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A Comprehensive Review of Approaches for Characterizing Natural Fractures in the Ahnet Basin, Algeria

Chanane Fares[1]*

[1]*Independent Researcher, Algeria*

INFORMATION

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Contact
*Chanane Fares
chananefares@yahoo.fr

ABSTRACT

This comprehensive review delves into fracture characterization in the Ahnet Basin, emphasizing the influence of lithology on natural fracture patterns and their implications for fluid flow dynamics in fractured reservoirs. By amalgamating cutting-edge research and advanced methodologies, the study explores geological structures, fracture properties, and the role of percolation theory in understanding fracture connectivity and permeability. The research highlights the significance of machine learning algorithms in fracture aperture estimation and the consideration of fracture roughness in fluid flow analysis. By investigating the interplay between lithology and fractures, the study contributes to a deeper understanding of fluid flow dynamics in fractured reservoirs, offering valuable insights for optimizing resource utilization and enhancing production performance in hydrocarbon and geothermal reservoirs.

1. Introduction

This comprehensive review delves into the intricate world of fracture characterization in the Ahnet Basin, exploring the influence of lithology on natural fracture patterns and their potential implications for fluid flow dynamics. By amalgamating cutting-edge research and advanced methodologies, this study seeks to deepen our knowledge of subsurface fracture systems, aiding in more informed decision-making and efficient utilization of hydrocarbon resources.

This study focuses on the Palaeozoic Ahnet Basin, which forms part of the Algerian Saharan Platform. It overlies an arm of the Late Proterozoic Pan-African Belt that developed against the West African Craton, along the Pan-African suture zone. The Palaeozoic sedimentary cover thickens northwards and westwards (Reggane Basin), and includes Late Cambrian to Late Carboniferous series. It consists of sandstones and shales and a few limestone intercalations, both of dominantly marine origin. Some major N–S-trending Late Pan-African fault zones were rejuvenated during the Palaeozoic and influence both the sedimentological and tectonical history (Buef, 1971). Folding, strike-slip faulting and reverse faulting occurred by the latest Palaeozoic, resulting in the development of structures which are unconformably sealed by Mesozoic formations (Boote et al., 1998).

In this paper, we first analyse these natural structures and then summarize the different properties of the natural fractures and natural fractures networks as described in the literature. We illustrate also the impact of these fractures on fluid flow and the different approaches utilized by scholars.

2. The Ahnet Basin: A Fractured Reservoir

The definition of "fractured reservoirs" varies according to different authors. After Badsi (1998), the term is used when producers observe a significant discrepancy between the overall calculated permeability from well tests and the permeability measured on core samples. The distribution of fractures can be defined at the scale of reflection seismic observations; it can also be extrapolated to sub-seismic scales to predict a certain number of faults. To constrain this data, among others, "fractal dimension," fracture characteristics (orientation, spacing, and others), as well as core and imaging data are also necessary (Badsi, 1998a).

An overview of the key features of significant geological structures in the Ahnet-Mouydir Basin, which span from the Cambrian to Early Moscovian series and are associated with Hercynian deformations is presented by Haddoum et al. (2001). The structures under consideration include N±S strike-slip faults, NNW±SSE- to N±S- striking reverse faults, and folds. These observations are derived from field studies, the analysis of 1:200,000 geological maps, and the interpretation of seismic reflection profiles (Badsi, 1998b). Consequently, we are able to determine the directions of shortening.

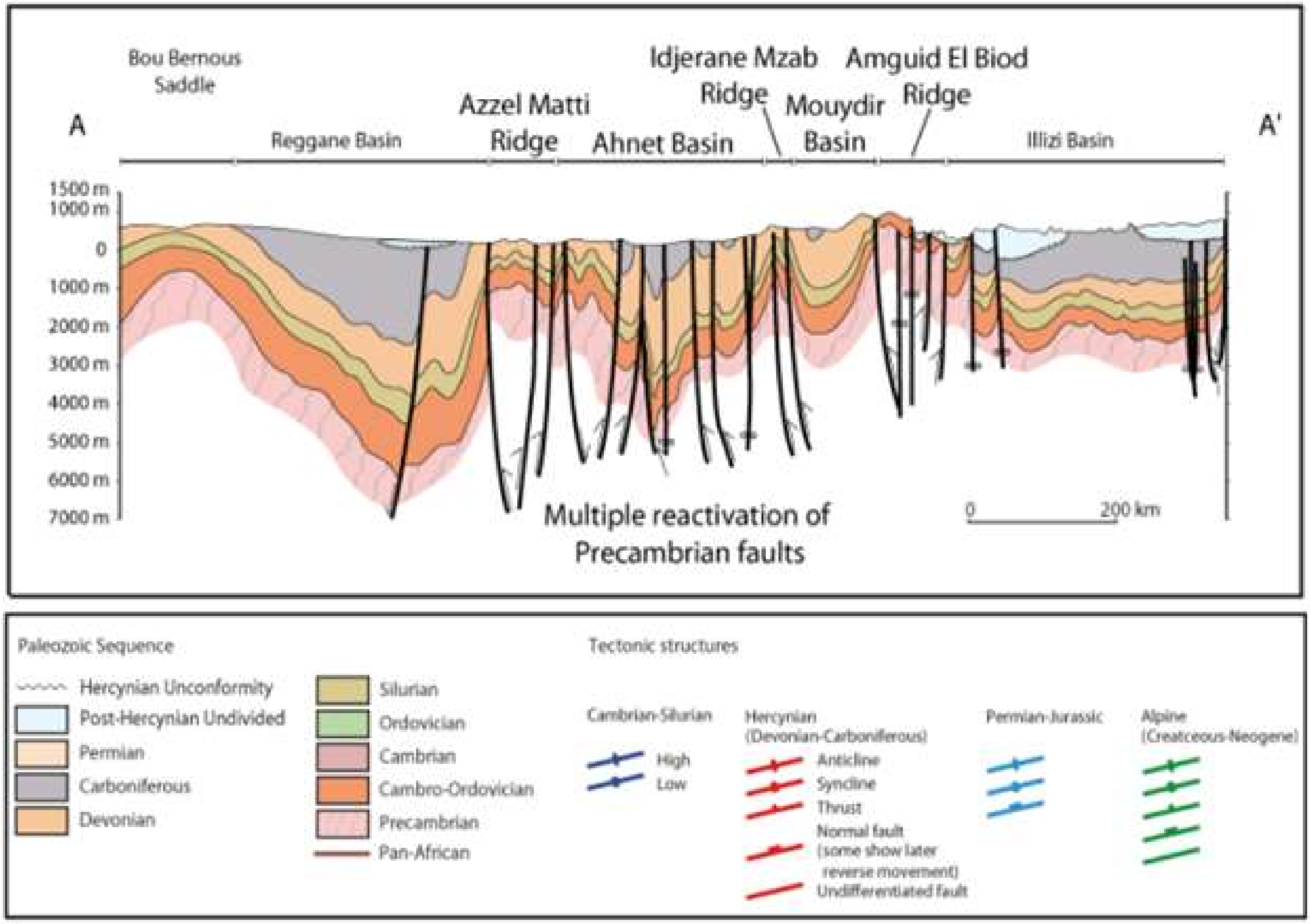

Fig. 1. Regional cross-section oriented N-S through the Reggane, Ahnet, Mouydir and Illizi Basins illustrating their geometry and the distribution of the main structural units (Zieliński, 2011)

Many reverse faults, oriented predominantly in the NNW±SSE to N±S direction, impact the Palaeozoic sedimentary cover of the Ahnet±Mouydir Basin (as shown in Fig. 1). These faults are most evident in the lower, more brittle layers of the sedimentary series, and they tend to diminish in intensity as they encounter the thicker and less competent Late Devonian shales. Depending on their location, these faults can dip either towards the east or the west. The most prominent among them is responsible for the Djebel Idjerane spur, representing a localized fault-bend involving layers from the Cambrian to Middle Devonian periods (as depicted in Fig. 1).

Seismic reflection studies, conducted by Badsi (1998), identified several reverse faults, one example being in the El Gaa Taatzebar Region (as illustrated in Fig. 1). Additionally, numerous minor reverse faults are prevalent, showing various offsets ranging from meters to tens of meters. Moreover, transpressive faults, displaying both reverse and strike-slip components, are also common. These transpressive faults have been analyzed at specific locations and interpreted using the P and T-dihedra method (Angelier and Mechler, 1977), revealing shortening directions in the NNE±SSW to ENE±WSW orientation (as shown in Fig. 1).

Based on field reconnaissance, Badsi (1998a) distinguished two main families of fractures in the Ahnet Field:

- A family of fractures grouping fractures with an orientation of N150
- The second family consists of fractures with preferred direction is N90.

3. Characterizing Natural Fractures and Their Implications for Fluid Flow in the Ahnet Basin

Regardless of the porosity of the matrix, fractures play a crucial role in increasing permeability. Attempts to demonstrate the contribution of fractures to enhancing permeability by examining the genetic relationship between complex fracture systems at different scales were made in the past years. In order to study the relationship between the hydraulic attributes of fractures and the in-situ stress orientation, they created a two-dimensional structural framework using seismic data.

Power and Durhem (1997) conducted a study on granites that showcased the significant impact of fractures and joints' topography on both their frictional strength and fracture permeability. Noteworthy attributes of these surfaces include the size, distribution, and density of contact points, which may be quantified through the utilization of topographic data.

Odling et al. (1999) compiled meticulously curated datasets for fracture systems, laying the groundwork for discerning fracture systems governed by distinct scaling laws. The researcher expounded on the crucial role of fracture connectivity in controlling the behavior of fractured rock masses. Extensive exploration of connectivity has been carried out within the domain of percolation theory (Fig. 2), a branch of statistical physics, with many fundamental principles applicable to the study of fluid flow through rock masses.

Stauffer and Aharony (2018) elucidated the mathematical methodology for assessing the permeability of a fracture-rock matrix system. Specifically, fractures were represented as traces in a two-dimensional context, and as their quantity grew significantly, they coalesced into clusters. As the number of fractures within these clusters approached the percolation threshold, the system exhibited characteristics akin to "critical phenomena".

Healy et al. (2017) conducted a comprehensive analysis of fracture patterns across a wide range of scales, spanning five orders of magnitude. These scales encompassed thin sections at the millimeter to centimeter range, outcrops at the meter to decimeter range, and regional maps at the kilometer scale. Through the use of graphs and maps, their study meticulously quantified the statistical and spatial variances in fracture pattern properties (Fig. 3).

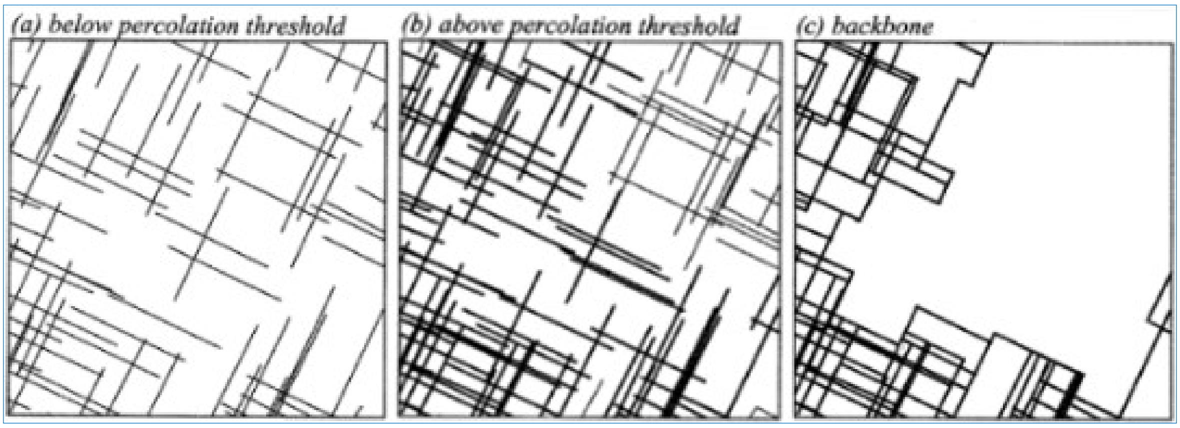

Fig. 2. Percolation theory applied to fracture systems. From left to right: (1) When fracture density is low, clusters of connected fractures are small and no cluster spans the entire area. (2) With increasing fracture density, clusters grow and at the 'percolation threshold' the largest cluster spans the sample area. (3) The 'backbone' is defined as all direct routes through the fracture network across the sample area. This is the largest cluster with all 'dead-ends' removed (Odling et al., 1999)

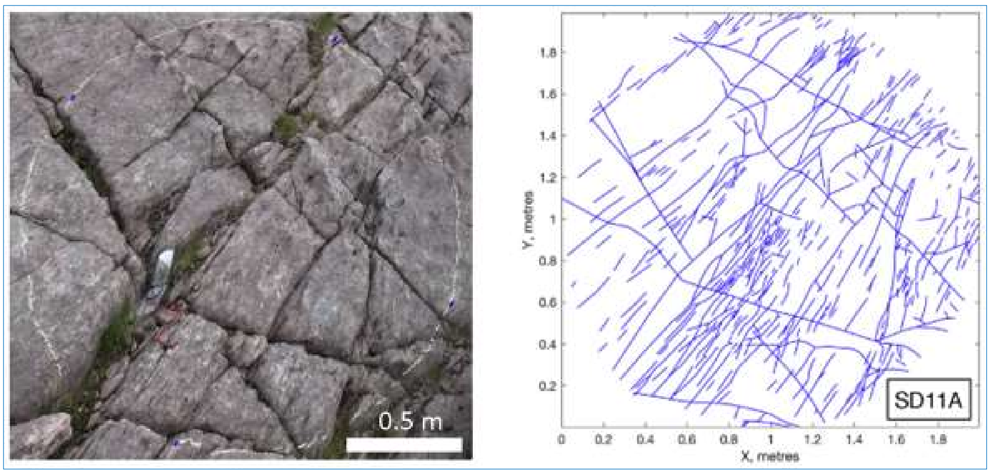

Fig. 3. On the left: outcrop photograph of a fractured bedding plane. On the right: Fracture trace map of area derived from the high-resolution version of the photograph showing the outcrop (Healy et al., 2016).

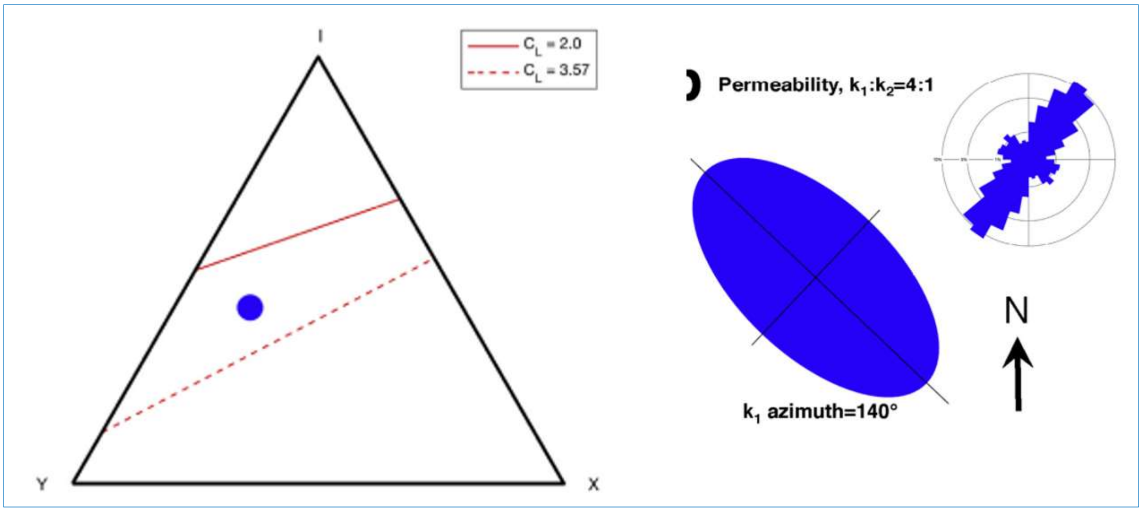

Fig. 4. Connectivity and estimated permeability of fracture networks (Healy et al., 2017)

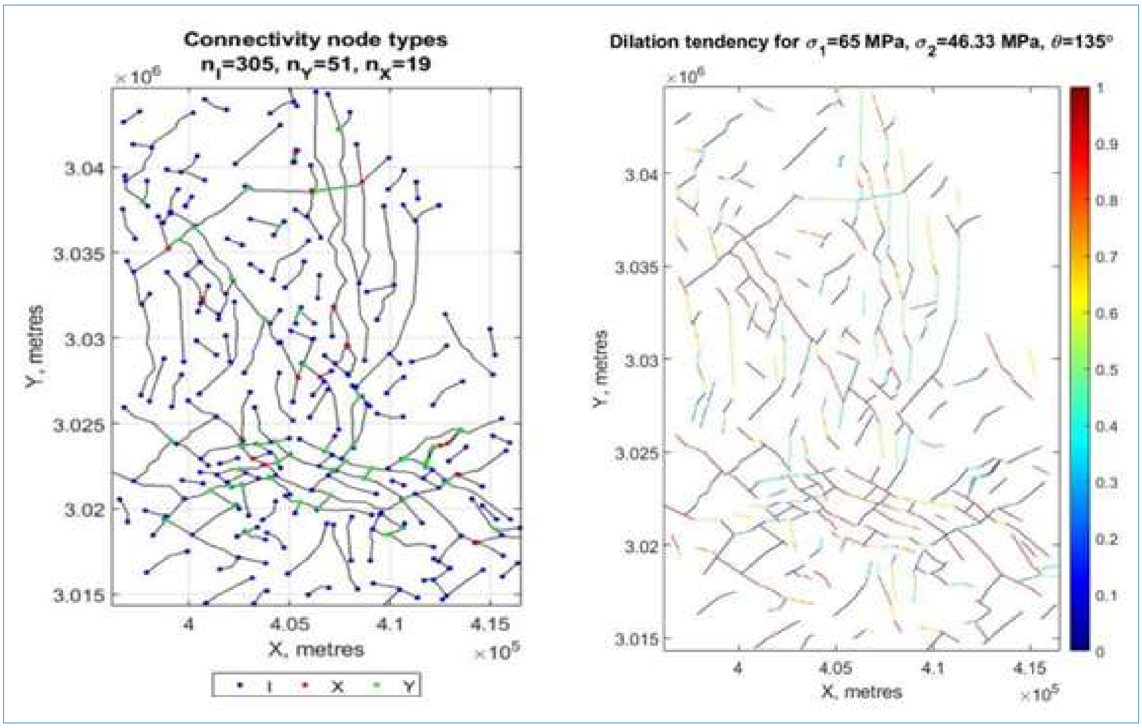

Fig. 5. On left: connectivity map of Field-1, Ahnet Basin. On right: dilation tendency map of Field-1, Ahnet Basin (Irofti et al., 2022)

Moreover, the researchers conducted insightful comparisons between diverse geographical regions and across different scales. Additionally, the investigation delved into the scaling laws governing fracture lengths and objectively compared orientation distributions among neighboring sub-areas.

Furthermore, they determined fracture connectivity and gave an example of the estimation of permeability anisotropy using Matlab Toolkit. In the context of exploring the potential influence of natural fractures on fluid flow enhancement within the Ahnet Basin, Irofti et al. (2022) undertook a comprehensive investigation into fracture orientations, sizes, and spatial distributions (Fig. 4). To facilitate their analysis, the researchers employed a 2D system incorporating branches and nodes, providing a novel framework for examining the intricate behavior of these fractures. To gain deeper insights into the fluid flow dynamics, the study encompassed the coupling of key hydraulic properties, namely dilation, shear tendency, and the prevailing current stress of the geological setting. By considering these factors, Irofti et al. (2022) aimed to elucidate the intricate interplay between natural fractures and their potential impact on fluid migration pathways (Fig. 5).

To effectively characterize the fractures and their interconnections, the researchers established three distinctive types of nodes within the 2D system. The I-nodes, representing the tips of individual fractures, provided valuable information on fracture termination points. Meanwhile, the Y-nodes, marking locations where fractures splayed or abutted one another, served as vital indicators of fracture interactions and potential fluid flow conduits.

Lastly, the X-nodes, situated at the junctions where two fractures intersected, offered essential insights into fracture network connectivity.

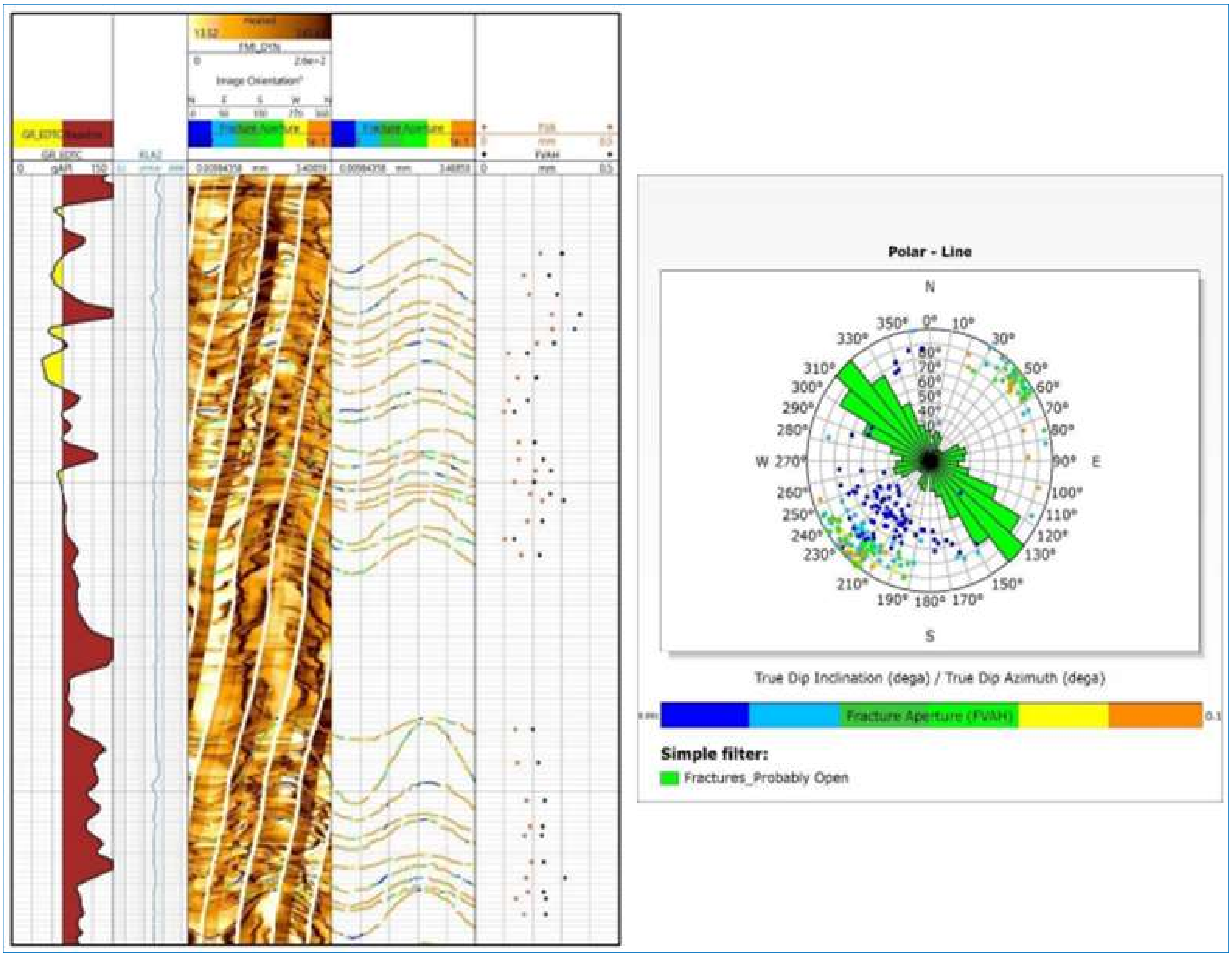

Fig. 6. On the left: Open fractures and apertures. The values of the mean Kinematic (FVA) and hydraulic (FVAH) apertures are also displayed. On the right: Cross-plot of fracture apertures after the execution of the advanced processing on image log (Ifrene et al., 2022)

In order to ascertain crucial data on the subsurface stress regime, borehole imaging techniques were employed to determine the maximum horizontal stress. Furthermore, Bouchachi et al. (2021) compiled a geomechanical model establishing in-situ stress in the Ahnet Basin. By integrating this stress information with the fracture orientation data, the researchers uncovered notable patterns. Specifically, fractures oriented along the N140 and N160 directions, parallel to the maximum horizontal stress, displayed a propensity to dilate.

Consequently, these fractures exhibited a heightened capacity to create preferential paths for fluid movement within the subsurface formations. In their scholarly endeavors, (Ifrene et al., 2022) undertook a comprehensive investigation of fracture aperture, employing a meticulous and well-structured workflow that incorporated a range of specialized tools, including acoustic scanning platform tool's dipole shear anisotropy, flexural dispersion analysis, and borehole image logs (Fig. 6). This systematic methodology yielded highly precise estimates of fracture aperture, thereby advancing the understanding of subsurface fracture systems.

In a related studies, Latrach et al. (2023) and Ifrene et al. (2023a) made noteworthy advancements in handling missing data pertaining to fracture characterization. Leveraging the capabilities of machine learning algorithms, they successfully predicted and synthesized the absent data points, presenting a pioneering approach with immense potential. This technique opens up promising avenues for its extension to other wells, addressing critical data gaps in the Ahnet Basin, and holds significant implications for reservoir characterization and resource assessment.

Furthermore, Khouissat et al. (2023) made valuable contributions by delivering insights into optimizing drilling operations and enhancing cost-effectiveness through the application of Machine Learning methodologies. Their research provided valuable guidance for the industry, facilitating improved efficiency and reduced operational expenses. The amalgamation of advanced techniques, such as machine learning algorithms, with robust methodologies for fracture aperture estimation, signifies a cutting-edge trajectory in the domain of subsurface exploration. By further refining and widespread application of these innovative methods across a broader spectrum of wells, researchers can delve deeper into the complexities of fracture systems, resulting in more accurate reservoir assessments, better-informed decision-making processes, and ultimately advancing the exploration and utilization of hydrocarbon and geothermal resources. They based their work on the equation provided by Luthi and Souhaite (1990) in order to estimate fracture aperture. The values they obtain were then The natural open fractures are oriented N140 which corresponds to the direction of the maximum horizontal stress. Irofti et al. (2023) extended then this workflow by estimating fracture porosity using borehole imaging and dipole shear waves.

It is essential to highlight the significance of considering fracture roughness when dealing with fluid flow in apertures (Ifrene et al., 2023b).

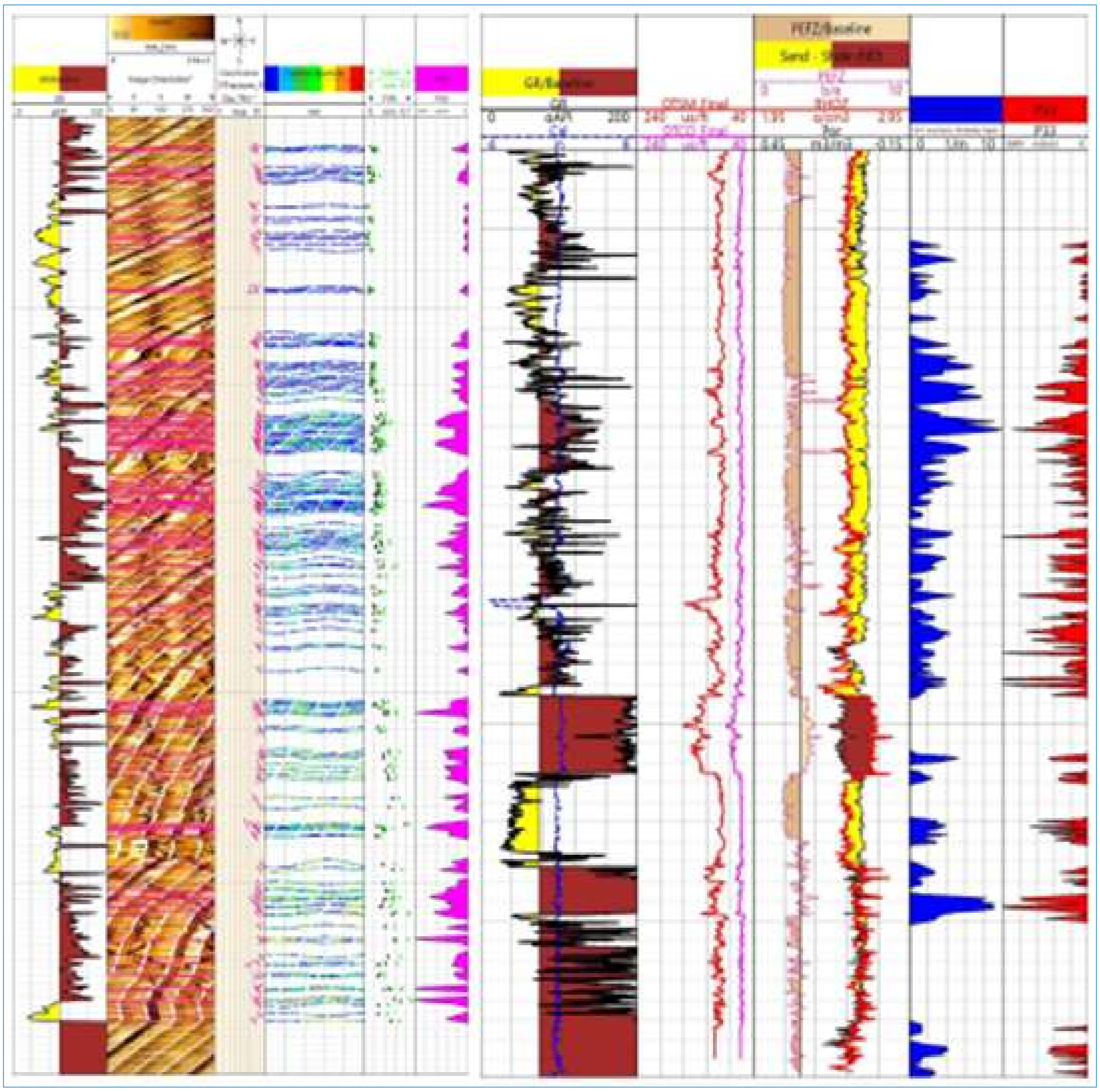

Fig. 7. Fracture porosity estimation (Irofti et al., 2023)

Recently, Ifrene et al. (2023c) conducted a study that convincingly demonstrated the interdependence of fracture aperture and JRC number, both of which play critical roles in governing fluid flow within natural fractures (Fig. 7).

The characterization of fracture roughness holds considerable importance in evaluating permeability and fluid flow in petroleum (Camac et al., 2006) and geothermal systems. Researchers are actively exploring methods to enhance reservoir permeability and flow rates, reduce operational issues (i.e. slugging) and increase production performances (Khetib et al., 2023) by accessing larger volumes of hot rock materials and creating an interconnected network of fractures (Aihar, 2023). Preliminary findings indicate that Fishbone Drilling exhibits several advantages over hydraulic fracturing, particularly in ultra-low permeability formations.

Considering fracture roughness in conjunction with aperture not only enriches our understanding of fluid flow dynamics but also holds practical implications for optimizing fluid flow in various subsurface systems (Ifrene et al., 2023d). By incorporating these insights, researchers and industry practitioners can make more informed decisions in the realm of fluid flow management.

4. Exploring the Influence of Lithology on Natural Fracture Patterns in the Ahnet Basin

Badsi (1998) were pioneers in investigating the variability of natural fractures based on lithology within the Garret el Gueffoul structure. Through the examination of oriented core samples using the FMI or FMS imaging technique, they compellingly established that in the Ahnet Basin, sandstone layers exhibit a high degree of fracturing, while clays show minimal fracturing (Fig. 8). Cherana et al. (2022), Doghmane et al. (2022) and Ifrene and Irofti (2023) further emphasized the significance of reservoir rock type in shaping the distribution of petrophysical characteristics, a critical aspect in reservoir characterization.

Recently, Irofti et al. (2023) conducted a noteworthy study wherein they employed a combination of heterogeneity analysis and interpreted fractures obtained from advanced imaging techniques. Their research demonstrated that lithology plays a prominent role in influencing both the number and type of fractures present. The integration of such findings from diverse studies contributes to a deeper understanding of the complex relationship between lithology and the behavior of fractures in the Ahnet's fractured reservoirs.

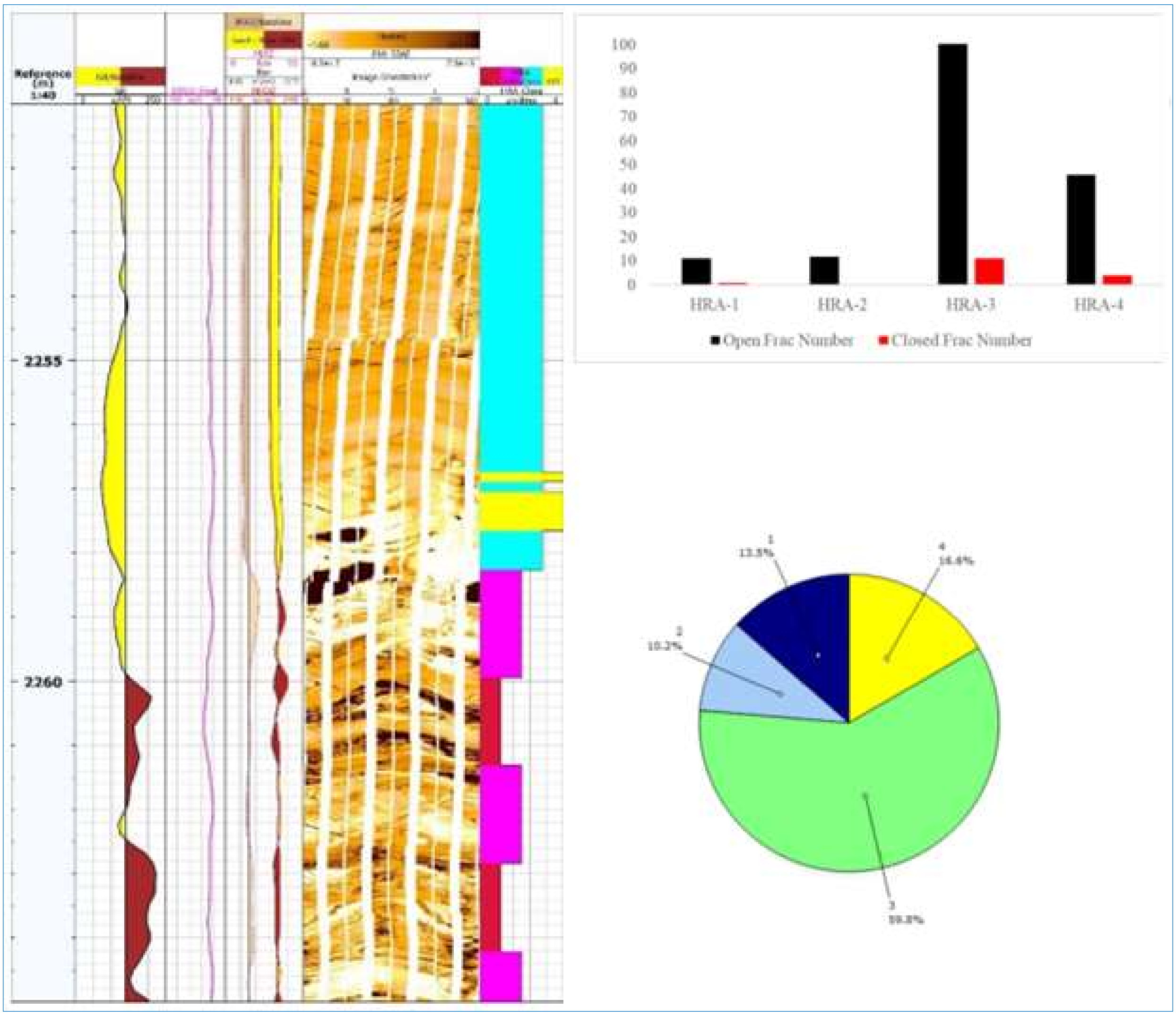

Fig. 8. On left: Interpretation of FMI images and HRA. On right: histogram open and closed fractures of each HRA and streonet of each HRA (Irofti et al., 2023)

Pothana et al. (2023) studied permeability changes with stress. They argued that the permeability-stress relationship data is best described by the exponential model. Their results showed that the stress-sensitive coefficient varied very little with the grain size and shows a general decreasing trend with an increase in the mean grain size in artificial rocks. We argue that the effect of other parameters such as pore morphology, micro-cracks, and cementation has a greater influence on the stress-sensitive permeability than the grain size alone. They also extended their research by investigating the effect of cementation on the mechanical properties of sandstone (Pothana et al., 2023). These parameters should therefore be considered for a complete characterization of natural fractures.

5. Conclusion

This paper provides a comprehensive review of fracture characterization in the Ahnet Basin, shedding light on the influence of lithology on natural fracture patterns and their implications for fluid flow dynamics. Through the amalgamation of cutting-edge research and advanced methodologies, this study advances our understanding of subsurface fracture systems, which is crucial for making informed decisions and optimizing the utilization of hydrocarbon resources.

The Ahnet Basin, part of the Algerian Saharan Platform, exhibits a complex geological history, with Pan-African tectonic events influencing the development of major fault zones. The presence of fractures, particularly reverse faults and strike-slip faults, significantly impacts the permeability of the reservoir rocks, making the basin a challenging but potentially rewarding fractured reservoir.

Characterizing natural fractures and their properties has been a focus of the study, with researchers employing various techniques to analyze their orientation, size, connectivity, and spatial distribution. Fracture networks are a critical component in enhancing permeability, and studies utilizing percolation theory have shed light on the behavior of these complex systems. Insights gained from fracture connectivity and permeability estimation can contribute to a better understanding of fluid flow pathways within the subsurface formations.

Moreover, recent advancements in fracture aperture estimation using machine learning algorithms and the consideration of fracture roughness in fluid flow analysis have opened up new avenues for improving reservoir assessment and optimizing fluid flow management. Understanding the interplay between fracture aperture and lithology further highlights the significance of rock type in shaping fracture distribution and petrophysical characteristics.

The findings presented in this paper emphasize the importance of considering lithology, fracture patterns, and fluid flow dynamics in fractured reservoirs, which can lead to more efficient resource utilization and improved production performances. As technology and methodologies continue to advance, further exploration of subsurface fracture systems will undoubtedly contribute to the sustainable development of hydrocarbon and geothermal resources, making significant strides in the field of subsurface exploration and reservoir characterization.

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