**Palacký University Olomouc**
**Faculty of Science**
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# Significance of Stylolite Development in Hydrocarbon Reservoirs: Emphasis on Cretaceous Carbonates in the Middle East

**Bachelor thesis**

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**Anotation:**

Stylolites are intricate structures formed through pressure dissolution in carbonate rocks, significantly influencing reservoir quality either positively or negatively. This study aims to evaluate the impact of stylolites on reservoir quality within the Kometan Formation in Iraqi Kurdistan, utilizing both field data and microscopic analysis.

During a comprehensive field investigation of a 36 square meter outcrop of the Kometan Formation, it was observed that the stylolites predominantly consist of seismogram pinning stylolites, suture and sharp-type stylolites, and peak simple wave-like stylolites. Furthermore, these stylolites exhibit a Y-type connectivity pattern, suggesting a strong tectonic influence. Microscopic examination of thin sections from the Kometan Formation revealed that, in contrast to the very low porosity and permeability in the mudstone and wackestone matrix, stylolites exhibit significantly higher porosity. This suggests that stylolites, along with fractures, can substantially enhance the reservoir quality by improving fluid flow and storage capacity. Overall, the findings indicate that the presence of stylolites, coupled with fractures, plays a crucial role in enhancing the reservoir properties of the Kometan Formation, highlighting their importance in hydrocarbon exploration and extraction strategies.

**Keywords:** Stylolites, carbonate reservoirs, Kometan Formation, Kurdistan, Iraq

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**Anotation:**

Stylolity jsou složité struktury vytvořené tlakem rozpouštění v karbonátových horninách, které mohou významně ovlivnit kvalitu rezervoáru pozitivně nebo negativně. Tato studie si klade za cíl zhodnotit vliv stylolitů na kvalitu rezervoáru v Kometanské formaci v iráckém Kurdistánu s využitím terénních dat a mikroskopické analýzy.

Během komplexního terénního průzkumu 36 čtverečních metrů velkého odkryvu Kometanské formace bylo zjištěno, že stylolity se převážně skládají ze seismogramových fixačních stylolitů, švových a ostrých typů stylolitů a jednoduchých vlnových stylolitů. Dále tyto stylolity vykazují Y-typ propojení, což naznačuje silný tektonický vliv.

Mikroskopické zkoumání tenkých řezů z Kometanské formace odhalilo, že na rozdíl od velmi nízké porozity a permeability v matrici mudstonu a wackstonu vykazují stylolity výrazně vyšší porozitu. To naznačuje, že stylolity spolu s frakturami mohou podstatně zlepšit kvalitu rezervoáru tím, že zlepšují tok tekutin a skladovací kapacitu.

Celkově výsledky ukazují, že přítomnost stylolitů spolu s frakturami hraje klíčovou roli při zlepšování rezervoárových vlastností Kometanské formace, což zdůrazňuje jejich význam v průzkumu a těžbě uhlovodíků.

Klíčová slova: Stylolity, karbonátové rezervoáry, Kometanská formace, Kurdistán, Irák

Počet stran: 40

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I declare that I have prepared the bachelor's thesis myself and that I have stated all the used information resources in the thesis.

In Olomouc, July, 2024 ..............................................

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## 1. Introduction

A stylolite is a distinctive geological structure commonly found in limestones and other carbonate rocks (Heald, 1955; Park and Schot, 1968; Dunnington, 1967). These structures are significant in geological studies due to their unique formation process and impact on rock properties. Stylolites are formed by pressure dissolution, a process where mineral matter is dissolved under high stress and transported away by fluid flow (Fletcher and Pollard, 1981; Tada and Siever, 1989). This typically occurs deep within the Earth's crust where the rocks are subjected to significant pressure over long periods (Fig. 1; Buxton and Sibley 1981). The dissolution process is driven by the differential stress acting on the rock, which leads to the removal of more soluble minerals like calcite (Koehn et al., 2020).

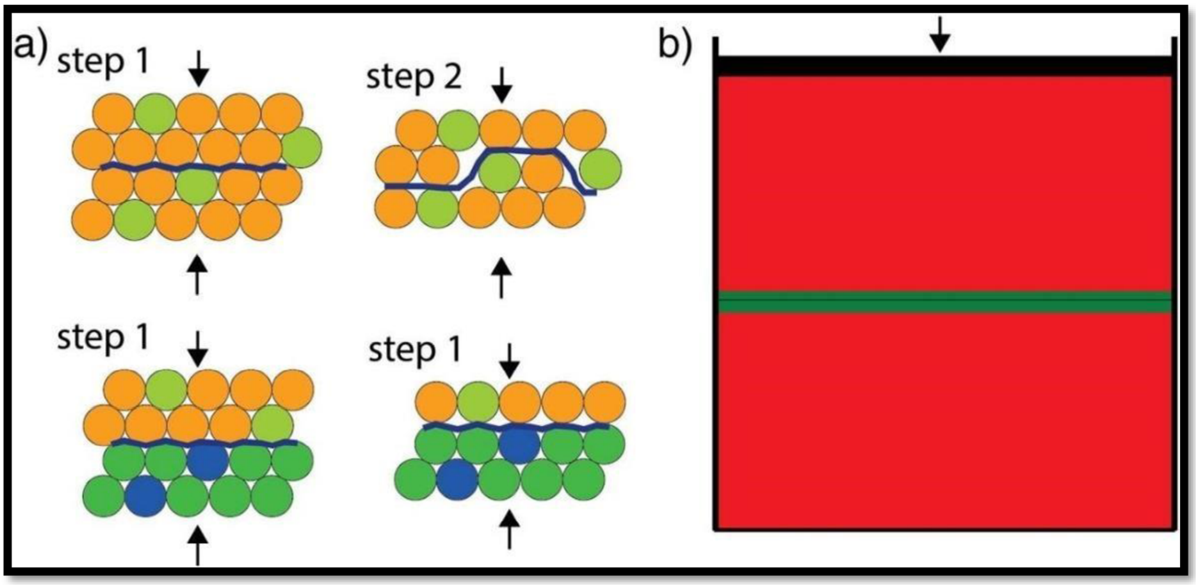


Figure 1 A) The sketch illustrates part of the numerical lattice, represented by round discs, with the initial stylolite interface marked by a blue line ((Koehn et al., 2016)). Particles in the lattice have varying dissolution constants, with light green particles dissolving at a slower rate. The upper setup generates small-scale roughening and complex dissolution patterns, with particles dissolving either above or below the interface based on their dissolution constants. In the lower model, an added layer contains particles below the stylolite that dissolve more slowly. Blue particles within this layer represent minor variations and dissolve even more slowly than the rest of the layer. This layer "pins" the interface, causing all particles above the stylolite to dissolve. B) The model setup shows a green layer in the center, where the stylolite begins within this layer (Sourced from Koehn et al., 2016).

Stylolite formation is closely linked to depth due to changes in pressure, temperature, and chemical environment (Laubach et al., 2010; Anders et al., 2014). As depth increases, higher pressure from overlying rock layers enhances mineral solubility at grain contacts, facilitating pressure solution and stylolite formation (Anders et al., 2014; Koehn et al., 2016). Higher temperatures at greater depths accelerate chemical reactions involved in pressure solution (Koehn et al., 2016). Differential stress, which is higher at greater depths due to tectonic forces, drives mineral dissolution at high-stress points and precipitation in low-stress areas (Anders et al., 2014; Koehn et al., 2016). Effective stress, the difference between total stress and pore pressure, also plays a crucial role, with higher effective stress enhancing pressure solution and stylolite development (Koehn et al., 2016). Stylolites formed at greater depths typically show larger amplitudes and closer spacing, indicating significant mineral dissolution and frequent stress concentration points (Laubach et al., 2010). The morphology of stylolites varies with depth, being simpler and more regular at shallow depths and more complex and jagged at greater depths due to more intense pressure solution and stress variations (Laubach et al., 2010).

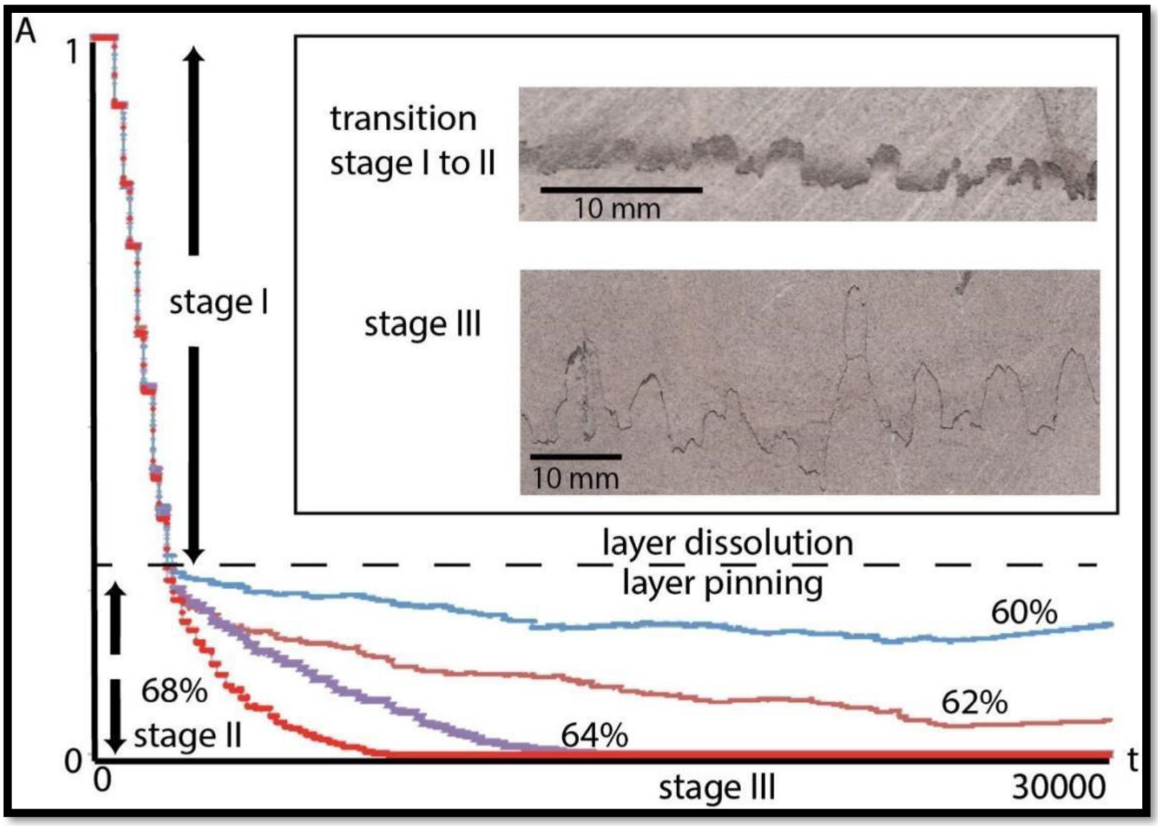


Figure 2 relationship between depth and stylolite formation (Koehn et al., 2016).

Stylolites appear as irregular, jagged, or serrated seams or surfaces within the rock (Fig.3). They often look like interlocking teeth or a suture line, creating a distinctive zigzag pattern (Nicol et al., 2019). These structures can vary significantly in size, from microscopic scales to several meters in length (Nicol et al., 2019; Koehn et al., 2020). The jagged nature of stylolites results from the differential dissolution rates of the minerals composing the rock, with the more soluble components dissolving away and the less soluble components remaining (Nicol et al., 2019; Koehn et al., 2020).

Figure 3 A stylolite created in Mudstone (Nikbin et al., 2023)

The dissolved material in carbonate rocks is usually calcite, and the residual material left behind often includes insoluble minerals such as clay, quartz, and organic matter (Paganoni et al., 2016; Fig. 4). This concentration of insoluble materials gives stylolites their characteristic dark appearance (Ebner et al., 2016). The presence of these insoluble residues within the stylolite seam can provide valuable information about the original composition of the rock and the conditions during its formation (Ebner et al., 2016; Beaudoin et al., 2021).

Stylolites are classified based on their morphology and orientation relative to the bedding planes of the rock. Common types include (Koehn et al., 2018):

1. Horizontal stylolites: These are parallel to the bedding planes and typically indicate compressive stress that was perpendicular to the bedding plane.
2. Vertical or inclined stylolites: These cut across the bedding planes and suggest a more complex stress regime or post-depositional tectonic activity.
3. Non-planar stylolites: These have irregular and wavy shapes, reflecting heterogeneous stress fields and varying dissolution rates during formation.

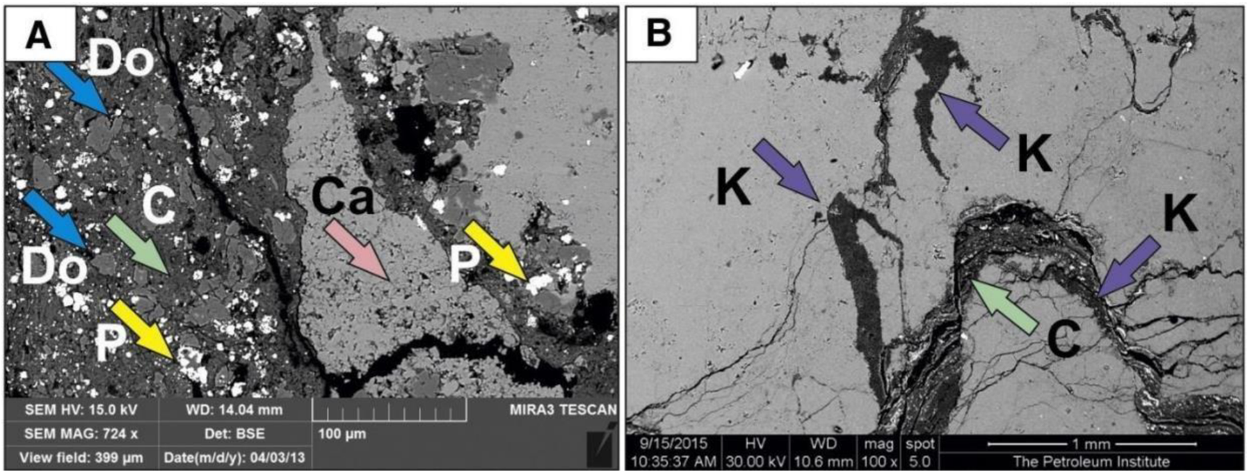


Figure 4 After Paganoni et al., 2016; (A) A BSE image displays various minerals along a stylolitic surface, including clay minerals (C, indicated by the green arrow), primarily illite, which are found with partially dissolved dolomite crystals (Do, indicated by the blue arrows), calcite (Ca, indicated by the pink arrow), and large pyrite crystals (P, indicated by the yellow arrow). (B) Another BSE image shows fractures filled with kaolin (K, indicated by the purple arrow) that are nearly perpendicular to a stylolite, which is primarily filled with illitic clay minerals (C, indicated by the green arrow). Additionally, kaolin cement is observed filling secondary pores along the stylolite (Sourced from Paganoni et al., 2016).

### 1.2 The effect of stylolite on hydrocarbon reservoirs

Stylolites can significantly affect the porosity and permeability of the rock, influencing fluid flow and the storage of hydrocarbons in reservoirs (Verhaert et al., 2019). They can act as barriers to fluid flow, which may impede the extraction of oil and gas (Koepnick, 1987; Gratier et al., 2020). However, in some cases, they can also create secondary porosity, enhancing reservoir quality by providing additional pathways for fluid migration (Nelson, 2001; Toussaint et al., 2018). Stylolites also serve as important stress indicators, revealing the magnitude and direction of stress the rock has undergone (Nelso, 2001). This information is crucial for understanding the tectonic history and structural evolution of the region. As diagenetic features, stylolites form after the initial deposition of the sediment and during its lithification (Engelder, 1990; Nelso, 2001). Their presence indicates a history of significant chemical alteration and mechanical compaction, which can provide insights into the diagenetic processes that have affected the rock (Beaudoin et al., 2021).

In the petroleum industry, stylolites present a complex interplay of benefits and challenges. Their impact on reservoir performance hinges on their unique structural and compositional characteristics, influencing both fluid flow and rock integrity in multiple ways (Koehn et al., 2020). Stylolites can act as barriers to fluid flow within a reservoir, complicating extraction processes. This barrier effect arises due to the concentration of insoluble minerals and organic matter along the stylolite seam (Paganoni et al., 2016; Fig. 5).

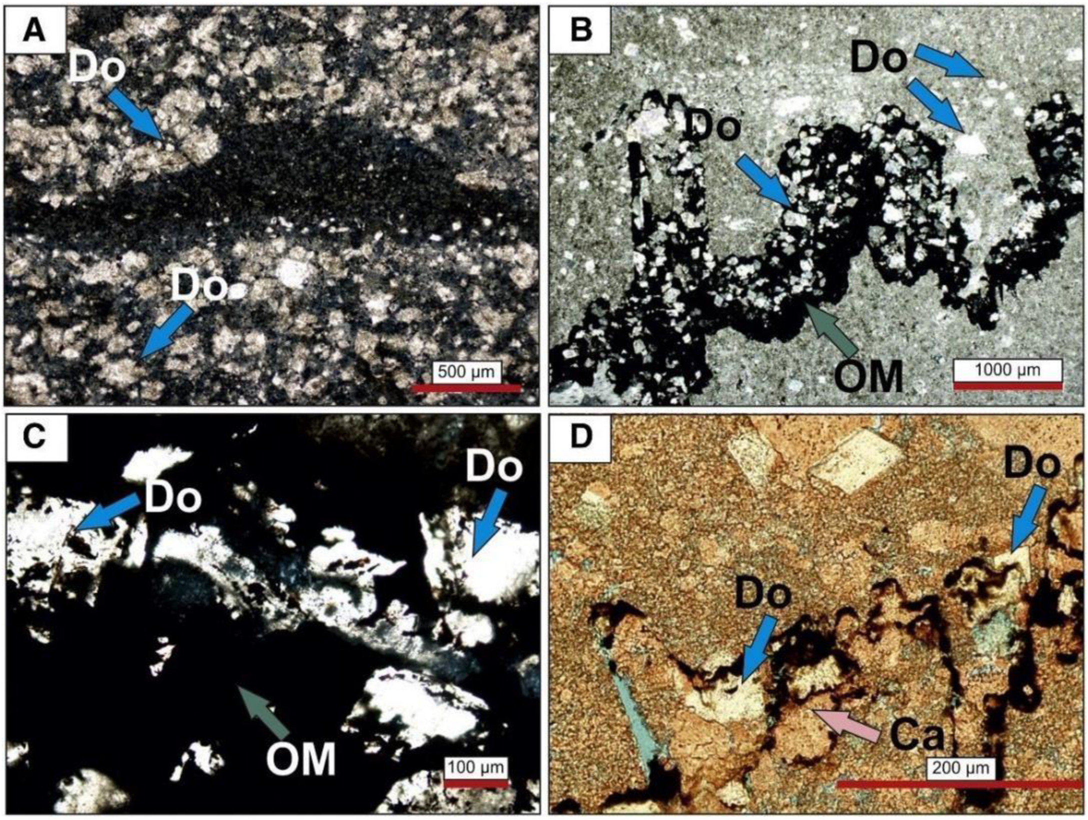


Figure 5 According to Paganoni et al., 2016: (A) An optical photomicrograph (PPL) shows rhombic dolomite crystals (Do, indicated by blue arrows) in limestone, with no signs of stylolitization. (B) An optical photomicrograph (PPL) reveals numerous partially dissolved rhombic dolomite crystals embedded in bitumen (OM) along a rectangular/jagged stylolite. (C) An optical photomicrograph

(PPL) displays dissolved dolomite crystals (Do, indicated by blue arrows) coated with bitumen (OM, indicated by the green arrow). (D) Optical photomicrographs (PPL) depict partially dissolved rhombic dolomite (Do, indicated by the blue arrow) and calcite (Ca, indicated by the pink arrow) crystals along a stylolite surface (Sourced from Paganoni et al., 2016).

These residual materials, such as clay, quartz, and other insoluble components, create zones of reduced permeability (Paganoni et al., 2016). When stylolites are abundant and welldeveloped, they can form continuous barriers that compartmentalize the reservoir, hindering the movement of hydrocarbons and water (Beaudoin et al., 2021). This can lead to uneven extraction, where some sections of the reservoir are drained more quickly than others, potentially leaving significant amounts of hydrocarbons unrecovered (Engelder, 1990; Beaudoin et al., 2021). Conversely, stylolites can also contribute positively to reservoir quality by creating secondary porosity (Fig. 6). Secondary porosity refers to the additional pore spaces formed after the initial deposition of the sediment. In the case of stylolites, the dissolution process that forms these structures can enlarge existing pores or create new ones around the stylolite seam (Engelder, 1990; Beaudoin et al., 2021). This can enhance the overall porosity of the rock, providing more space for hydrocarbons to accumulate and improving the reservoir's capacity. In some instances, the dissolution of calcite along stylolites can also enhance connectivity between pore spaces, facilitating better fluid flow and extraction efficiency (Engelder, 1990; Nelson, 2001).

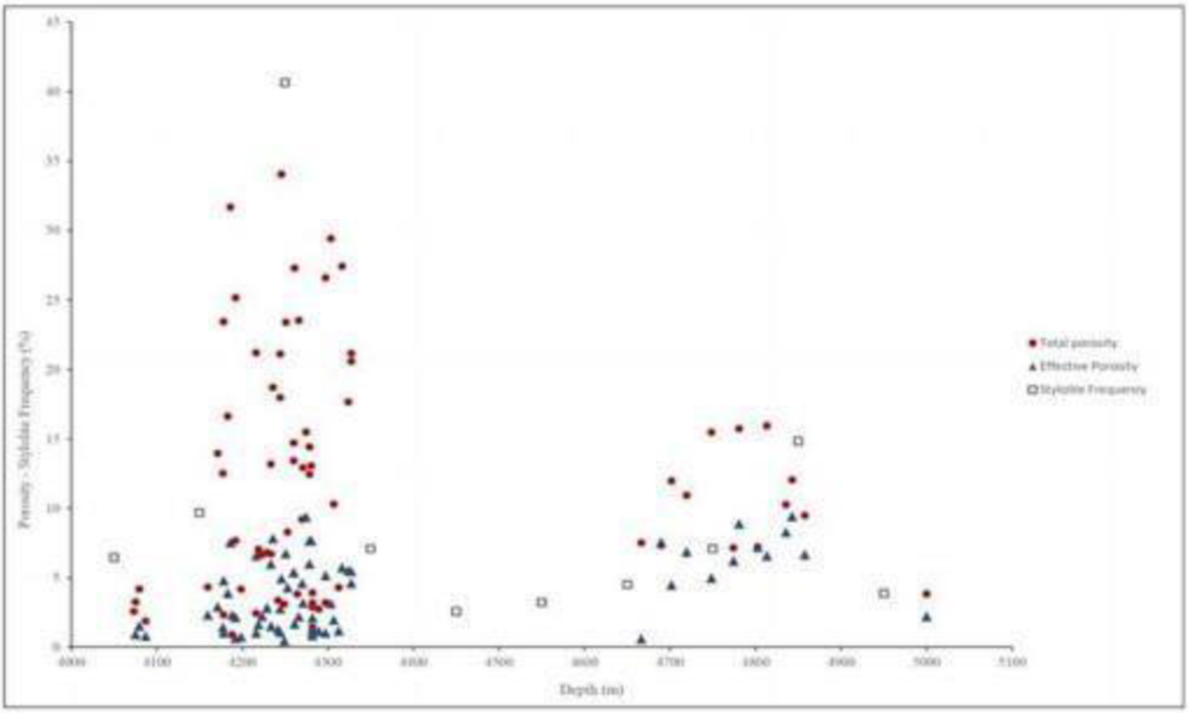

Figure 6 Scatter plot of total porosity and effective porosity of stylolite samples based on the depth changes. Based on the diagram in Figure 7, the average depths of 4200-4300 and 4800-4900 m with an increase in the concentration of stylolites and the porosity of stylolite-bearing samples also increased, which is proof of the effect of stylolitic zones on the increase in porosity (Sourced from Nikbin et al., 2023).

The presence of stylolites introduces heterogeneity within the reservoir rock, meaning that different parts of the reservoir may have significantly different properties (Engelder, 1990; Nelson, 2001). This heterogeneity can affect the reservoir's behavior during production. For instance, stylolites may channel fluids along their length, leading to preferential pathways for fluid migration (Toussaint et al., 2018). Understanding this heterogeneity is crucial for reservoir modeling and simulation, allowing for more accurate predictions of fluid behavior and more effective planning of extraction strategies (Toussaint et al., 2018). To optimize hydrocarbon recovery, it is essential to understand the distribution, orientation, and characteristics of stylolites within a reservoir (Renard and Fossen, 2010). Detailed geological and geophysical studies, including core sampling, imaging techniques (such as CT scans and MRI), and seismic surveys, can help map the presence and extent of stylolites (Fig. 7; Beaudoin et al., 2021). By integrating this information into reservoir models, engineers can design more effective extraction strategies. For example, horizontal drilling techniques can be used to avoid stylolite-rich zones that act as barriers, while hydraulic fracturing can be employed to enhance connectivity in areas where stylolites contribute to secondary porosity (Beaudoin et al., 2021). Numerous case studies from oil fields worldwide demonstrate the varying impacts of stylolites (Beaudoin et al., 2021).

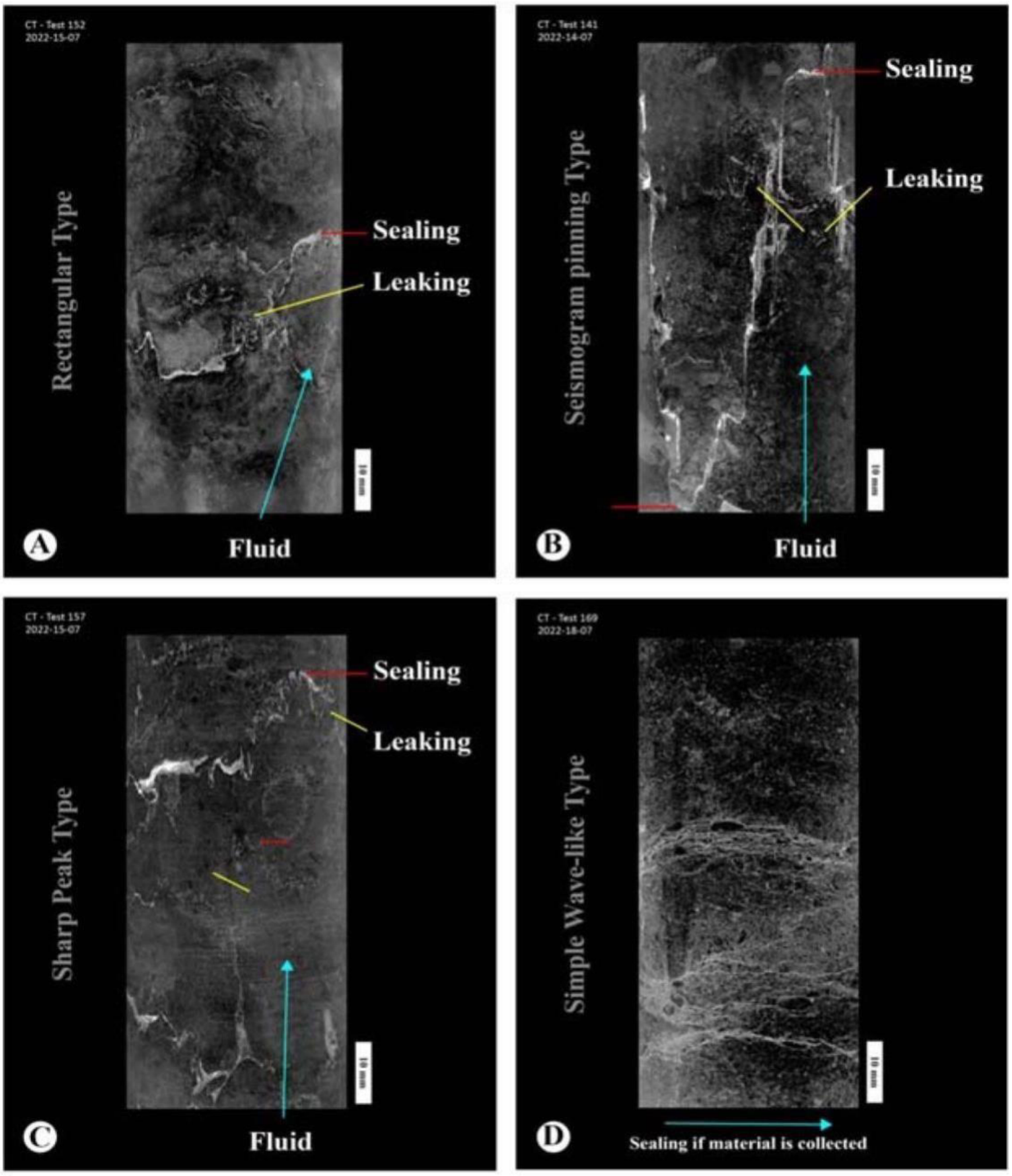


Figure 7 Stylolite type detection using CT-Scan image of some sample (Nikbin et al., 2023)

In some reservoirs, stylolites have been found to significantly hinder production, necessitating the development of specialized techniques to manage their effects (Koehn et al., 2020). In others, the enhanced porosity associated with stylolites has been leveraged to improve recovery rates (Koehn et al., 2020). For instance, in the Middle East and North Sea, stylolite-related secondary porosity has been a critical factor in the high productivity of certain carbonate reservoirs (Beaudoin et al., 2021).

In summary, stylolites play a dual role in the petroleum industry, offering both challenges and opportunities. Their ability to act as barriers to fluid flow can complicate extraction, while their potential to create secondary porosity can enhance reservoir quality. A thorough understanding of the distribution and characteristics of stylolites is essential for developing effective extraction strategies, ultimately leading to more efficient and profitable hydrocarbon recovery.

### 1.3 Stylolite classification

Stylolites can be classified based on various characteristics such as their morphology, orientation, and the geological processes that lead to their formation (Renard and Fossen, 2010; Koehn et al., 2016; Koehn et al., 2020; Fig. 5).

- Rectangular Stylolites
- Seismogram Pinning Stylolites
- Suture and Sharp Stylolites
- Peak Simple Wave-Like Stylolites

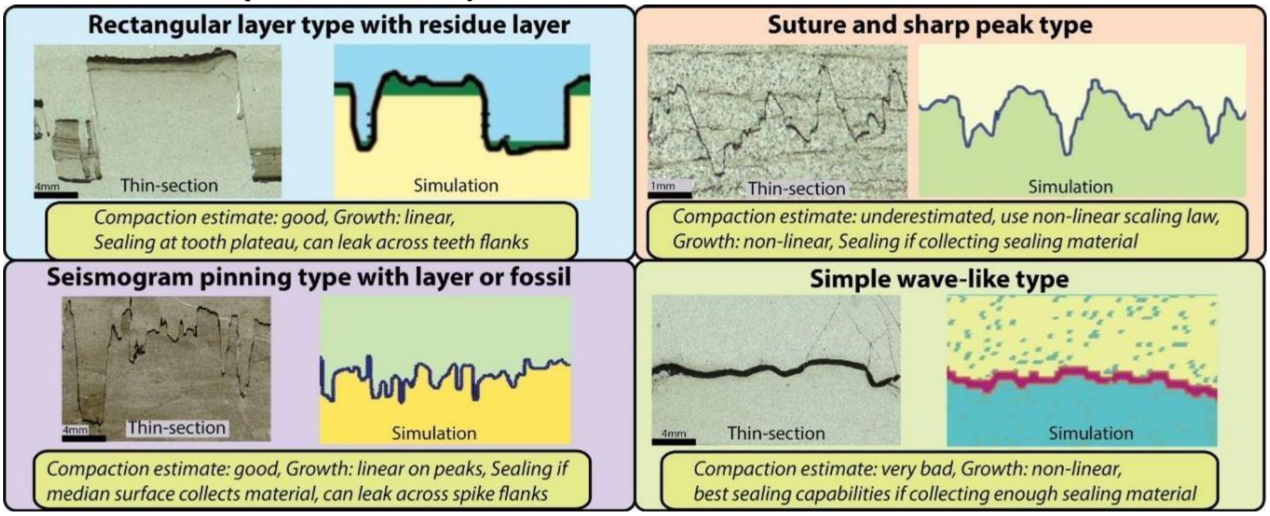


Figure 8 Comparison of real-world examples and computer simulations of the four suggested types of stylolites provides insights into their ability to predict compaction and their impact on local sealing (Sourced from Koehn et al., 2016).

Rectangular stylolites are characterized by a more angular or boxy shape compared to other stylolite types (Renard and Fossen, 2010; Koehn et al., 2016; Koehn et al., 2020). They typically appear as sharp-edged, straight-line features within the rock matrix. This morphology often suggests that the stress field during their formation was relatively uniform and consistent, leading to a more regular pattern of pressure dissolution along bedding planes or within the rock fabric (Renard and Fossen, 2010; Koehn et al., 2016).

Seismogram pinning stylolites refer to stylolites that exhibit a pattern resembling seismogram readings, with peaks and troughs that appear similar to seismic waves on a graph. This classification emphasizes the wavy or undulating nature of the stylolite surface, which can indicate variations in stress intensity and direction during its formation. Seismogram pinning stylolites are typically found in rocks subjected to complex stress regimes, where the stress direction changes over time (Koehn et al., 2016).

Suture and sharp stylolites are characterized by their jagged or serrated appearance, resembling interlocking teeth or a suture line. These stylolites often have irregular edges that fit together like puzzle pieces. They form under conditions of significant differential stress, where pressure dissolution occurs along multiple intersecting planes within the rock. The sharp edges and complex geometry of suture and sharp stylolites reflect the dynamic stress history and the mechanical interactions between mineral grains or beds (Koehn et al., 2016).

Peak simple wave-like stylolites exhibit a repetitive pattern of peaks and troughs along their surface, resembling a sine wave or simple waveform. This classification emphasizes the regularity and periodicity of the stylolite morphology, suggesting a consistent stress regime with periodic variations in stress intensity. Peak simple wave-like stylolites are indicative of rhythmic pressure dissolution processes within the rock, often associated with cyclic changes in stress or fluid flow conditions (Koehn et al., 2016).

## 1.4 Stylolite classification and permeability

Rectangular stylolites demonstrate highly variable local permeability, featuring barriers at the tips of their teeth that restrict fluid flow, while potential leaks along the flanks of these teeth can allow for fluid migration. However, seismogram pinning stylolites present a complex impact on permeability. Larger teeth within this category can disrupt original seals, while the median surfaces may accumulate sealing materials, potentially influencing fluid flow dynamics (Park and Schot, 1968; Koehn et al., 2016).

Stylolites classified as suture and sharp pose significant barriers to fluid flow due to their jagged and interlocking morphology, which hinders permeability by creating extensive sealing contacts. Moreover, stylolites of the peak simple wave-like type typically display smoother surfaces and often preserve the original layer material, thereby effectively blocking fluid flow due to their uniformity and sealing properties (Park and Schot, 1968; Koehn et al., 2016).

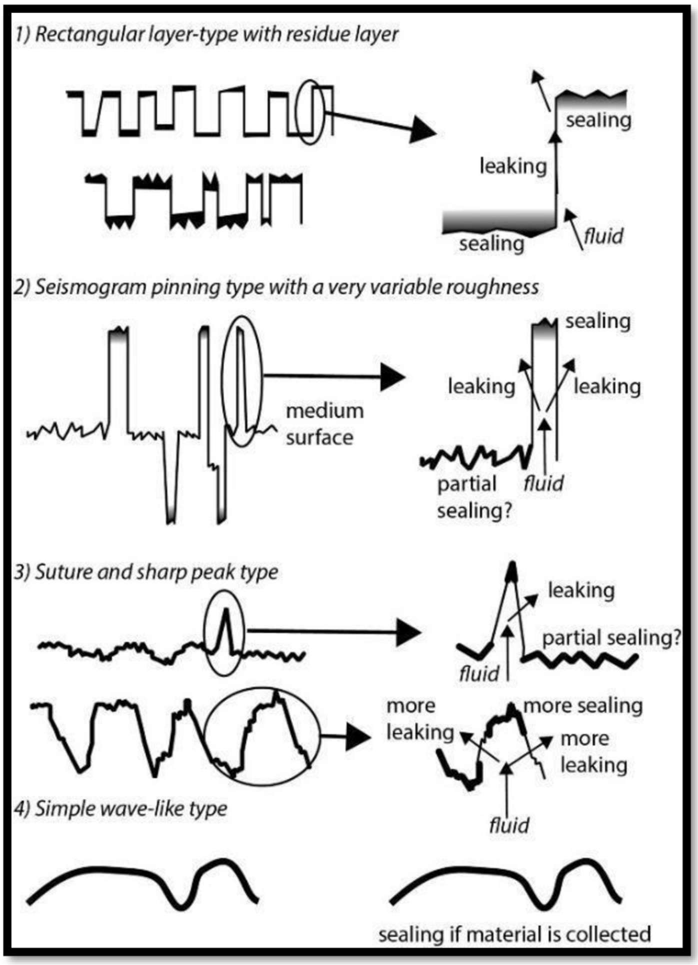


Figure 9 A new classification introduced by Park and Schot (1968) distinguishes four types of stylolites: 1) rectangular layer type, 2) seismogram pinning type, 3) suture and sharp peak type, and 4) simple wavelike type. The left side illustrates the shapes of these stylolites based on numerical simulations, while the right side depicts the local variability in permeability across the different types, assuming that collected material acts as a seal. Rectangular layer type stylolites disrupt seals along their flanks, creating leakage paths, while the tops and bottoms of their teeth act as barriers. Seismogram pinning type stylolites also disrupt seals, potentially collecting sealing material on median surfaces but may leak along steep teeth. Suture and sharp peak type stylolites can collect sealing material but may leak at sharp peaks and teeth due to their structural complexity. Simple wave-like type stylolites can act as effective seals if sufficient material is present or collected, lacking structures that disrupt existing seals (Sourced from Koehn et al., 2016).

Given the significant role of stylolites in hydrocarbon reservoirs, particularly in the

Middle East, this study focuses on an in-depth analysis of stylolites within the Kometan Formation in the Zagros Basin. The primary objectives of this research are to classify and quantify the types and proportions of stylolites present in the Komitan Formation, as well as to assess their impact on the reservoir properties. By examining the morphological characteristics and distribution of these stylolites, the study aims to elucidate how they influence porosity and permeability, ultimately affecting the overall quality and performance of the hydrocarbon reservoir. This investigation contributes to a better understanding of the geomechanical and petrophysical properties of the Kometan Formation, providing valuable insights for more effective reservoir management and hydrocarbon extraction strategies.

## 2. Geological setting

The Zagros basin, located in the Middle East, represents a significant geological structure renowned for its rich hydrocarbon resources and complex tectonic history. Spanning across Iran, Iraq, Turkey, and Syria, this basin is characterized by its unique structural evolution shaped by the convergence of the Arabian and Eurasian plates (Alavi, 2004; Aqrawi et al., 2010; Karim et al., 2011; Mouthereau et al., 2012).

The Kometan Formation stands out as a pivotal hydrocarbon reservoir in the Kurdistan region of Iraq, characterized by its geological complexity, stratigraphic importance, and favorable reservoir properties (Fig. 10). Continued research and exploration efforts in this formation are essential for unlocking its full hydrocarbon potential and sustaining the region's energy resources into the future (Aqrawi et al., 2010; Karim et al., 2011; Mouthereau et al., 2012) The basin's diverse geological formations, particularly its carbonate reservoirs, play a crucial role in the region's oil and gas production. The Kometan Formation (upper Turonian to lower Campanian) is primarily known from its type locality situated in Kometan Village, northeast of Ranya near Sulaimani, Kurdistan region of Iraq (Van Bellen et al., 1959; Hussain et al., 2024). This region exposes thin-bedded, white to light grey limestone characterized by globigerinid–oligosteginid composition, interspersed with chert nodules predominantly near the base and occasional layers enriched with glauconite. Extensively documented in both outcrop sections and subsurface samples across the Imbricated Zone, High Folded Zone, and Low Folded Zone of the Zagros Foreland Basin, Kurdistan Region, Iraq, its thickness ranges from 63 to 185 m (Aqrawi et al., 2010).

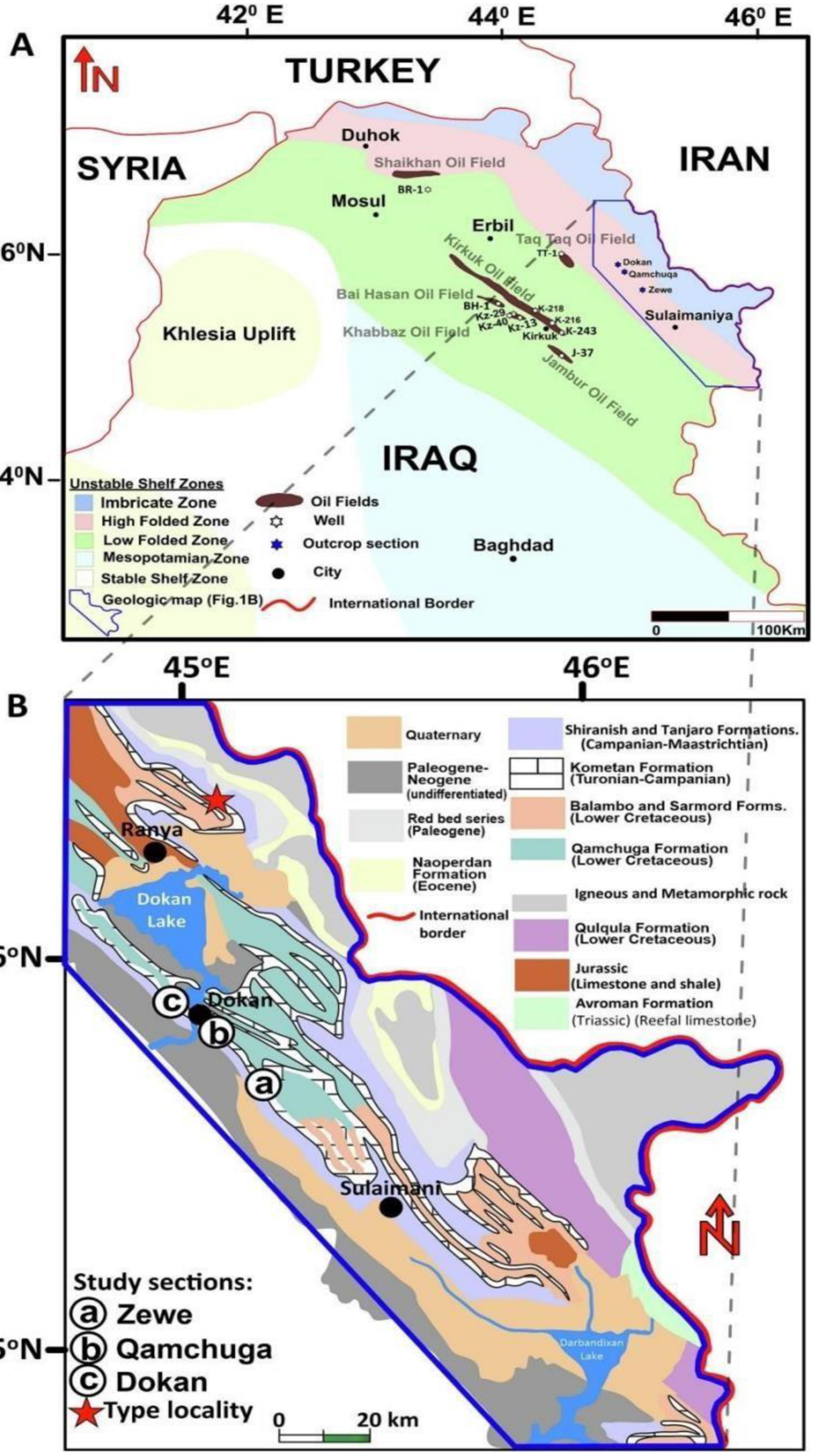


Figure 10 illustrates the geographic location and tectonic divisions of the research area according to Buday and Jassim (1987) (A), alongside a geological map depicting the surface distribution of the Kometan Formation, its type locality, and the sections studied, adapted from Sissakian (2000) and Karim et al. (2011) (B) Sourced from Hussein et al., 2024. In this study main focus is a section C.

In various parts of the basin, the Kometan Formation stratigraphically overlies the oligosteginid limestone of the Balambo Formation, as well as limestones and dolomites from the Dokan, Gulneri, and Qamchuga Formations, spanning from Early Cretaceous to Coniacian ages (Fig. 11) (Jassim and Goff, 2006). Conformably or unconformably above the Kometan Formation lie the Shiranish Formation and Tanjero Formation of Campanian to Maastrichtian age (Buday, 1980; Jassim and Goff, 2006). A distinct, glauconite-rich layer at the base of the Shiranish Formation serves as a lithostratigraphic marker bed (van Bellen et al., 1959). Across the Imbricated, High Folded, and Low Folded Zones, the Kometan Formation grades laterally into bioturbated chalky limestone, shale, marly limestone of the Khasib Formation, lagoonal shale and carbonate of the Tanuma Formation, and open shelf globigerinid limestone of the Sa'di Formation within the Mesopotamian Zone and the Stable Platform extending from central Iraq to southern Iraq (Fig. 11) (Al-Qayim, 2010).

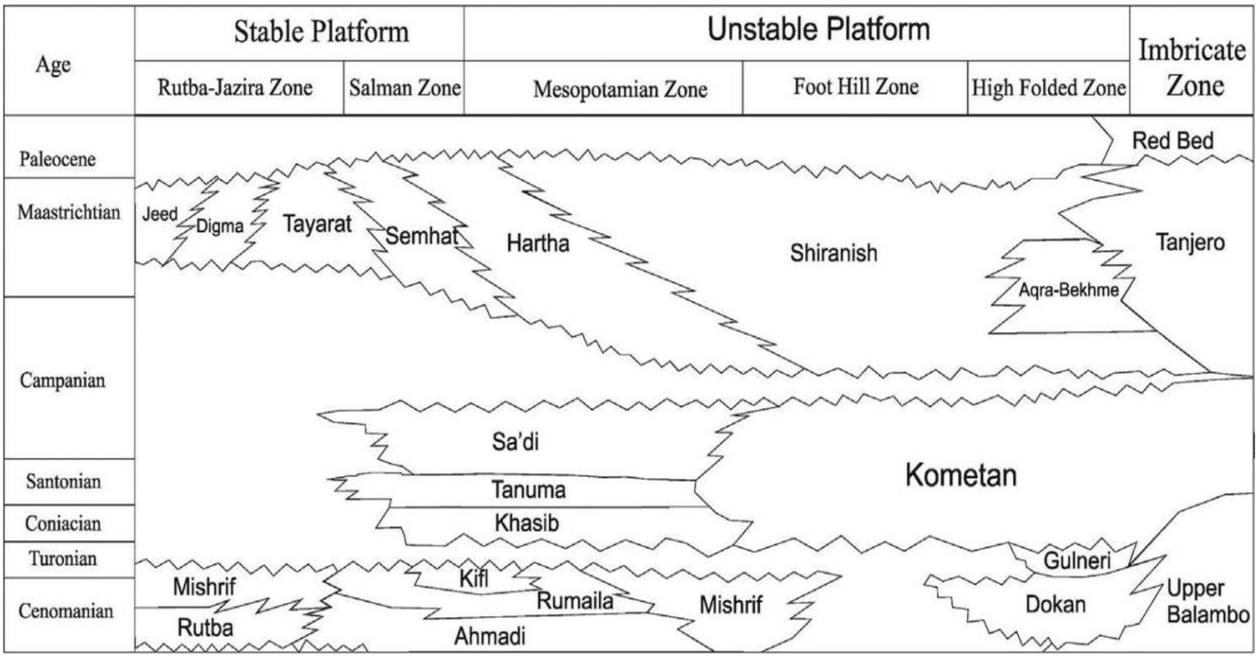

Figure 11 Chronostratigraphic division of Cretaceous rock in Iraq (Al-Qayim, 2010; Hussein et al., 2024).

# 3. Materials and Methods

## 3.1 Library Research and Literature Review

The initial phase of this study involved comprehensive library research focused on the Kometan Formation and the various types of stylolites that can be found within it. A thorough review of existing literature was undertaken to gather relevant information on the geological characteristics, depositional environment, diagenetic processes, and previous studies pertaining to the Kometan Formation. Additionally, detailed studies on the morphology, classification, and implications of stylolites in carbonate reservoirs were reviewed. This literature review provided a strong foundational understanding necessary for the subsequent field and laboratory analyses.

## 3.2 Field Sampling and Sample Collection

To investigate the stylolites within the Kometan Formation in greater detail, a specific outcrop was selected based on its representative geological features and accessibility. The chosen outcrop is located at the coordinates 35°56'36.7"N 44°58'50.2"E in the Kurdistan region of Iraq (Fig. 12). The site was selected to ensure a comprehensive representation of the formation's characteristics, including the presence and variability of stylolites.

Upon arrival at the designated outcrop, systematic sampling was conducted to obtain representative specimens from various layers of the Kometan Formation. Careful attention was paid to collecting samples that displayed distinct stylolitic features, ensuring a diverse representation of the formation's lithological and structural variations. Each sample was carefully labeled and cataloged for subsequent laboratory analysis.

Stylolites were identified based on their distinct dissolution seams and morphological features. To measure stylolite spacing, three 1 m-length vertical scanlines, with a horizontal offset of 50 cm, were created in each 1 $m^2$ sampling window. These scanlines were drawn perpendicular to stylolites to avoid orientation bias. The vertical distances between stylolites intersecting each scanline were recorded in the field using a tape measure, with vertical spacing measurements from each scanline being totaled per window. Stylolite spacing measurements were collected insitu, while other parameters, such as stylolite connection angles and intersection types, were collected from scaled window photographs.

Stylolite wavelength and amplitude measurements were collected using a single vertical scanline situated in the middle of the sampling window. All stylolites intersecting the scanline were measured. Wavelength was recorded as the horizontal distance between the nearest peakpeak or trough-trough situated on the scanline, while amplitude measurements were represented by the vertical height of a stylolite tooth on or closest to the scanline.


Figure 12 A and B Field visit and sample collection of the Kometan Formation near Dukan City.

### 3.3 Thin Section Preparation and Microscopic Imaging and Analysis

The collected samples were transported to the laboratory for preparation of thin sections. Thin section preparation involved cutting the rock samples into thin slices, mounting them on glass slides, and polishing them to a thickness of approximately 30 micrometers. This process was carried out using precision equipment to ensure high-quality sections suitable for microscopic examination. The thin sections provided a detailed view of the mineralogical and textural characteristics of the samples, essential for analyzing the stylolites.

Microscopic analysis was performed on the prepared thin sections using a polarized light. These imaging techniques enabled high-resolution visualization of the stylolites and the surrounding matrix. The morphology, orientation, and mineralogical composition of the stylolites were meticulously documented. Additionally, to determine the types and properties of the pores within the samples, epoxy resin was injected into the samples. This technique involves infusing the samples with epoxy resin, which infiltrates the pore spaces and solidifies, making the pores more visible under microscopic examination. This approach enhances the visualization of the pore structures and provides crucial insights into the porosity and permeability characteristics of the samples.

### 3.4 Data Analysis and Interpretation and Synthesis

The microscopic images and observations were analyzed to classify the different types of stylolites present within the Kometan Formation. The classification was based on established morphological criteria, including shape, orientation, and the nature of the dissolved and residual materials. Additionally, the potential impact of stylolites on porosity and permeability was assessed, considering their role as barriers or conduits for fluid flow within the reservoir. The data obtained from the field observations, thin section analyses, and microscopic imaging were synthesized to develop a comprehensive understanding of the stylolites within the Kometan Formation. The findings were interpreted in the context of the broader geological framework of the Zagros basin, with particular emphasis on the implications for hydrocarbon reservoir quality and behavior. The results were compared with existing literature to validate the observations and to draw meaningful conclusions about the role of stylolites in the Kometan Formation.

## 4. Results and discussion

### 4.1 Microscopic Observations

Microscopic studies reveal that the samples from the Kometan Formation predominantly classify as mudstone, wackestone, and packstone according to the Dunham classification system. These sedimentological characteristics indicate deposition in deep marine environments, consistent with previous findings (Hussein et al., 2024). The overall porosity in these samples is generally very low and often undetectable. However, instances of microporosity are occasionally observed within the matrix of some mudstone samples, suggesting limited primary porosity. A noteworthy finding is the significant porosity observed within the stylolites (Fig. 13A-B). Stylolites, characterized by their complex interlocking textures, appear to serve as critical pathways for fluid flow. These features, despite the generally low matrix porosity, substantially enhance the overall porosity and permeability of the formation. The intricate morphology of the stylolites creates a network of interconnected pores and channels, which likely facilitates fluid migration and accumulation.

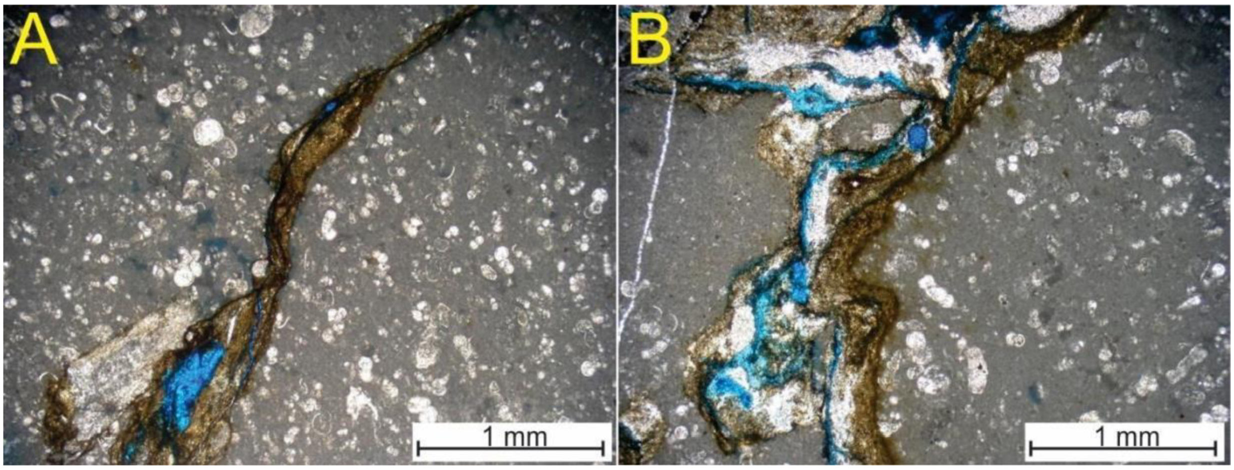


Figure13 Polarizing microscope images of the Kometan Formation illustrating (A-B) wackestone to packstone textures, and stylolites with notable porosity within the stylolite structures.

Given the role of the Kometan Formation as a reservoir rock in the Kurdistan region, it can be inferred that the numerous fractures and stylolites within this formation play a crucial role in hydrocarbon storage (Rashid et al., 2017). These structural features not only enhance secondary porosity but also significantly influence the permeability of the reservoir. The presence of stylolites can create heterogeneities within the reservoir, acting as conduits for hydrocarbon migration and accumulation. This interconnected network of stylolites and fractures likely improves the overall reservoir quality by providing additional storage spaces and pathways for fluid flow.

The implications of these findings are significant for reservoir characterization and management. The stylolites and fractures contribute to a more complex porosity and permeability distribution, which must be considered when developing reservoir models. Accurate characterization of these features is essential for predicting fluid flow behavior and optimizing hydrocarbon recovery strategies. Advanced imaging techniques and detailed petrographic analyses are necessary to quantify the impact of stylolites on reservoir properties accurately. Furthermore, the enhanced porosity within stylolites suggests that these features may serve as preferential pathways for hydrocarbon migration, potentially improving the connectivity between different parts of the reservoir. This enhanced connectivity can lead to more efficient hydrocarbon extraction, as fluids can move more freely through the stylolitic networks. However, the variability in stylolite morphology and distribution also poses challenges for reservoir modeling, as it introduces uncertainty in predicting fluid flow patterns.

### 4.2 Stylolite morphology and distribution

Stylolite populations were initially characterized through outcrop-scale measurements to define their statistical properties. The morphological properties used for this characterization included vertical spacing, amplitude, and wavelength. The analysis revealed that stylolites with a vertical spacing of 14 to 15 cm were the most prevalent, comprising 55% of the observed population. This suggests a relatively regular interval at which stylolites occur within the formation, which could indicate a consistent diagenetic process influencing their formation (Fig. 14).

Stylolites with an amplitude of 4 to 5 cm were the most common, accounting for 20% of the total (Fig. 15). The amplitude of stylolites, representing the height difference between peaks and troughs, is a crucial factor in understanding the degree of dissolution and pressure solution that has occurred (Fig. 15). Additionally, stylolites with wavelengths of 4 and 7 cm were more frequently encountered, with a cumulative frequency of 25% (Fig. 15). Wavelength, the distance between successive peaks, provides insight into the lateral extent of pressure solution seams. These statistical measurements provide a comprehensive understanding of the morphological variability of stylolites within the Kometan Formation.

Table 1 Stylolite wavelength data for Kometan Formatio

| Sample No. | Stylolite amplitude (m) | | | | | |
|---|---|---|---|---|---|---|
| 1 | 0.015 | 0.03 | 0.056m | 0.104m | | |
| 2 | 0.018m | 0.019m | 0.082m | 0.041m | 0.009m | 0.029m |
| 3 | 0.049m | 0.024m | 0.019m | 0.019m | 0.048m | 0.019m |
| 4 | 0.047m | 0.131m | 0.021m | 0.021m | 0.011m | 0.058m |
| 5 | 0.027m | 0.041m | 0.011m | 0.016m | 0.014m | 0.039m |
| 6 | 0.045m | 0.076m | 0.044m | 0.076m | 0.047m | 0.102m |
| 7 | 0.009m | 0.041m | 0.008m | 0.063m | 0.01m | |
| 8 | 0.028m | 0.033m | 0.023m | 0.008m | 0.012m | |
| 9 | 0.019m | 0.04m | | | | |
| 10 | 0.031m | 0.016m | 0.029m | 0.19m | 0.038m | |
| 11 | 0.043m | 0.022m | 0.026m | 0.062m | | |
| 12 | 0.02m | 0.012m | 0.012m | 0.085m | | |
| 13 | 0.112m | 0.009m | 0.035m | 0.058m | | |
| 14 | 0.01m | 0.106m | 0.058m | 0.01m | | |
| 15 | 0.033m | 0.012m | 0.016m | 0.021m | 0.023m | 0.034m |
| 16 | 0.029m | 0.016m | 0.028m | 0.047m | | |
| 17 | 0.015m | 0.012m | 0.039m | 0.033m | | |
| 18 | 0.043m | 0.037m | 0.01m | | | |
| 19 | 0.087m | 0.012m | 0.028m | 0.021m | | |
| 20 | 0.014m | 0.091m | 0.038m | | | |
| 21 | 0.023m | 0.083m | 0.075m | | | |
| 22 | 0.027m | 0.061m | 0.017m | | | |
| 23 | 0.036m | 0.023m | 0.011m | 0.013m | 0.016m | 0.031m |
| 24 | 0.05m | 0.055m | 0.056m | | | |
| 25 | 0.004m | 0.032m | 0.017m | 0.05m | 0.037m | 0.015m |
| 26 | 0.015m | 0.03m | 0.021m | 0.113m | 0.056m | |
| 27 | 0.029m | 0.062m | 0.022m | 0.011m | 0.026m | |
| 28 | 0.029m | 0.016m | 0.043m | 0.017m | 0.026m | |
| 29 | 0.021m | 0.077m | | | | |

|  |  |  |  |  |  |  |
|---|---|---|---|---|---|---|
| **30** | 0.05m | 0.034m |  |  |  |  |
| **31** | 0.042m | 0.036m |  |  |  |  |
| **32** | 0.027m | 0.012m | 0.03m | 0.015m |  |  |

Table 2 Stylolite amplitude data for Kometan Formation

| **Sample No.** | **Stylolite amplitude (m)** |  |  |  |  |  |
|---|---|---|---|---|---|---|
| **1** | 0.01m | 0.016m | 0.054m | 0.019m |  |  |
| **2** | 0.016m | 0.01m | 0.026m | 0.013m | 0.009m | 0.009m |
| **3** | 0.024m | 0.021m | 0.014m | 0.013m | 0.033m | 0.011m |
| **4** | 0.011m | 0.026m | 0.007m | 0.006m | 0.018m | 0.015m |
| **5** | 0.013m | 0.019m | 0.007m | 0.02m | 0.007m | 0.009m |
| **6** | 0.014m | 0.039m | 0.008m | 0.014m | 0.041m | 0.015m |
| **7** | 0.008m | 0.013m | 0.008m | 0.017m | 0.021m |  |
| **8** | 0.009m | 0.011m | 0.023m | 0.006m | 0.008m |  |
| **9** | 0.012m | 0.014m |  |  |  |  |
| **10** | 0.01m | 0.01m | 0.031m | 0.012m | 0.04m |  |
| **11** | 0.023m | 0.011m | 0.009m | 0.012m |  |  |
| **12** | 0.018m | 0.014m | 0.011m | 0.024m |  |  |
| **13** | 0.035m | 0.007m | 0.014m | 0.03m |  |  |
| **14** | 0.009m | 0.015m | 0.039m | 0.006m |  |  |
| **15** | 0.017m | 0.011m | 0.013m | 0.011m | 0.011m | 0.031m |
| **16** | 0.016m | 0.008m | 0.012m | 0.01m |  |  |
| **17** | 0.013m | 0.009m | 0.016m | 0.018m |  |  |
| **18** | 0.025m | 0.021m | 0.009m |  |  |  |

| | | | | | | |
|---|---|---|---|---|---|---|
| **19** | 0.016m | 0.011m | 0.009m | 0.012m | | |
| **20** | 0.014m | 0.027m | 0.013m | | | |
| **21** | 0.016m | 0.031m | 0.012m | | | |
| **22** | 0.013m | 0.019m | 0.013m | | | |
| **23** | 0.013m | 0.008m | 0.007m | 0.008m | 0.01m | 0.02m |
| **24** | 0.013m | 0.019m | 0.024m | | | |
| **25** | 0.008m | 0.014m | 0.008m | 0.018m | 0.025m | 0.016m |
| **26** | 0.012m | 0.014m | 0.014m | 0.029m | 0.025m | |
| **27** | 0.009m | 0.033m | 0.01m | 0.008m | 0.02m | |
| **28** | 0.018m | 0.009m | 0.02m | 0.027m | 0.015m | |
| **29** | 0.008m | 0.038m | | | | |
| **30** | 0.018m | 0.021m | | | | |
| **31** | 0.041m | 0.013m | | | | |
| **32** | 0.015m | 0.008m. | 0.01m | 0.018m | | |

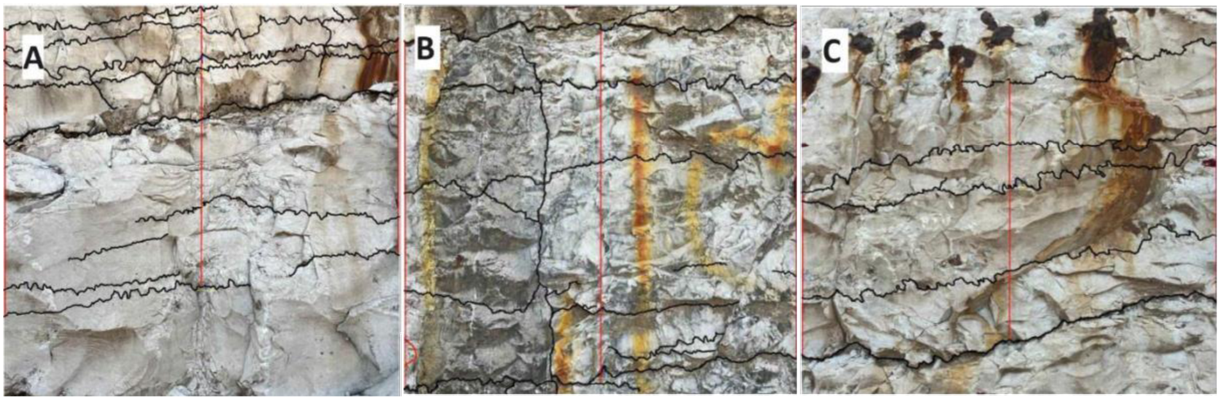


Figure 14 Stylolite Spacing Measurements Stylolite spacing measurements collected in the field (red line is 1 m).

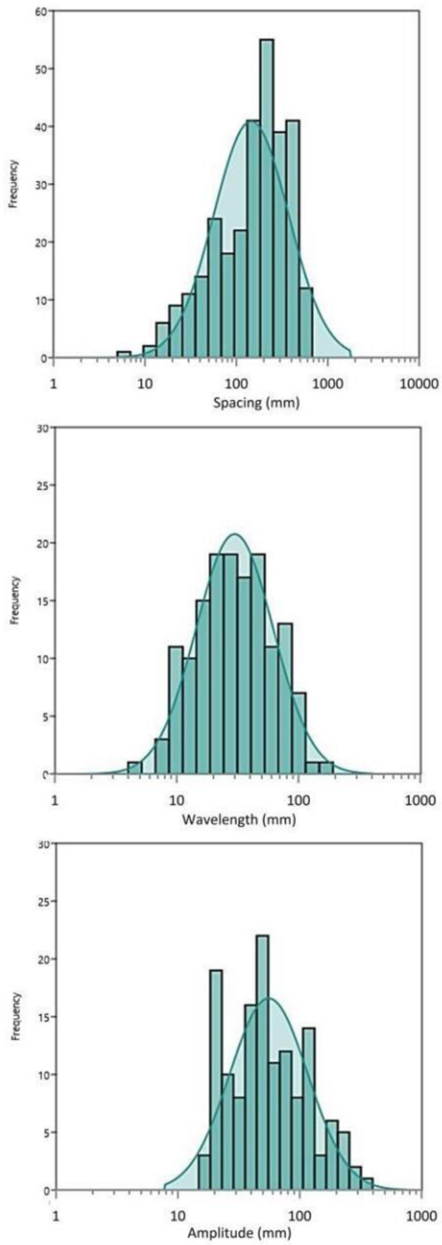

Figure 15 stylolite spacing, wavelength, and amplitude.

The characterization of stylolite morphology is essential for understanding their impact on reservoir quality. The vertical spacing, amplitude, and wavelength of stylolites can significantly influence porosity and permeability, which are critical parameters for hydrocarbon reservoirs. The vertical spacing of stylolites suggests a regular pattern that may create predictable pathways for fluid flow. Stylolites with greater amplitude can lead to increased dissolution of the surrounding rock matrix, potentially enhancing secondary porosity. However, they can also act as barriers if the dissolution residues, such as clay minerals, fill the pore spaces. The wavelengths of stylolites indicate the extent of their lateral continuity. Stylolites with shorter wavelengths may create more localized barriers or conduits, affecting the heterogeneity of the reservoir. In contrast, longer wavelengths could result in more extensive pressure solution seams that might act as continuous barriers or flow pathways.The high frequency of stylolites with specific vertical spacing, amplitude, and wavelength within the Kometan Formation suggests that these features are a significant component of the reservoir rock. Understanding their distribution and morphological characteristics can help predict zones of enhanced porosity and permeability, aiding in the identification of sweet spots within the reservoir. Comparing these results with other formations can provide further insights into the diagenetic processes that have shaped the Kometan Formation. For instance, formations with less frequent or smaller amplitude stylolites may exhibit different reservoir properties, highlighting the unique geological history of the Kometan Formation. The statistical characterization of stylolite populations within the Kometan Formation reveals significant variability in their morphological properties, which has important implications for reservoir characterization.

### 4.3 The main stylolite types in the Kometan Formation

A variety of stylolite measurements were performed across different lithofacies within the Kometan Formation to characterize stylolite network morphologies. The analysis of the stylolites in the Komitan Formation reveals that the most recognizable types are seismogram pinning, suture and sharp-type, and peak simple wave-like. These classifications are based on the distinct morphologies and characteristics observed during microscopic and field studies (Fig. 16).

- Seismogram Pinning Stylolites: These stylolites are characterized by their large, serrated teeth that resemble the peaks and troughs of a seismogram (Koehn et al., 2016). Their morphology suggests a complex history of stress and pressure dissolution, which could influence the fluid flow properties within the reservoir (Koehn et al., 2016).
- Suture and Sharp-Type Stylolites: These stylolites display jagged, interlocking teeth that resemble sutures (Koehn et al., 2016). This type is indicative of significant compaction and dissolution processes, potentially creating substantial barriers to fluid flow while also affecting the structural integrity of the rock (Koehn et al., 2016).
- Peak Simple Wave-Like Stylolites: Characterized by smoother, wave-like undulations, these stylolites are less jagged and often retain original layer material. They typically indicate a less aggressive dissolution process compared to the other types, but they still play a crucial role in the porosity and permeability of the formation (Koehn et al., 2016).

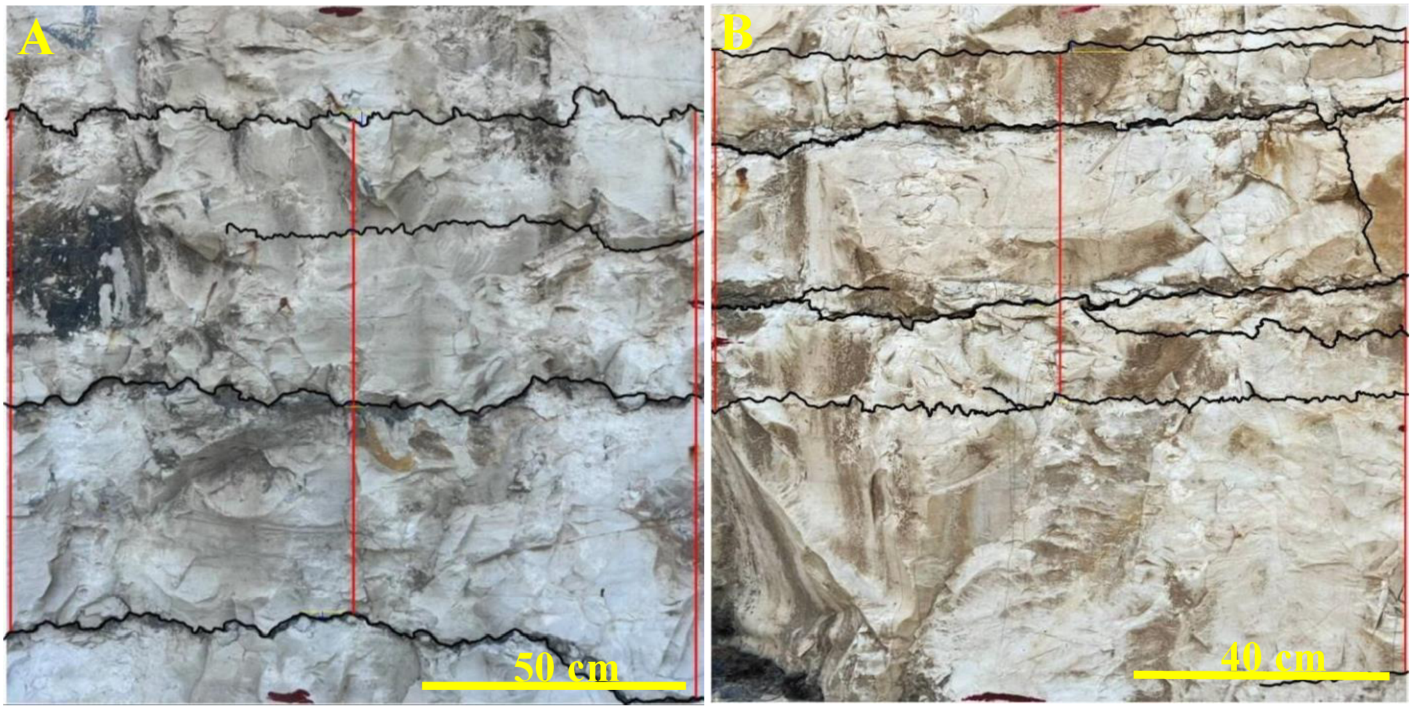


Figure 16 A and B Field photo of the Kometan Formation showing distinct stylolite types

### 4.4 Stylolite connectivity types in the Kometan Formation

In the Kometan Formation, two primary contact types between stylolites are observed: X-like and Y-like contacts (Table 3; Fig. 17 A-C). These contact types refer to the nature of the interfaces between the teeth of the stylolites and the surrounding rock matrix and are crucial for interpreting the geological history and fluid dynamics of the rock formations (Park and Schot, 1968; Railsback, 1993; Nelson, 2001).

Table 3 Number and type of contacts of stylolites in Kometan Formation

| Sample No. | X type | Y type | Sample No. | X type | Y type |
|---|---|---|---|---|---|
| **1** | 0 | 1 | **17** | 0 | 0 |
| **2** | 0 | 2 | **18** | 0 | 0 |
| **3** | 0 | 1 | **19** | 0 | 2 |
| **4** | 0 | 1 | **20** | 1 | 0 |
| **5** | 0 | 1 | **21** | 0 | 1 |

| | | | | | |
|---|---|---|---|---|---|
| **6** | 1 | 1 | **22** | 0 | 0 |
| **7** | 0 | 1 | **23** | 0 | 0 |
| **8** | 0 | 0 | **24** | 0 | 1 |
| **9** | 0 | 1 | **25** | 0 | 0 |
| **10** | 0 | 2 | **26** | 0 | 0 |
| **11** | 0 | 0 | **27** | 0 | 1 |
| **12** | 0 | 1 | **28** | 0 | 0 |
| **13** | 0 | 0 | **29** | 1 | 1 |
| **14** | 0 | 2 | **30** | 0 | 0 |
| **15** | 0 | 0 | **31** | 0 | 3 |
| **16** | 0 | 0 | **32** | 0 | 1 |

X-like contacts are characterized by smooth, planar surfaces that often form parallel to the primary bedding planes of the rock (Nelson, 2001). These contacts typically develop under uniform stress conditions, where the dissolution process is evenly distributed along the bedding planes (Nelson, 2001). This type of contact suggests minimal differential stress across the stylolite interface, indicating a relatively stable diagenetic environment with consistent pressure and minimal tectonic disturbance. Consequently, X-like contacts usually show less permeability contrast compared to more jagged stylolite types (Park and Schot, 1968; Railsback, 1993; Nelson, 2001).

In contrast, Y-like contacts are more irregular and serrated, with interlocking teeth that can penetrate into the rock matrix, exhibiting a more complex morphology compared to X-like contacts (Park and Schot, 1968). Y-like contacts form under differential stress conditions, where pressure dissolution is more localized (Park and Schot, 1968). The interlocking nature of these contacts indicates that stress was not evenly distributed, leading to more aggressive dissolution at specific points (Park and Schot, 1968; Railsback, 1993). Y-like contacts are often associated with significant tectonic activity and stress variations. They can act as both barriers and conduits for fluid flow, depending on the degree of dissolution and the nature of the residual material. These contacts can enhance porosity and permeability in specific zones but may also create strong barriers in others (Nelson, 2001).


Figure 17 Stylolite Connectivity Stylolite connectivity analysis showing intersection angles and dimensions (A and C are Y types and B is a X type).

Understanding X and Y contact types in stylolites is vital for several reasons. The type of contact affects the porosity and permeability of the rock (Nelson, 2001). Y-like contacts, with their complex morphologies, can create heterogeneities in the reservoir that influence fluid flow and storage (Nelson, 2001). Additionally, the nature of the contacts provides insights into the diagenetic and tectonic history of the rock. X-like contacts suggest a relatively stable diagenetic environment, while Y-like contacts indicate more dynamic stress conditions. The permeability barriers created by these contacts can significantly impact hydrocarbon migration and entrapment, and understanding these barriers helps in developing more accurate models for reservoir simulation and management (Railsback, 1993; Nelson, 2001).

In terms of the prevalence of these contact types within the Kometan Formation, most stylolite contacts are of the Y-like type. Table 1 shows that out of a total of 32 square meters of the Kometan Formation, 24 were Y-like contacts, while only 3 were X-like contacts. This distribution indicates a dominant influence of differential stress conditions and tectonic activity in the formation's history, which has significant implications for the reservoir properties and hydrocarbon potential of the Kometan Formation.

## Conclusions

The investigation of the stylolites in the Kometan Formation reveals significant insights into their characteristics and potential impact on reservoir properties. The study identifies that the stylolites in the Kometan Formation predominantly fall into three categories: seismogram pinning stylolites, suture and sharp-type stylolites, and peak simple wave-like stylolites. Analysis of microscopic sections from the formation samples indicates that the rock is primarily composed of wackestone and mudstone, exhibiting very low porosity and permeability. Contrastingly, the stylolites themselves demonstrate notably high porosity and permeability. A key observation from this study is that the most common type of connectivity within these stylolites is of the Ylike type, which is closely linked to the tectonic activities in the Zagros basin. This specific connectivity pattern suggests that the tectonic processes have a significant influence on the development and characteristics of the stylolites.

Overall, the findings underscore the critical role that stylolites, alongside fractures, play in enhancing the reservoir properties of the Kometan Formation. The high porosity and permeability within the stylolites contribute to improved fluid flow and storage capacity, which are essential factors for the effectiveness of hydrocarbon reservoirs. This study highlights the importance of considering both stylolites and fractures in reservoir evaluation and development strategies, as they collectively enhance the potential for hydrocarbon extraction in the Kometan Formation.

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