Introduction to the Khalij Limestone Member Type Section in the Gadvan Formation of Iran: A Comprehensive Analysis Utilizing 38 Exploration and Development Wells and 1 Surface Section of Gadvan

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Abstract: The Khalij limestone member, well-known for its abundant benthic facies, is situated in the middle segment of the Gadvan shaly formation, boasting an average thickness of approximately 14 meters. This specific member is exclusively found below the surface, devoid of any exposed outcrops, and is characterized by the presence of easily identifiable orbitolinid limestone. Well logging techniques, such as Gamma Ray and Density measurements, prove particularly effective in identifying this distinct layer. The primary objective of this study was to conduct a comprehensive analysis of the lithostratigraphy and microstratigraphy within the Gadvan formation, with a specific emphasis on the Khalij limestone member. A regional stratigraphic assessment covered an extensive area of about 100,000 square kilometers in the Fars and Dezful regions within the Zagros region. To achieve this, data from 38 exploration and development wells were utilized, and approximately 1,400 microscopic thin sections from the Gadvan formation were meticulously examined. The paramount contribution of this research lies in the establishment of a representative type section for the Khalij limestone member, characterized by a thickness of 13 meters. Detailed microscopic analysis has revealed that this member predominantly comprises wackestone carbonate, featuring microfossils, particularly foraminifera from the orbitolindae family. Based on the observed species index, it has been determined to be of Barremian age and linked to a lagoon-like depositional environment.

Key-Words: Khalij limestone member, Gadvan, Barremian, orbitolindae, lagoon

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1 Introduction

The study area is situated in the Zagros Basin, which evolved along the northeastern continental margin of Africa during the Paleozoic Era (Fig 1and Fig 2). A significant geological event during the Permian Period involved the detachment of the Iran plate, which includes Alborz, the east-central Iran microcontinent, and Sanandaj-Sirjan, from the Arabian plate. This detachment led to the formation of the Neotethyan Ocean. Subsequently, individual microcontinents separated from this assembly and moved northward, ultimately suturing to Eurasia prior to and during the Miocene Epoch, coinciding with the collision of Africa and Eurasia. The Alpidic-Himalayan Orogeny played a pivotal role in deforming all Iranian terrains and shaping their present-day configuration. Geographically, the Zagros mountains are part of the Alpine-Himalayan chain, but they do not neatly conform to models for the Alps or Himalayas. previously discussed some of these challenges and concluded that Iran exhibits a distinctive form of Alpine tectonics [1]. The Gadvan Formation is a well-known oil source rock in the Zagros area [2] [3] Within the Zagros region, the Gadvan formation stands as a distinctive geological unit, composed of shale and positioned between two prominent limestone formations, namely Fahliyan at the base and Dariyan at the top.

In the middle of the Gadvan formation, there is a distinct limestone layer known as the "Khalij" limestone. Gadvan shales, found both at the base and the top of the Gulf, are sometimes referred to as lower Gadvan and upper Gadvan shale formations. These shale layers act as cap rocks for the Fahliyan reservoir and are characterized by their richness in organic matter, playing a fundamental role in hydrocarbon production. The Gadvan Formation's type locality is in the Fars Province, located at Kuh-e-Gadvan, east-northeast of Shiraz, Iran. In the southwestern region of Iran (except for the south-southwest of Lorestan), the Gadvan formation is equivalent to the Zubair Formation in the Arabian countries.

Numerous prior studies have extensively explored the Gadvan formation, with a specific focus on biostratigraphy and microfacies ([4]; [5]; [6]; [7]). The primary objective of this study was to provide a detailed understanding of the sedimentary environment through a biostratigraphy analysis rooted in foraminiferal biozones and microfacies. This analysis ultimately seeks to offer a high-resolution representation contributing to the reconstruction of paleogeography.

In contrast to previous studies that predominantly concentrated on the paleontological and stratigraphical aspects of the Gadvan Formation, recent research strives to gain a deeper insight into the facies, sedimentary conditions, and age of this geological unit, which continue to pose unresolved questions.

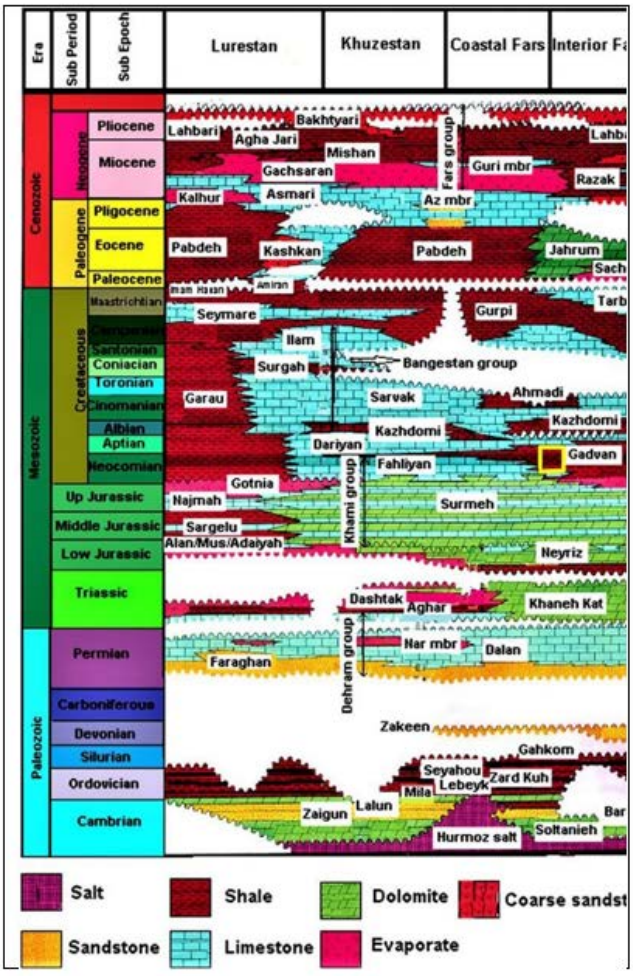

Fig 1: A Simplified Lithostratigraphic Diagram of the Zagros Region (Ghavidel Syooki et al., 2003).

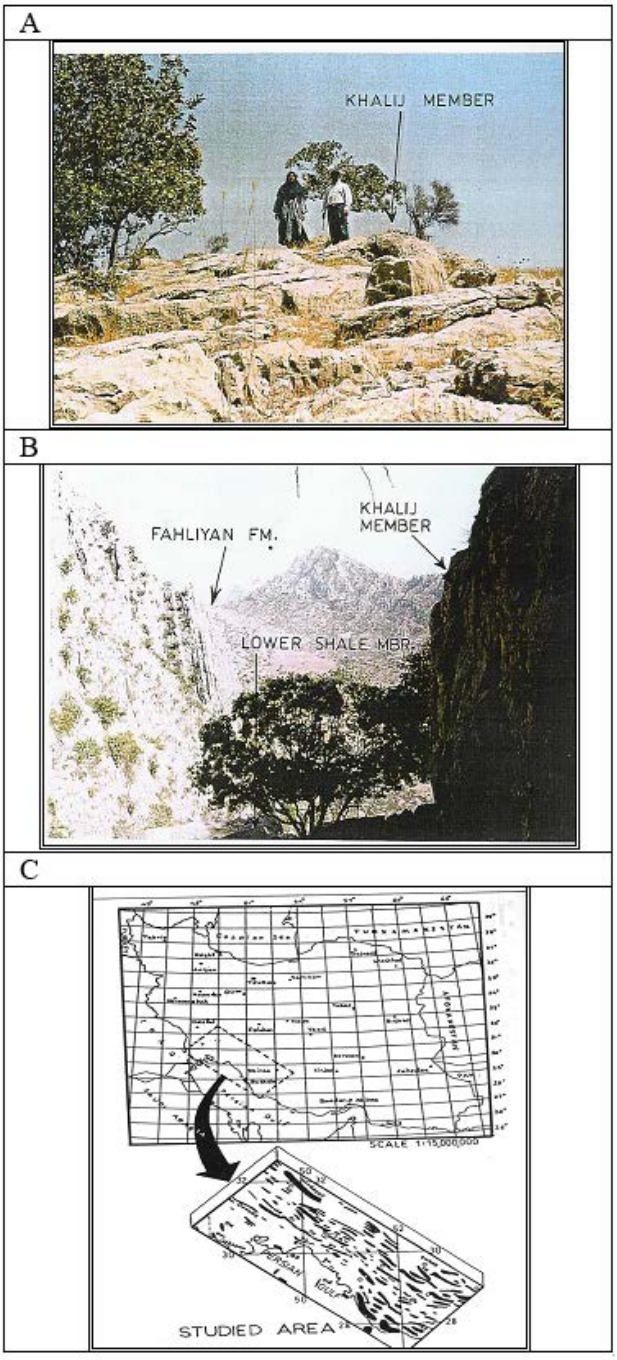

Fig 2: a) Outcrop of the Khalij Limestone Member. The Khalij member has been thoroughly analyzed in a well-defined stratigraphic section situated on the southern flank of the Kuh Mish anticline, Tang Gurguda, which serves as a representative Kazhdumi type section. b) Location of the Studied Section The geographical position of the studied section is indicated on the Lower Cretaceous sequence,

illustrating the Fahliyan, Gadvan, and Dariyan formations.

c) Study Area in Tang Gurguda, Gachsaran.

2 Problem Formulation

To conduct a comprehensive regional stratigraphic analysis, an area spanning 100,000 square kilometers within the Fars and Dezful regions of the Zagros region was investigated. The primary focus of this study was to perform a detailed lithostratigraphic and microstratigraphic analysis of the Gadvan formation, with specific emphasis on the Khalij limestone member. The characterization of facies and sedimentary environments within the Gadvan formation was accomplished using the following datasets:

1. Petrophysical logs
2. Graphic well logs obtained from 38 wells
3. Paleo logs
4. Drilling cuttings, resulting in the creation of 1000 thin sections
5. Cores, which yielded 400 thin sections

The study area was situated at the surface location known as Tang Gurguda, located approximately 40 kilometers to the northeast of Gachsaran city. Over 100 oriented surface samples were systematically collected from the early Cretaceous formation (Fig 2). Microfossil identification was conducted using the classification systems developed by Dunham (1962) and Wilson (1975) ([8]; [9]). Foraminifers and calcareous algae were identified based on the methodologies outlined in publications by Premoli Silva and Verga (2004) [10], Husinec and Sokač(2006) [11], Afghah (2006) [12], Hosseini and Conrad (2008) [13], Parvaneh Nejad Shirazi (2009) [14], Schroeder et al. (2010) [15], Bucur et al. (2012) [16], Abyat et al. (2016) [17], Afghah et al. (2016) [7], Brovina (2017) [18], Coccioni (2019) [19], and Abedpour et al. (2021) [20]. Comprehensive descriptions of the samples, both from field and laboratory analyses, were meticulously recorded and integrated into a detailed stratigraphic section.This study introduces an innovative workflow designed to provide a precise and comprehensive analysis, outlined as follows:

3 Problem Solution

3.1. Lithostratigraphy, Characterization of Type Section, and Surface-to-Subsurface Correlation

In the broader context of the Zagros region, the Khalij Limestone Member assumes a critical role as a significant lithostratigraphic unit, serving as a reservoir rock for the Khami reservoir. This specific member, known for its rich benthic facies, is situated in the mid-section of the Gadvan shaly formation, boasting an average thickness of approximately 14 meters. Notably, the Khalij Limestone Member is exclusively subsurface, lacking any exposed outcrops, and is distinguished by easily identifiable orbitolinid limestone, as illustrated in Fig 3. The utilization of well logging techniques, particularly through Gamma Ray and Density measurements, has proven to be highly effective in detecting and characterizing this distinctive layer. The primary objective of the conducted study was to undertake a comprehensive analysis of the lithostratigraphy and microstratigraphy within the Gadvan Formation, with a specific focus on the Khalij Limestone Member. This regional stratigraphic assessment covered an extensive area spanning approximately 100,000 square kilometers in the Fars and Dezful regions within the Zagros region. To achieve this, data from 38 exploration and development wells were leveraged, and an exhaustive examination of around 1,400 microscopic thin sections from the Gadvan Formation was carried out. A significant contribution of this research lies in the establishment of a representative type section for the Khalij Limestone Member, characterized by a thickness of 13 meters. Notably, the Khalij Limestone Member was not originally included in the type section of the Gadvan Formation. Its introduction took place for the first time in the Khalij Limestone type section on the surface at Tang Gurguda. The tracing of the Khalij Limestone Member was accomplished through well logging techniques, particularly employing Gamma Ray and Density measurements, utilizing data collected from the 38 exploration and developmental wells, as depicted in Fig 2 and Fig 3. This facilitated

the identification of rock properties and layer geometries within the Khalij Member and the Gadvan Formation through log analysis, providing valuable insights into both.

In the broader context of the Zagros region, the Khalij Limestone Member assumes a critical role as a significant lithostratigraphic unit, serving as a reservoir rock for the Khami reservoir. This specific member, known for its rich benthic facies, is situated in the mid-section of the Gadvan shaly formation, boasting an average thickness of approximately 14 meters. Notably, the Khalij Limestone Member is exclusively subsurface, lacking any exposed outcrops, and is distinguished by easily identifiable orbitolinid limestone, as illustrated in Fig 3. The utilization of well logging techniques, particularly through Gamma Ray and Density measurements, has proven to be highly effective in detecting and characterizing this distinctive layer. The primary objective of the conducted study was to undertake a comprehensive analysis of the lithostratigraphy and microstratigraphy within the Gadvan Formation, with a specific focus on the Khalij Limestone Member.

This regional stratigraphic assessment covered an extensive area spanning approximately 100,000 square kilometers in the Fars and In addition to the previously mentioned tasks, our research involved the meticulous creation of ten lithostratigraphic correlation cross-sections specifically focused on the Fars and Dezful embayment regions. This detailed examination aimed to enhance our understanding of the geological formations present in these areas. To provide a more comprehensive illustration, we present two exemplary cases that delve into the lithostratigraphy of the Gadvan Formation. The first cross-section extends from the Masjed-Suleyman field to Tang Gurguda. This cross-section spans from the Masjed-Suleyman field to Tang Gurguda and is designed to provide a comprehensive visual overview of the geological features present in the Gadvan Formation. The section encompasses a significant geographical distance and meticulously showcases various rock types, sedimentary layers, and geological boundaries encountered along the transect. The lithostratigraphic section begins at the Masjed-Suleyman field, unraveling a spectrum of geological formations. These may include sandstones, shales, and limestones, each contributing to the understanding of the environmental conditions, depositional processes, and tectonic events that shaped the region over time. As the section progresses towards Tang Gurguda, it continues to reveal geological intricacies, such as changes in lithology, variations in sedimentary structures, and notable stratigraphic boundaries. This visual representation serves as a crucial tool for researchers, offering insights into the stratigraphic relationships between different layers. In essence,

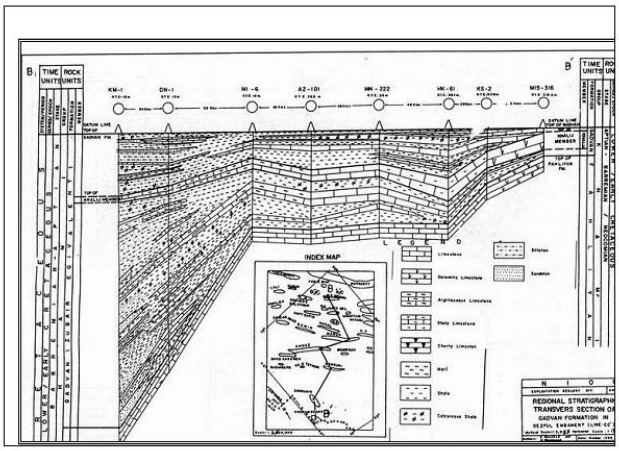

Fig 4 is a vital resource for geoscientists, providing a detailed visual guide to the geological formations along the Masjed-Suleyman to Tang Gurguda transect. It encapsulates the geological diversity of the Gadvan Formation, forming a foundation for further studies and a deeper exploration of the geological history of the region.

while the second spans are from Masjed Suleyman to Khorramshahr (Fig 5). The lithostratigraphic section presented in Fig 5 provides a comprehensive view of the geological formations within the Gadvan Formation, extending from Masjed Suleyman field to Khorramshahr field. This section is invaluable for understanding the composition, structure, and depositional history of the subsurface rocks in this region. Starting from Masjed Suleyman field, which is a significant hydrocarbon reservoir, the lithostratigraphic column illustrates the various sedimentary layers that have accumulated over geological time. These layers represent distinct periods of deposition, including

information about the types of rocks, their mineral composition, and any fossil content.

Masjed Suleyman field is renowned for its hydrocarbon resources, and the lithostratigraphic section aids in identifying specific geological horizons associated with oil and gas reservoirs. The study of this field contributes to a deeper understanding of the subsurface geology and facilitates effective exploration and extraction strategies. Continuing the lithostratigraphic journey towards Khorramshahr field, the section provides insights into the geological variations and formations encountered along the way. Khorramshahr field is another significant area with geological importance, possibly hosting its own unique characteristics and hydrocarbon reservoirs within the Gadvan Formation. The lithostratigraphic section allows geologists and researchers to correlate and compare the geological features between Masjed Suleyman and Khorramshahr fields. This comparative analysis can reveal similarities or differences in the sedimentary sequences, aiding in the interpretation of the regional geological history. Understanding the lithostratigraphy is crucial for the petroleum industry, as it provides essential information for reservoir characterization, well logging, and overall subsurface modeling. By examining the lithological variations along the transect from Masjed Suleyman to Khorramshahr fields, geoscientists can infer the depositional environments, sedimentary facies changes, and potential reservoir properties. In summary, Fig 5 offers a detailed lithostratigraphic representation of the Gadvan Formation, unraveling the geological story from Masjed Suleyman field to Khorramshahr field. This information serves as a foundation for geological studies, enhancing our knowledge of the subsurface structure and supporting strategic decision-making in oil and gas exploration and production.

Furthermore, we developed an Isopach map specifically focusing on the Khalij Limestone Member. This map provides a visual representation of the thickness variations of the Khalij Limestone Member within the studied area. Additionally, a fence diagram was meticulously crafted to portray the distribution of the Khalij Limestone Member throughout the Fars and Dezful embayment region. This diagram serves as a nuanced depiction, emphasizing the intricate patterns and variations in the presence of the Khalij Limestone Member across the studied region. The culmination of these efforts is represented in Fig 6 and Fig 7, where the Isopach map and fence diagram are presented. These figures act as crucial tools for researchers and geologists, offering a detailed and insightful portrayal of the geological characteristics and distributional nuances of the Khalij Limestone Member within the specified geographical area. Through careful depiction of geological features and their relative positions, these figures contribute significantly to advancing our understanding of the geological complexities in the studied regions.

In conclusion, our comprehensive study provides instance, the formation incorporates dark shale and argillaceous limestone. On the other hand, as one progresses towards the Lorestan Province, the limestone undergoes a gradual transition, evolving into dark to black, argillaceous limestone, a resemblance to the Garau Formation is noted. detailed insights into the stratigraphy and characteristics of the Gadvan Formation, particularly at the Tang Gurguda site. The Gadvan Formation, identified in this region, exhibits a substantial thickness of approximately 107 meters. The predominant lithology consists of dark-gray, argillaceous, bioclastic limestone, interspersed with marl layers that display varying hues of gray, green, and brownish-yellow.

The significance of our research lies in the detailed examination of lateral facies variations within the Gadvan Formation, a geological unit situated in the Khuzestan Province. This area holds particular importance due to its proximity to the Arabian Gulf, adding an additional layer of complexity to the stratigraphic evolution.

As we move closer to the Arabian Gulf from the Khuzestan Province, a noteworthy pattern emerges within the Gadvan Formation. The shaly components within this formation exhibit a consistent reduction, eventually reaching a point where they disappear entirely. This spatial trend is indicative of a distinct

transition from the Gadvan Formation to the subsequent Dariyan Formation.

To visually represent these transitional features and lithological variations, we have included figures (Fig 1,

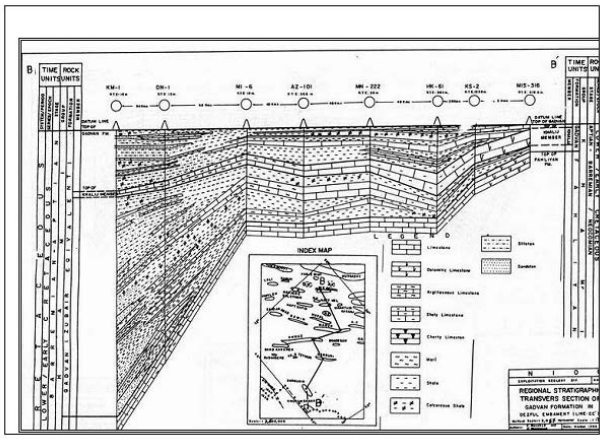

Fig 4, and Fig 5) in our study. These figures serve as invaluable tools for researchers and geologists, offering a clear depiction of the stratigraphic changes and lateral facies variations along the studied profile.

Our findings not only contribute to the regional geological knowledge of the Khuzestan Province but also have broader implications for the field of stratigraphy and geological mapping in the area. The comprehensive understanding of the Gadvan Formation's characteristics, particularly its lateral facies variations, enhances our ability to interpret and predict geological formations. This, in turn, aids in the development of accurate geological maps and contributes to the advancement of broader stratigraphic studies in the region. Overall, our research provides valuable insights that extend beyond the immediate geographical scope, impacting the broader context of geological understanding and mapping.

The thickness of the Khalij Limestone Member displays significant variability across distinct geographical locations, with notable extremes observed in specific areas. Haftkel stands out as the location where the member attains its maximum thickness, showcasing a robust geological presence. In contrast, the Khorramshahr field within the Dezful embayment reveals the minimum thickness of the Khalij Limestone Member, indicating spatial heterogeneity in its distribution.

Further investigation into Fars unveils additional nuances in the thickness patterns of the Khalij Limestone Member. Kuh E Mand emerges as the locality where the member achieves its maximum thickness, presenting geological characteristics distinct from other locations. Conversely, the Sabzpushan field in Fars exhibits the minimum thickness of the Khalij Limestone Member, contributing to the understanding of the geological variations within the region.

A noteworthy geological phenomenon is the transition of the Khalij Limestone Member into sandstone and siltstone formations. This transformation is particularly evident in Iraq and Kuwait, where the Khalij Limestone Member seamlessly gives way to the Zubair Formation. The distinct geological features of the Zubair Formation are visually represented in

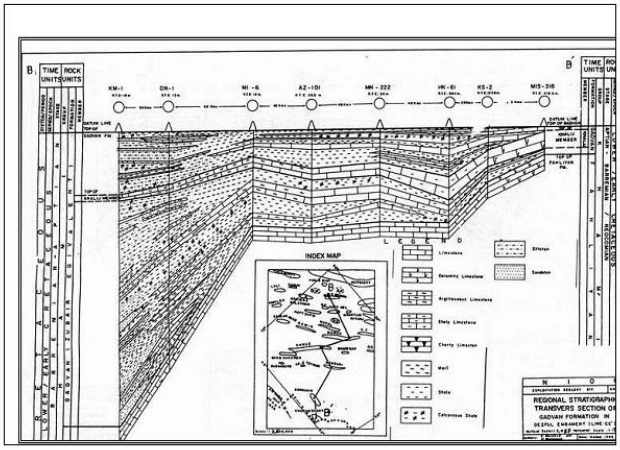

Fig 4 and Fig 5, emphasizing the intricate interplay between different lithological components. In the northern Gurcharan area, specifically within Tang Gurguda, the Khalij Limestone Member takes on particular significance within the Gadvan Formation. This region is proposed as the type section for the Khalij Limestone Member, offering a comprehensive representation of its geological attributes. Fig 2 and Fig 3 provide graphical depictions, elucidating the key characteristics of the Khalij Limestone Member within the broader context of the Gadvan Formation in the Tang Gurguda area.

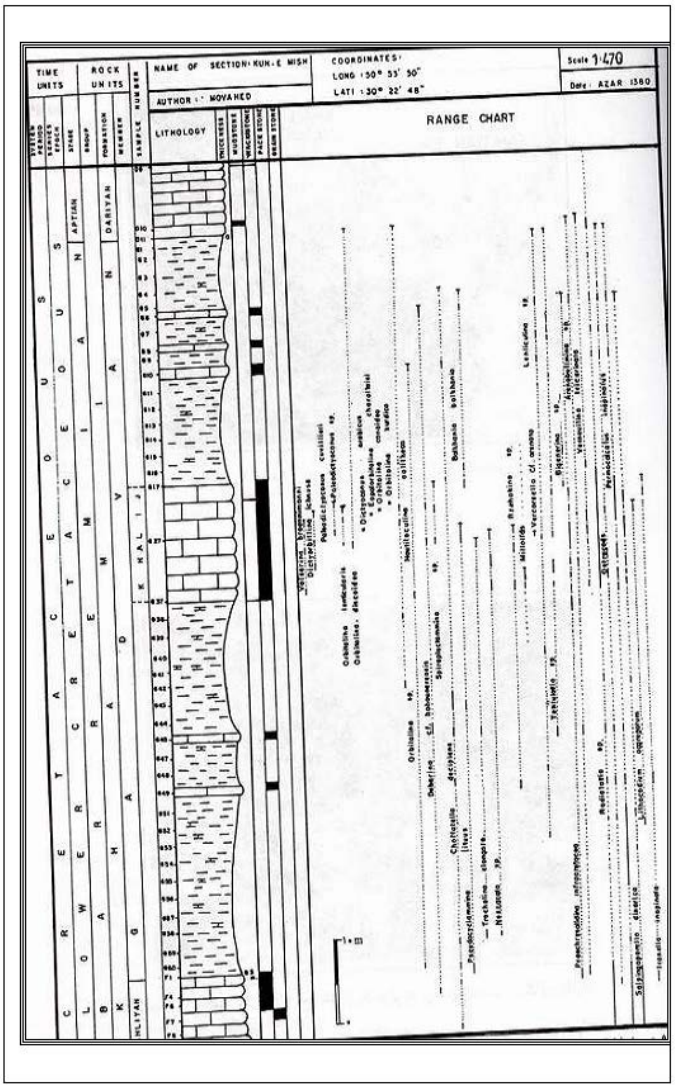

Fig 3: Stratigraphic section of Khalij limestone member in the studied area (Tang Gurguda). The presented figure encapsulates a comprehensive overview of the stratigraphic composition of the Khalij limestone member within the specified geological locale, identified as Tang Gurguda. This visual representation offers a detailed insight into the vertical arrangement of rock layers and geological formations, providing a valuable resource for researchers and geologists examining the region's geological history.

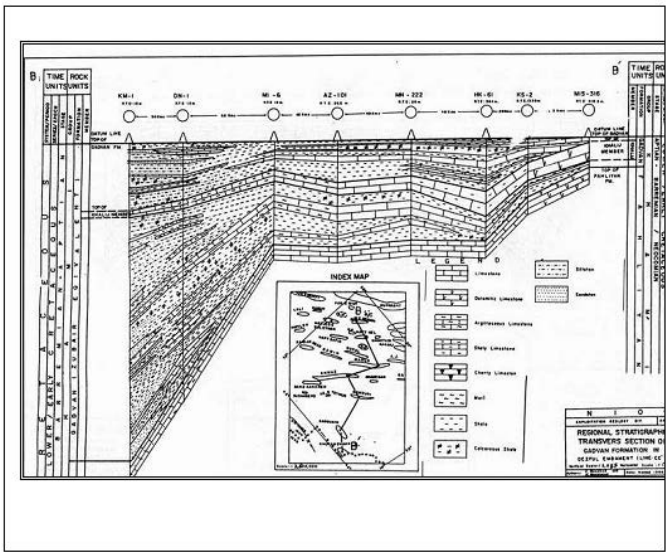

Fig 4: The lithostratigraphic section depicted provides a comprehensive illustration of the geological formations within the Gadvan Formation, extending geographically from the Masjed-Suleyman field to Tang Gurguda surface section. This section serves as a visual representation of the various layers and rock types encountered along this specific stretch, offering valuable insights into the geological history and composition of the region.

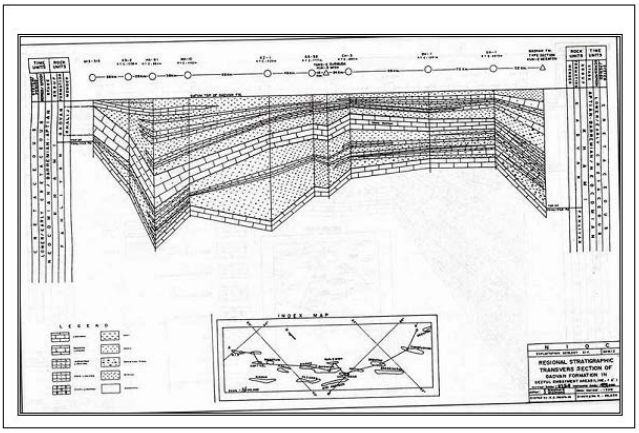

Fig 5: Presents a lithostratigraphic section of the Gadvan Formation from Masjed Suleyman field to Khorramshahr, offering a detailed view of the geological composition and structure along this geological profile, with Masjed Suleyman and Khorramshahr serving as key reference points in the analysis. This section is invaluable for understanding the composition, structure, and depositional history of the subsurface rocks in this region.

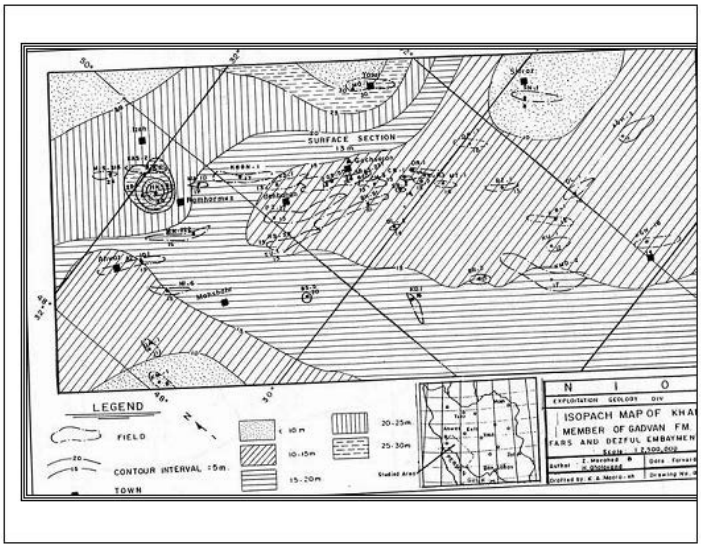

Fig 6: Presents an Isopac map depicting the distribution of the Khalij limestone member within the Fars and Dezful embayment area. This map provides a visual representation of the isopachous variations, illustrating the thickness of the Khalij limestone member across the specified geographical region. The contours on the map help to convey the spatial patterns of sedimentary deposition or erosion, offering valuable insights into the geological characteristics of the studied area.

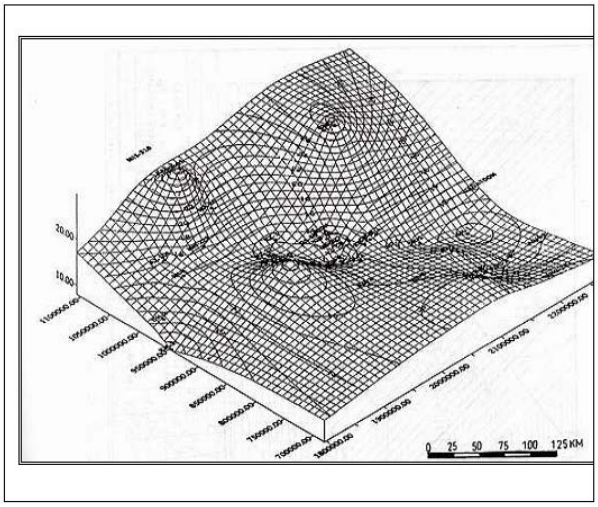

Fig 7: Fence Diagram Illustrating the Distribution of the Khalij Limestone Member in the Fars and Dezful Embayment Area.In this detailed illustration, a fence diagram has been meticulously crafted to provide a comprehensive visual representation of the spatial distribution of the Khalij Limestone Member within the geographic expanse of the Fars and Dezful embayment area.

3.2. Biostratigraphy Study

In our pursuit of biostratigraphy insights, we conducted a comprehensive examination of the Khalij Member within the Gadvan Formation. This meticulous study, involving the scrutiny of 100 thin sections, has unveiled the Khalij Member to have an approximate thickness of 13 meters. The primary lithological composition of this substantial layer is predominantly composed of yellow and clayey limestones. Notably, a distinct erosional contact is observed, demarcating the upper and lower shale layers within the Gadvan Formation. Our microstratigraphic analysis culminated in the identification of 12 families, 26 genera, and 21 species, collectively defining an assemblage zone. Remarkably, the Orbitolina family stands out as the most prominent microfossils within this zone(Fig 3 and Fig 8).Upon conducting an extensive microscopic analysis, it was discerned that this particular geological specimen is primarily constituted of wackestone carbonate. This composition exhibits a notable enrichment of microfossils, with a significant presence of foraminifera belonging to the orbitolindae family. The meticulous scrutiny of the observed species index has led to the identification of its geological age as Barremian. Furthermore, the specimen is strongly indicative of a depositional environment that bears a resemblance to a lagoon. This comprehensive examination provides valuable insights into the intricate geological history and environmental conditions associated with this specific member.

The following microfossils were identified within the Khalij Limestone Member:

1 Choffatella decipiens SCHLUMBERGER
2 Pseudocyclammina lituus YOKOYAMA
3 Balkhania balkhanica MAMONTOVA
4 Nautiloculina Oolithica MOHLER
5 Debarina cf. hahouneresis FOURCAD & ROUTT & VILA
6 Spiroplectammina sp.
7 Vercorsella cf. arenata ARNAUD-VANNEAU
8 Trocholina elongate LEUOPOLD
9 Rzehakina sp.
10 Lenticulina sp.
11 Valserina broennimannl SHROEDER & CONRAD

The microfacies interpretations consistently indicate the presence of a shallow lagoon environment, with an estimated sedimentary depth of approximately 35 meters. This deduction is supported by the identification of various indicators such as algal remains, including Lithocodium (found in the 0-40m depth range), Salpingoporella (0-30m), Choffatella (30-40m), Debarina, Praechrysalidina (0-38m). Additionally, the discovery of Gastropods, Echinoids, Cephalopods, Shell debris, Ostracods, and Pellets further reinforces the characterization of the environment.

This sedimentary setting aligns closely with the typical features of a lagoon and corresponds to Microfacies 7 in the Wilson model, as illustrated in both Fig 3 and Fig 8. The presence and distribution of these microfacies types provide valuable insights into the depositional environment. Furthermore, the observed species index contributes to the determination of a Barremian age and supports its association with a lagoon-like setting. The combined evidence from microfacies analysis and species identification enhances our understanding of the geological context, emphasizing the significance of the Barremian age within a lagoon environment.

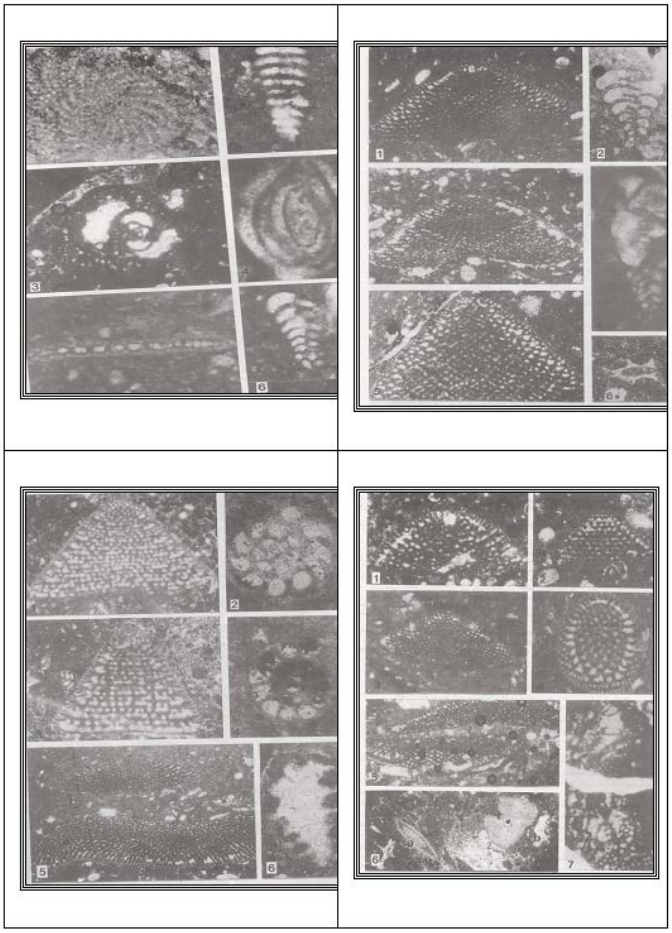

Fig 8: A visual representation of the microfossils found within the Kalhur Member, a geological unit with a Barremian age, contributing valuable data to the broader field of paleontology and enhancing our understanding of the Earth's history during the Barremian epoch.

4 Conclusion

The comprehensive investigation of the lithostratigraphy, biostratigraphy, and microfacies analysis of the Gadvan Formation as a Lower Cretaceous oil reservoir in the Zagros Basin is of paramount significance. Within the northern Gachsaran region, we recommend considering the Khalij Limestone Member within the Gadvan Formation as the ideal type section. Notably, the thickness of the Khalij Limestone Member exhibits variation across different locations, with its maximum extent observed in Haftkel and the minimum in the Khorramshahr field of the Dezful embayment. In Fars, the member reaches its maximum thickness in Kuh E Mand and its minimum in Sabzpushan field. Additionally, the Khalij Limestone Member transforms into sandstone and

siltstone formations, specifically the Zubair Formation in Iraq and Kuwait. In the context of Fars and Dezful employment, the Khalij Limestone Member predominantly comprises benthic facies and is distinguished by a noteworthy abundance of Orbitolina microfossils. The thorough microstratigraphic analysis successfully identified 12 families, 26 genera, and 21 species, collectively confirming a Barremian age within the assemblage zone. Furthermore, the microfacies analysis consistently characterizes a shallow lagoon environment, aligning seamlessly with the characteristics of Microfacies 7 as described in the Wilson model. The observed species index lends further support to the assertion of a Barremian age and its close association with a lagoon-like depositional setting

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