Analytical Methods to Develop Accurate Structural Model for the Asmari Reservoir

[1]ZOHREH MOVAHED, [2]ALI ASGHAR MOVAHED
[1]Schlumberger, Kuala Lumpur, MALAYSIA
[2]Ahawz Oil and Gas Research Department, IRAN

Abstract: Crossing of Asmari can be a challenging endeavor in certain instances, particularly when dealing with structural complexities, compounded by the presence of a substantial layer of Gachsaran formation evaporates overlying the reservoir. The primary aim of this study was to establish a precise and comprehensive structural model for the Asmari reservoir. Utilizing geological logs for dip classification offers the advantage of directly depicting the structural origin. This approach helps in identifying the Asmari fault and fracture systems and their impact on production, ultimately resolving structural complexities. To investigate the reasons behind the intersection of the Kalhur member and the unexpected increase in the thickness of the Asmari formation, FMI data was acquired over the interval ranging from 1550m to 2065m. The analysis of picked bedding dips revealed abrupt variations in dip magnitude and azimuth reversals. These observations were pivotal in unraveling the structural intricacies of the reservoir. A significant fault was identified within zone five of the Kalhur member, and its interpretation suggests that it is a reverse fault. This conclusion is based on the observed dip pattern and the distinctive characteristics of the logs. Around the fault, the beds and layers exhibit elevated dips, largely attributed to the plastic nature of anhydrite and marly/shaly anhydrite within the formation. The anhydrite-indicator curve obtained from the FMI and gamma-ray logs provides further evidence that the well entered the Kalhur member after intersecting the major fault located within this particular zone. The interpretation of structural dip played a pivotal role in resolving structural complexities, leading to the precise determination of the well's location within the Asmari reservoir. This achievement was particularly critical as it enabled the well to reach the lower contact of the Asmari formation. This interpretation was facilitated by analyzing FMI images and petrophysical logs in well LL-26.

Keywords: Structural complexity, FMI, fractured reservoir, geological, petrophysical log, structural model, strucview, Fracture analysis

Received: July 15, 2022. Revised: September 9, 2023. Accepted: October 5, 2023. Published: November 27, 2023.

1. Introduction

The Zagros Mountains are a geological wonder characterized by their concentrically folded formations, a result of tectonic forces shaping the Earth's crust over millions of years (Movahed et al., 2015). Within this mountain belt lie complex and intricate geological structures, each playing a crucial role in determining the success of various development projects, particularly in the oil and gas industry(Fig. 1).

Understanding the precise angles at which these geological layers dip and identifying subsurface fault patterns becomes paramount for planning and executing well developments. However, the challenge lies in the variability and unpredictability of these formations. Sometimes, the thickness of these geological layers surpasses initial expectations due to numerous factors. It could be the result of steeper-than-anticipated bedding dips or the presence of unexpected reverse faults.

Pinpointing the exact cause of these unpredictably greater thicknesses can be a significant challenge (Eynollahi, 2009). Imagine drilling a well with a certain projection of the layers' thickness, only to discover that the actual thickness far exceeds the projections. This discrepancy can arise due to geological complexities, such as encountering unexpected steep dips or faults that weren't accounted for initially.

Even regions that seem to have low dip angles at the surface may unveil steep dips as drilling progresses deeper into the Earth (Movahed et al.,2022). This sudden variation can lead to wells missing their intended targets, resulting in an inability to access the desired reservoirs or oil columns, despite penetrating what was believed to be the reservoir zone. Consequently, wells might need to be redirected or sidetracked in the correct direction to access these previously overlooked reservoirs or oil pools.

The intricate nature of the Zagros Mountains' geological formations presents a constant challenge for those involved in drilling and exploration. It underscores the importance of not only initial surveys but also continuous monitoring and adaptive planning during the drilling process to ensure accurate targeting of valuable resources hidden beneath the Earth's surface.

Well LL-26 is a significant location within the Lali field, positioned specifically in the Eastern south region of the onshore site in Iran. The drilling operations for this well were executed using an 8.500” bit, a substantial tool in the oil drilling process, with a maximum deviation of 24 degrees towards the North-Earth direction over the image log interval(Fig. 2).

The choice of an 8.500” bit indicates a sizable borehole diameter, allowing for efficient drilling while considering the geological formations encountered. The 24-degree deviation is crucial as it denotes the directional drilling technique used to reach the desired target or reservoir while avoiding obstacles or unfavorable formations. Such precision in directional drilling is vital in optimizing the extraction process and ensuring the efficient recovery of resources.

The Lali field itself holds significant importance within the oil and gas industry, characterized by its onshore location in Iran. The geographical positioning in the Eastern south part of the field suggests a strategic placement, potentially tapping into specific reserves or geological formations unique to this area.

Furthermore, the duration of the study, conducted for a period of 2 months at Schlumberger, signifies a comprehensive evaluation and analysis of the well. This study period likely involved a detailed assessment of various parameters, including geological data, wellbore conditions, reservoir characteristics, and production potential.

The information collected during this study at Schlumberger would contribute significantly to understanding the behavior of well LL-26, aiding in decision-making processes related to further drilling operations, reservoir management, and overall field development strategies.

The combination of the well's location, drilling specifications, and the comprehensive study period at Schlumberger reflects a meticulous approach to extract valuable resources while ensuring efficient and sustainable oil and gas production within the Lali field in Iran.

The target reservoir is the Asmari Formation. The Asmari Formation, characterized by its substantial carbonate sequence from the Oligocene-Miocene period, is renowned as one of the world's most prominent carbonate reservoirs(Hassan et al.,2010). The Asmari Formation is lithologically characterized by limestone, dolomite, marly limestone, and the presence of anhydrite within the Kalhur Member, all of which are relevant to the geological composition in this area. The primary drilling objective for this well was to achieve production from the upper Asmari zones while determining the fluid contact within the reservoir.

During the drilling process, an unexpected occurrence took place, with the well penetrating the top of the Asmari Formation at an unexpected depth, approximately 1542 meters, as indicated by both log and cutting data. Subsequently, the well intersected the Kalhur members after drilling through about 521 meters. Despite continued drilling efforts, the well was unable to exit the Kalhur member.

In this complex geological setting, borehole imaging logs(Chokthanyawat et al.,2012) played a critical role in detecting the structural and reservoir geometry. Accurate reservoir description through the use of image logs, particularly in thinly laminated reservoirs, emerged as a key factor in facilitating effective field development (Yang, et al.,2011). Structural and reservoir geologists can readily identify fracture features and classify different types of fractures along the wellbore by directly utilizing the FMI (Formation MicroScanner) log (Rezaie et al.,2006), moreover, in situations where seismic data is unavailable, the FMI log serves as a valuable tool for these geologists, enabling them to provide essential information that can be used to develop dependable solutions for significant geological challenges. (Soliman et al.,2010).

To unravel the intricacies behind the convergence of the Kalhur member and the unanticipated surge in the Asmari Formation's thickness, a meticulous Formation MicroImager (FMI) survey was meticulously carried out. Spanning from 1550 meters to 2065 meters, this survey was a critical endeavor aimed at scrutinizing the dip patterns along the well trajectory. Its primary objective was to craft an intricate structural model, serving as a navigational blueprint for the National Iranian South Oil Company (NISOC) to undertake a targeted sidetrack, specifically accessing the upper zones of the Asmari reservoir.

This investigative endeavor was fraught with multiple challenges. The initial well's failure to breach the Asmari reservoir, leading to the initiation of Sidetrack 1, necessitated meticulous planning for a subsequent sidetrack, further compounded by stringent time constraints. Complicating factors included a steep structural dip, a labyrinthine fault system, and the considerable depth of the geological formations involved. Overcoming these obstacles became imperative for the successful fruition of the project.

The fundamental aim of this comprehensive study lay in comprehending the unexpected intersection of the Kalhur member, the abrupt thickening of the Asmari formation, and devising a strategic roadmap for a new sidetrack based on these revelations. To accomplish this, the study harnessed an extensive array of datasets, notably relying on the comprehensive Full set and Formation Micro-Imager (FMI) log data. These datasets formed the cornerstone of an exhaustive analysis, precisely tailored to meet the study's objectives.

The essential role played by FMI log data in this investigative pursuit cannot be overstated. Its exceptional image quality provided an unparalleled, intricate portrayal of the geological structures ensconced within the well. This high-fidelity data facilitated precise interpretations of the well's structural nuances, enabling the meticulous identification, description, and quantification of fractures and faults inherent within the formations.

The identification and characterization of these fractures and faults stood as pivotal milestones in comprehending subsurface geology. These geological features wield significant influence over fluid behavior within reservoirs, ultimately impacting the efficacy of drilling operations. The study's primary endeavor revolved around accurately pinpointing and gauging these attributes to fathom how they might have influenced the unexpected Kalhur formation intersection and the sudden Asmari formation thickening.

Furthermore, the insights derived from studying the FMI data, synergized with other relevant datasets such as the Full set logs, well-found invaluable insights for orchestrating a new sidetrack. A profound comprehension of the encountered geological intricacies and anomalies within the wellbore forms the bedrock for devising a strategically optimized sidetrack, adept at navigating these complexities while optimizing drilling success.Hence, the study required to harness the granular analysis of the Full set and FMI log data not only to comprehend the underlying reasons behind the encountered geological anomalies but also to steer strategic decisions pertaining to future drilling endeavors. Particularly, the study focused on crafting an efficient sidetrack blueprint, meticulously tailored to circumvent the challenges posed by these unforeseen geological formations and variations.

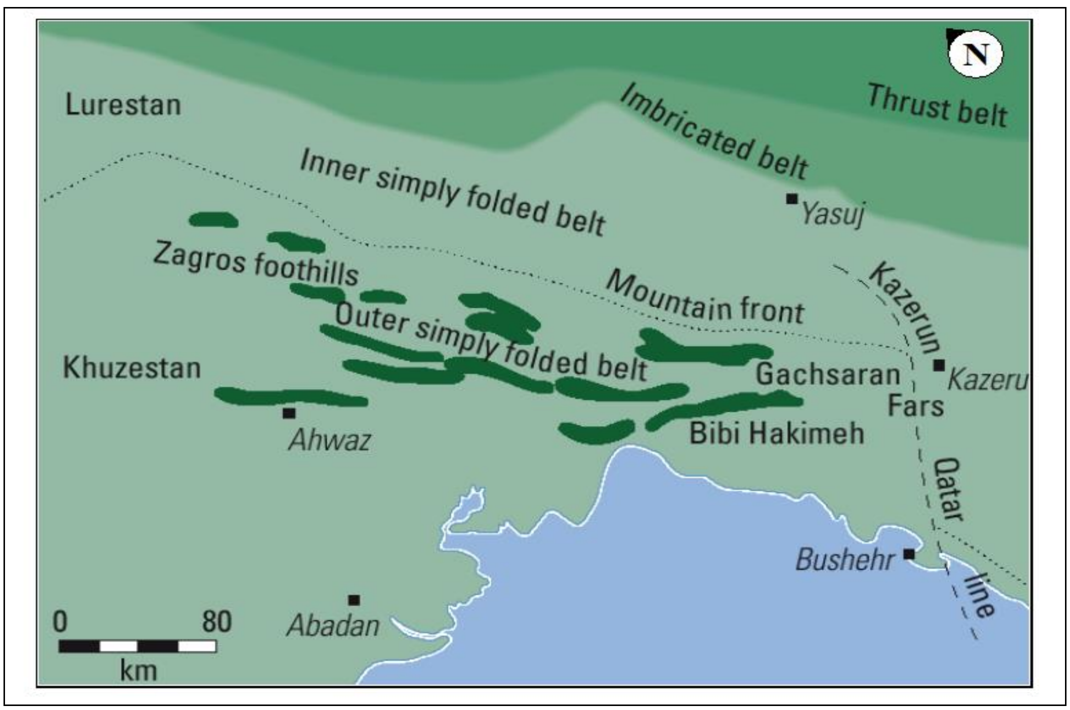

Fig. 1: Illustrates the notable anticline formations within the Foreland basin of the Zagros Mountains, exhibiting a trend from the northwest to the southeast (Motiei, 1995).

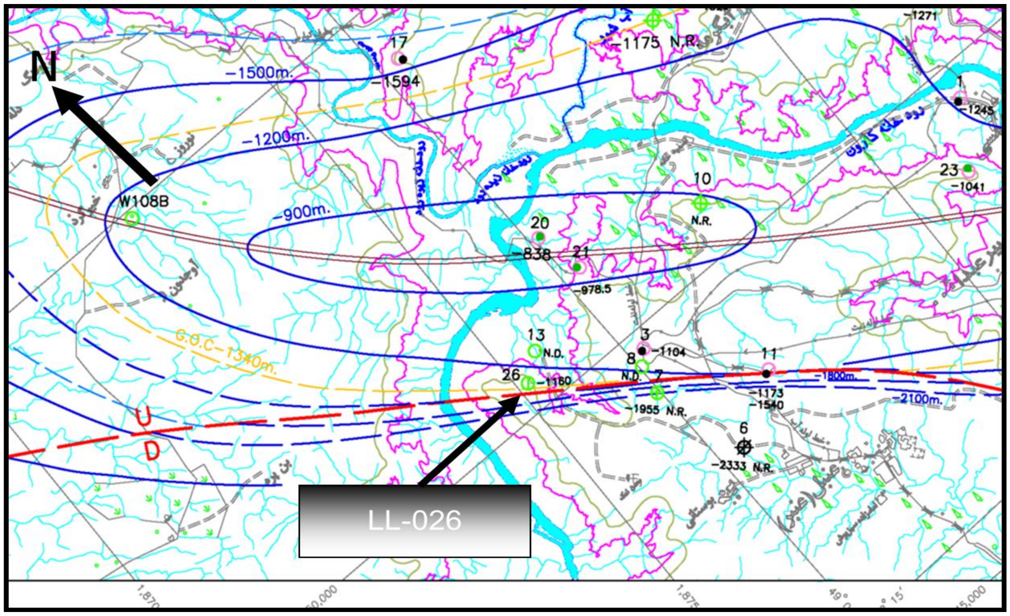

Fig. 2: Displays the location map of well#LL-26 situated within the Lali field. Source: (NIOC South UGC map).

2. Materials and Methods

The methodology encompassed a thorough utilization of the FMI (Formation Micro-Imager) and the Full set log data, ensuring a comprehensive analysis. The initial step involved processing the FMI data with BorEid to heighten log quality, ensuring accuracy and reliability in subsequent assessments. All petrophysical logs and accompanying images were meticulously matched to a reference log based on their respective depths. To enhance the interpretability of formation features, the images underwent equalization and normalization via BorNor, refining their visualization.

The representation of image logs was strategically designed: resistive units appeared vividly in bright hues, while lower resistivity conductive units were visualized in darker shades. The interpretation process kicked off with a meticulous manual selection of dips, employing sinusoidal techniques on oriented images presented at a scaled-down ratio of 1:20. This downscaled representation aimed to minimize potential human errors in the selection process.

The selected dips were then meticulously classified into two categories: bed boundaries and fractures, leveraging the capabilities of Borview. The primary geological structures, notably visible in the FMI image log, predominantly comprised bedding and various sedimentary features. To handle the geological dip information efficiently, Strucview was employed, facilitating the display and categorization of dips into distinct sets representing different geological structures.

Within these categorized sets, the computation of cross-sections was carried out with precision. Specifically, a computer-generated cross-section was developed in Strucview, following an NNE-SSW plane, relying on the compiled dip data .This cross-sectional representation offered a comprehensive visualization of the geological formations along the specified plane, aiding in the subsequent analysis and interpretation of the geological features captured within the dataset(Fig. 3).

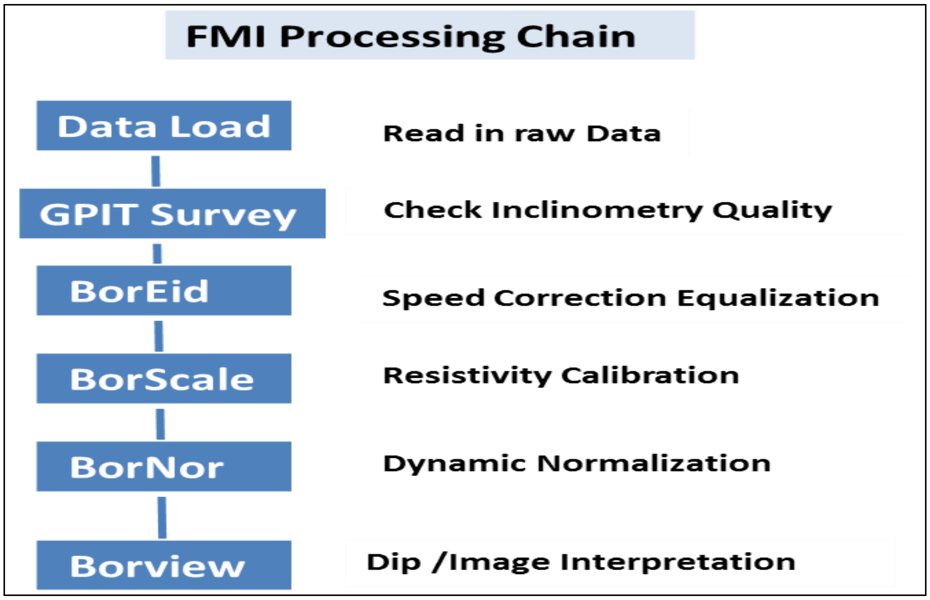

Fig. 3:A comprehensive visualization of the study's workflow, offering an intricate overview of the step-by-step processes undertaken during the research. This workflow acts as a roadmap, outlining the sequential stages and methodologies employed in the study, guiding researchers through the systematic approach used to analyze the Asmari Reservoir.Additionally, there's a flowchart specifically delineating the processing chain utilized for the Formation Micro-Imager (FMI) images.

3. Result and Discussion

Borehole image logs are pivotal tools within the oil and gas industry, particularly for exploring and developing reservoirs. These logs provide invaluable insights into the geological structures below the surface. Specifically, they are instrumental in detecting and characterizing both the structural makeup and reservoir geometry, which is crucial for successful field development.

In thinly laminated reservoirs, where rock or sediment layers are extremely thin, accurately understanding their composition becomes challenging yet absolutely essential for effective field development. Borehole image logs step in to address this challenge by offering comprehensive details regarding the composition, orientation, and distribution of these thin layers within the reservoir.

These logs capture high-resolution images of the borehole walls, uncovering intricate details like bedding planes, fractures, faults, and other geological features that traditional logging methods might overlook. Geoscientists and reservoir engineers analyze these images to deduce critical information about the reservoir's nature, including its porosity, permeability, and other vital properties.

Precise interpretation of borehole image logs leads to more accurate reservoir modeling and assists in optimizing well placement and completion strategies. Understanding the structural and reservoir geometry in thinly laminated reservoirs holds immense importance in estimating reserves, predicting fluid flow behavior, and designing efficient production strategies.

Fundamentally, employing borehole image logs to characterize thinly laminated reservoirs is indispensable for making informed decisions during field development. It allows the industry to maximize hydrocarbon recovery while minimizing operational risks and costs. Ultimately, this significantly contributes to the overall success of oil and gas operations by enabling informed and strategic decision-making throughout the development process.

3.1 Complex Structural Study Results in Asmari Formation

The comprehensive investigation into the Complex Structural Analysis of the Asmari Formation was a thorough endeavor that delved deeply into the geological layers. By meticulously examining Full Set and Formation Micro-Imager (FMI) images, a wealth of multifaceted insights emerged. These analyses served as a cornerstone, revealing the presence of five unique lithological units embedded within the formation.

So far, what truly piqued curiosity was the intricate nature of their arrangement. Despite the clarity in identifying these distinct units, their distribution exhibited a fascinating pattern marked by fragmentation. Within the well section that was explored, these units lacked continuous connections, presenting a puzzling aspect to the geological composition of the Asmari Formation.

The distinct geological formations within the Asmari formation can be classified into several lithological units: anhydrite, shaly/marly anhydrite, shale/marl, dolomite, and calcite. These units predominantly populate the upper strata of the formation. Among these formations, a keen focus lies on the stratification evident within the shaly/marly limestone and its associated intervals.

What captures particular attention are the visually arresting patterns discernible in the upper layers. These patterns are characterized by a rhythmic alternation between porous carbonate layers and tight, low-porosity carbonate layers. Adding to the complexity, this stratification also exhibits streaks or layers of anhydrite. In some instances, these anhydrite layers intertwine intricately with carbonate formations, imparting a multifaceted structural composition to the geological landscape. This interplay of different materials hints at a dynamic history and intricate processes shaping the Asmari formation over time.

A total of 133 boundaries were carefully identified from the FMI (Formation MicroScanner) images through an interactive process. Due to the limited certainty in identifying bed boundaries, we also included lower-confidence indications of bedding dips in our analysis to determine structural dip. Considering the various types of bedding dips, an average dip magnitude of 33 degrees across the entire interval (as illustrated in Fig. 4 can be used to calculate the structural dip.

The investigation into the bedding dips right below the casing shoe reveals a consistent pattern: an average dip of approximately 24 degrees, consistently aligned in the S38W direction. These specific structural features hold significant importance due to the intricate nature of the Asmari carbonate formations. Understanding these complexities is vital for effectively characterizing and managing the reservoir. The challenges posed by the unique properties of Asmari carbonates emphasize the critical nature of comprehending these structural intricacies for successful reservoir characterization and management.

This in-depth examination delves into the intricate variations in rock composition, layering patterns, structural intricacies, and the characterization of fractures within the Asmari formation. Its significance lies in being a pivotal cornerstone for crafting highly efficient strategies to manage reservoirs effectively and devising the most optimal methods for extracting hydrocarbons.

Moving beyond structural considerations, a critical aspect of the study involves the detailed characterization of fractures within the Asmari formation. These fractures wield significant influence over the reservoir's behavior, impacting fluid flow dynamics and reservoir productivity.

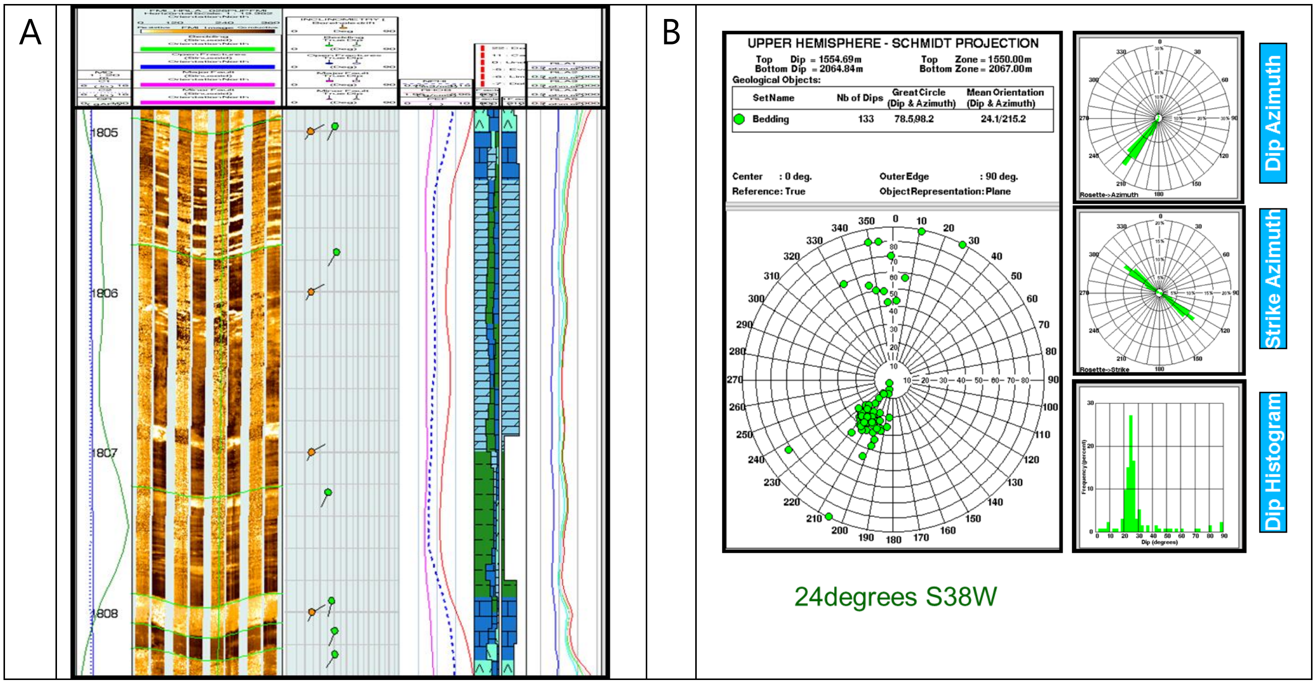

Fig. 4: A)A comprehensive depiction of the layering within the Asmari formation is presented. This visual representation likely showcases the intricate stratification and arrangement of the geological layers within the formation. Each layer may vary in terms of composition, density, or other geological characteristics, contributing to the overall structure and behavior of the Asmari reservoir,B) offers statistical plots that specifically highlight the bedding dips within this geological formation. These plots serve to illustrate the distribution and orientation of the bedding planes. The indicated average dip of 24 degrees, inclined in the direction of S38W and striking along the N52W-S52E axis, emerges as a key finding. This average dip inclination serves as a crucial characteristic, considered highly representative of the entire span or interval covered by the Asmari Formation.

3.1.1 Analytical Fracture Characterization Result in Asmari formation

Fractures play a crucial role in facilitating fluid movement, whether it's water or hydrocarbons. Highly fractured rocks can serve as excellent aquifers or hydrocarbon reservoirs due to their ability to maintain both significant permeability and fracture porosity. These fractures create pathways that allow fluids to flow more readily through the rock, making them valuable for various subsurface fluid containment and transport applications. (Park, 2005).

In addition to dealing with structural complexities, it is crucial to determine the presence of productive fractures in a well that is intersecting a reservoir with very low matrix permeability. Given that most reservoirs in this basin are composed of carbonates and have undergone a complex tectonic history, the likelihood of encountering both favorable and unfavorable fractures in these reservoirs is quite high. The fractures and faults in such formations reveal intricate geometry and timing relationships, making their assessment and characterization a vital aspect of reservoir exploration and development. (Movahed et al.,2015).

The primary challenge lies in pinpointing the locations within the reservoir where fractures are most concentrated and determining their orientations concerning the structural axis, predominant stress regime, and the positions of gas-oil or oil-water contacts. It's essential to recognize that fracture apertures can vary, ranging from open (permeable), tight (closed), to those filled with minerals such as clays, calcite, anhydrite, and pyrite. These variations can significantly impact fluid flow within the reservoir, affecting both productivity and reservoir management strategies.

Hence, a comprehensive understanding of fracture intensity, orientation, and mineral infill is crucial for optimizing reservoir production(Nimmagadda et al.,2010). Fractures typically manifest as linear features with a steeper dip than the structural dip observed in the FMI images. Open fractures appear conductive in the images due to the intrusion of conductive drilling mud into their apertures, particularly in clay-free formations. In contrast, mineralized or sealed fractures exhibit resistive characteristics when their apertures are densely filled with materials like calcite or anhydrite. On the other hand, fractures filled with clay or pyrite display a conductive response.

Distinguishing between mud-filled and clay/pyrite-filled conductive fractures necessitates a deep understanding of the depositional and stratigraphic context in the study area. Open hole logs can be extremely useful in addressing this distinction.

In the existing well, a comprehensive analysis has revealed the presence of fractures across five separate zones, with sporadic instances of isolated occurrences. What sets these fractures apart is that each of them exhibits open apertures, categorizing them as open fractures. These fractures, crucially, are distributed within the depth range of 1560 to 1760 meters. This particular observation holds immense significance as it provides crucial insight into the reservoir's characteristics, offering valuable information for assessing its potential. Moreover, this knowledge becomes instrumental in devising and refining optimal production strategies, as depicted in Fig. 5

In the well analysis, a comprehensive count of 430 fractures has been meticulously documented. These fractures, when observed collectively, showcase a unique and intriguing pattern. This distinctiveness becomes apparent when examining the dip azimuth plot, revealing a widely scattered arrangement. Despite this scattered distribution, a predominant southwest-oriented azimuth emerges, accompanied by a noteworthy inclination in the dip.

To investigate further into the details, it's notable that fractures within the Asmari formation, as identified in the analysis, tend to conform to a prevailing northwest-southeast (NW-SE) strike orientation. However, what's particularly intriguing is the considerable variability observed within this orientation, indicating a broad spectrum of orientations within this overarching trend. This variability suggests a complex interplay of geological factors influencing the fracture distribution and orientation within the Asmari formation.

The fractures' dip inclination, or their angle of deviation from the horizontal plane, displays a significant range, spanning from a gentle 34 degrees to a steep 90 degrees. This diversity in angles offers crucial information about the reservoir's structural makeup. Understanding these angles is vital because they shed light on how fluids might traverse through the formation. This data, as illustrated in Fig. 6, holds key insights into the reservoir's structural intricacies and the potential pathways for fluid flow within it.

DOI: 10.37394/232031.2023.2.12

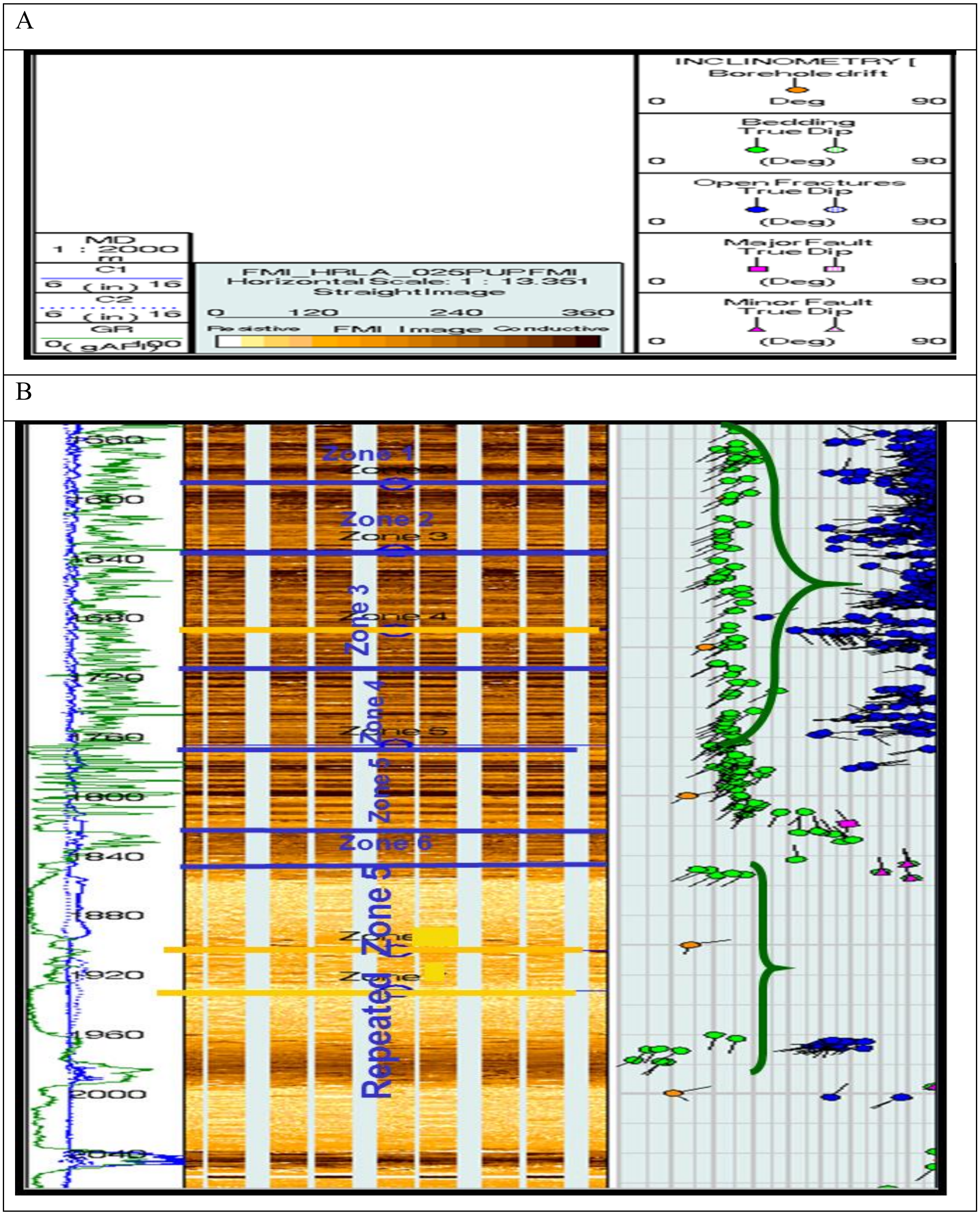

Fig. 5: A)Header details ,B)The presence of open fractures highlighted by blue circles within the Asmari formation. These fractures exhibit an oblique orientation concerning the bedding strike. The fractures, represented by the blue circles, are visibly distinct and appear to intersect the bedding plane at an angle rather than perpendicular or parallel to it. This oblique angle suggests a unique geological phenomenon, possibly indicating the manner in which these fractures were formed or influenced by various forces acting upon the Asmari formation.

International Journal of Chemical Engineering and Materials
DOI: 10.37394/232031.2023.2.12

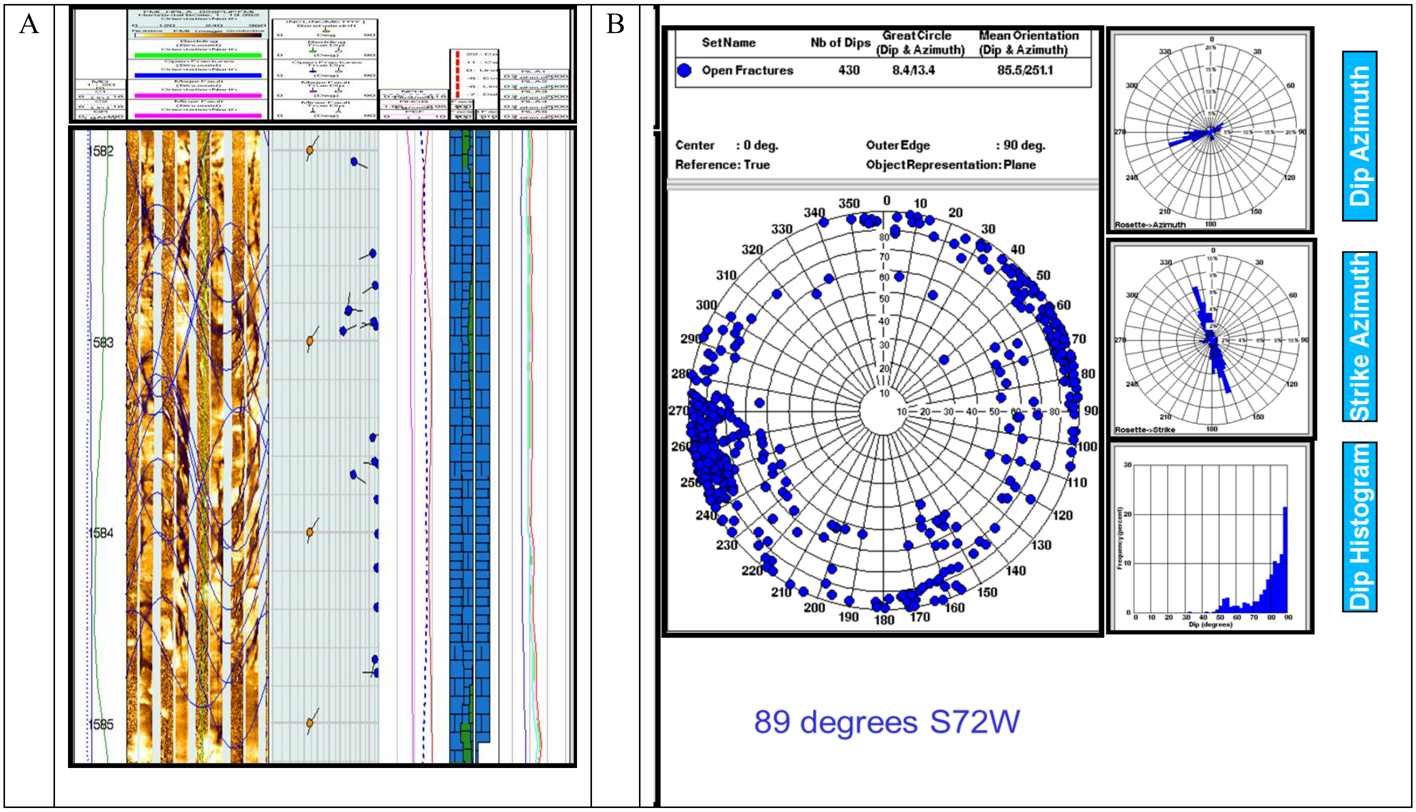

Fig. 6: A) Exposed fractures within the Asmari formation, B) A Schmidt projection plot (upper hemisphere) showcasing the distribution of fracture dip poles. The histogram depicting their dip inclinations reveals a broad range, while the dip azimuth rosette indicates a predominant southwest dip direction, albeit with considerable variability. Similarly, the strike rosette displays a prevailing NW-SE strike, yet with significant dispersion in orientations.

3.1.2 New Analytical Discovery in Complex Fault System Analysis :

Faults are typically defined as joints or fractures with evident displacement. In the interpretation of FMI/FMS images, several factors are considered to identify a feature as a fault. The most commonly observed criteria for fault identification are outlined below. However, it's important to note that not all of these criteria need to be present for every fault encountered in a well:

- **Abrupt Change in Dip Attitude:** This includes a sudden shift in either the magnitude or azimuth of the dip across the high-angle feature or zone.
- **Drag Patterns:** Dips indicating short or long drag patterns may be observed in either the up-thrown block, down-thrown block, or both.
- **Disturbed or Crushed Zone:** The presence of a disturbed or crushed zone surrounding the fault can be indicative.
- **Change in Borehole Drift:** An unexpected change in the borehole's drift or deviation azimuth may occur in the vicinity of the fault.

- **High Angle Resistive or Conductive Events:** Significant high-angle resistive or conductive events that develop across the wellbore.
- **Enlarged Borehole:** The borehole may exhibit enlargement at the point of intersection with the fault.
- **Shift in In-Situ Stresses:** A shift in the trend of in-situ stresses may be associated with the fault.
- **Abrupt Termination of Layers:** In cases where no drag pattern is evident, abrupt termination of layers on the fault plane can be a sign.
- **Change in Fault-Bounded Layer Thickness:** Variations in the thickness of the fault-bounded layer as it crosses the wellbore.
- **Occurrence of Fractures:** The presence of fractures is a well-accepted method for determining the potential fault direction in a given area, as it can provide valuable insights into fault orientation.

When identifying faults, it holds huge significance to precisely factor in a range of criteria. These criteria should be carefully analyzed within the unique geological and structural makeup of the well and its immediate surroundings. Understanding the intricate interplay of these criteria within the geological context is pivotal. It involves scrutinizing the well's specific characteristics, such as its geological formations, structural integrity, and the broader geological landscape encompassing it. Only by delving into these intricate details can one effectively pinpoint and comprehend the faults present in this complex geological setting.

Anhydrite, with its distinctively high resistivity and remarkably low conductivity, stands out as a notable feature within the Asmari formation. Identification of this mineral involves a thorough analysis of various data sources, including detailed examination of images and careful study of conductivity/resistivity curves. These tools serve as crucial indicators in recognizing the presence and distribution of anhydrite within the formation.

The examination of images and conductivity/resistivity curves unveils the distinct signature of anhydrite, allowing for its precise identification and mapping within the Asmari formation. Furthermore, the data gleaned from each pad's readings emphasizes a noteworthy finding: a substantial and continuous occurrence of anhydrite within the geological strata. This continuity of anhydrite presence underscores its significance and prevalence within this specific geological context, providing valuable insights into the composition and structure of the Asmari formation.

The cross-section provided by NISOC initially lacked precision due to its intersection with the Kalhur members, specifically the Anhydrite, which were not originally intended to be part of the analysis. Consequently, this deviation from the planned course led to an oversight in recognizing the productive permeable zones within the Asmari reservoir.

To rectify this, a new structural model was developed using Formation Micro-Imager (FMI) data alongside petrophysical logs. This updated model shed light on the previously missed productive zones within the Asmari reservoir. The incorporation of the FMI data and petrophysical logs provided a more comprehensive understanding of the structural dynamics, allowing for a refined assessment of the reservoir's potential.

In response to these critical insights, a detailed analysis was carried out specifically on the FMI images and open-hole logs, focusing on resistivity readings, for the LL-026 well. This analysis aimed to meticulously examine the geological formations and assess the presence of permeable zones within the Asmari reservoir. By leveraging these advanced imaging and logging techniques, a more accurate evaluation of the reservoir's characteristics and potential productivity was pursued.

At approximately 1819 meters within zone five of the Kalhur member, a significant fault was identified through a comprehensive analysis that took various critical observations into account. These observations served as pivotal markers in identifying and characterizing the fault:

- The structural dip within the Asmari reservoir presents a consistent upward trend in inclination as depth increases. This gradual rise culminates in its peak value of 50 degrees at a depth of 1810 meters, characterized by a specific azimuth of NNW. However, a notable deviation in this pattern occurs at 1819 meters, where a high-angle dip of 59 degrees is observed. This 59-degree dip stands in contrast to the typical bedding dips, showing a nearly opposite direction inclined towards SSW.Fig. 7 illustrates a significant fault within the geological structure, prominently manifesting at 1819 meters. This fault exhibits a steep dip of 59 degrees with an orientation of N18W and a striking direction spanning N72E-S72W. The juxtaposition of this fault's characteristics against the surrounding geological features highlights its distinctiveness within the Asmari reservoir, marking a pivotal structural element that significantly diverges from the general dip trends and orientations observed in the area.Moreover, an additional potential fault was discerned within zone five of the Kalhur members, indicating a repeated section. This identification suggests the likelihood of a fault-induced repetition of geological layers within this specific zone of the Kalhur members, further contributing to the structural complexity and geological variations within the reservoir.

- Between the depth levels of 1805 to 1820 meters, a distinctive geological feature known as a "drag zone" shows within the up-thrown block. This zone is characterized by a obvious and notable downward surge in the magnitude of dip. This dip magnitude signifies the angle at which the rock layers or geological strata are inclined concerning the horizontal plane.The occurrence of this downward increase in dip magnitude denotes an area where geological forces or structural movements have exerted an influence, resulting in a dragging effect on the formations within the up-thrown block. This alteration in dip angle within this specified depth range signals localized geological complexities, possibly arising from various tectonic activities, faulting, or other subsurface processes.Identifying this drag zone holds paramount significance in unraveling the intricate geological dynamics within the Asmari Reservoir. It serves as a significant sign of potential structural disturbances or differential movements within this specific depth interval, contributing profoundly to the comprehension of the reservoir's geological evolution and aiding in more accurate predictive models of its behavior(Fig. 8).

- Within the interval of 1823.5 to 1844 meters, a distinct and disrupted zone is identified within the Asmari reservoir. This zone exhibits a notable characteristic where the dips of geological layers point in diverse directions, showcasing a lack of consistent orientation. Additionally, a specific high-angle feature is observed in a NNW (north-northwest) dipping direction around the depth of 1825 meters within this disturbed zone.As the analysis descends below this disturbed zone, the pattern of bedding dips undergoes a shift. Specifically, in the subsequent interval spanning from 1844 to 1998 meters, the bedding dips within the Asmari reservoir regress to an average inclination of approximately 22 degrees in the SSW (south-southwest) direction.This shift in the dip behavior denotes a transition from the earlier disrupted zone, where the dips were scattered in various directions, to a more uniform bedding orientation characterized by an average dip of 22 degrees in the SSW direction. Understanding this transition aids in comprehending the structural alterations and variations within the reservoir, delineating distinct zones with different dip characteristics that can significantly impact the reservoir's geological behavior and fluid flow dynamics(Fig. 8).

In addition to the direct examination of the images, open-hole logs were employed to confirm a fault or qualify a feature as a fault in cases where the factors listed in the above-mentioned criteria did not entirely apply. This helps validate the interpretation of the fault.Log analysis involves two crucial steps to interpret potential faults or fractures:

- **Identification through Log Characteristics:** One fundamental step is recognizing abrupt changes in log characteristics coinciding with distinct features in Formation Micro-Imager (FMI) images. These changes often indicate a fault. For instance, a sharp, sudden alteration in the logs across a notable feature might signal either a fracture or a fault with a minimal displacement, where the same geological layer or formation appears on either side of the feature (refer to Fig. 8 for visual representation).

- **Correlation of Logs for Validation:** Another significant aspect involves cross-referencing logs obtained from different boreholes or various segments within the same well. This comparison aims to ascertain if a particular zone repeats itself or disappears concerning the feature interpreted as a fault in the images (as shown in Fig. 8). This correlation process serves as a crucial validation method to support the interpretation of the identified fault or fracture.

These methodical steps work together in a coordinated manner, combining their effects to profoundly enhance our grasp and verification of potential faults or fractures found within geological formations. By harmonizing these processes, they collectively elevate the precision and depth of interpretation when delving into the exploration or analysis of subsurface conditions.

This comprehensive approach not only identifies potential faults or fractures but also strengthens the confidence and accuracy in understanding the intricate dynamics of the underground environment. It's an interwoven strategy that validates and refines our insights, ensuring a more reliable understanding of the geological structures hidden beneath the surface.

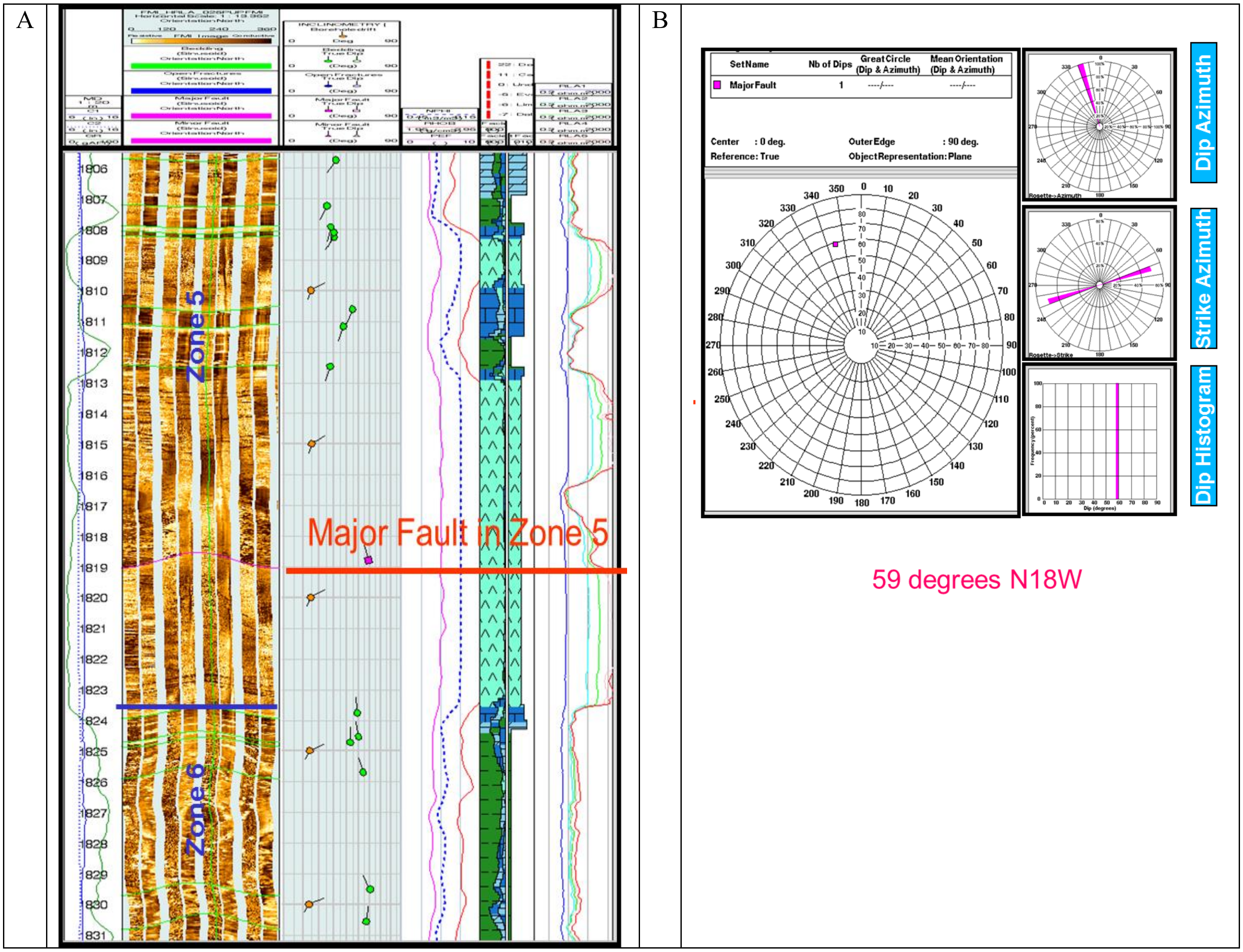

Fig. 7: A) It presents a composite representation that amalgamates several vital data sets, including orthogonal calipers (C1 and C2), GR (Gamma Ray), FMI (Formation MicroScanner) static normalized images, dip measurements, well deviation details, FMI-detected fractures, as well as RHOZ (Density), NPHI (Neutron Porosity), PEFZ (Photoelectric Factor), and resistivity curves. This comprehensive compilation offers a holistic view of various aspects crucial for understanding the formation's geological attributes and potential reservoir characteristics.B) Notably, the visualization highlights a significant fault within zone five of the Asmari formation. This fault exhibits a distinct inclination, dipping toward the NNW (North-Northwest) at an angle of 59 degrees. Understanding the presence and orientation of this major fault is pivotal in comprehending the structural layout of the formation, its potential impact on fluid flow dynamics, and the distribution of reservoir properties within the Asmari formation.

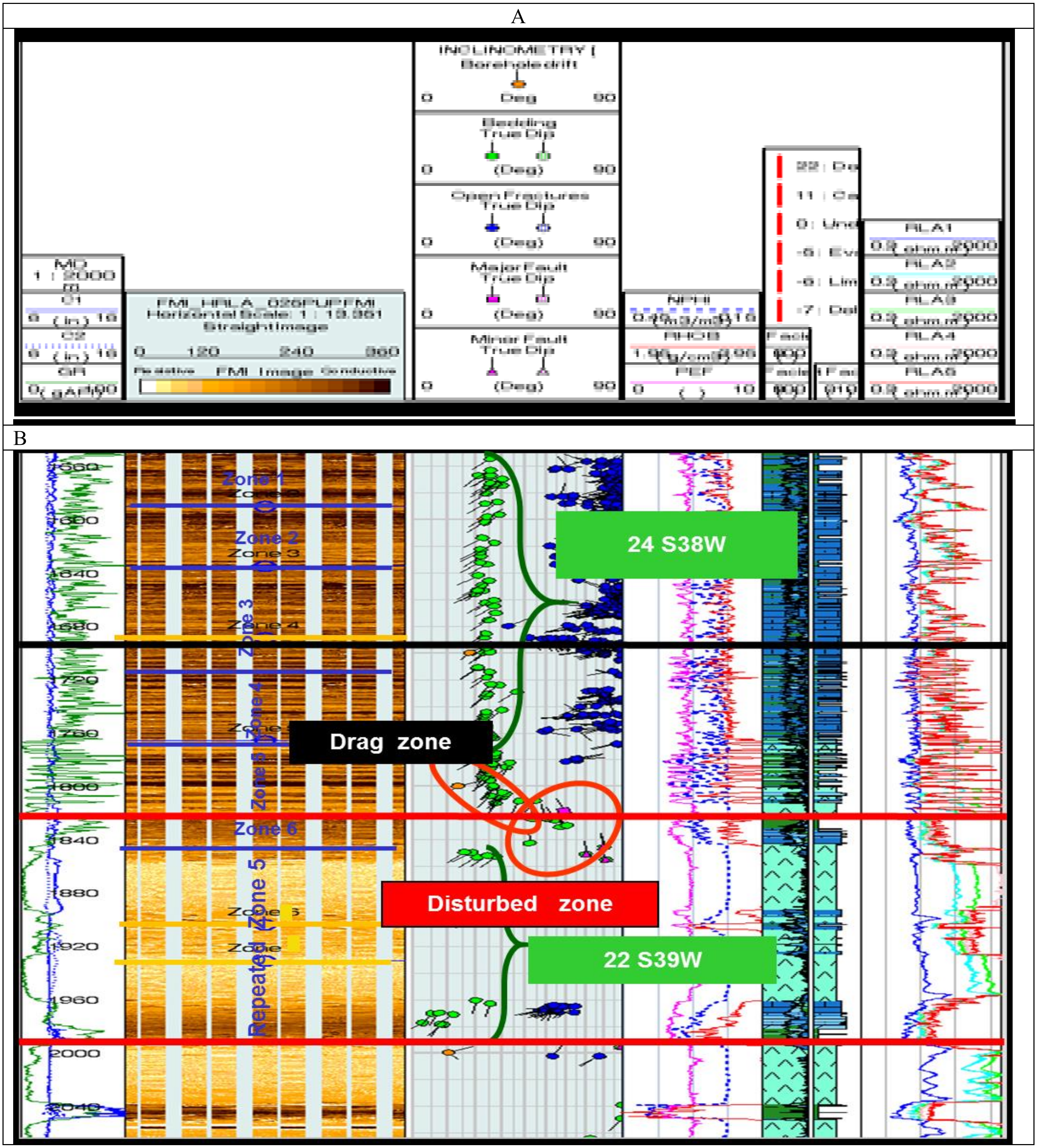

Fig. 8: A) Header details. B) Composite plot featuring orthogonal callipers (C1 and C2), GR, FMI static normalized images, dips, well deviation, FMI fractures, RHOZ, NPHI, PEFZ, and resistivity curves within the Asmari formation. The amalgamation of FMI and open hole logs (resistivity) reveals a significant fault at 1819m within zone five of the Kalhur member.

Strucview, a specialized software tool, played a pivotal role in creating a computer-generated cross-section following an NNE-SSW orientation. This construction heavily relied on the wealth of dip data collected through geological surveys.

One of the standout features of Strucview lies in its proficiency in managing and interpreting geological dip data. This software doesn't just visualize dip data; it goes further by autonomously grouping this data into distinct sets that correspond to diverse geological structures and formations.

Utilizing this automated grouping feature, Strucview categorizes the dip data into coherent clusters, each representing specific geological features or structural elements found within the surveyed area. These categorized groups act as a means to organize and categorize the complexities of geological structures, allowing for a clearer depiction of the subsurface environment.

The computation of the cross-section within Strucview functions based on these grouped sets of dip data. By organizing the data into meaningful clusters that represent different geological structures, the software facilitates a more detailed and precise visualization of the subsurface along the specified NNE-SSW plane. This process significantly aids geologists and researchers in comprehending the intricate geological makeup and structural patterns within the surveyed region, offering valuable insights into the subsurface geology and its structural complexities.

Utilizing Strucview, a computer-generated cross-sectional representation was meticulously crafted along an NNE-SSW plane. This sophisticated software harnessed the dip data acquired from the geological surveys. Strucview stands out for its specialized capabilities in managing and interpreting geological dip data.

One of its key functionalities lies in its ability to not only exhibit dip data but also to intelligently categorize this data into distinct sets that correspond to diverse geological structures. This automated grouping feature within Strucview organizes the dip data into coherent sets, each representing specific geological formations or structural elements.

The cross-sectional computation performed by Strucview operates on these categorized groups of dip data. By organizing the data into meaningful clusters based on geological characteristics, the software facilitates a clearer and more comprehensive visualization of the subsurface structures along the designated NNE-SSW plane. This approach aids geologists and researchers in deciphering and analyzing the intricate geological formations present within the surveyed area, offering valuable insights mposition and structural arrangements.

The resulting cross-section reveals certain irregular bedding planes, potentially indicating diagenetic alterations within the geological formations. These irregularities can be crucial in understanding the history and characteristics of the rock layers, as they may signify changes and transformations that have occurred over time.

Using Strucview, a computer-generated cross-section was constructed along an NNE-SSW plane, utilizing the dip data specific to geological formations. This software specializes in handling geological dip data, enabling the visualization and automatic grouping of this data into sets that represent various geological structures.

The cross-section computation within Strucview is accessible through categorized groups, facilitating a more organized and comprehensive understanding of the geological features being studied.

Upon analysis, the resulting cross-section reveals the presence of irregular bedding planes. These deviations from typical, uniform bedding patterns suggest potential diagenetic alterations within the geological formations. These alterations may signify processes such as mineralogical changes, cementation, or other geological transformations that have occurred over time, influencing the structural arrangement of the bedding planes (Fig. 9).

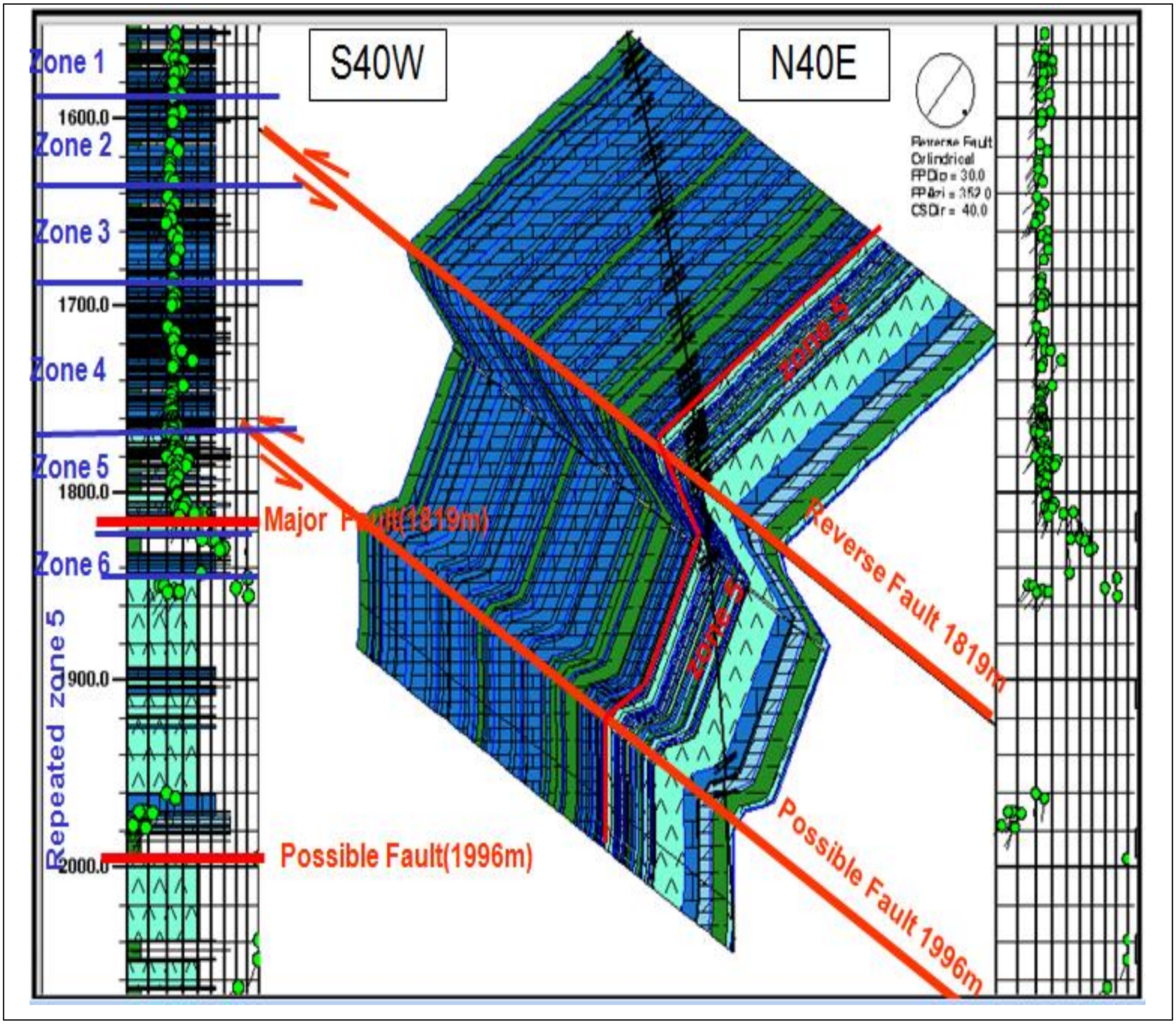

Fig. 9: presents a schematic representation generated by computer modeling, specifically utilizing the reverse-fault model, focusing on a major fault within zone 5 of the geological structure.The schematic illustration provides a synthesized visual depiction created through computational techniques. It aims to simulate and represent the geological structure, particularly emphasizing a significant fault characterized by its reverse movement within zone 5.

The pattern of inclination, known as the dip, around the significant fault seems to maintain a similar trend to what's observed in the adjacent regions. Specifically, a structural dip of about 24 degrees toward the south-southwest (SSW) is identifiable and can be attributed to both the sections above and below the fault. This inclination holds true for both the drag zone and the zone disrupted by the fault's presence.

This consistent dip pattern, approximately 24 degrees in the SSW direction, extends across the geological intervals located both above and below the faulted area. It's noteworthy that this inclination remains relatively uniform within the zones affected by the fault: the drag zone, where material has moved due to the fault's movement, and the zone that has been disturbed directly by the fault's presence.

Such uniformity in the structural dip pattern above and below the fault, irrespective of the areas affected by either drag or direct disturbance, implies a consistent geological behavior in terms of inclination. Understanding and mapping this consistent dip pattern are critical as it provides insights into the structural characteristics and orientation of the geological formations affected by the fault, aiding in the comprehensive analysis of subsurface conditions and fault-related effects within the studied area.

Below the juncture where the fault intersects, a notable augmentation in the thickness of anhydrite within the Kalhur member of the Asmari reservoir becomes apparent. This increase in anhydrite content serves as a significant indicator that the well has re-entered the Kalhur member of the Asmari reservoir.

Anhydrite, a mineral composed of calcium sulfate, manifests itself distinctly within geological formations and often indicates specific changes in lithology or sedimentary environments. In this context, its heightened presence suggests a re-entry into the Kalhur member, a distinct section of the Asmari reservoir.

This observation finds validation through various data sources, notably the well logs and cross-sectional data. These sources provide further evidence and support for the re-entry into the Kalhur member of the Asmari reservoir. The well logs, which record various geological parameters and formations encountered during drilling, likely exhibit characteristic signatures indicative of the Kalhur member. Additionally, cross-sectional data, which offer a visual representation of subsurface geological structures, likely display distinct features that align with the Kalhur member's known attributes.

This convergence of evidence—augmented anhydrite thickness below the fault intersection, supported by well logs and corroborated by cross-sectional data—strengthens the conclusion that the well has indeed re-entered the Kalhur member of the Asmari reservoir. Such observations are pivotal in refining geological interpretations and understanding reservoir dynamics, contributing significantly to informed decision-making in reservoir exploration and development strategies.

It's critical to explore into the variations in anhydrite content because of the far-reaching impacts it holds. In the context of the Asmari formation (as shown in

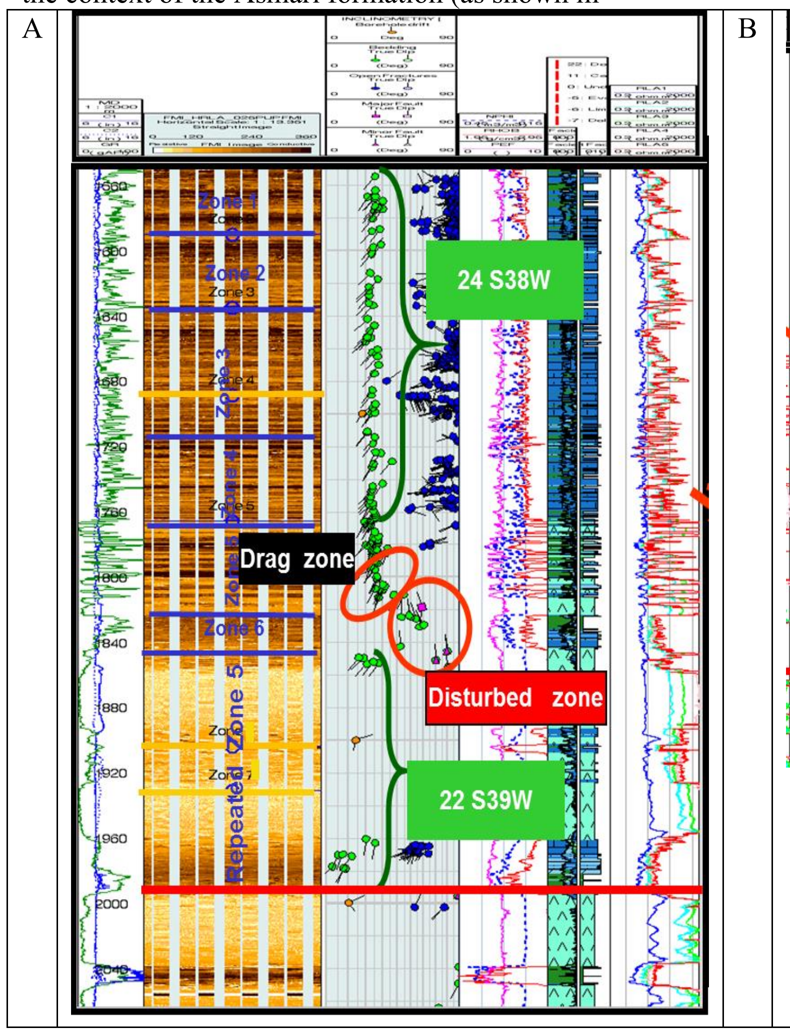

Fig. 10), this variation plays a fundamental role in shaping several critical aspects. Firstly, it significantly influences reservoir properties, dictating the permeability, porosity, and overall quality of the reservoir. Anhydrite content can either enable or impede fluid movement within the formation, thereby affecting the flow of hydrocarbons or other fluids through the reservoir.

Moreover, understanding these variations is essential for drilling operations. Anhydrite, due to its differing hardness and composition compared to other materials in the formation, can present challenges during drilling. It affects the drilling process, impacting the choice of drilling techniques, tools, and strategies required to navigate through the formation effectively and efficiently.

Overall, a comprehensive grasp of anhydrite content variations within the Asmari formation is indispensable. It extends beyond mere compositional knowledge; it's intricately tied to the fundamental characteristics that govern the behavior of the reservoir, fluid movement, and the practical aspects of drilling operations in this geological context.

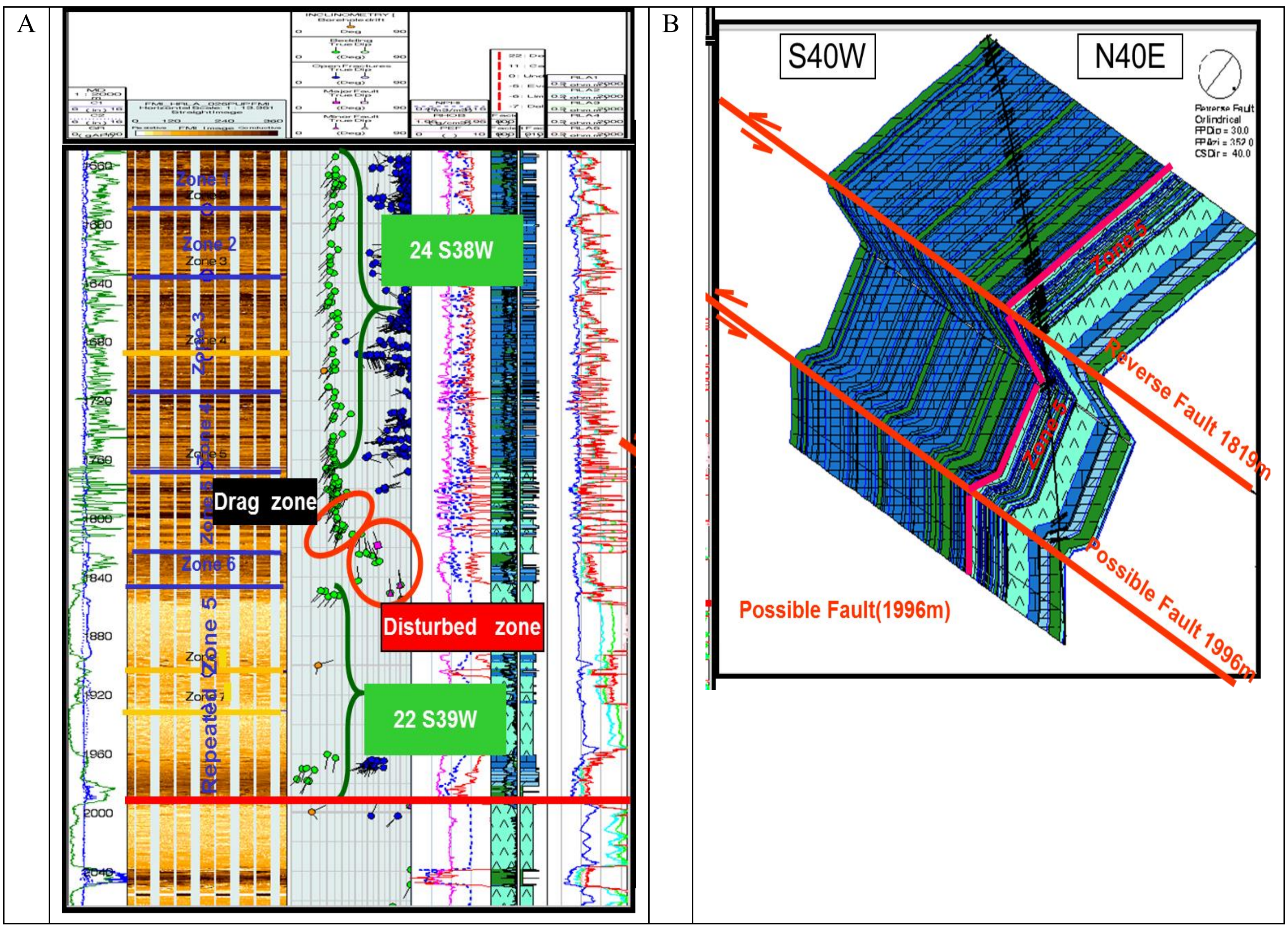

Fig. 10: A)Composite plot of orthogonal callipers (C1 and C2), GR, FMI static normalized images, dips, well deviation in Asmari formation. B) A schematic computer-generated model using a reverse-fault model is presented. The illustration highlights the

drag and disturbed zones associated with the fault. The model demonstrates the overturning of beds within the fault-influenced area. Additionally, structural dips of the sections both above and below the faulted region are indicated for reference.

4. Validation and Accomplishment

The study aimed to investigate specific geological occurrences and optimize drilling strategies. It primarily focused on understanding why the Kalhur member intersected unexpectedly and the increased thickness of the Asmari formation. The goal was to plan a new sidetrack based on these insights.To achieve this, comprehensive datasets such as the Full set and FMI log data were employed. These datasets provided crucial information about fractures, faults, and their characteristics. Through meticulous identification and description, the attributes of these geological features were measured accurately.

Subsequently, leveraging the findings from StrucView, geologists from NIOC South Operations made informed decisions to drill a new sidetrack within the well. This strategic move was rooted in the insights derived from the data analysis.The success of this new sidetrack was evident as it effectively intersected all the reservoir zones within the upper Asmari formation. This accomplishment is pivotal in the realm of reservoir development and production optimization. By precisely targeting these zones, the project significantly enhances the prospects of efficient resource extraction from the Asmari formation.

In essence, the study's validation lies in the successful execution of the new sidetrack, aligning drilling operations with the geological findings. It not only addressed the unexpected intersections but also facilitated a more targeted and effective approach toward reservoir development, marking a significant milestone in maximizing production potential(Fig. 11).

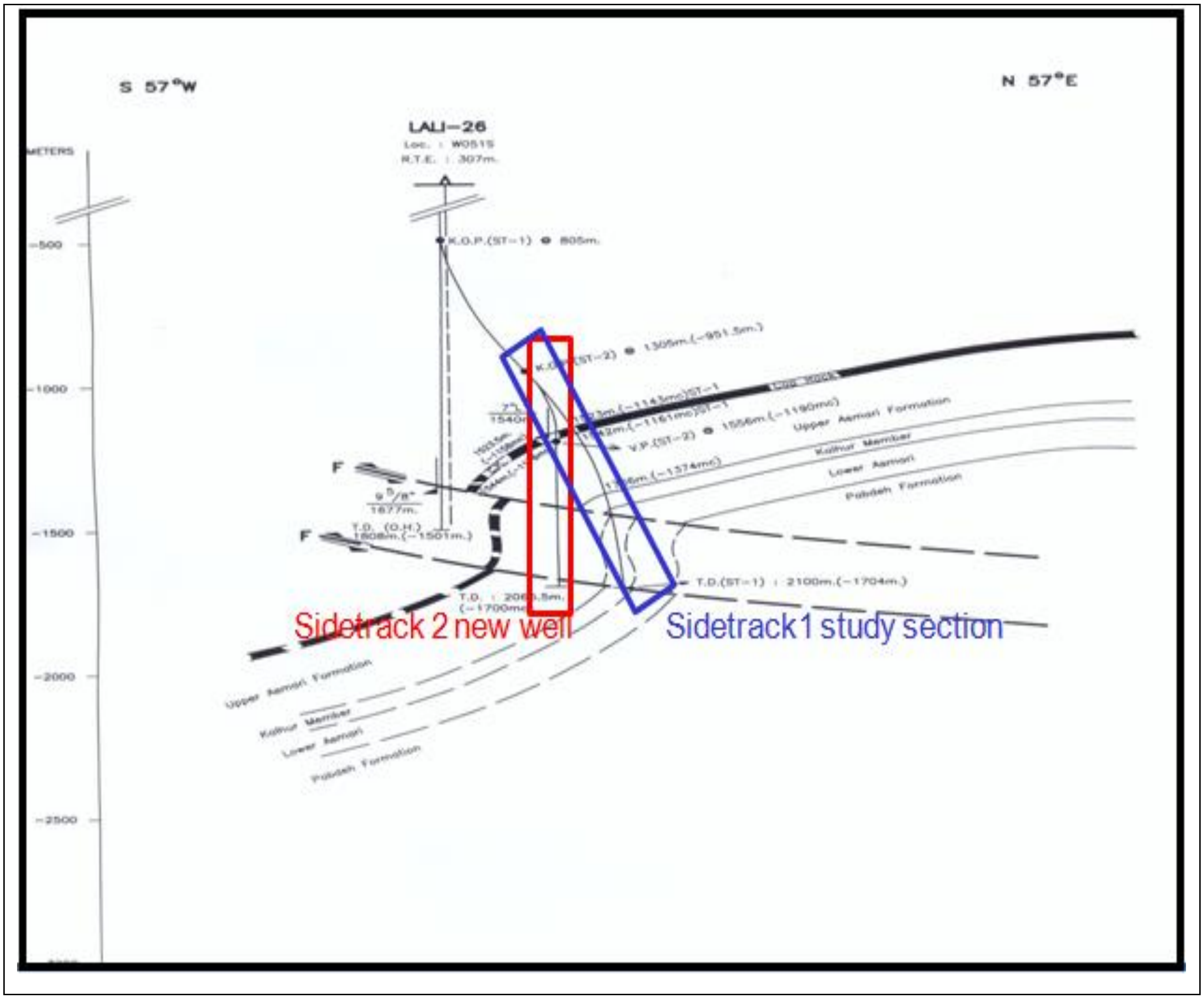

Fig. 11: Displays the recently created sidetrack, highlighted in red, which has been meticulously drilled based on the structural model derived from the analysis of sidetrack 1, shown in blue. This new sidetrack was strategically planned and executed in alignment with the insights and conclusions drawn from the previous drilling operation, ensuring a cohesive and informed approach to further exploration and development.

5. Conclusion

This research has played a pivotal role in pinpointing the Asmari fault and fracture systems and understanding their profound effects on production dynamics. It has adeptly untangled the intricate structural intricacies, enabling an exact determination of the precise position of the well within the expansive Asmari Reservoir. This accomplishment holds immense significance as it paved the way for the well to access and tap into the lower reaches of the Asmari formation, a critical milestone in maximizing reservoir potential and enhancing production efficiency.

The meticulous classification of dip angles, derived from geological logs, has unveiled a vivid and easily interpretable map of the structural intricacies within the Asmari formation. This newfound depth of understanding has yielded a significant boon to the operator's reservoir modeling techniques. Specifically, it has served as a cornerstone, enabling scientists to delve into the reservoir's potential with unparalleled precision.This deeper comprehension has led to a transformative effect on their utilization of Formation Micro-Imager (FMI) data. In scenarios where access to robust 3D seismic data is limited or compromised, the enhanced structural understanding derived from dip classification has emerged as a crucial resource. It's facilitated a more nuanced and accurate assessment of the reservoir's capabilities and behavior, enriching the insights drawn from FMI data in a manner previously unattainable.

Ultimately, this advancement not only optimizes the reservoir model but also bolsters the scientific community's capacity to glean invaluable insights, particularly when conventional data sources fall short. The convergence of enhanced structural understanding and refined data utilization marks a pivotal step forward in maximizing the reservoir's potential.

This research endeavor stands as a comprehensive solution, addressing not just fundamental structural challenges but also significantly amplifying the operator's capacity to intricately model and assess the Asmari Reservoir. This advancement proves especially valuable when conventional data sources are scarce or restricted, thereby enabling a more nuanced and robust evaluation of the reservoir's dynamics and potential.

6.Significance Statement

This study has successfully addressed and resolved structural complexities, ultimately pinpointing the precise location of the well within the Asmari reservoir. This achievement carries significant benefits, as it can lead to cost savings in drilling projects and also pave the way for the drilling of additional wells within the field. Moreover, this research will serve as a valuable resource for researchers, enabling them to explore critical areas of structural complexity within the reservoir that have remained uncharted.

The methodologies and insights gained from this study are expected to set a standard workflow for similar fractured carbonate reservoirs. This will contribute to the advancement of research and exploration in the field of reservoir characterization and development, offering guidance and best practices for future endeavors in similar geological settings.

7.Directions of Future Research

The research on the Asmari fault and fracture systems has made significant strides, but there are still avenues for future exploration and study:

Enhancement of Structural Understanding: While the research has provided a comprehensive understanding of the structural intricacies within the Asmari formation, further investigation into the finer details of fault systems and fractures could enhance reservoir characterization. Employing advanced imaging techniques or integrating different data sources could contribute to a more nuanced structural model.

Integration of Multi-disciplinary Data: Expanding the scope to integrate various data sources beyond geological logs and FMI data could provide a more holistic view of the reservoir. Incorporating geochemical analysis, geomechanics, or even advanced machine learning algorithms to integrate diverse datasets might offer deeper insights into reservoir behavior and potential.

Long-term Reservoir Behavior Prediction: Investigating the temporal behavior and long-term evolution of the reservoir under varying production scenarios could be valuable. Predictive modeling that factors in production history, geological changes, and fluid dynamics might aid in understanding how the reservoir will behave over extended periods.

Enhanced Reservoir Simulation Techniques: Developing more sophisticated reservoir simulation techniques that incorporate the newfound structural understanding could refine predictive capabilities. This includes accounting for complex fluid flow within fractured carbonate reservoirs and their interaction with fault systems.

Environmental Impacts and Sustainability: Exploring the environmental impacts of extensive drilling and production in fractured carbonate reservoirs is becoming increasingly relevant. Future research might focus on sustainable extraction methods or mitigation strategies to minimize environmental footprints.

Field Application and Validation: Applying the insights gained from this research to real-world scenarios and validating these findings through field experiments or pilot projects could strengthen the practical application of the study's outcomes.

Collaborative Research Endeavors: Collaborating with industry partners, academic institutions, and research organizations could leverage diverse expertise and resources, accelerating the pace of discoveries and innovations in fractured carbonate reservoir studies.

Technology Advancements: Keeping up-to-date of technological advancements in imaging, sensing, and data analytics can offer new tools and methodologies to further unravel the complexities of such reservoirs.
By exploring into these areas, future research could continue to push the boundaries of knowledge in fractured carbonate reservoirs, fostering more accurate predictions, sustainable practices, and enhanced reservoir management techniques.

Acknowledgment

We extend our heartfelt gratitude to all those who contributed to the success of this project. Without their unwavering support, this achievement would not have been possible. We would like to express our appreciation to NIOC South for generously providing the essential data and resources that were indispensable in the completion of our project.

References

[1]. Chokthanyawat, S., Daungkaew S., Athichanagorn, S. (2012). Well Productivity Prediction for Laminated Reservoir Using Borehole Electrical Image Logs. IPTC 14399.
[2]. Eynollahi, A. (2009). Microfacies and Sedimentary Environment of the Asmari Formation in Lali Oil Field, NW Masjed-e-Soleyman.
[3]. Hassan, S., Biagi, M., Mohie, M., Fasto, A., Juandi, D., Abuelfotoh, A., ElFouly, M. A., Emam, M. (2010). Integrated Logging While Drilling and
[4]. Offshore Nile Delta Reservoirs. SPE 125390.
[5]. Motiei, H. (1995). Petroleum Geology of Zagros. Geological Survey of Iran with cooperation of Deputy Ministry of project and planning, no. 25.
[6]. Movahed, Z., Junin, Amiri Bakhtiary, H., Safarkhanlou, Z., Movahed, A., Alizadeh, M. (2015). Identification of a Sealing Fault in the Asmari Reservoir Using FMI and RFT in an Iranian Naturally Fractured Oil Field. Arabian Journal of Geoscience, Volume 8, Issue 12, Pages 10919-10936.
[7]. Movahed, Z., Aghajari, F., Movahed, A. (2022). Characterization of Reservoir by Using Geological, Reservoir and Core Data, Journal of Applied Sciences, 23: 34-46. DOI: 10.3923/jas.2023.34.46.
[8]. Nimmagadda, Shastri, Dreher, and Heinz (2010). Ontology-Based Warehouse Modeling of Fractured Reservoir Ecosystems for Effective Borehole and Petroleum Production Management. DOI link.
[9]. Park, R. G. (2005). Foundations of Structural Geology. Routledge, Abingdon, England.
[10]. Rezaie, A. H., Salehie, F. (2006). Interpreted Faults and Structural Setting from Image Logs in the Absence of Seismic Data: A Case Study from Dalpari Field, Iran.
[11]. Soliman, Osama M., Saad Aba, A., Bader, A. (2010). Tectonic and Climatic Controls of Post-Glacial Terminal Fluvial Systems, Permian Unayzah Reservoir.
[12]. Yang, J., Gou, X., Hilmi, N., Xia, R., Sun, X., Li, P., Wu, Q., Liu, J. (2011). An Integrated Approach for Fracture Characterization and Prediction Using FMI Logs, Post-stack Seismic Attributes, and Pre-stack Anisotropy: A Case Study in Tishrine West Oilfield, Northeast Syria.

Contribution of Individual Authors to the Creation of a Scientific Article (Ghostwriting Policy)
The authors equally contributed in the present research, at all stages from the formulation of the problem to the final findings and solution.

Sources of Funding for Research Presented in a Scientific Article or Scientific Article Itself
No funding was received for conducting this study.

Conflict of Interest
The authors have no conflicts of interest to declare that are relevant to the content of this article.