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REVIEW ARTICLE

A Critical Review of Tectonic Effect on the Nanopore Structure Evolution of Shale Gas Reservoirs

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Abstract

Nanopores in shale are critical controls on shale gas storage and transport, and their formation, transformation, and preservation during geological evolution have long been major research topics in unconventional oil and gas geology. Considerable progress has been made in understanding the evolution of shale nanopore structures during sedimentation, diagenesis, and hydrocarbon generation from organic matter. However, the modification of shale nanopores by tectonic stress and the underlying mechanisms remain insufficiently understood. Organic-rich shale formations in South China commonly serve as regionally important detachment layers and have undergone multiple phases of tectonic activity involving diverse deformation mechanisms. Repeated and intense modification of their primary structures has resulted in exploration risks associated with low $in-situ$ gas contents and complex preservation conditions. This study systematically analyzes the multiscale structural deformation of shale during tectonic deformation and investigates the intrinsic relationships and mechanisms linking tectonic deformation to the evolution of shale nanopore structures. Physical simulation experiments for shale deformation and experimental techniques for the high-resolution characterization of shale nanopore structures are also reviewed. The findings provide a scientific basis for marine shale gas exploration in tectonically complex areas surrounding the Sichuan Basin.

Keywords: tectonic deformation, organic-rich shale, shale gas, nanopore structure.

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1 Introduction

Over the past three decades, organic-rich shale has rapidly emerged as one of the most important targets for global unconventional oil and gas exploration, accompanied by explosive growth in shale oil and gas production [1–3]. The discovery of nanopore systems with pore diameters of less than 1 μm in unconventional hydrocarbon reservoirs has challenged the traditional view that micrometer-scale pores constitute the lower limit of microscopic reservoir space and has extended the recognized pore-size range of conventional petroleum reservoirs [4]. The structural characteristics of shale nanopores and their roles in the storage, transport, and accumulation of continuously distributed hydrocarbons have consequently become major research focuses and frontiers in petroleum geoscience [5–7]. In China, substantial breakthroughs in shale gas exploration and development have been achieved in marine shale formations within tectonically stable and weakly deformed areas of the Sichuan Basin [8–10]. Exploration has also been actively pursued in strongly tectonically modified areas outside the basin, but with limited success, highlighting the complexity of shale gas accumulation and preservation under conditions of multistage tectonic evolution, intense deformation, and extensive structural modification [8, 9]. Previous studies have demonstrated that the complex tectonic setting of South China exerts a major influence on the gas-bearing properties of marine shale reservoirs [9]. However, the specific mechanisms by which tectonic deformation modifies reservoir structures and causes anomalous shale gas-bearing characteristics remain a major bottleneck in shale gas exploration.

In recent years, marine shale gas exploration and research have focused primarily on the Sichuan Basin and its surrounding areas [9–13], with substantial advances achieved in nanopore systems, fracture networks, reservoir properties, gas-bearing characteristics, preservation conditions, and enrichment mechanisms. Although the Sichuan Basin and its periphery share fundamental geological conditions for shale gas accumulation with those of North America, they also exhibit several distinctive features. First, these successions have undergone superimposed modification by multiple tectonic events, including the Caledonian, Indosinian, Yanshanian, and Himalayan orogenies, resulting in stratigraphic uplift and erosion, folding, fault dissection, and severe disruption of formation-pressure systems [14–17]. Second, the Wufeng–Longmaxi source-rock succession serves not only as the principal target for shale gas exploration but also as an important regional detachment layer in the tectonic framework of South China [18–20]. Compressional and shear deformation coexist within the succession, together with both brittle and ductile deformation dominated by these stress regimes. Multistage bedding-parallel slip and tectonic activity have promoted the anomalous development of interconnected fracture networks in the high-quality source rocks of the lower interval [18], thereby facilitating active lateral migration of shale gas. Third, under the combined influence of multistage tectonic evolution, uplift, and erosion, tectonic setting and preservation conditions constitute the primary controls on shale gas enrichment and accumulation [22]. Advances in nanoscale analytical techniques, such as AFM-IR spectroscopy, have further enabled direct characterization of the mineralogical and organic structural responses of shale to such tectonic and diagenetic controls [21]. Through the joint efforts of research institutions and industrial organizations, a series of theories, technologies, and methods adapted to the geological characteristics of South China have been developed for marine shale gas exploration [8–10].

As mechanically weak intervals, shale successions are susceptible to bedding-parallel slip of varying intensity depending on the applied stress and deformation environment [18], resulting in different degrees of structural deformation. Tectonic deformation, particularly compressional and shear deformation, can substantially modify shale architecture, organic–mineral structures, nanopore systems, fracture networks, and the associated reservoir properties and gas-bearing characteristics, thereby severely constraining shale gas occurrence and enrichment [12–15]. Meanwhile, variations in shale mineral composition, organic matter content and type, and thermal maturity, together with structural heterogeneity and diverse secondary alteration processes, further complicate the dynamic evolution of shale reservoir structures during tectonic deformation [19, 20].

Previous studies have generally emphasized the overall controls of deformation stages, structural styles, roof and floor conditions, fault scale, uplift, and erosion on shale gas preservation and enrichment [8–10], while paying insufficient attention to the constraints imposed by tectonic stress on the evolution of shale structures at the micro- and nanoscale, particularly the modification of shale nanopore systems. As an important external geological factor, tectonic deformation can: (1) directly modify pre-existing sedimentary and thermogenic organic–mineral structures and pore systems [12–15]; (2) indirectly alter the pore-supporting framework of organic matter and mineral grains through their directional rearrangement and structural reorganization, thereby generating tectonically induced pores [16–18]; and (3) induce pronounced adsorption and desorption responses of shale gas through changes in tectonic stress [17]. Because shale gas reservoirs are continuous accumulations, such stress-induced responses can affect sustained gas supply and continuous accumulation, resulting in dynamic changes in the modes of shale gas occurrence.

Marine shale successions in South China have undergone superimposed modification by multiple tectonic events and are characterized by diverse structural styles and complex geological architectures, making it difficult to evaluate the conditions controlling shale gas enrichment and preservation. The intense deformation and extensive structural modification of these shale successions indicate that tectonic processes are a key control on the distribution and enrichment of shale gas reservoirs and represent a core scientific challenge for marine shale gas exploration in the structurally complex regions of South China. Accordingly, this study systematically analyzes the multiscale structural deformation occurring within shale during tectonic deformation and investigates the intrinsic relationships and mechanisms linking tectonic deformation to the evolution of shale nanopore structures. Physical simulation experiments used to investigate shale succession deformation and experimental methods for the high-resolution characterization of shale nanopore structures are also reviewed. The results provide new evidence for understanding shale gas accumulation systems and contribute to the further development of shale gas enrichment theory. They also improve the accuracy of shale reservoir evaluation and provide a scientific basis for marine shale gas exploration in structurally complex areas surrounding the Sichuan Basin.

2 Coupling Mechanism Between Deformation of Organic-rich Soft Rocks and Hydrocarbon Occurrence

Since the 1970s, the concept and research framework of tectonically deformed coal have gradually been established [23–26]. Studies have shown that organic-rich rocks at shallow crustal levels readily develop into various types of tectonically deformed rocks with distinct structural characteristics under different stress–strain regimes and tectonic stresses [27–31]. As distinctive dual-porosity reservoirs comprising both pores and fractures, coal seams commonly undergo complex brittle, brittle–ductile, and ductile deformation, together with varying degrees of dynamic metamorphism [24–26], during subsequent tectonic modification. These processes alter not only the nanopore and fracture systems, optical fabrics, and macromolecular structures of coal, but also their physical properties, gas-bearing characteristics, and mechanical strength [24, 25]. Coal and shale are both organic-rich, mechanically weak rocks with broadly similar material properties. Therefore, studies of structural deformation and nanostructural evolution in coal provide valuable insights for understanding comparable processes in shale. In recent years, increasing attention has also been directed toward shale deformation and rheological behavior in shallow sedimentary successions [27, 28]. Rheological deformation may induce nanoscale grain sliding or aggregation, thereby substantially modifying nanoscale gas-bearing structures in shale, including clay nanolayers, organic–clay nanocomposites, and nanopores, and producing pronounced nanostructural effects [17, 30]. The following reviews the current state of research in China and elsewhere on the structural deformation of organic-rich, mechanically weak rocks at shallow crustal levels and its relationship with gaseous energy-resource accumulation.

Shale and coal seams are widely distributed at shallow levels of the upper crust, where they serve as both important tectonic horizons, particularly detachment layers, and major gas-bearing reservoirs [24–28]. They are therefore of considerable theoretical significance for understanding crustal deformation and of substantial practical importance for unconventional resource exploration. From a structural-geological perspective, shale and coal are mechanically weak media characterized by low Young's modulus, high Poisson's ratio, and abundant fluids [28]. Their mechanical response is further sensitive to fluid-induced effects; for example, CO_2 phase fluctuations within the pore network can induce topological damage that paradoxically enhances bulk rock strength [31]. They are highly sensitive to metamorphic and deformational conditions, including temperature, pressure, and tectonic stress, and exhibit pronounced plasticity and flow behavior.

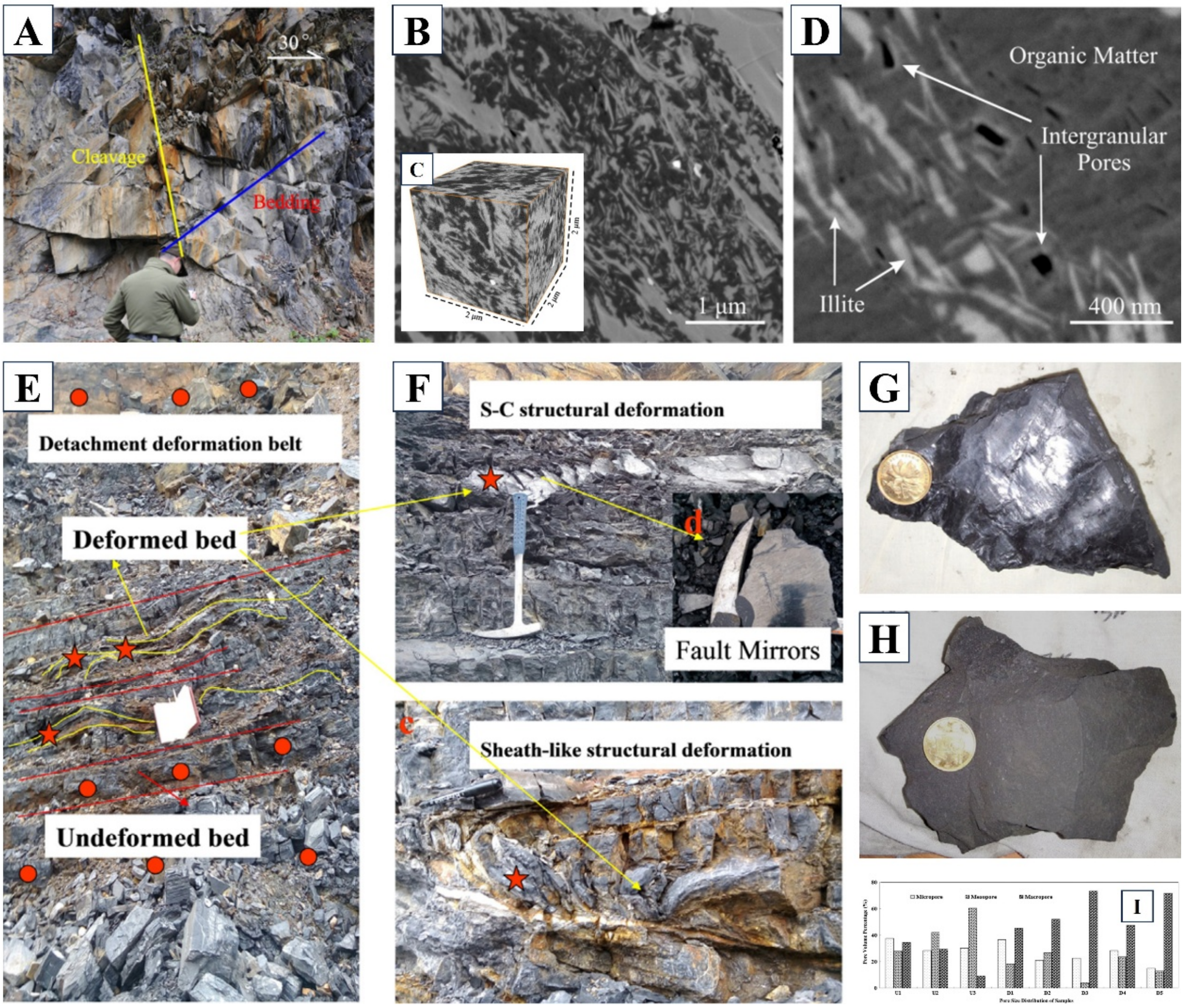

Figure 1. (A) Outcrop of the Lujiaping Shale near the C1 well, showing the stratification and cleavages. (B) Backscattered electron (BSE) images of the Lujiaping Shale showing the organic and inorganic particles. (C) 3-D reconstruction of shale volume from sequential backscattered electron (BSE) images showing the directionally arranged clay minerals filled with organic matter particles. (D) Backscattered electron (BSE) images of the Lujiaping Shale showing the intergranular nanopores between the organic and inorganic particles. Figs. A-D are modified from Ma et al. [14]. (E): The stratigraphic relationships and structural deformation characteristics of the shale samples, (F): Images showing the S-C structural deformation shale, sheath-like structural deformation shale, and fault mirrors of the deformed shale. Images showing the Undeformed shale (G) and deformed shale (H) samples. (I) The pore volume percentages for shale samples. Figs. E-H are modified from Liang et al. [15].

Consequently, they commonly form detachment layers in foreland basins, passive continental margins, strike-slip basins, and compressional tectonic settings, constituting major interfaces within shallow intracontinental deformation systems [27, 28]. From an energy-geological perspective, shale and coal seams contain abundant unconventional natural gas resources.

Substantial advances have been made in understanding the evolution of shale ultrastructure, including particle assemblages and pore–fracture systems, as well as shale gas occurrence and its tectonic controls, yielding numerous important findings and new insights. In their investigation of crustal rheology and ductile shear zone dynamics, Fusseis et al. [32] characterized the microscale features of ductile shear zones and identified cataclastic flow structures formed by brittle mineral grains, including feldspar and quartz. Their results demonstrated that rock rheology involves a progressive deformation process in which localized movement of fragmented particles at the microscale develops into bulk migration and detachment at the macroscale. Ma et al. [14] identified cleavage domains and mylonitic structures composed of clay minerals intercalated with organic matter particles in the shale matrix of the Chengkou fault zone in northeastern Sichuan Basin (Figure 1). These structures contain hierarchical systems comprising nanoscale interparticle pores, interlamellar void assemblages, and interconnected pore networks (Figure 1D). Liang et al. [15] investigated the evolution of pore–fracture structures in Wufeng–Longmaxi shale within a multilevel detachment deformation zone on the western flank of the Xuefeng Mountains in southeastern Sichuan (Figure 1(E-H)) and proposed that shear stress can weaken shale anisotropy and alter the relative proportions of different pore types (Figure 1(I)). Zhu et al. [13] suggested that under high compressive stress, macropores with diameters >50 nm are susceptible to impact-induced collapse, whereas micropores with diameters $\leq$2 nm are less affected. Using an integrated focused ion beam–scanning electron microscopy–transmission electron microscopy system (FIB–SEM–TEM), Zhu et al. [12, 13, 17] identified ultrastructural assemblages, including organic–clay nanocomposites and nanospheres, within shale detachment layers in southeastern and northeastern Sichuan. Their observations provided preliminary nanoscale evidence of deformation products within shale detachment layers and their constraints on shale gas storage space. In addition, Ju et al. [23, 24] systematically examined the coupled mechanisms linking the evolution of the chemical structure and micro- to nanoscale pore–fracture systems of tectonically deformed coal with methane occurrence. Their findings demonstrate that tectonic stress is a key factor controlling the evolution of organic macromolecular and pore–fracture structures in coal and, consequently, methane occurrence.

These findings indicate that tectonic stress can substantially modify shale organic matter molecules, micro- to nanoscale particles, and pore–fracture structures, thereby reducing structural heterogeneity and improving reservoir properties. Such modifications exert profound effects on shale gas storage and transport.

3 Research Progress on Shale Deformation Experiments and Fine Evaluation of Shale Nanopores

3.1 Shale Deformation Experiment

Shale structural deformation is currently investigated through two principal approaches: analysis of natural geological samples and physical simulation experiments. The first involves direct observation of naturally deformed shale that has undergone multiple phases of tectonic deformation under geological conditions, with the aim of characterizing its structures and fabrics at different scales. Guo et al. [9] investigated detachment deformation within the basal Longmaxi Formation shale penetrated by Well JY1 on the eastern margin of the Sichuan Basin. The detachment surfaces exhibit distinct slickensides, steps, and polished friction surfaces, which, together with high-angle fractures formed during subsequent multistage tectonic events, constitute an interconnected fracture network. Based on field outcrops from Lower Paleozoic shale successions in Chongqing, Zhu et al. [18] classified bedding-parallel detachment deformation domains into compressional and gravitational types, providing important lithostratigraphic evidence for the compressional and shear deformation of shale reservoirs. Other researchers have attempted to identify tectonic products generated by shale detachment deformation to determine the principal controls on brittle and ductile deformation and their effects on shale structure [15]. These studies provide important direct evidence for shale structural deformation and its tectonic controls. However, they primarily characterize the preserved multiscale structural states of shale after tectonic deformation, whereas the deformation processes and underlying mechanisms remain insufficiently understood.

High-temperature and high-pressure deformation experiments under controlled laboratory conditions provide an important complementary approach for investigating the controls exerted by tectonic stress on the evolution of shale nanopore structures [33–35]. Numerous triaxial compression, high-temperature triaxial compression, high-temperature and high-pressure rheological, and rotary shear friction experiments have been conducted worldwide to simulate the dynamic deformation of shale and coal under complex conditions, and various rheological and failure models have been established. For example, Han et al. [36] conducted two sets of high-temperature and high-pressure rheological experiments on anthracite with loading orientations parallel and perpendicular to the bedding, revealing the response of organic macromolecular structures to applied stress. Hou et al. [37] used previously deformed coal as experimental material and developed a high-temperature and high-pressure experimental procedure involving specimen preparation, heating, confining-pressure application, and deformation. On

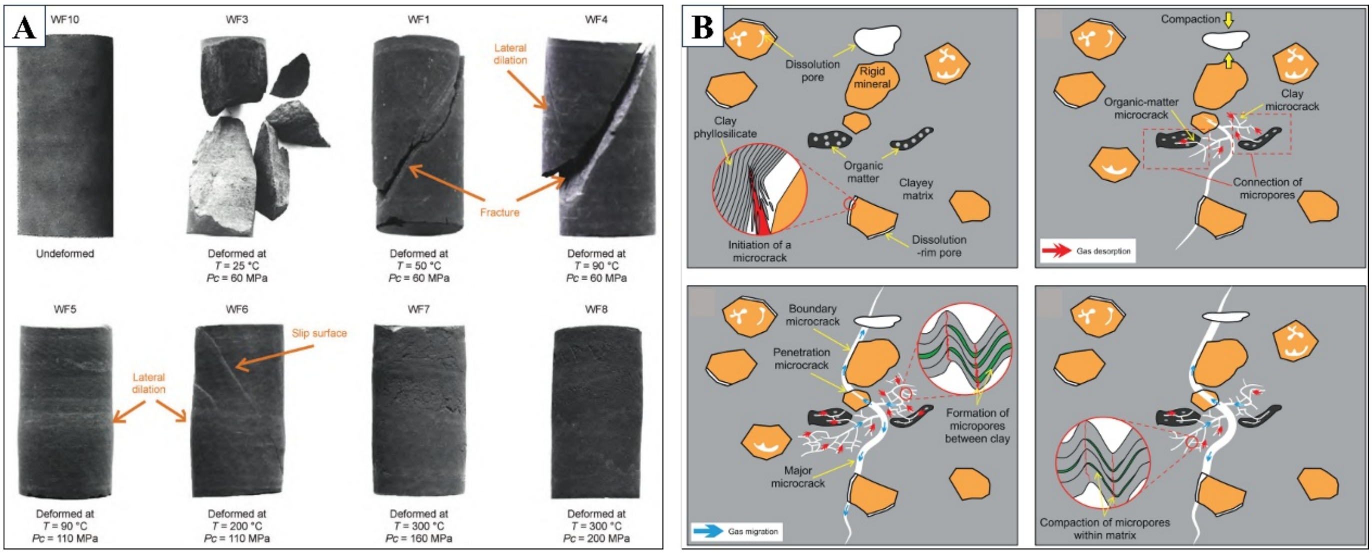

Figure 2. (A) Images of shale samples deformed after different conditions. (B) Sketch of the formation and evolution of a micro pore-crack system in shale during brittle deformation stage, brittle-ductile transitional deformation stage, and ductile deformation stage. Modified from Ju et al. [33].

this basis, they proposed a preliminary experimental scheme for investigating the effects of multistage tectonic movements on coal deformation and obtained satisfactory results. Ju et al. [33] simulated shear deformation in shale successions through high-temperature and high-pressure deformation experiments (Figure 2(A)) and analyzed the development of shale pores and fractures before and after deformation (Figure 2(B)), together with the principal geological controls. Cheng et al. [34, 35] used shale deformation experiments under different temperatures, confining pressure and differential stress to clarify the characteristic textures and structures of brittle and ductile deformation in organic-rich shale and reveal the conditions and mechanisms of the brittle-to-ductile transition under the deep *in situ* environment of high temperature, high confining pressure, and high-stiffness surrounding strata (Figure 3).

Complementing these laboratory-based approaches, systematic investigation of naturally deformed shale samples from tectonically complex regions provides direct geological evidence for assessing the structural controls on nanopore systems. Guo et al. [38] systematically characterized matrix composition, porosity, and pore structure in core samples of the Wufeng–Longmaxi shale from multiple structural domains within the Anchang Syncline of the Central Yangtze Block, the first commercial shale gas field situated within a fold-thrust belt. Their results demonstrated that shale porosity generally decreases from the syncline limb to the hinge zone and with decreasing interlimb angle, consistent with increasing deformation strain during folding. Axial compression experiments further confirmed that porosity reduction intensifies with elevated compressive stress, with clay mineral slippage under intensive deformation generating a positive relationship between clay content and bulk porosity. These findings highlight how the interplay between tectonic position and stress magnitude governs nanopore preservation in fold-thrust settings.

Building on natural sample observations, Yang et al. [39] systematically investigated the behavior of organic matter-hosted pores in shale gas reservoirs subjected to differential tectonic deformation. By integrating scanning electron microscopy, low-pressure gas adsorption, and mercury intrusion porosimetry across shale samples spanning a spectrum of deformation intensities, they proposed a series of innovative conceptual models elucidating the potential mechanisms by which brittle and ductile deformation differentially modify organic pore morphology, connectivity, and size distribution. Their framework revealed that brittle deformation preferentially increases interparticle pore volumes, whereas ductile deformation promotes specific surface area enlargement through grain reorientation and organic matter flow, thereby exerting contrasting controls on gas adsorption capacity and migration efficiency.

At the field scale, Zeng et al. [40] examined the microstructures and pore structures of naturally

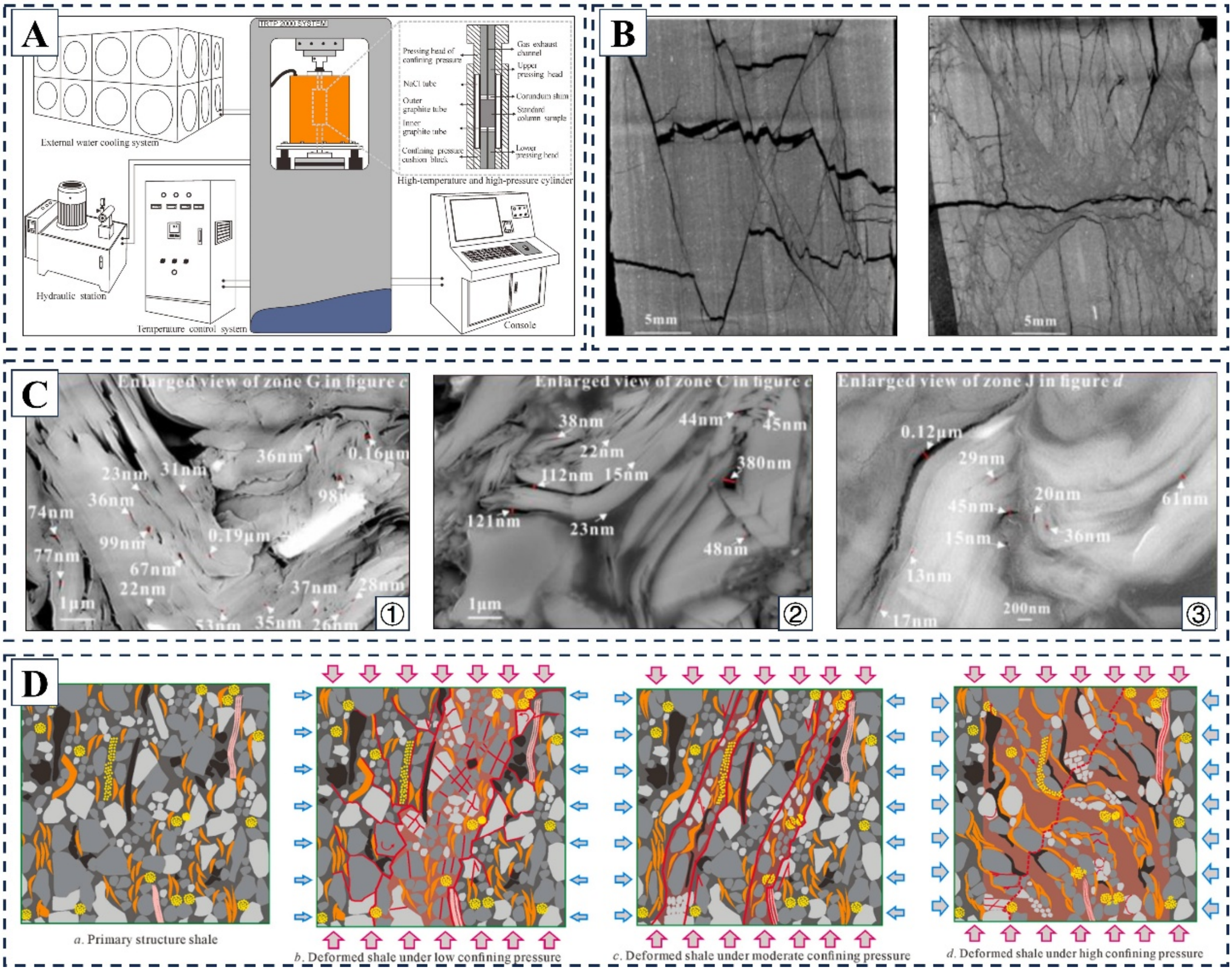

Figure 3. (A) Schematic diagram of the triaxial rock deformation system. (B) Images showing the shale deformation characteristics. (C) SEM images showing micro-structure deformation features of the deformed shale. (D) Diagram of brittle-to-ductile transition mechanism with increasing confining pressure. Modified from Cheng et al. [35].

deformed shales from the tectonically complex margins of the Sichuan Basin in South China. Their observations revealed that original sedimentary fabrics and pore networks are progressively destroyed with increasing deformation intensity, giving rise to diverse deformation microstructures including microfolds, microfaults, and cataclastic flow textures—recording ductile, brittle, and brittle–ductile deformation regimes, respectively. Quantitative analyses using low-pressure gas adsorption and mercury intrusion porosimetry further demonstrated that macropore volumes and fracture pore fractions increase relatively with escalating tectonic deformation, with implications for gas migration pathway development in structurally complex exploration targets.

To isolate the organic contribution to pore structure modification under tectonic stress, Cheng et al. [41] conducted a systematic comparative study of pore structure evolution in tectonically deformed shales (TDSs) using paired whole-rock and kerogen samples. They first proposed a TDS classification scheme based on deformation features and mechanisms, then applied N_2 and CO_2 adsorption tests to quantify micro- and mesopore evolution across deformation types. Their results demonstrated that both organic pore collapse and mineral grain reorganization contribute to mesopore reduction under compressional deformation, whereas ductile shear promotes micropore development in kerogen, thereby providing a mechanistic framework for predicting pore structure evolution in structurally complex shale reservoirs.

Laboratory deformation experiments are conducted under controlled conditions of temperature, confining

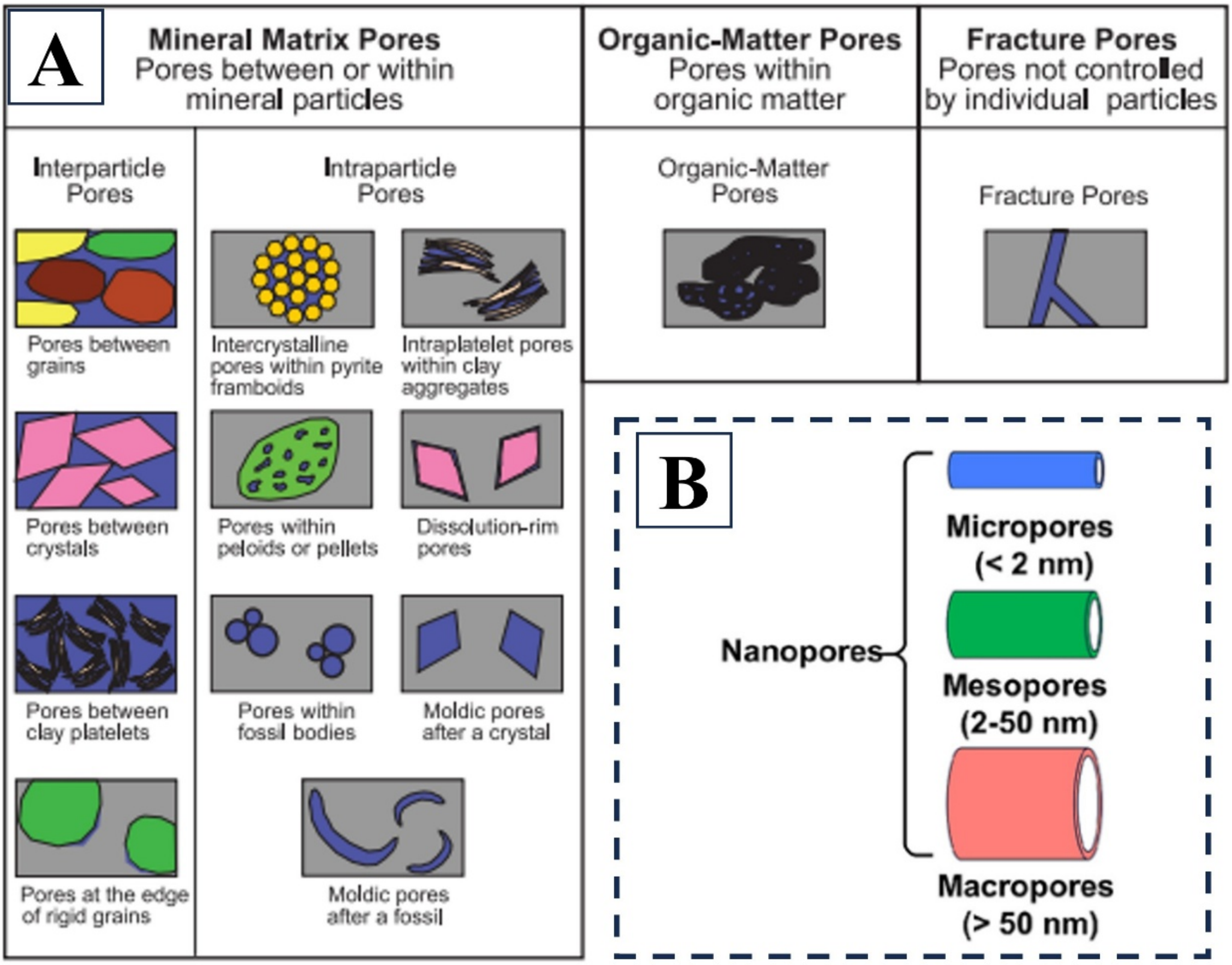

Figure 4. (A) Spectrum of pore types occurring within mudrocks. General pore types include interparticle and intraparticle pores associated with mineral matrix, organic-matter pores associated with organic matter, and fracture pores that crosscut matrix and grains. Modified from Loucks et al. [3]. (B) Spectrum of shale pore types based on pore size.

pressure, and strain rate. Based on the principle of tectonic similarity, experimentally produced deformation structures can be compared with naturally deformed geological structures, thereby allowing the deformation environments and mechanisms responsible for their formation to be inferred. Deformation experiments under different temperature and pressure conditions can therefore reconstruct the tectonic modification of shale during geological evolution and provide a scientific and reliable approach for simulating the effects of tectonic stress on the evolution of shale nanopore structures. Although such methods remain controversial because of limitations associated with experimental conditions, equipment precision, pore-fluid pressure, and other factors, they can theoretically compensate for the inability of natural geological samples to fully reveal deformation processes and their underlying mechanisms.

3.2 Classification and Evaluation Methods for the Shale Nanopores

Research on shale gas occurrence mechanisms and seepage behavior depends heavily on the accurate characterization of nanopore structures, making the establishment of a scientifically robust pore-classification system essential. Existing classification schemes generally consider multiple dimensions, including pore morphology, pore-size distribution, spatial topology, and connectivity. Morphology- and geometry-based classifications have attracted considerable attention because of their intuitive nature, whereas pore-size-based classifications dominate reservoir-property evaluation because they correlate readily with quantitative data obtained from mercury intrusion and gas adsorption experiments.

With respect to pore morphology and genesis, several classification schemes have been proposed for geological applications. Slatt and O'Brien [42] emphasized the responses of pores to sedimentary and diagenetic processes and subdivided the pores into six major categories, with detailed descriptions of their occurrence and morphological characteristics. By contrast, the classification proposed by Loucks et al. [3] has greater relevance to reservoir geology. In this scheme, the pore system is simplified into matrix pores and microfractures, with matrix pores further classified as interparticle pores, intraparticle pores, and organic matter-hosted pores (Figure 4(A)). Among pore-size classification systems, the standard proposed by the International Union of Pure and Applied Chemistry (IUPAC) has been widely adopted. Using 2 nm and 50 nm as threshold values, this standard classifies pores into micropores ($\leq$2 nm), mesopores (2–50 nm), and macropores ($>$50 nm) (Figure 4(B)). This three-tier system not only clarifies the capillary-condensation behavior of pores at different scales but also provides a theoretical basis for distinguishing the storage spaces of adsorbed and free gas.

At present, the IUPAC pore-size classification is commonly used as a standardized framework for interpreting laboratory data, whereas the pore classification by Loucks et al. [3] has become the principal template for pore identification at the core scale. These two schemes are complementary: the former defines pore size, whereas the latter identifies pore type and genesis. Together, they constitute the core methodological framework for investigating pore systems in shale reservoirs. Because pore-structure investigations of organic-rich shale are conducted at microscopic and ultrastructural scales, particularly at the micro- to nanoscale, appropriate analytical techniques are essential. The principal challenges in shale reservoir characterization arise from pronounced rock heterogeneity and the need to resolve structures at nanometer scales, rendering conventional petroleum reservoir evaluation methods and frameworks inadequate. Accordingly, researchers have integrated established experimental techniques for reservoir evaluation with analytical methods developed in nanomaterials science to achieve accurate qualitative and quantitative characterization of organic-rich shale reservoir structures [3, 4, 43].

With the increasing application of nanomaterials science and technology in the geosciences, visualization techniques such as field-emission scanning electron microscopy (FE-SEM), focused ion beam–scanning electron microscopy (FIB–SEM), focused ion beam–helium ion microscopy (FIB–HIM), transmission electron microscopy (TEM), and atomic force microscopy (AFM) have attracted considerable attention because they enable direct observation of micro- to nanoscale organic and inorganic particles, as well as nanopore morphology and size (Figure 5) [4]. Their principal advantages include high-resolution, intuitive imaging and the capability for two- and three-dimensional reconstruction. Particularly, these techniques allow precise qualitative and visual characterization of reservoir structures and are highly effective for investigating the morphology and genesis of organic and inorganic particles and pores [3, 43]. However, limitations in imaging coverage and difficulties associated with specimen preparation continue to pose substantial challenges for addressing rock heterogeneity, quantitatively characterizing pore-size distributions at high resolution, and determining pore volume and specific surface area.

Accordingly, the introduction of quantitative methods has effectively addressed several limitations of image-based analytical techniques. These methods can be broadly divided into fluid-intrusion and non-fluid-intrusion techniques [43]. Representative fluid-intrusion techniques for quantitative characterization include mercury intrusion porosimetry (MIP), N_2, CO_2, and Ar adsorption, as well as helium porosimetry and permeability measurements. In these techniques, fluids or gases such as mercury, CO_2, N_2, and Ar are introduced into rock samples under different pressures while the injected or adsorbed volumes are recorded. Porosity, permeability, pore-size distribution, specific surface area, pore volume, pore-throat radius, maximum adsorption capacity (Figure 5), and other parameters are then derived using appropriate theoretical methods and models. Because these experiments are relatively simple, provide comprehensive information, and are inexpensive, they are currently among the most widely used methods for investigating the micro- and nanostructures of unconventional hydrocarbon reservoirs. However, their principal limitation is that they characterize only connected or open pores and cannot resolve closed or isolated pores. The results are also readily affected by sample crushing and preparation procedures.

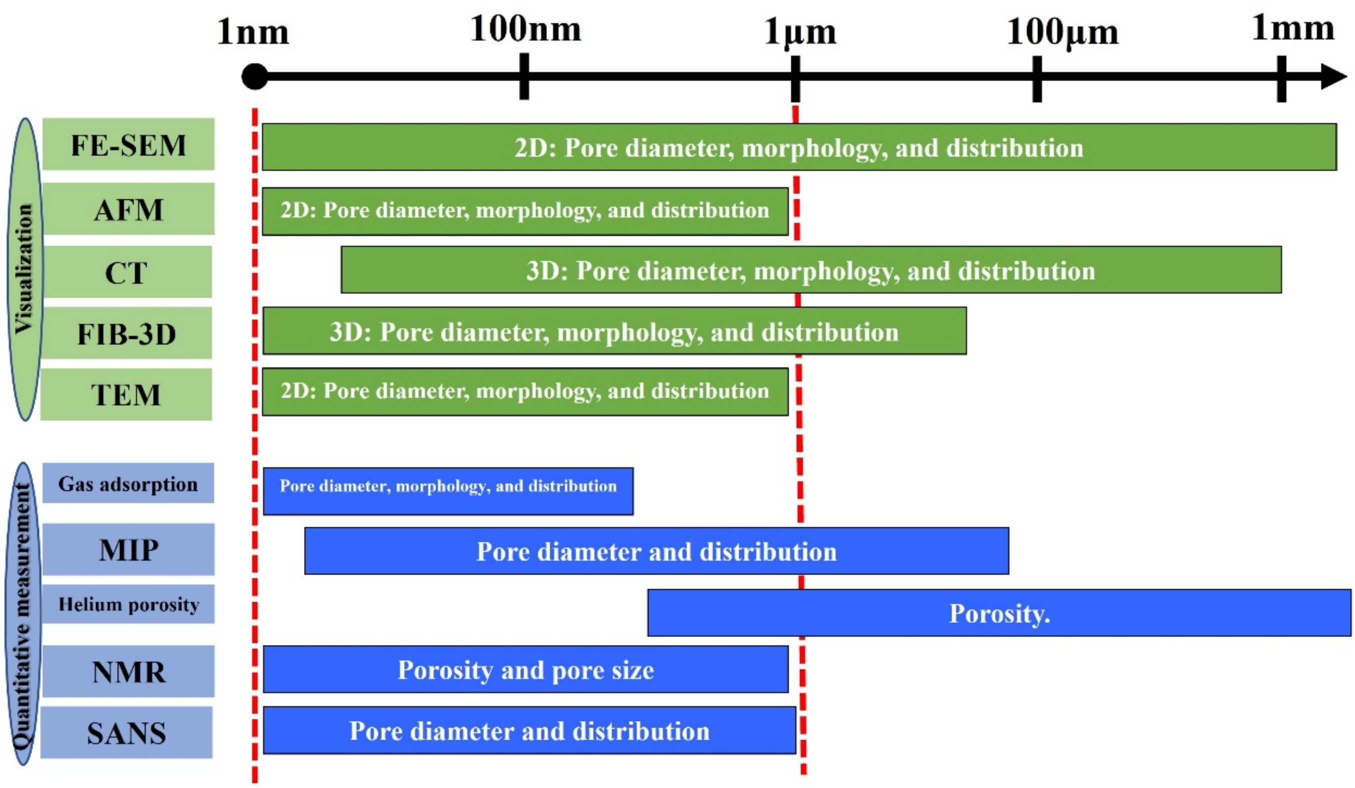

Figure 5. Multi-scale techniques used to study microstructural properties of shale pores.

Representative non-fluid-intrusion techniques include nuclear magnetic resonance (NMR), small-angle neutron scattering (SANS), and micro- and nano-computed tomography (CT). NMR can be used to determine rock porosity and pore-size distribution (Figure 5) [43]. SANS enables nondestructive characterization of rock microstructures under different temperature and pressure conditions and is unaffected by fluid–surface interactions, shielding effects, or pore connectivity [44]. However, its application remains limited because suitable neutron sources are scarce worldwide, the computational models are complex, and the required instrumentation is expensive and highly specialized. CT enables nondestructive analysis and three-dimensional reconstruction of shale microstructures and is therefore particularly effective for addressing the pronounced heterogeneity of shale at micro- to nanoscale resolutions [4]. The mechanical anisotropy of shale arising from lamination and tectonic reorientation of clay particles further complicates pore structure interpretation and should be considered when integrating multimethod characterization data [45].

Shale pore structures span multiple orders of magnitude, from the micrometer to the nanometer scale, while individual characterization techniques differ in their applicable scale ranges and resolutions. Consequently, no single method can comprehensively reveal the micro- and nanostructural characteristics of a sample or fully cover the entire pore-size range. The integrated application of multiple experimental techniques, together with cross-validation of the resulting data, has therefore become an important trend in the characterization of structurally complex unconventional reservoirs.

4 Conclusions

(1) Tectonic deformation is not confined to the formation of macroscopic structural styles but extends to the micro- and nanoscale, where it acts as a key external factor modifying the pore structure of shale reservoirs. Unlike primary pores formed during sedimentation and diagenesis, tectonic stress—particularly compression and shear—substantially reduces shale structural heterogeneity through the directional alignment of particles, fragmentation of brittle minerals, and rheological deformation of organic–clay composites. This process not only directly induces the collapse of large pores (macropores) while preserving micropores, but also profoundly affects shale gas adsorption–desorption equilibrium and transport efficiency by altering pore connectivity and specific

surface area.

(2) High-temperature and high-pressure deformation experiments provide an effective means of reconstructing natural tectonic deformation processes and elucidating the dynamic evolution of pore structures, thereby overcoming the inability of geological sample observations alone to capture deformation processes. Given that shale pores span multiple orders of magnitude from the micrometer to the nanometer scale, any single characterization technique is inherently limited. The IUPAC pore-size classification and the Loucks morphology-based classification provide standardized frameworks for quantitative pore evaluation and geological classification, respectively. Comprehensive, quantitative, and high-resolution characterization of the full pore-size spectrum in tectonically modified shale can therefore be achieved only by integrating high-resolution imaging techniques such as FIB–SEM with fluid-intrusion methods, including mercury intrusion and gas adsorption, as well as nondestructive techniques such as NMR and SANS.

(3) Marine shales in southern China, such as those of the Wufeng–Longmaxi formations, constitute important detachment layers whose gas-bearing properties are strongly controlled by preservation conditions under the superposition of multiple tectonic events. Although intense tectonic modification may locally enhance permeability through brittle fracturing, it more commonly causes pressure dissipation and pore-structure damage associated with tectonic uplift and erosion, ultimately resulting in shale gas loss. Consequently, the shale gas exploration potential of structurally complex areas along the margins of the Sichuan Basin depends not only on source-rock quality but, more critically, on the compatibility between tectonic deformation intensity and sealing conditions. Future exploration should therefore prioritize weakly deformed zones, which represent a key scientific target for achieving shale gas breakthroughs in structurally complex regions.

Data Availability Statement

Data will be made available on request.

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Conflicts of Interest

Zhe Cao, Zongquan Hu, Xin Wang, Peng Li, and Ranran Hao are affiliated with the SINOPEC Petroleum Exploration and Production Research Institute, Beijing 100083, China; Kunyu Wu is affiliated with the PetroChina Qinghai Oilfield Company, Dunhuang 736202, China. The authors declare that these affiliations had no influence on the study design, data collection, analysis, interpretation, or the decision to publish, and that no other competing interests exist.

AI Use Statement

The authors declare that generative AI was used in the preparation of this manuscript. Specifically, ChatGPT was used for translation and language polishing purposes only. The authors reviewed and edited the content as needed and take full responsibility for the final version of the manuscript.

Ethical Approval and Consent to Participate

Not applicable.

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