

Review

Natural Fracturing in Marine Shales: From Qualitative to Quantitative Approaches

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Abstract

Natural fractures in marine shales are crucial storage spaces and migration pathways for oil and gas, making the study of their formation mechanisms and distribution patterns essential for hydrocarbon exploration and development. This review systematically evaluates the progress in natural fracture studies, transitioning from qualitative to quantitative approaches, with a focus on the genetic mechanisms, distribution patterns, and methodological advancements of fracture types. The review finds that: (1) Integrated “geological-geophysical-dynamic” analyses significantly improve the prediction accuracy of tectonic fracture networks compared to traditional stress-field models. Bedding-parallel fracture development is primarily controlled by the interplay between diagenetic evolution and in situ stress, with their critical opening conditions now being quantifiable; (2) Crucially, the application of micro-scale in situ techniques (e.g., Laser Ablation Inductively Coupled PlasmaMass Spectrometer, laser C-O isotope analysis, carbonate U-Pb dating) has successfully decoded the geochemical signatures and absolute timing of fracture fillings, revealing multiple episodes of fluid activity directly tied to hydrocarbon migration. (3) The combined application of multiple techniques holds promise for deepening the understanding of the coupling mechanisms between fractures. The combined application of these techniques provides a robust framework for deciphering the coupling mechanisms between fracture dynamic evolution and hydrocarbon migration, offering critical insights for future exploration.

Keywords: natural fractures; genetic mechanisms; tectonic fractures; bedding-parallel fractures; geochemistry; isotopic dating



Academic Editors: Ruyue Wang,
Jianhua He, Andrew D. La Croix,
Jim Underschultz, Hucheng Deng,
Hao Xu and Rui Liu

Received: 24 August 2025

Revised: 7 September 2025

Accepted: 10 September 2025

Published: 4 January 2026

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1. Introduction

In hydrocarbon-bearing reservoirs, natural fractures can provide flow pathways and storage space for oil and gas, while also playing a critical role in connecting hydraulic fractures, matrix pores, and wellbores [1–7]. Therefore, their formation mechanisms and distribution patterns understanding for hydrocarbon exploration and development is crucial. Investigating the formation mechanisms and distribution patterns of natural fractures is of great significance for assessing the distribution of hydrocarbon sweet spots and has the potential to help optimize drilling and completion costs [3,8–11]. The types of natural fractures developed in marine shales are controlled by different geological processes. For instance, regional tectonic activity primarily can form tectonic fractures,

while hydrocarbon generation results in overpressure and dissolution fractures. Early studies mostly focused on the developmental characteristics, fine characterization, and controlling factors of natural fractures but lacked quantitative research [12–15]. In recent years, with advancements in experimental techniques, scholars have been able to accurately reveal the timing and genetic mechanisms of fracture formation through geochemical and geochronological studies of fluids within filled natural fractures [16–19].

Fluids, act as the dominant factor in energy redistribution within hydrocarbon-bearing basins, providing critical insights into the tectonic, sedimentary, and diagenetic processes of marine shales [20–22]. Deep to ultra-deep hydrocarbon reservoirs generally exist under high confining pressure conditions, where early-stage fractures are mostly closed or filled, making it difficult for fluid ingress. Tectonic activity and hydrocarbon generation/expulsion can induce new fracture formation and reactivate pre-existing fractures, providing conduits for fluid migration and leading to the formation of fracture fills [23,24]. Therefore, investigating fluid circulation within shales is significant for revealing the formation mechanisms of natural fractures.

Fracture cements are direct products of fluid circulation. Their study can be used to trace the source, origin, and evolutionary stages of fluids within shales [25–27], thereby elucidating the formation mechanisms and evolutionary history of natural fractures. However, multi-phase tectonic activity complicates fluid flow, and cements often record characteristics of overprinting by multiple fluid events, with their geochemical signatures frequently representing a mixture from these activities [28]. Consequently, determining the timing of fluid activity remains a major challenge. Previous studies primarily relied on dating concomitant products of fluid activity (such as fluid inclusions or authigenic illite) to constrain its timing [29,30]. However, these methods often struggle to fully reconstruct all fluid events that shales have experienced and are susceptible to the effects of later alteration [31,32].

In recent years, advances in micro-scale in situ analysis techniques have enabled high-precision characterization of fluid geochemistry, while breakthroughs in isotopic geochronology have propelled fluid-related research into a quantitative stage. This paper reviews the research evolution of natural fractures in marine shales by integrating methodologies from diverse disciplines including statistics, geomechanics, numerical simulation, and geochemistry.

2. The Traditional Research History of Natural Fractures

2.1. Tectonic Fractures

Research on tectonic fractures has a long history [33,34]. Previous research on tectonic fractures can be broadly divided into two main stages.

The first stage (prior to the 1980s) saw international scholars, building upon the theoretical foundations of structural geology and rock mechanics, is to analyze and study the types, genetic mechanisms, distribution patterns, and the relationships between tectonic deformation and fracture development in reservoirs. As early as the 1960s, scholars investigated the relationship between principal curvature of tectonic deformation and fracture distribution, establishing quantitative relationships between tectonic fracture porosity/permeability and tectonic deformation [35]. In 1966, the British scholar Price proposed the theory of a positive correlation between the elastic strain energy of rock and tectonic fracture density [36]. In the 1970s, with the development of fracture mechanics theory, researchers both in China and abroad intensified their studies on the mechanics, kinematics, and geometry of joints in rock [37]. In 1974, the Soviet scholar Cmexob proposed an inverse relationship between distance to a fault and the intensity of tectonic fracture development, suggesting that tectonic fracture development is essentially unaffected by

faults at distances greater than 500 m [38]. By the 1980s, scholars such as Narr proposed the Fracture Spacing Index method. This method evaluates fracture intensity by calculating the ratio of the median bed thickness to the median fracture spacing within a fractured interval. They proposed that within a certain range of bed thickness, bed thickness is positively correlated with fracture spacing, and the two exhibit a strong linear functional relationship [39].

The second stage (from the 1980s to the present) witnessed significant advancements. With progress in experimental and simulation techniques, coupled with the discovery and development of numerous fractured hydrocarbon reservoirs globally, research on reservoir tectonic fractures gained increased attention. The methodologies for studying reservoir tectonic fractures became substantially more diverse, and the research focus shifted from qualitative to quantitative approaches.

During this period, international scholars such as Crampin (1981), Scholz and Aviles (1985), Barton and Withjack (1995), Hudson (2010) [40–43], among others, conducted pioneering work and established foundational research in various areas. These included evaluating fractures using seismic data, understanding the relationships between stress/strain and fracture development, applying fractal theory to fracture characterization, and investigating the development patterns of fractures near major faults in extensional tectonic settings [40–44]. Nelson classified tectonic fractures into three genetic types based on their mechanics: dilational fractures, tensional fractures, and shear fractures [12,45].

In the early 1990s, Chinese scholars like Wang (1994) and colleagues [46], based on studies of tectonic stress fields, began employing numerical simulation methods for the quantitative prediction of tectonic fracture intensity. Concurrently, building upon the principle proposed by Price, Zhou et al. (2006) introduced the “Energy Method” [47]. This method involves calculating stress components, principal tectonic curvature, and subsequently strain energy based on the structural configuration of rock layers. The observed core fracture density is then fitted to the calculated strain energy using the least squares method to predict tectonic fracture development.

By the mid-1990s, scholars [48,49], and others, utilizing rock failure criteria, predicted zones of tectonic fracture development and their dominant orientations. In the late 1990s, Ding et al. (1998) separately employed the rock failure method and the energy method to simulate and predict fracture intensity [50]. They found the results from these two methods to be complementary and proposed a binary prediction method that utilizes both fracture potential and energy value parameters to evaluate tectonic fracture development.

Since the 21st century, scholars such as Wei et al. (2006), Shen (2008) and Shi (2008) have successfully applied tectonic stress field numerical simulation technology to predict zones of intense tectonic fracture development, achieving favorable results [51–53]. Zeng et al. (2008) adopted an integrated research approach combining geology, geophysics, and dynamic production data [54]. They systematically elucidated the genetic types, formation mechanisms, distribution characteristics, and developmental patterns of tectonic fractures in different types of low-permeability sandstone reservoirs using a multi-dimensional methodology encompassing “surface-subsurface,” “static-dynamic,” and “macro-micro” analyses.

2.2. Bedding-Parallel Fractures

Compared to tectonic fractures, research on bedding-parallel fractures is relatively limited. Studies on the controlling factors for the formation, aperture, and closure of bedding-parallel fractures have primarily focused on fracture fillings. Séjourné et al. (2005) found that cements within bedding-parallel fractures in the Appalachian region formed by infilling after the parting of weak bedding planes and utilized K/Ar isotopic values

of the fill material to trace the timing of fracture opening [55]. Swanson (2007) suggested that the development of bedding-parallel fractures in siliciclastic sandstones in southern Wisconsin is mainly controlled by tectonic stress and lithology [56]. Cobbold et al. (2013), by studying quartz, gypsum, and calcite fills in bedding-parallel fractures, concluded that their development is primarily controlled by sedimentary microfacies [57]. Matthaei et al. (1995), through a study of the Cosmopolitan Howley gold deposit in northern Australia, found that tectonic activity is also a factor in the opening of bedding-parallel fractures, with gold veins infilling them primarily derived from metamorphic and magmatic fluids [58]. Doolin et al. (2001) demonstrated the interrelationship between the aperture/closure behavior and permeability of bedding-parallel fractures through experimental modeling [59].

Wu et al. (2003) studied bedding-parallel fractures in the tight sandstones of the Upper Shaximiao Formation in the Xinchang area, western Sichuan Basin, proposing that increasing internal pressure gradients within closed compartments are a primary factor in their formation [60]. Various scholars have investigated the controlling factors and genetic characteristics of bedding-parallel fractures, suggesting that sedimentary microfacies, diagenesis, formation heterogeneity, and tectonic stress are the main factors controlling their development, with sedimentary microfacies being the foundational control. They identified abnormal overpressure, fluid dissolution, and tectonic stress as the main causes for the formation of bedding-parallel fractures [61–66]. Chang et al. (2015) studied the critical conditions for the formation of bedding-parallel fractures, proposing that the stress acting on the bedding plane must reach a critical intensity for the interface to open and de-laminate [67]. Current research methodologies for studying bedding-parallel fractures include field outcrop observation [68], core description [12], thin section analysis [9], well log identification [69], inter-well interpolation [70], curvature analysis [71], energy and rock failure (binary) methods [72], seismic techniques [73], fractal dimension analysis [74], and tectonic stress field modeling [75]. Although recent research has begun to focus on elucidating the mechanisms of aperture and closure (evolving from the analysis of controlling factors), it largely remains within the realm of qualitative study and has not yet fully transitioned to a quantitative paradigm.

3. Advances in Fracture Timing Analysis

The acoustic emission (AE) technique can effectively reveal the characteristics of paleo-tectonic stresses experienced by rocks. Dense, brittle rocks within formations, subjected to paleo-tectonic stresses, exhibit a stress memory effect [76–78]. Under the influence of tectonic stress fields, subsurface rocks commonly develop micro-fractures ranging from microscopic to concealed scales. When the applied stress reaches the intensity threshold of the paleo-stress field, the propagation of these micro-fractures triggers an abrupt change in the AE response (both in frequency and intensity); the stress value at this point corresponds to the paleo-stress field intensity. Therefore, by counting the number of Kaiser effect points (manifested as a sharp step-like increase) in the AE experimental curve, the minimum number of stress events and their intensities experienced by the rock can be determined. It is important to note that although these Kaiser effect points appear in a step-like sequence, their adjacent order does not necessarily indicate the chronological sequence of the stress events.

Generally, Kaiser effect points can reveal fracture phases. Taking the Permian Lucaogou Formation in the Jimsar Sag of the Junggar Basin as an example, AE curves from core samples commonly show three Kaiser effect points (Figure 1), indicating three distinct tectonic fracture formation events in this area [79]. Figure 1a–h present the test results of samples from the Jimsar Lucaogou Formation. The vertical coordinate represents the acoustic emission vibration frequency, while the horizontal coordinate indicates the pressur-

ization time. The vertical coordinate of the inset illustrates the signal intensity at different pressurization times. The varying signal strengths may reflect the differences in geostress experienced at a certain node during geological history. Each Kaiser effect point exhibits a certain range of stress field intensity, suggesting that the fractures (or micro-fractures) corresponding to these three Kaiser effect points were all products of tectonic activity. However, four fracture sets can be observed on some cores, which might be attributed to two coupled fracture sets generated by a single tectonic phase.

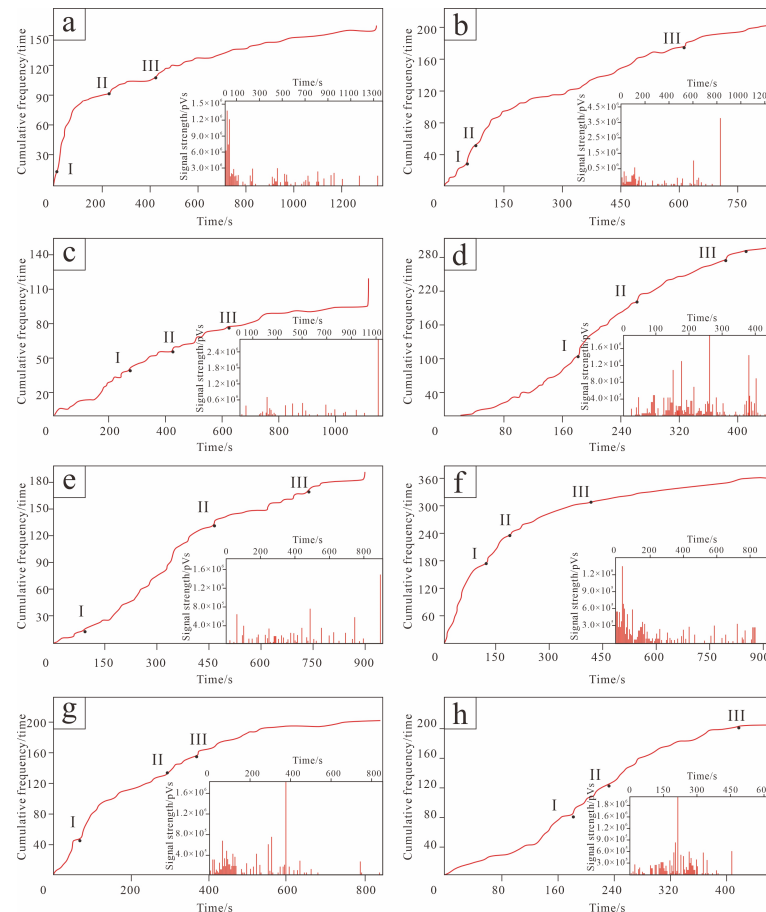


Figure 1. Acoustic emission (AE) curve (a–h) of rocks from the Lucaogou Formation in Jimsar Sag, Junggar Basin [79]. I, II, III represent the points of the Kaiser effect that occur during the acoustic emission experiment.

Meanwhile, the development of discrete fracture network (DFN) research, as well as the use of scanning lines and scanning areas, and virtual outcrop methods, have also provided a very important approach for natural fracture research [80–82]. For an example, in the study of Midland Basin, natural fractures predicted by the DFN model were validated by comparison to fractures identified from core and image logs from two horizontal wells and one slant well in the HFTS-1 project area [83].

4. Advances in Geochemical Analysis of Fracture Cements

4.1. Traditional “Bulk Rock” Analysis

Fracture cements, as direct products of fluid activity, record crucial information such as fluid properties and the timing of activity [1,27,84,85]. Shales typically undergo multiphase tectonic events, coupled with multistage sedimentary-diagenetic processes and hydrocarbon generation/expulsion, thereby resulting in fluids of markedly diverse origins and complex nature. Based on their origin, fluids within shales can be classified into two major

types: internal fluids and external fluids [86]. Internal fluids include diagenetic fluids, hydrocarbon-bearing fluids, and formation water [87,88], while external fluids comprise meteoric water and deep-seated hydrothermal fluids [89,90]. Different geological events give rise to distinct types of fluid activity; for instance, diagenetic fluids are associated with sedimentary-diagenetic processes (compaction-pressure solution and mineral dehydration), hydrocarbon-bearing fluids are linked to the generation and expulsion of hydrocarbons from source rocks, and deep fluid activity is related to tectonic-thermal events [91–95].

Cements precipitated from different types of fluid activity often exhibit significant differences in cathodoluminescence (CL) characteristics, trace element composition, and C-O and Sr isotopic signatures (Figure 2) [96–99]. Elements such as Fe and Mn, which are sensitive to redox conditions, control the color of cathodoluminescence [97]. Rare earth elements (REEs) are highly sensitive to changes in the aqueous media of the formation environment; cements formed by different fluid types thus display distinct REE distribution patterns, as well as variations in Ce/Ce* and Eu/Eu* ratios [100]. The C-O and Sr isotope systems provide key tracers for identifying fluid source regions, enabling accurate determination of fluid provenance [101–103].

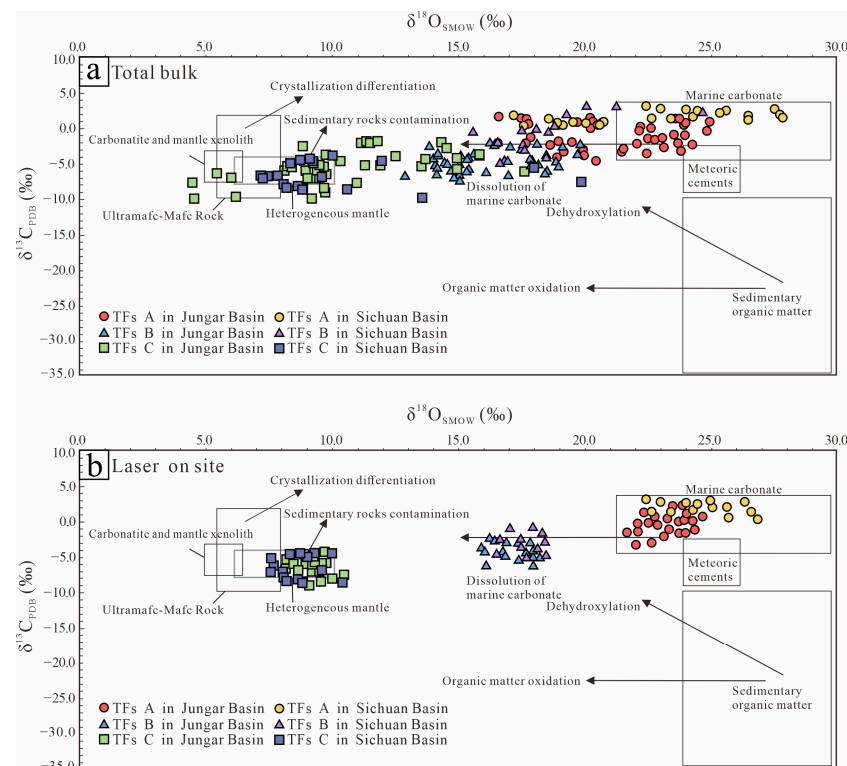


Figure 2. Cross-plot of $\delta^{13}\text{C}$ - $\delta^{18}\text{O}$ isotopes of structural fracture cements in the Lucaogou Formation of Jimsar Sag, Junggar Basin and the Ediacaran Dengying Formation of Gaoshiti-Moxi area, Sichuan Basin (TF: Tectonic fracture). The SMOW indicator standard is standard average seawater, while the PDB indicator standard is the American planktonic foraminifera. (a) Whole-rock method (data from [79,104]); (b) Laser in situ method (Unpublished data).

Traditional methods primarily rely on the “bulk-rock” approach to analyze the trace and rare earth element contents [105], as well as the C-O and Sr isotopic compositions of fracture cements [106,107]. However, due to overprinting by multiple fluid events, the results from such analyses often show significant scatter. For example, the Permian Lucaogou Formation in the Jimsar Sag of the Junggar Basin has experienced multiple phases of tectonic movement, diagenesis, and hydrocarbon generation and expulsion since the Paleozoic, resulting in the formation of abundant tectonic and bedding-parallel

fractures [99]. While calcite cements from different fracture phases often show distinct cathodoluminescence characteristics, their bulk rock C-O-Nd isotopic compositions typically exhibit a broad range of values [108]. Similarly, the Ediacaran Dengying Formation in the Gaoshiti-Moxi area of the Sichuan Basin has undergone complex tectonic movements during the Caledonian, Hercynian, Indosinian, Yanshanian, and Himalayan orogenies, leading to multiple fracture generations. Nonetheless, the bulk rock C-O-Sr-Nd isotopic compositions of dolomite cements from different fracture phases also commonly display wide ranges [109] (Figure 3). These findings indicate that the “bulk rock” method is often inadequate for effectively identifying and distinguishing between multiple fluid events (Figures 2a and 3a).

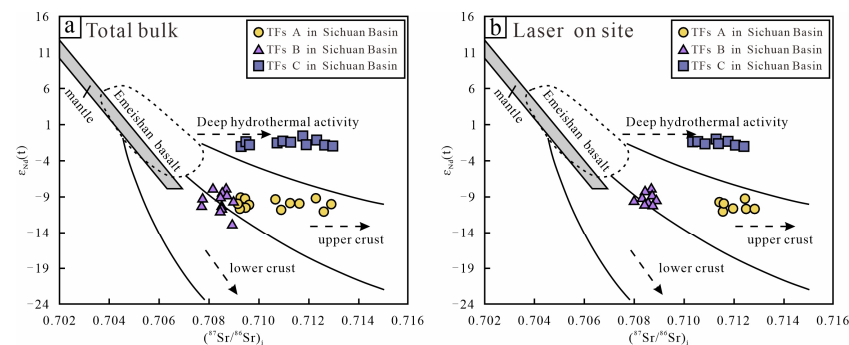


Figure 3. Cross-plot of Sr-Nd isotopes for structural fracture cements in the Sichuan Basin (TF: Tectonic fracture). (a) Whole-rock method (data from [104]); (b) Laser in situ method (Unpublished data).

4.2. High-Precision Micro-Area In Situ Geochemical Analysis

In recent years, breakthroughs in micro-analytical techniques such as Laser Ablation Inductively Coupled Plasma Mass Spectrometry (LA-ICP-MS) have enabled high-precision in situ microanalysis of trace elements (including REEs) and isotopes, significantly improving the accuracy of fluid activity analysis [110–112]. The LA-ICP-MS in situ micro-analytical method for minerals offers several advantages, including a simple sample preparation workflow, relatively low instrument acquisition and analysis costs, short analysis time, low detection limits, multi-element surface analysis ($<5 \mu\text{m}$), and a near-non-destructive nature [113]. In addition to single-point in situ analysis, it can also perform two-dimensional or three-dimensional elemental or isotopic mapping. Currently, numerous laboratories and research institutions worldwide have successfully applied this method for in situ microanalysis of trace elements in minerals [112,114,115]. Similarly, Laser Ablation Multi-Collector Inductively Coupled Plasma Mass Spectrometry (LA-MC-ICP-MS) allows for in situ microanalysis of Sr isotopes in minerals [116–118], while the Sensitive High-Resolution Ion Microprobe (SHRIMP) enables in situ microanalysis of C-O isotopes [119–122]. With the advancement of these analytical techniques, research in fluid geochemistry has entered a more microscopic and precise stage.

Taking fracture cement samples from different phases in the Permian Lucaogou Formation of the Jimsar Sag, Junggar Basin, and the Ediacaran Dengying Formation of the Gaoshiti-Moxi area, Sichuan Basin, in situ micro-analytical C-O isotopic measurements were conducted on the fracture cements using a Delta V isotope mass spectrometer coupled with a laser C-O fusion system. Strontium (Sr) isotope ratio analysis was performed on the fracture cement minerals using a Multi-Collector Inductively Coupled Plasma Mass Spectrometer (MC-ICP-MS) equipped with a 193 nm laser ablation (LA) system. Neodymium (Nd) isotope ratio analysis was conducted on adjacent spots of the same fracture cement minerals using an MC-ICP-MS equipped with a 343 nm femtosecond laser ablation (fs-LA) system. The results show that all isotopic measurements exhibit relatively homogeneous

value ranges compared to those obtained by the bulk rock method. This advancement confirms that micro-analytical techniques can effectively resolve the overprinting characteristics of multi-phase fluids (Figures 2b and 3b).

5. Advances in Fracture Geochronology Analysis

5.1. Fluid Inclusion Methodology

Under the premise of combining with other dating techniques, the fluid inclusion technique is one of the most commonly used methods for determining the temperature and composition of fluid events [123–129]. Fluid inclusions within minerals record information such as the pressure-temperature (P-T) conditions [130–133]. By measuring the homogenization temperatures (T_h) of fluid inclusions within cement minerals, combined with inclusion petrography and compositional analysis, and subsequently comparing these data with the basin's burial and thermal history, the timing and phases of fluid activity can be determined [3,134–137]. However, this method often struggles to fully reconstruct all fluid events that shales have experienced and can be subject to multiple interpretations, particularly in shales with complex tectonic histories. The same homogenization temperature might correspond to different geological ages, and the accuracy of the method is highly dependent on the precise reconstruction of the sedimentary burial and thermal history [32,138,139]. Typical case studies show that homogenization temperatures $> 100\text{ }^{\circ}\text{C}$ in the Lucaogou Formation of the Jimsar Sag correspond to three distinct fluid events (Figure 4), while temperatures $> 160\text{ }^{\circ}\text{C}$ in the Dengying Formation of the Gaoshiti-Moxi area are associated with two events (Figure 5). This ambiguity illustrates the limitation of the fluid inclusion method in effectively reconstructing the complete history of fluid events in shales.

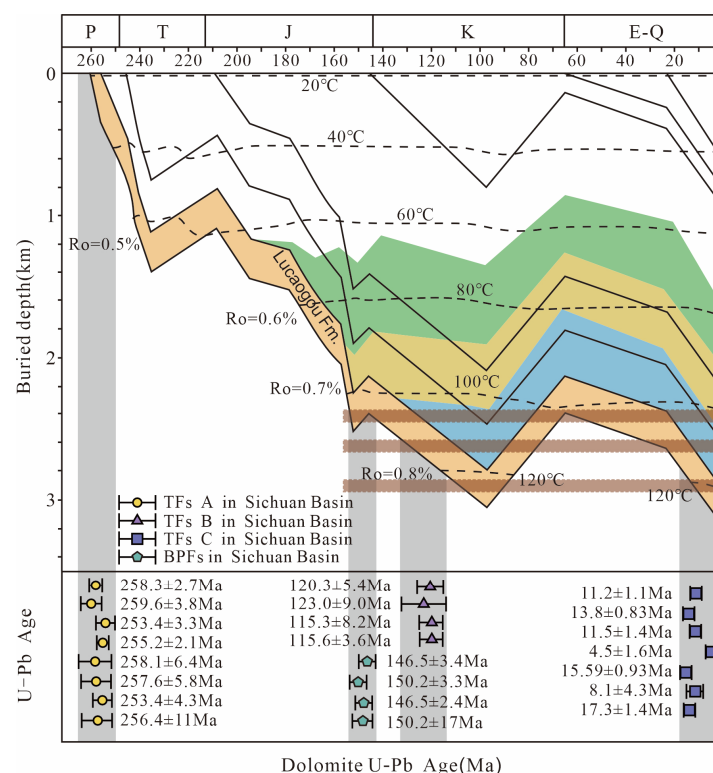


Figure 4. Burial history of the Lucaogou Formation in the Jimsar Sag, Junggar Basin (from [79,104,140]) (TF: Tectonic fracture; BPF: bedding-parallel fracture). The red horizontal bars in the figure indicate that the homogenization temperatures of similar inclusions may originate from different times. P: Permian; T: Triassic; J: Jurassic; K: Cretaceous; E-Q: Paleogene-Quaternary. Ro: the reflectance of vitrinite.

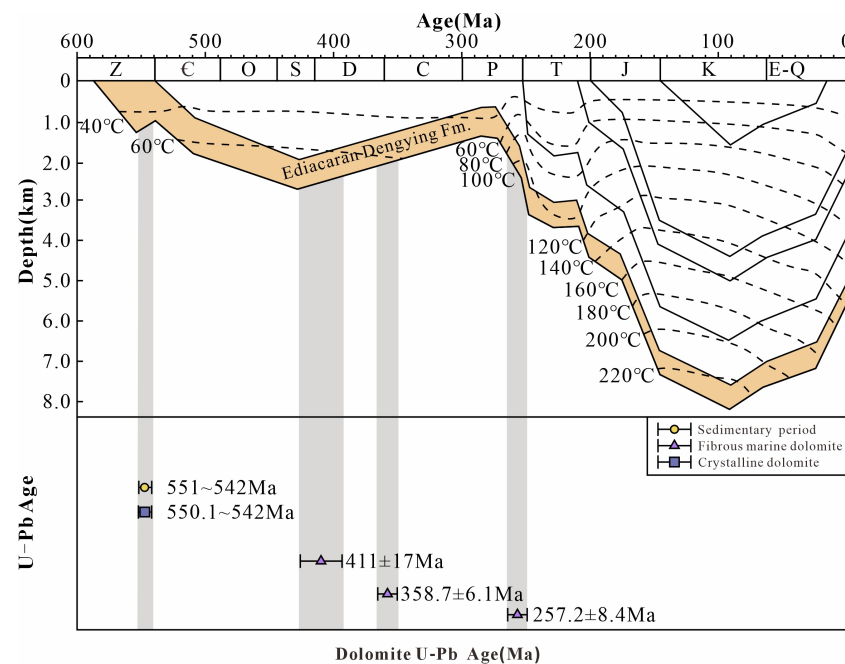


Figure 5. Burial history of the Dengying Formation in the Gaoshiti-Moxi area (from [104]).

5.2. K-Ar and Ar-Ar Dating

K-Ar or Ar-Ar dating of authigenic illite provides an indirect analytical approach for determining the timing of fluid activity in reservoirs [141–144]. The successful application of this method is highly dependent on the purity and grain size of the separated authigenic illite minerals. Reliable results are typically obtained from fine-grained ($<0.3\ \mu\text{m}$) authigenic illite samples [145–149]. However, in shales with complex tectonic histories, authigenic minerals are susceptible to later alteration, which can compromise the closure of the K and Ar isotopic systems and lead to unreliable or skewed dating results [31].

5.3. Isotope Dilution Methods

Isotope dilution methods, specifically Rb-Sr, Sm-Nd, and U-Pb dating of authigenic calcite, were among the early techniques used for analyzing the timing of fluid activity [17,150–155]. The successful application of this method requires that the dated samples be products of a single fluid event and that there is significant variation in isotopic ratios (e.g., $^{87}\text{Rb}/^{86}\text{Sr}$, $^{147}\text{Sm}/^{144}\text{Nd}$, $^{238}\text{U}/^{206}\text{Pb}$) between different samples. However, this method suffers from a relatively low success rate and involves complex sample preparation, including thin sectioning, micro-drilling, chemical dissolution, and mass spectrometric measurement. Furthermore, it imposes high requirements on the isotopic content and ratios of the dating samples [156,157]. For instance, its application has proven challenging in studies of carbonate-hosted hydrothermal fluids. This is because basin fluid activity is often multi-phase, and the calcite samples targeted for dating frequently represent products of multiple fluid events, compromising the fundamental assumption of a single, closed system [158].

5.4. Carbonate U-Pb Dating

In situ carbonate U-Pb dating via laser ablation is an emerging high-precision geochronological method [159,160]. This technique involves selecting analytical domains within carbonate cements in the target sample (Figure 6A). Through thin-section observation and cathodoluminescence (CL) imaging (Figure 6B), phases of fluid activity are delineated. LA-ICP-MS elemental mapping (Figure 6C) is then employed to identify the distribution characteristics of U and Pb within the mineral. Areas with high U and low Pb

content are selected for subsequent LA-ICP-MS U-Pb isotopic analysis to obtain isochron ages. This method overcomes the limitations inherent in traditional approaches such as fluid inclusion studies, K-Ar/Ar-Ar dating, and isotope dilution methods. It eliminates the need for complex chemical separation and purification prior to analysis, significantly simplifying sample preparation. Furthermore, it enables in situ, high-spatial-resolution (down to $\sim 50\ \mu\text{m}$) dating, substantially lowering the required thresholds for isotopic concentrations. This technique holds broad application potential in shales with complex fluid histories, and numerous successful applications have already been reported both domestically and internationally [25,97,114].

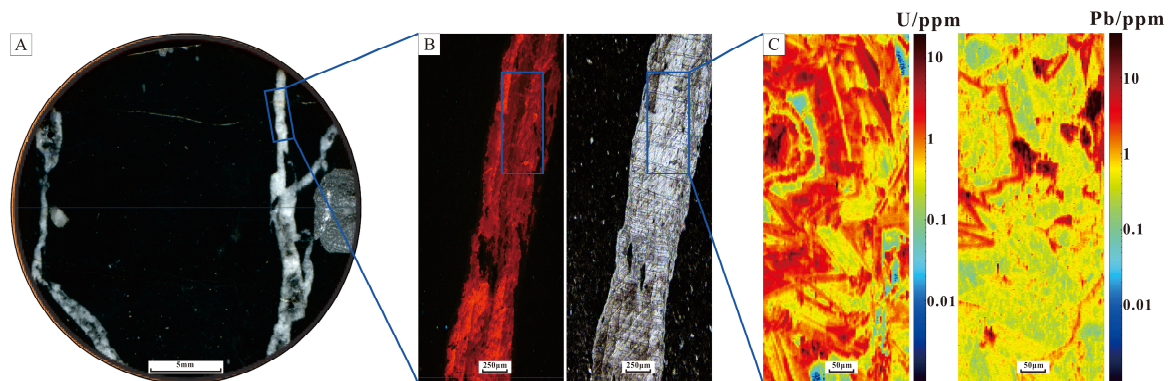


Figure 6. Workflow for selecting test points during LA-ICP-MS U-Pb dating of carbonate cements. (A) Target sample of carbonate cement; (B) Cathodoluminescence (CL) and transmitted light images of carbonate cement; (C) Two-dimensional distribution maps of U and Pb elements in carbonate cement. The target sample, CL/transmitted light images, and elemental distribution maps are all from unpublished data.

Therefore, we have formulated a methodological framework for investigating the genetic mechanisms of natural fractures in marine shale. Firstly, based on fracture system characterization and geomechanical analysis, fracture types are identified, controlling factors are analyzed, and the spatial distribution of fractures is quantified and predicted. Subsequently, geochemical analysis of fracture fillings is conducted to determine the phases of fluid activity associated with the fractures, as well as the properties (temperature, salinity), sources, and evolution of the fluids. Finally, absolute geochronological dating is employed to provide absolute age constraints for fracture formation and fluid activity, establishing a precise chronological sequence. Through this approach, the genetic mechanisms and evolutionary history of natural fractures in the study area are comprehensively elucidated [161–167].

6. Conclusions

This paper systematically reviews the advances and challenges in quantitative research on natural fractures within marine shales. The main conclusions are as follows:

- (1) **Evolution of Research Methods:** The quantitative evolution of tectonic fracture research—from theoretical models based on structural curvature and elastic strain energy to numerical stress field simulations—has significantly improved the efficiency of fracture prediction and the accuracy of distribution patterns. The integration of geomechanics and fractal theory has enhanced the clarity and applicability of fracture characterization. For bedding-parallel fractures, the adoption of cement geochemistry and critical stress analysis has elucidated the synergistic interactions among sedimentary microfacies, tectonic stress, and fluid activity, contributing to a more systematic and mechanistically transparent understanding. However, research in this

area remains largely qualitative, particularly regarding the dynamic mechanisms of fracture aperture and closure, limiting current practical applicability.

- (2) **Technological Breakthroughs:** Advances in micro-scale in situ analytical techniques (e.g., LA-ICP-MS, femtosecond laser ablation) allow high-precision spatial resolution of trace elements and isotopes within fracture cements. These methods reduce ambiguity in fluid interpretation and provide clearer geochemical fingerprints compared to traditional approaches. Similarly, carbonate U-Pb dating offers more reliable geochronological constraints on fluid events.
- (3) **Identification of Multi-phase Fractures:** The application of the rock acoustic emission (Kaiser) effect combined with stress-field reconstruction has made it possible to efficiently identify multi-phase fracture events. Coupling these with geochemical and geochronological data provides explicit insights into the spatiotemporal relationships among tectonic events, hydrocarbon generation/expulsion, and fracture development, greatly improving interpretive clarity.
- (4) **Current Challenges and Future Outlook:** Despite progress, key challenges remain, including the difficulty in distinguishing overlapping multi-phase fluid events and the limited capacity for dynamic simulation of fracture behavior. Future work should focus on integrating artificial intelligence, multi-scale numerical simulations, and 4D modeling to achieve quantitative permeability characterization and predictive accuracy of fracture networks. Further research into the cross-scale coupling of fractures, fluids, and hydrocarbon migration will be critical to supporting practical applications in deep and ultra-deep exploration.

In summary, research on natural fractures is transitioning from static description to dynamic quantification, driven by interdisciplinary integration and technological innovation. These developments are steadily enhancing the practical applicability, interpretive clarity, and efficiency of fracture analysis in shale systems.

Funding: This study was financially supported by the National Natural Science Foundation of China (Nos. 92255302, U20B6001).

Data Availability Statement: We declare that data is contained within the article. The original contributions presented in this study are included in the article.

Acknowledgments: The authors thank all the editors and reviewers for their valuable suggestions on this review.

Conflicts of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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