated the DFIT, which helped narrow the permeability uncertainty to an acceptable range, enabling decision-making for the DST operation. Figure 12 and Figure 13 illustrate the two-step DFIT data examination process: first using real-time surface pressure and rate, then analyzing downhole pressure data from the retrieved gauge.

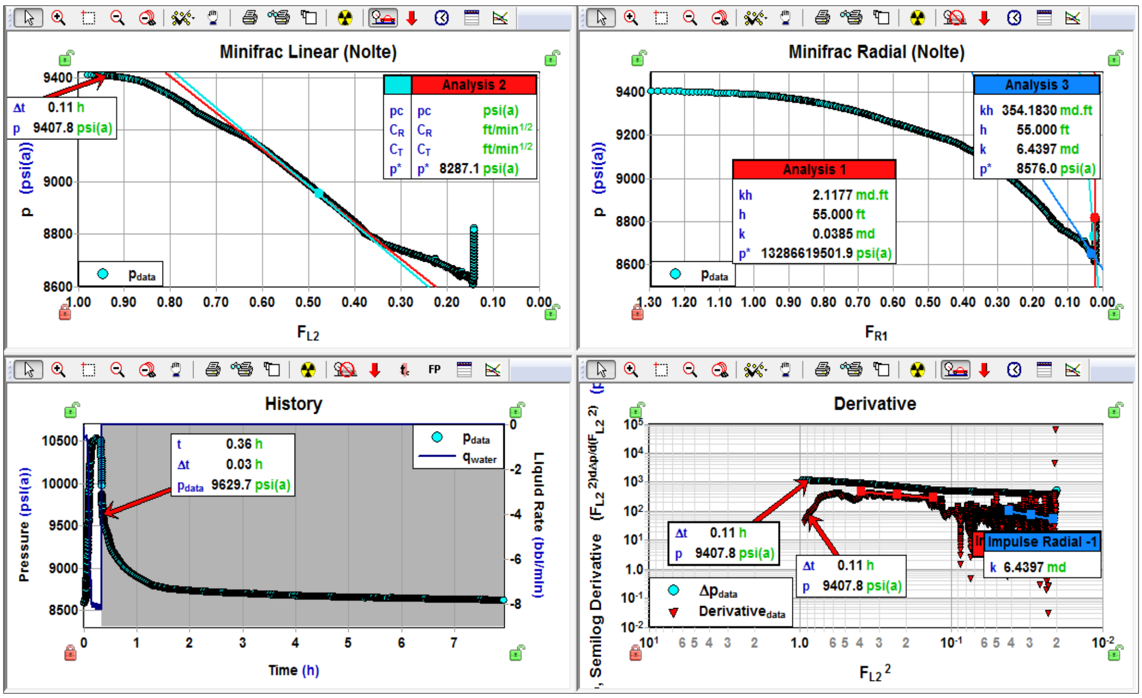

Figure 12. *Post closure analysis of DFIT based on real-time and surface pressure data, Top left: linear fracture flow, Top Right: Semi Radial flow, Bot. Left: Historical data, Bot. Right: Derivative plot.*

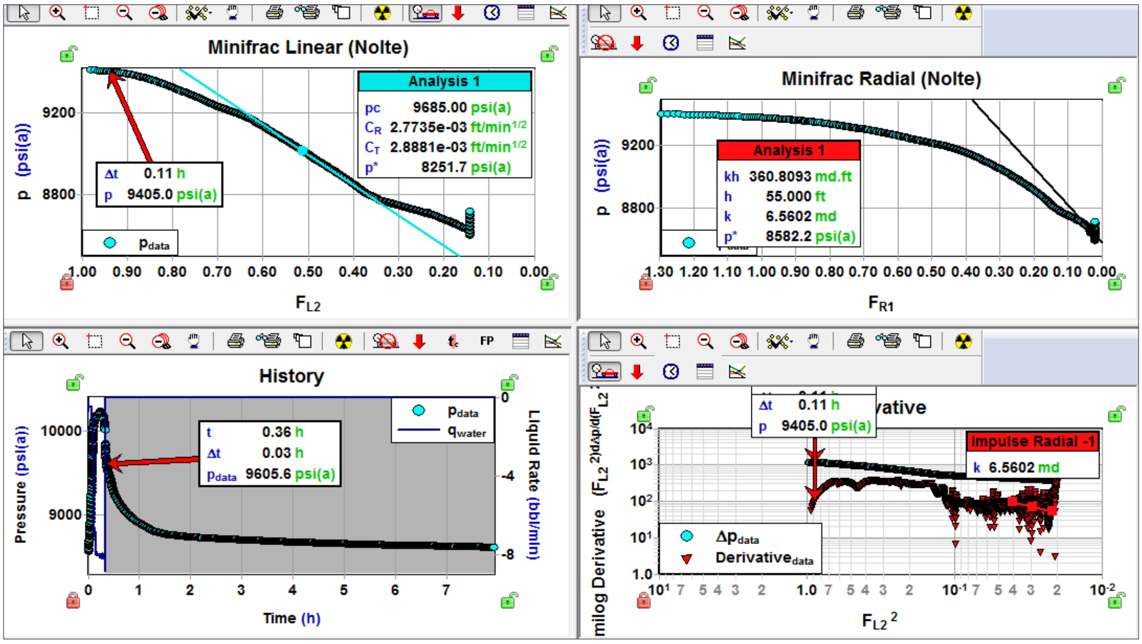

Figure 13. Post closure analysis of DFIT based on down-hole memory gauge pressure, Top left: linear fracture flow, Top Right: Semi Radial flow, Bot. Left: Historical data, Bot. Right: Derivative plot.

Although the decision was made based on real-time data and later validated by downhole pressure analysis, the results of both studies were sufficiently comparable and consistent in terms of permeability range.

The reservoir permeability was calculated from the semi-radial flow, and the reservoir pressure was measured using the linear flow plot (Top Left plot in Figure 12). The downhole pressure response analysis yielded the same conclusions. This consistency between real-time and downhole analyses may allow for the removal of downhole measurement efforts and further optimization of test costs in future DFIT jobs.

Figure 14 summarizes the data acquisition chronology, depicting the journey from pre-drill to post-drill up to DST decision-making. As shown, the understanding of well deliverability has improved and the uncertainty range has narrowed significantly, enabling the development project team to formulate an accurate model for techno-commercial evaluation.

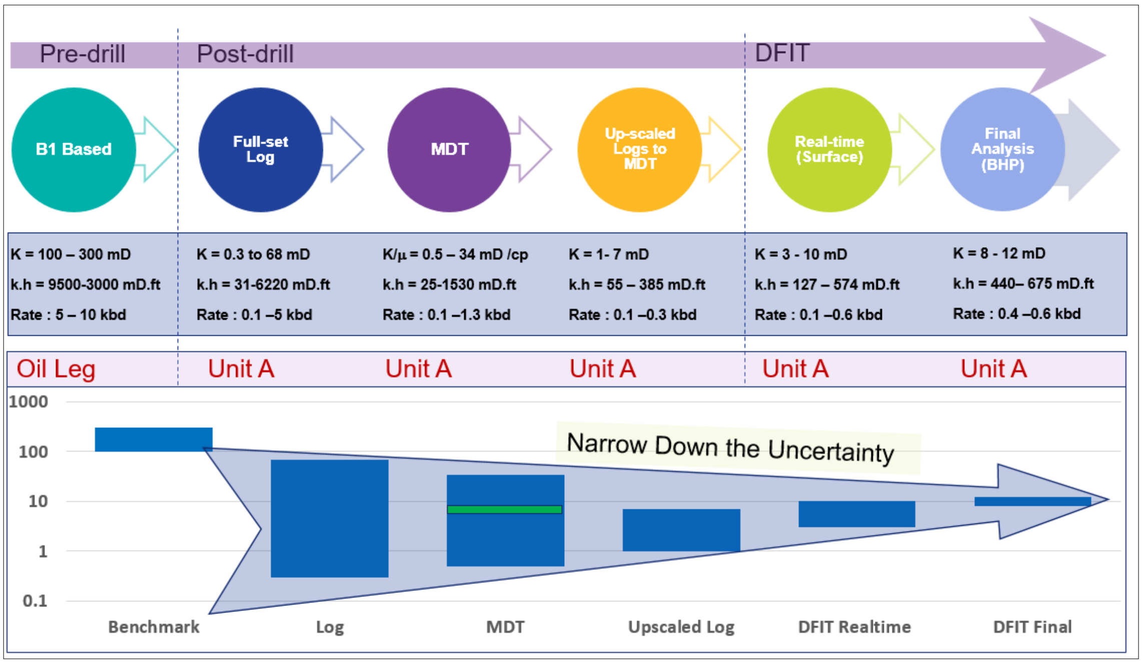

Figure 14. *Data Acquisition Journey to narrow down uncertainty in G2 well*

OPTIMIZING RESERVOIR CHARACTERIZATION WITH DFIT

The implementation of DFIT brought significant optimizations and new contributions in several ways. It reduces uncertainty and provides more reliable data for decision-making processes, thereby improving capabilities related to reservoir development and management. DFIT enables a comprehensive assessment of the entire tested layer, ensuring a holistic understanding of reservoir dynamics. Proper consideration of logistics ensures smooth operations, optimizes resource utilization, and minimizes downtime in upstream tasks. This approach also enhances consistency between liquid sampling stations and obtained results, improving data reliability and accuracy.

DFIT's contribution to DST cancellation in G2 prevents potential value loss and optimizes resource allocation. Furthermore, it allows for accurate measurement of reservoir pressure and KH/µ using the drill string in significantly less time, enabling more efficient operations. The results can be effectively used for upscaling various rock types without additional testing, accelerating the process of expanding and improving efficiency. Overall, DFIT streamlines operations, enhances data quality, and contributes to more informed decision-making in reservoir management.

Due to the high cost of conducting well testing in distant locations and deep-water horizons, the Diagnostic Fracture Injection Test (DFIT) is carried out prior to the well test with little expense and little rig time in order to make an informed choice on the well test. Without performing the DFIT test, the G2 well may undergo well testing, need time to empty the well and attempt to flow it, fail to achieve continuous flow, and incur costs without any useful data capture. Figure 15 displays the decision tree for the DST (well test) and illustrates how the DFIT adds value.

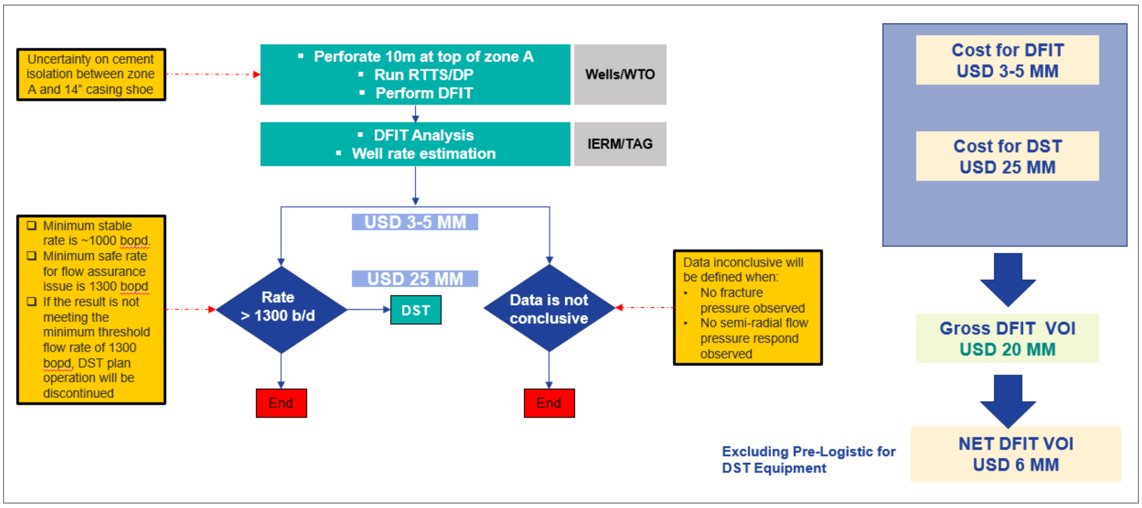

Figure 15*. Value of Information of DFIT in G2 Well*

CONCLUSIONS

The integration of data from Wireline Formation Testers (WFT), particularly advanced tools like the Modular Dynamics Formation Tester (MDT), with Diagnostic Fracture Injection Testing (DFIT) techniques has emerged as a crucial strategy for mitigating reservoir permeability uncertainties. By leveraging these complementary technologies, operators gain a more comprehensive understanding of reservoir behaviour, leading to improved decision-making in both technical and commercial assessments. As industry continues to explore deepwater reservoirs where economic considerations are paramount, the adoption of DFIT as a value-based option will become increasingly vital. This integrated approach enhances reservoir characterization accuracy, optimizes resource allocation, and ultimately contributes to more efficient and cost-effective exploration and production strategies in challenging environments.

To address the complexities associated with deepwater exploration, operators are urged to prioritize DFIT implementation in high-visibility wells and ensure meticulous planning and execution of each test phase. By conducting well testing using DFIT during the exploration and evaluation phase, operators can systematically collect critical data that influence reservoir characterization and more accurately delineate reservoir boundaries. Additionally, analysis of MDT station data provides invaluable insight into the potential for permeability improvement and facilitates the design and optimization of DFIT and Drill Stem Test operations.

Essentially, this integrated approach not only strengthens reservoir characterization efforts but also streamlines operational workflows and ultimately enables operators to maximize the value of Deepwater assets. By leveraging technological advances and refining testing methods, operators can meet the challenges of deepwater reservoirs with confidence, realize their full potential and ensure long-term, sustainable success in exploration and production efforts.

Abbreviations

DFIT Diagnostic Fracture Injection Test

DST Drill Stem Test

LOT Leak Off Test

MDT Modular Dynamic Tester

MEFS Minimum Economic Field Size

VOI Value of Information

WFT Wireline Formation Testers

Conflict of interest statement

On behalf of all the co-authors, the corresponding author states that there is no conflict of interest.

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