energies

Review

Characteristics of Tight Gas Reservoirs in the Xujiahe Formation in the Western Sichuan Depression: A Systematic Review

Jiongfan Wei, Jingong Zhang * and Zishu Yong

Department of Geology, Northwest University, Xi'an 710069, China; wjf021535@stumail.nwu.edu.cn (J.W.)
* Correspondence: zhjgnwu@126.com

Abstract: In current energy structure adjustments, the prominence of unconventional oil and gas resources continues to grow, with increasing attention being paid to tight gas, a major component of natural gas production. The Xujiahe Formation gas reservoir in the Western Sichuan Depression represents a typical tight gas reservoir and the study of its reservoir characteristics is a key focus for current and future exploration and development efforts. This review employs the PRISMA method to screen and integrate the primary findings of 26 documents spanning the period from 2008 to 2023, with the aim of providing a comprehensive overview of the progress and outcomes of research on the tight gas reservoir characteristics of the Xujiahe Formation in the Western Sichuan Depression. The selected research documents summarize the characteristics of the Xujiahe Formation tight gas reservoir in the Western Sichuan Depression from four perspectives: lithology, physical properties, reservoir space, and the main factors influencing reservoir quality. Through a review of these previous studies, it is evident that existing research has predominantly focused on the relationship between diagenesis and reservoir densification, indicating certain limitations. We also delve into the characteristics of tight gas sandstone reservoirs in the study area, considering their depositional systems, fracture development, cementation, and impact on the exploration and development of tight gas reservoirs. Additionally, we propose measures to stabilize and enhance tight gas production in the Xujiahe Formation in the Western Sichuan Depression. Moreover, we outline the next steps for further research and exploration.

Keywords: reservoir characteristics; tight gas; Western Sichuan Depression; Xujiahe Formation; systematic literature review

Citation: Wei, J.; Zhang, J.; Yong, Z. Characteristics of Tight Gas Reservoirs in the Xujiahe Formation in the Western Sichuan Depression: A Systematic Review. *Energies* **2024**, *17*, 587. https://doi.org/10.3390/en17030587

Academic Editor: Slawomir Kędzior

Received: 28 December 2023
Revised: 21 January 2024
Accepted: 23 January 2024
Published: 25 January 2024

1. Introduction

Tight gas constitutes a crucial unconventional natural gas resource and is defined as natural gas trapped within low-porosity and low-permeability sandstone reservoirs. The categorization of tight gas reservoirs has prompted diverse classification standards proposed by experts and scholars worldwide, each tailored to the unique circumstances of oil and gas exploration and development in their respective countries. In the 1970s, the U.S. Federal Energy Regulatory Commission initially defined sandstones with an air permeability of less than 0.1×10^{-3} μm^2 as tight gas-bearing sandstones. Subsequently, the U.S. Department of Energy proposed the concept of tight gas sandstones in 1987, coinciding with the rapid development of unconventional natural gas fields in the United States. In 1997, Li Daopin established that reservoirs with an average permeability of lower than 50×10^{-3} μm^2 qualify as low-permeability oil layers, taking into account the specific conditions of China's low-permeability oil fields [1]. In 2004, Holditch supplemented the definition of tight gas-bearing sandstones with the assertion that such reservoirs must undergo large-scale stimulation or adopt technologies, such as horizontal wells, to achieve industrial gas flow [2]. After analyzing global "continuous" oil and gas reservoirs, Zou Cai et al. established classification standards for low-to-ultra-low-porosity and -permeability (tight) gas sandstone reservoirs, defining them as having a porosity of less than 10%, a permeability of less than 0.1×10^{-3}, and a pore size ranging from 0.1 to 1 μm [3]. Furthermore, in 2011, the National Energy Administration of China issued the first tight gas industry standard (SY/T6832-2011) [3], stipulating that the overlying matrix permeability of tight gas layers should not exceed 0.1×10^{-3} μm^2 and that technologies, such as fracturing, horizontal wells, or multi-branch wells, are required to obtain industrial gas flow when the natural production capacity is lower than the lower limit of industrial gas flow or even non-existent.

With the ongoing advancements in oil and gas accumulation theory and the continuous progression of exploration and development technologies, tight gas has gradually emerged as the largest source of unconventional natural gas globally [4–7]. While the development of tight gas in our country commenced relatively late, its resource reserves and exploration potential are indeed substantial. Dai Jinxing et al. systematically underscored the significance of tight gas within the realm of unconventional natural gas, drawing from the conditions of 15 major tight gas sandstone fields in our country. They advocated for prioritizing the exploration and development of tight gas [4]. As a pivotal region for the exploration of tight gas, the Sichuan Basin has undergone five resource assessments. The national oil and gas resource evaluation from the "Thirteenth Five-Year Plan" (2016–2020) indicated that the Sichuan Basin is rich in natural gas, with total resources of nearly 40×10^{12} m^3 [8,9]. By the end of 2022, proven geological reserves were expected to reach 7.5×10^{12} m^3. According to 2021 statistics from the PetroChina Southwest Oil and Gas Field Company, recoverable natural gas content is estimated to be 20×10^{12} m^3, with geological tight gas resources accounting for 3.98×10^{12} m^3 and recoverable reserves approaching 1.79×10^{12} m^3. Among these, the geological reserves of tight gas amount to 3.98 trillion cubic meters and recoverable reserves stand at a substantial 1.79 trillion cubic meters, signifying significant development potential. Taking into account comprehensive considerations of geological oil and gas conditions and actual exploration and development situations, the favorable tight gas areas in the Sichuan Basin have been categorized into three levels: core production construction areas, accelerated evaluation areas, and replacement evaluation areas. The Western Sichuan Depression (encompassing southwestern and northwestern Sichuan) is situated in the hydrocarbon source center and features well-developed reservoirs and faults. It has yielded certain exploration and development outcomes. This area is a crucial accelerated evaluation zone and also represents the first important research area to be established following the identification of the production area in central Sichuan.

While the overall physical properties of tight gas reservoirs may be low, they are distributed over a vast area, with numerous "sweet spots" exhibiting well-developed physical properties that can enhance oil and gas enrichment [10]. In comparison to tight gas fields, like those in the Ordos Basin, the development of the Xujiahe Formation reservoirs in the Western Sichuan Depression was influenced by more intricate tectonic processes and diagenesis. Previous studies have predominantly concentrated on reservoir characteristics, with the mechanisms behind the high-quality reservoir formation remaining unclear. To comprehensively bridge the gaps in previous research, this review strictly adheres to the Statement of Systematic Reviews and Meta-Analyses (PRISMA) guidelines and selects 26 relevant research documents from the past 15 years. The review involves a thorough analysis of various characteristics of the tight gas sandstone reservoirs in the Xujiahe Formation, primarily aiming to address the following research questions:

RQ1: What are the lithological characteristics of the tight gas sandstone reservoirs in the study area?
RQ2: What are the pore and physical properties of the reservoirs in the study area?
RQ3: What are the controlling factors that affect the quality of the tight gas sandstone reservoirs in the study area?

2. Regional Geological Background

The Sichuan Basin, situated in the northwest of the Yangtze quasi-platform, is a multi-cycle sedimentary basin characterized by a typical dual structure of basement and sedimentary cover. Its initial formation occurred during the Indosinian movement and multiple subsequent tectonic movements in Yanshan and Xishan led to the finalization of its folds, establishing the current structural pattern of the basin [11–14].The Western Sichuan Depression, located in the western part of the Sichuan Basin, is bordered by the Longquan Mountain fault and Nanjiang River to the east, while its western side is adjacent to the Longmenshan orogen and Anxian, Dujiangyan. To the north, it extends to the Micang Mountain and Daba Mountain areas and to the south, it reaches the Sichuan–Yunnan tectonic belt. It forms a foreland basin, extending in a northeasterly direction with the Emei–Yingjing fault (Figure 1a). During the Late Triassic period, the Upper Yangtze region underwent a significant transformation from a shallow sea platform to an inland lake basin. The depositional environment transitioned from marine facies to transitional and continental facies, leading to the rapid deposition of a large amount of terrigenous clastic rocks. This process resulted in the formation of the thick Upper Triassic and Jurassic Xujiahe Formation strata.

The Xujiahe Formation in the Sichuan Basin is stratigraphically divided into six sections: T_3x^1, T_3x^2, T_3x^3, T_3x^4, T_3x^5, and T_3x^6, from bottom to top. Due to denudation, the T_3x^6 section is no longer present in most areas of the Western Sichuan Depression [15] (Figure 1b). The T_3x^1, T_3x^3, and T_3x^5 sections consist of mud and shale interbedded with coal seams, serving as significant hydrocarbon source rock layers that also have the capacity to store natural gas. On the other hand, the T_3x^2 and T_3x^4 sections serve as primary reservoirs, characterized mainly by tight gas sandstone lithology. This interactive and overlapping distribution of reservoirs and source rock formations gives rise to a typical "sandwich" structure [16].

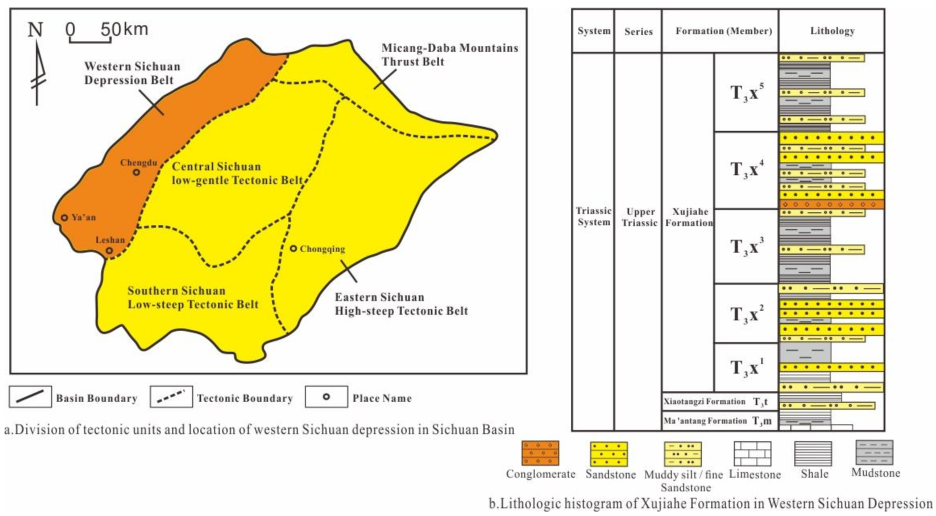

Figure 1. Structural location of the Western Sichuan Depression and a lithology histogram of the Upper Triassic Xujiahe Formation (modified from [17,18]).

3. Risk and Uncertainty Analysis in Tight Gas Exploration and Development

The imbalance between domestic and foreign oil and gas supply and demand, along with the shift from conventional to unconventional oil and gas, has heightened the need for increased precision and efficiency in tight gas exploration and development in our country. This has also raised concerns about the significant risks and uncertainties involved in this process, making evaluation and analysis crucial issues that cannot be overlooked. Mahjour categorized these risks and uncertainties into technical and non-technical aspects, as well as operational, financial, and political risks [19]. Additionally, research has encompassed uncertainties in oil and gas reservoir exploration and development from a geological engineering perspective, taking into account factors such as relevant reservoirs, oil prices, and operational considerations [20].

The unique exploration and development processes for tight gas necessitate fundamentally different approaches to risk and uncertainty assessment compared to conventional oil and gas resources. In our country, the natural gas market is robust, with substantial recoverable resources and relatively advanced technical equipment, all of which are favorable factors for the exploration and development of tight gas. Nonetheless, the lower quality of resources and high development costs, coupled with potentially unfavorable economic and fiscal policies, represent significant factors for risk and uncertainty evaluation. Moreover, for the tight gas reservoirs in the Western Sichuan Depression in the Sichuan Basin, local complex geological conditions and frequent tectonic movements must also be considered as influential factors as they can cause disturbances and even destruction. Table 1 provides a non-exhaustive list of possible risks and uncertainties in the exploration and development of tight gas reservoirs in the study area.

Table 1. A non-exhaustive list of risk and uncertainty evaluation indicators in the exploration and development of tight gas reservoirs in the study area.

Risk and Uncertainty Evaluation Indicator		Factors to Consider
Technical	Geological resources	Basic geological conditions, such as sedimentation and the structure of the Western Sichuan Depression
		The development characteristics of the tight gas accumulation elements of the Xujiahe Formation in the Western Sichuan Depression
		Configuration relationships between various tight gas accumulation factors of the Xujiahe Formation in the Western Sichuan Depression
	Technology and equipment	Fine reservoir and fault characterization technology
		The selection of tight gas enrichment zones and the locations of deployed wells in the study area
		Single well production and recovery rate improvement technology
		Equipment update, optimization technology, and equipment supply, demand, and deployment issues
Non-technical	Market and policy aspects	The guarantee of capital investment and increase in market demand
		Improvements in government supervision and relevant laws and regulations
		Policies and special funds related to the oil and gas resources industry
	Business management	The adjustment and innovation of management models

4. Method

4.1. Systematic Literature Review Background

The systematic literature review is a relatively recent research method, initially introduced into the medical field toward the end of the 20th century. It has since been refined and is now applicable to research across various disciplines. Its ability to ensure scientific rigor through the meticulous and repetitive screening, analysis, and integration of collected information makes it an effective method for reviewing scientific evidence [21–24]. The PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) method, utilized in this study, was first proposed by Moher et al. in 2009 [25] and has become widely adopted following improvements by Page et al. in 2020 [26].

4.2. Data Collection and Processing

This review utilized two prominent index databases as the primary search engines: Web of Science (WoS) and Scopus. These databases were selected due to their comprehensive coverage of academic topics and their extensive collections of peer-reviewed literature across various research areas.

This study extended the research questions and keywords proposed in previous studies and developed a comprehensive Boolean logic search chain, as illustrated in Table 2. A preliminary literature search was performed in each of the two designated index databases using this search chain, yielding a total of 418 documents, with 232 retrieved from Web of Science and 186 from Scopus. The obtained data were imported into the literature screening software Rayya (https://rayyan.ai/ accessed on 22 January 2024) [27], which facilitated the identification and removal of duplicate documents. Consequently, 144 duplicate documents were identified across the two databases, leaving 274 documents after deduplication.

Table 2. The search chain.

Database	Search Chain
Web of Science (WoS)	TS = ((“Western Sichuan Basin” OR “West Sichuan Basin” OR “Western Sichuan Depression” OR “West Sichuan Depression”) AND (“Xujiahe Formation” OR “Xujiahe Group”) AND (“tight sandstone reservoir” OR “tight reservoir” OR “reservoir”))
Scopus	TITLE-ABS-KEY ((“Western Sichuan Basin” OR “West Sichuan Basin” OR “Western Sichuan Depression” OR “West Sichuan Depression”) AND (“Xujiahe Formation” OR “Xujiahe Group”) AND (“tight sandstone reservoir” OR “tight reservoir” OR “reservoir”))

To ensure the quality and relevance of the selected literature to this study, specific inclusion and exclusion criteria were established, as outlined in Table 3. Following the removal of duplicate documents, the literature was meticulously screened and reviewed based on these criteria to assess its suitability for further analysis. During this screening process, five documents unrelated to the exploration field were excluded, along with one document that did not focus on the Western Sichuan Depression and seven documents that did not center on the Xujiahe Formation or tight gas reservoirs. Ultimately, 241 documents meeting the predetermined standards were identified.

During the document download process, it was discovered that out of the 241 documents obtained following the initial screening, 4 were inaccessible and 71 were written in languages other than English. After excluding these, 166 documents remained. Subsequently, a final round of screening was conducted by thoroughly reviewing the full texts of these documents to ascertain their direct relevance to this review’s focus areas. During this stage, 140 documents were excluded as they did not specifically address various types of reservoirs, leaving a total of 26 documents that met all of the established criteria. Figure 2 depicts the complete search and screening process employed in this systematic literature review. The 26 selected documents were then summarized, sorted, labeled as ID1-ID26 based on their publication date, and categorized according to the main issues under study, as presented in Table 4.

Table 3. Inclusion and exclusion criteria.

Inclusion Criteria	Exclusion Criteria
Research conducted on oil and gas exploration	Research conducted on development or other non-exploration fields
Research area located in the western Sichuan Basin/Western Sichuan Depression	Research area not located in the Sichuan Basin
Research horizon is Xujiahe Formation strata	Research horizon is not Xujiahe Formation strata
Research object is a tight gas reservoir	Research object is a shale gas reservoir or other non-tight gas reservoir
Main research content is the lithology and physical properties of reservoirs	Main research content is not the characteristics of various types of reservoirs
Research published in a journal	Review papers, conference reports, books, etc.
Written in English	Written in languages other than English

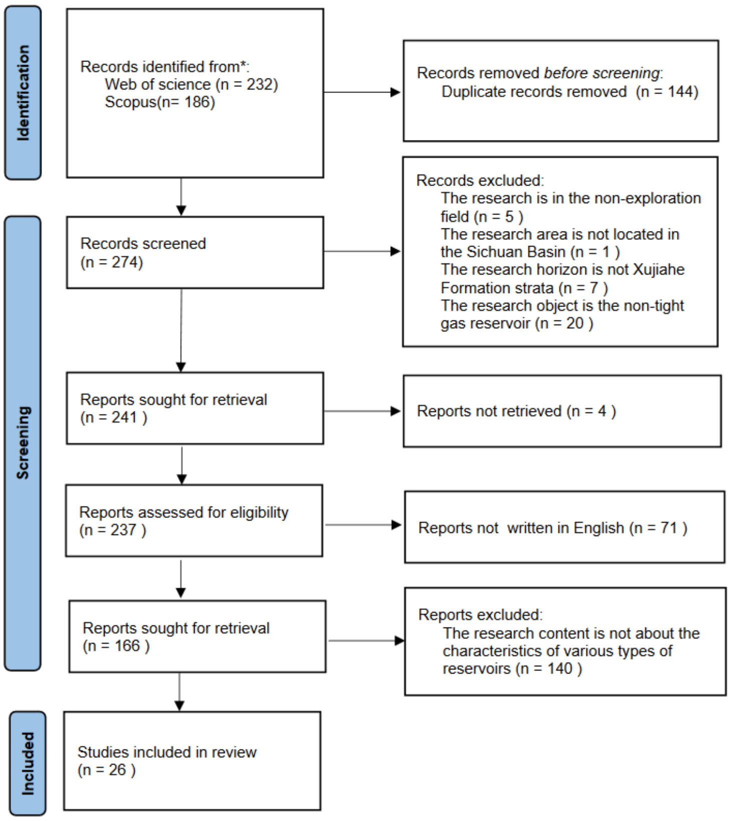

Figure 2. Literature selection process (Records identified from*: The screening scope is designed with two mainstream databases, which are emphasized here).

Table 4. Classification and summary of filtered documents.

ID [Reference] Author (Year)	Characteristics of Tight Gas Reservoirs					
	Lithology	Reservoir Space	Physical Properties	Deposition	Tectonic (Fracture)	Diagenesis
ID1 [28] LIU Junlong et al. (2023)					√	
ID2 [29] Yuhao Guo et al. (2023)			√			
ID3 [30] Zhengxin Duan et al. (2023)					√	
ID4 [31] Yu Yu et al. (2022)						√
ID5 [32] MA Jianfei et al. (2022)	√		√			√
ID6 [33] Yu Yu et al. (2022)	√		√			√
ID7 [34] Bo Pan et al. (2021)	√		√			√
ID8 [35] FENG Dongjun et al. (2021)		√				
ID9 [36] Wei Cheng et al. (2021)		√				
ID10 [37] Jie Ren et al. (2021)	√					√
ID11 [38] Peng Yang et al. (2021)	√		√	√		√
ID12 [39] Yangqing Huang et al. (2020)	√			√		
ID13 [40] Qiaochu Wang et al. (2020)	√	√	√			√
ID14 [41] Wu Feng et al. (2020)		√	√			
ID15 [42] Yijiang Zhong et al. (2020)	√					√
ID16 [43] Yu Yu et al. (2019)	√		√			√
ID17 [44] Mengyao Li et al. (2019)	√		√			√
ID18 [45] Mengyao Li et al. (2019)	√		√			√

Table 4. *Cont.*

ID [Reference] Author (Year)	Characteristics of Tight Gas Reservoirs					
	Lithology	Reservoir Space	Physical Properties	Deposition	Tectonic (Fracture)	Diagenesis
ID19 [46] Dali Yue et al. (2018)	√			√	√	√
ID20 [47] Sibing Liu et al. (2018)						√
ID21 [48] Lei Gong et al. (2016)	√	√	√	√	√	√
ID22 [49] Hongyu Song et al. (2015)	√		√	√	√	√
ID23 [50] Dongxia Chen et al. (2014)	√		√			√
ID24 [51] Sibing Liu et al. (2014)	√	√				√
ID25 [52] Lianbo Zeng et al. (2010)					√	
ID26 [53] Zhangyou Xu et al. (2008)				√	√	√

4.3. Risk of Bias and Limitation Analysis

Risks and uncertainties are inherent in all scientific research. In the context of systematic literature reviews, these challenges primarily manifest in the form of potential bias and limitations associated with the process of literature screening. In this review, the literature screening process adhered strictly to the PRISMA method, thereby mitigating bias arising from subjectivity to a certain extent. Potential bias and limitations in the literature selection process were analyzed based on the inclusion criteria. The selected documents were exclusively sourced from the Web of Science and Scopus databases, with a primary emphasis on journal publications from the past 15 years, thereby excluding conference papers, monographs, and other materials. This approach inevitably introduced certain inherent limitations to the final screening results. Given the imperative of prioritizing the quality of the selected literature during screening, non-English documents were deliberately excluded. Despite this bias, its actual impact on the review is believed to be minimal. To mitigate this impact, future research will incorporate findings from high-quality non-English documents into the discussion and analysis.

5. Results

5.1. General Findings from the Literature Selected in this Study

The statistics regarding the publication dates of the 26 screened documents were analyzed to explore the relationship between the year of publication and the selection frequency for this study, as illustrated in Figure 3. It is noteworthy that all selected documents were published between 2008 and 2023, reflecting the sustained scholarly interest in research on tight gas reservoirs in the Western Sichuan Depression over the past 15 years. The peak in publications from 2018 to 2023 was particularly striking, from which period 18 documents were selected for this study, underscoring the growing significance of this research domain in the realm of tight gas and unconventional oil and gas studies. Furthermore, no articles were retrieved from 2009, 2011–2013, or 2017.

According to the statistics, the literature obtained after screening was primarily published in the 14 journals listed in Table 5. By correlating the CiteScore of each journal with the WoS Sciences Division Level, we established that half of the journals achieved a CiteScore exceeding 7.5 and the majority of them were positioned within Q1 or Q2 in the WoS Sciences Division. This indicates that the quality of these journals is widely acknowledged by scholars, both domestically and internationally. It also underscores that the selected literature was of notably high quality, sufficiently supporting the subsequent analysis and discussion within this systematic literature review.

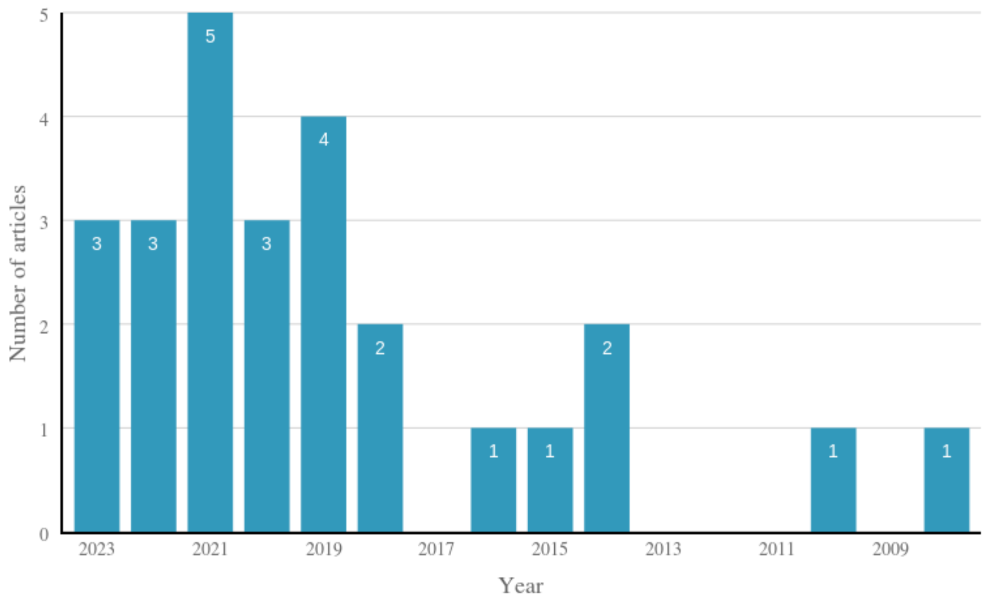

Figure 3. Years of publication of the screened documents.

Table 5. Distribution and quality assessment of the journals in which the selected documents were published.

Main Journals in which the Selected Literature Was Published	CiteScore	Web of Science Sciences Division Level
SCIENCE CHINA-EARTH SCIENCES	9.9	Q1
MARINE AND PETROLEUM GEOLOGY	9.3	Q1
JOURNAL OF PETROLUEM SCIENCE AND ENGINEERING (Continue as: GEOENERGY SCIENCE AND ENGINEERING)	8.8	Q3
PETROLEUM EXPLORATION AND DEVELOPMENT	8.1	Q1
PETROLEUM SCIENCE	7.7	Q1
AAPG BULLETIN	7.5	Q2
TERRA NOVA	5.6	Q3
WATER	5.5	Q2
JOURNAL OF PETROLUEM EXPLORATION AND PRODUCTION TECHNOLOGY	5	Q1
GEOLOGICAL JOURNAL	4.2	Q3
PETROLEUM SCIENCE AND TECHNOLOGY	3.3	Q2
FRONTIERS IN EARTH SCIENCE	3.2	Q2
OPEN GEOSCIENCES	2.8	Q3
ACTA GEOLOGICA SINICA-ENGLISH EDITION	2.4	Q2

When summarizing and categorizing the 26 chosen documents, the research topics were classified into six distinct areas: petrology, the physical properties of reservoirs, reservoir storage space, sedimentation, diagenesis, and tectonics. Instead of narrowly focusing on a single issue, the documents collectively explored various dimensions of tight gas reservoirs in the Western Sichuan Depression. This multidimensional approach is aptly depicted in Figure 4. Notably, the largest proportion of these articles (18 documents) delved into diagenesis, signifying the heightened attention this area garners within the field.

Additionally, over 10 studies centered on the petrology and physical properties of reservoirs, making it the second most prevalent theme after diagenesis. This emphasis is justified by the fact that many reservoir investigations necessitate a foundational understanding of petrology and physical properties. Furthermore, research into the remaining three aspects also captured scholarly interest, with seven studies pertaining to tectonic processes and faults and six studies focusing on reservoir space and sedimentation.

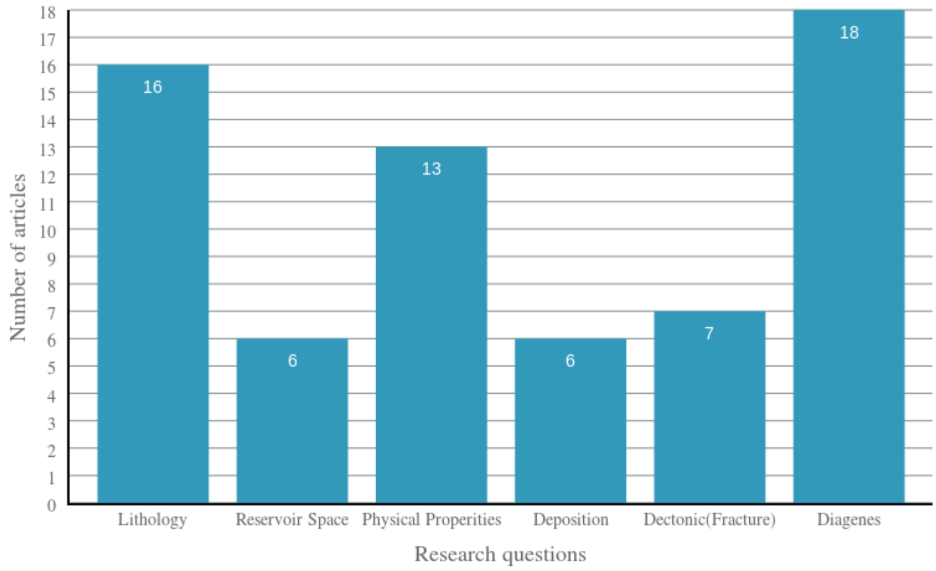

Figure 4. Research questions involved in the screened literature.

5.2. Petrological Characteristics of Reservoirs

The study of petrological characteristics is an essential aspect of reservoir research and serves as a crucial foundation for subsequent investigations. The primary rock types in the Xujiahe Formation in the Sichuan Basin are terrigenous clastic rocks, including sandstone, mud shale, and conglomerate. More specifically, the tight gas sandstone reservoirs (T_3x^2 and T_3x^4) in the Western Sichuan Depression are primarily associated with deltaic and lacustrine sedimentary systems, with finer-grained sandstone being prevalent [48].

5.2.1. Clastic Rock Components and Interstitial Material Characteristics of Reservoirs

There are numerous classification schemes for sandstone types, both domestic and international, with most of the selected studies adopting the classification scheme proposed by Folk in 1968 [54]. Quartz, feldspar, and rock debris collectively constitute the framework of sandstone. These clastic particles significantly determine the properties of clastic rocks. Table 6 summarizes the characteristics of the clastic particles identified via thin section analysis in eight studies and details their average contents [34,38,42–46,51]. The rock types of the T_3x^2 and the T_3x^4 sections in the Western Sichuan Depression exhibit slight differences due to changes in provenance. This primarily manifests in the higher feldspar content in the T_3x^2 sandstone compared to the T_3x^4 sandstone. However, both sections are composed of lithic sandstone, with feldspar being the primary component of lithic and lithic quartz sandstone.

The interstitial materials between clastic particles comprise mechanically derived heterogeneous groups and chemically derived cements. In the tight gas reservoirs in the Xujiahe Formation in the Western Sichuan Depression, the components of the interstitial materials primarily consist of mud, carbonates, silica, and other cements. The contents of the heterogeneous groups in the T_3x^2 and T_3x^4 sandstone are minimal, with various cements formed by precipitation during the diagenetic process being more prevalent. This phenomenon may be attributed to the greater impact of cementation, which is closely linked to pore fluid, compared to mechanical sedimentation on these sandstone reservoirs.

The specific characteristics of various cements, along with their cementation functions, are elaborated in subsequent chapters.

Table 6. Statistics on the average contents of clastic particles in reservoirs in the Xujiahe Formation in the Western Sichuan Depression.

ID [Reference] Author (Year)	Section	Number of Thin Sections	Average Contents of Detrital Components		
			Detrital Quartz	Detrital Feldspar	Rock Fragment
ID7 [34] Bo Pan et al. (2021)	T_3x^2	218	65.90%	7.00%	27.10%
ID11 [38] Peng Yang et al. (2021)	T_3x^2	243	67.50%	7.20%	25.30%
ID15 [42] Yijiang Zhong et al. (2020)	T_3x^2	105	65.00%	16.00%	19.00%
	T_3x^4		53%	0%	47%
ID16 [43] Yu Yu et al. (2019)	T_3x^4	302	56.68%	3.40%	39.92%
ID17 [44] Mengyao Li et al. (2019)	T_3x^4	216	65.1%	1.80%	18.00%
ID18 [45] Mengyao Li et al. (2019)	T_3x^4	35	56.30%	1.50%	42.20%
ID19 [46] Dali Yue et al. (2018)	T_3x^2	158	69%	8.20%	22.80%
	T_3x^4	86			
ID24 [51] Sibing Liu et al. (2014)	T_3x^4	—	58.55%	2.06%	39.39%

5.2.2. Clastic Rock Structural Characteristics of Reservoirs

The structure of sandstone significantly influences reservoir pore space, particularly the particle size and sorting, serving as the basis for high-quality reservoir formation [53,55]. In the Western Sichuan Depression, the sandstone grain size of T_3x^2 is generally finer than that of T_3x^4, mostly falling within the fine-to-medium-grained range and exhibiting relatively good sorting. The clastic particles are typically rounded and predominantly sub-angular to sub-round [34,38,50]. Some variations in structure between the T_3x^4 sandstone and T_3x^2 sandstone are evident. Overall, the grain size and sorting of the T_3x^4 sandstone are slightly inferior to those of T_3x^2, largely comprising medium-sized clastic particles with moderate sorting [43,49]. In summary, the sandstone in reservoirs in the Xujiahe Formation in the Western Sichuan Depression is predominantly fine-to-medium-grained, with a higher proportion of medium-grained components. The particles are mostly round in shape and the sorting is relatively moderate [48,53].

5.3. Pores and Physical Characteristics of Reservoirs

The pore characteristics and physical properties of reservoirs play crucial roles in assessing reservoir quality. Simultaneously, the evolution of pore type and structure directly impacts the porosity and permeability of reservoirs. The reservoirs in the Xujiahe Formation in the Western Sichuan Depression are classified as tight gas sandstone reservoirs, exhibiting distinct differences in pore throat development, pore structure, reservoir, and seepage capability compared to conventional clastic rock reservoirs. They are characterized by finer pores, more intricate pore structures, greater heterogeneity, low porosity, and low permeability.

5.3.1. Pore Type Characteristics

Reservoir pores are commonly categorized into primary and secondary pores based on their origin and formation time. Primary pores form during sedimentation or diagenesis, while secondary pores result from subsequent changes in reservoir rocks, such as dissolution or fracturing. The pores found in the tight gas sandstone reservoirs in the Western Sichuan Depression primarily consist of residual intergranular pores, intergranular dissolution pores, intragranular dissolution pores, mold pores, and intercrystalline pores. Moreover, the study area also exhibits the development of microfractures, which are significant in providing additional reservoir space (Table 7). The pore type characteristics of reservoirs in T_3x^2 and T_3x^4 are essentially similar. They predominantly feature secondary pores, with few primary pores, and a significant presence of intergranular and intragranular dissolution pores. Additionally, the development of microfractures is notable.

Table 7. Space types and development characteristics of reservoirs in the Xujiahe Formation in the Western Sichuan Depression.

Reservoir Space Type			Development Characteristics
Pores	Primary pores	Residual intergranular pore	Spaces where primary intergranular pores are filled with interstitial materials during the diagenetic process, which are mostly in the shape of triangles, long strips, etc.
	Secondary pores	Intergranular dissolution pores	Unstable components between quartz grains formed by dissolution, mostly caused by the dissolution of feldspar or lithic debris
		Intragranular dissolution pores	Mainly formed by the dissolution of feldspar particles along the cleavage direction
		Mold pores	Particles are completely dissolved under selective dissolution, and the size and shape of pores are consistent with the particles
		Intercrystalline pores	Developed between kaolinite, illite, chlorite, and other authigenic clay minerals, with irregular shapes
Microfractures	Intragranular microfractures		Mainly develop inside quartz and feldspar particles, do not penetrate the edges of particles, and have small pore sizes
	Intragranular microfractures		Mainly distributed along straight lines at the boundaries between mineral particles and are narrow and short
	Transgranular microfractures		Generally cut through multiple mineral particles and are longer and wider

Due to deeper burial and increased compaction, the sandstone of T_3x^2 retains very few primary pores, with only a limited number of residual intergranular pores being developed [34]. In the case of T_3x^4, certain studies have indicated that the scarcity of residual intergranular pores in this section is attributed to carbonate cementation and excessive quartz growth [40]. The residual intergranular pores observed in those studies exhibit predominantly triangular, elongated, or linear shapes, with small and narrow dimensions, typically not exceeding 200 μm [38].

Secondary pores are the predominant type of pores in the study area, encompassing four main categories: intergranular dissolution pores, intragranular dissolution pores, mold pores, and intercrystalline pores. Intergranular dissolution pores are primarily localized at the edges of feldspar and rock debris, with feldspar dissolution accounting for the formation of a significant portion of these pores [38,43,48,49]. Intragranular dissolution pores occur along the edges of feldspar particles, developing from internal cleavage or the dissolution of cracks within rock debris. Residual clay skeletons or fillers are sometimes evident, often forming network structures and potentially evolving into mold cavities under substantial selective dissolution [35,38,40,49]. Notably, a comparison of intragranular dissolution pore development in the T_3x^2 and T_3x^4 sections revealed that the pores in T_3x^4 are better preserved and exhibit fewer or even no fillers [40]. Intercrystalline pores are more prevalent in T_3x^4, arising from the dissolution of authigenic clay minerals, and are more commonly found in sandstones with low feldspar contents and high kaolinite contents [38,43].

Microfractures can be categorized into three types based on their associations with particles: intragranular, grain edge, and transgranular microfractures. These features not only function as natural gas storage spaces but also significantly enhance pore structures and reservoir permeability [52]. Intragranular microfractures form within quartz and feldspar particles, with lengths not exceeding the grain size and pore diameters that are generally less than 10 mm. Grain edge microfractures develop at the junctions of mineral particles, with pore diameters that are slightly larger than those of intragranular microfractures. Transgranular microfractures intersect multiple mineral particles, exhibiting greater lengths and pore diameters than the other two types, and may exceed 40 mm under the influence of dissolution.

5.3.2. Pore Structure Characteristics

The pore structure encompasses the geometric shape, distribution, and configuration of reservoir pores and throats, directly influencing the storage and seepage capacity of reservoirs. In comparison to conventional sandstone reservoirs, tight gas sandstone reservoirs exhibit low porosity, low permeability, and significant heterogeneity, resulting in a more complex pore structure.

In tight gas reservoirs in the Xujiahe Formation in the Western Sichuan Depression, nanoscale pore throats often take the form of sheets or bent sheets, with their formation primarily linked to compaction during diagenesis [29,36,38,41,49]. Studies comparing pore throat development in the T_3x^2 and T_3x^4 sections have suggested that the latter exhibits a greater number of throats, with larger throat radii. High-pressure mercury injection tests (HPMI) have indicated a higher final mercury injection saturation (Sf) in T_3x^4 samples compared to T_3x^2 samples, suggesting greater effective storage space in T_3x^4 [40]. In the study area, the quality of the pore structures in tight gas reservoirs is significantly influenced by pore throat radius and distribution. Previous research has classified the pore structure of tight gas reservoirs into four types: large pore and large throats, large pores and small throats, small pores and large throats, and small pores and small throats. The upper sub-section of T_3x^4 predominantly features large pores connected by large throats, indicating a high-quality tight gas sandstone reservoir [35].

5.3.3. Physical Characteristics of Reservoirs

Porosity and permeability are fundamental physical properties of reservoirs and play crucial roles in evaluating reservoir quality. Several studies have conducted detailed analyses of the physical properties of reservoirs in the Xujiahe Formation in the Western Sichuan Depression and the statistical data are presented in Table 8. The study area's tight gas sandstone reservoirs exhibit significant heterogeneity, showing a weak positive correlation between porosity and permeability with a large distribution range. Overall, the physical properties remain poor, with average porosity levels of below 10% and permeability levels of mostly below 0.1×10^{-3} μm^2. Based on the reservoir classification standard (SY/T5601-93) in the oil and gas industry, these reservoirs typically fall into the categories of extra-low porosity–low permeability or extra-low porosity–extra-low permeability [3,4]. Statistical results have indicated that the average porosity of T_3x^2 is mainly concentrated between 3% and 4%, with average permeability concentrated between 0.02×10^{-3} μm^2 and 0.09×10^{-3} μm^2. In contrast, the porosity of T_3x^4 is within the range of 2% to 6%, with average permeability concentrated between 0.02×10^{-3} μm^2 and 0.08×10^{-3} μm^2. Consequently, the porosity of T_3x^2 generally tends to be lower than that of T_3x^4, while the permeability is generally higher in the former. Some studies have suggested that the widely developed microfractures in T_3x^2 contribute to the better tight gas sandstone reservoirs in the fourth section [40]. From a lithofacies perspective, medium-coarse sandstones exhibiting crossbedding, horizontal bedding, or massive bedding, as well as those containing carbonaceous debris, display favorable porosity and permeability, representing rocks with promising exploration potential [28,39]. Specifically, underwater distributary channels and mouth bar microfacies exhibit the highest reservoir quality, boasting maximum porosity levels exceeding 6% and permeability approaching 0.1×10^{-3} μm^2. This suggests that reservoirs developed with these microfacies generally possess relatively favorable physical properties [38,46].

Table 8. Porosity and permeability statistics for reservoirs in the Xujiahe Formation in the Western Sichuan Depression.

<table>
<tr><th rowspan="2">ID [Reference] Author (Year)</th><th rowspan="2">Section</th><th rowspan="2">Lithofacies Assemblage or Microfacies</th><th colspan="3">Porosity (%)</th><th colspan="3">Permeability (×10^{−3} μm²)</th></tr>
<tr><th>Avg.</th><th>Max.</th><th>Min.</th><th>Avg.</th><th>Max.</th><th>Min.</th></tr>
<tr><td rowspan="2">ID1 [28] LIU Junlong et al. (2023)</td><td rowspan="2">T_3x^2</td><td>Medium–coarse sandstone with trough/parallel bedding</td><td>4.85</td><td>5.6</td><td>4.5</td><td>19.95</td><td>33.2</td><td>0.01</td></tr>
<tr><td>Medium sandstone with massive bedding and diagonal bedding</td><td>4.35</td><td>4</td><td>4.9</td><td>0.3</td><td>4.5</td><td>0.001</td></tr>
<tr><td>ID7 [34] Bo Pan et al. (2021)</td><td>T_3x^2</td><td>—</td><td>3.34</td><td>9.34</td><td>0.43</td><td>0.17</td><td>2.816</td><td>0.001</td></tr>
<tr><td>ID11 [38] Peng Yang et al. (2021)</td><td>T_3x^2</td><td>—</td><td>3.82</td><td>9.38</td><td>0.44</td><td>0.05</td><td>2034.7</td><td>0.01</td></tr>
<tr><td rowspan="3">ID12 [39] Yangqing Huang et al. (2020)</td><td rowspan="3">T_3x^2</td><td>Medium–coarse sandstone with crossbedding</td><td>4.01</td><td>—</td><td>—</td><td>0.0915</td><td>—</td><td>—</td></tr>
<tr><td>Medium–coarse sandstone with crossbedding</td><td>4.32</td><td>—</td><td>—</td><td>0.0996</td><td>—</td><td>—</td></tr>
<tr><td>Medium–coarse sandstone with crossbedding</td><td>3.73</td><td>—</td><td>—</td><td>0.936</td><td>—</td><td>—</td></tr>
<tr><td rowspan="2">ID13 [40] Qiaochu Wang et al. (2020)</td><td>T_3x^2</td><td>—</td><td>3.26</td><td>7.79</td><td>0.67</td><td>0.178</td><td>12.22</td><td>0.002</td></tr>
<tr><td>T_3x^4</td><td>—</td><td>5.92</td><td>12.71</td><td>0.47</td><td>0.078</td><td>0.86</td><td>0.001</td></tr>
<tr><td>ID15 [42] Mengyao Li et al. (2019)</td><td>T_3x^4</td><td>—</td><td>5.9</td><td>12.1</td><td>1</td><td>1.41</td><td>287.82</td><td>0.001</td></tr>
<tr><td rowspan="10">ID19 [46] Dali Yue et al. (2018)</td><td rowspan="5">T_3x^2</td><td>Subaqueous distributary channel</td><td>3.94</td><td>10.4</td><td>1.2</td><td>0.064</td><td>0.48</td><td>0.005</td></tr>
<tr><td>Mouth bar</td><td>2.92</td><td>9.2</td><td>1.25</td><td>0.049</td><td>0.42</td><td>0.004</td></tr>
<tr><td>Distal bar</td><td>1.56</td><td>2.58</td><td>1.18</td><td>0.021</td><td>0.182</td><td>0.002</td></tr>
<tr><td>Sheet sand</td><td>1.73</td><td>3.2</td><td>1.2</td><td>0.028</td><td>0.115</td><td>0.005</td></tr>
<tr><td>Interdistributary bay</td><td>1.46</td><td>1.92</td><td>1.1</td><td>0.013</td><td>0.163</td><td>0.002</td></tr>
<tr><td rowspan="5">T_3x^4</td><td>Subaqueous distributary channel</td><td>6.47</td><td>12.14</td><td>2.26</td><td>0.09</td><td>0.75</td><td>0.007</td></tr>
<tr><td>Mouth bar</td><td>6.2</td><td>11.5</td><td>2.17</td><td>0.081</td><td>0.68</td><td>0.008</td></tr>
<tr><td>Distal bar</td><td>2.75</td><td>6.59</td><td>2.07</td><td>0.026</td><td>0.106</td><td>0.004</td></tr>
<tr><td>Sheet sand</td><td>2.93</td><td>6.62</td><td>2.05</td><td>0.028</td><td>0.115</td><td>0.005</td></tr>
<tr><td>Interdistributary bay</td><td>2.72</td><td>5.99</td><td>2.05</td><td>0.013</td><td>0.214</td><td>0.004</td></tr>
<tr><td rowspan="2">ID21 [48] Lei Gong et al. (2016)</td><td>T_3x^2</td><td>—</td><td>3.59</td><td>6</td><td>2</td><td>0.064</td><td>0.1</td><td>0.01</td></tr>
<tr><td>T_3x^4</td><td>—</td><td>2.73</td><td>5</td><td>1</td><td>0.038</td><td>0.1</td><td>0.005</td></tr>
</table>

A comprehensive analysis of the reservoir pore development and physical characteristics mentioned above reveals that despite the density of the T_3x^2 and T_3x^4 sandstones in the study area, the presence of dissolution pores and microfractures enhances their porosity and permeability, rendering them viable as reservoirs. In the case of T_3x^2 reservoirs, although their pore structures are not as favorable as those of the T_3x^4 reservoirs, the degree of microfracture development is superior, enabling the formation of high-quality reservoirs with higher permeability, although with lower porosity. Conversely, in T_3x^4, the physical properties of reservoirs are primarily influenced by pore throat size and pore structure, with microfractures exerting a limited impact.

5.4. Factors Controlling Reservoir Quality

The development of reservoirs is influenced by myriad factors. Throughout their formation, burial, and subsequent transformation, processes such as sedimentation, diagenesis, and tectonics have played pivotal roles. It is through the combined influence of these processes that reservoirs ultimately take shape. The current low-porosity and low-permeability reservoirs are a result of these cumulative actions. In general, the initial depositional environments fundamentally establish the material foundations of reservoirs. Subsequent diagenetic processes, including compaction, cementation, and dissolution, either enhance or compromise reservoirs, thereby dictating their physical properties. Tectonic effects primarily expand reservoir storage space, increase permeability, and create pathways for oil and gas migration through the formation of fractures.

5.4.1. Sedimentation Is a Necessary Prerequisite for the Formation of Tight Gas Reservoirs

Various initial depositional environments often entail distinct hydrodynamic conditions, leading to the formation of diverse sedimentary microfacies. This, in turn, results in variations in the distributions of sand bodies, sediment components, and particle size, sorting, and roundness. These differences directly influence the original porosity and permeability of reservoirs and also impact the type and intensity of subsequent diagenetic processes.

During the Late Triassic, the Western Sichuan Depression underwent a transition from marine sedimentation to continental sedimentation, leading to the development of sedimentary facies, such as deltas, alluvial fans, and lacustrine facies. At a macroscopic level, sand bodies in different facies zones exhibit distinct spatial distributions. The delta plains and delta front subfacies are thick and widely distributed, fostering the development of favorable sand bodies, while the lake facies are predominantly characterized by mudstone deposits, resulting in the limited development of sand bodies and the formation of poor tight gas sandstone reservoirs. From a microscopic perspective, sedimentation influences the original physical properties of reservoirs by controlling factors such as sediment composition and particle size, sorting, and roundness, as evidenced in the analysis of reservoir physical properties in [53]. The high-energy depositional environments of underwater distributary channels and mouth bars result in the deposition of clasts with large particle sizes, good sorting properties, and high degrees of roundness, leading to sediments with high original porosity and permeability. These sediments exhibit high efficiency and strong resistance to compaction, making them more likely to form secondary pores under the influence of fluids. Conversely, microfacies, such as distant sand bars and sheet sands, are characterized by low energy and fine, poorly sorted sediment particles and tend to form small pores and are not conducive to the development of tight gas reservoirs [46,48]. It is evident that sedimentation determines the material basis of reservoirs, with high-energy depositional environments being a prerequisite for the development of high-quality reservoirs.

5.4.2. Diagenesis Is the Key Factor Controlling the Quality of Tight Gas Reservoirs

The impact of diagenesis on reservoirs permeates the entire burial diagenesis process and stands as the foremost factor governing reservoir quality. The reservoirs within the Western Sichuan Depression's Xujiahe Formation have undergone profound burial over an extended period, rendering them significantly influenced by diagenesis. It can be asserted that diagenesis serves as the intrinsic cause of the development of tight gas sandstone reservoirs in T_3x^2 and T_3x^4. The diagenesis of reservoirs in the Xujiahe Formation in the Western Sichuan Depression is intricate and multifaceted, chiefly encompassing compaction, cementation, and dissolution, among other processes. Different diagenetic types yield highly disparate impacts on the reservoirs. Compaction and cementation substantially diminish reservoir porosity and detrimentally affect reservoir performance, whereas dissolution facilitates the creation of additional pore space, thereby enhancing the physical properties of reservoirs (Table 9).

Table 9. Characteristics and impacts of various types of diagenesis in reservoirs in the Xujiahe Formation in the Western Sichuan Depression.

<table>
<tr><th colspan="2">Diagenesis</th><th>Main Characteristics</th><th>Impact on Reservoirs</th></tr>
<tr><td rowspan="2">Compaction and pressure solution</td><td>Mechanical compaction</td><td>Ductile minerals deform, brittle minerals fracture along weaker surfaces, and skeleton particles are severely compacted, manifesting as bumpy and sutured contacts</td><td rowspan="2">Occurs in the early stage of diagenesis and is the main reason for reductions in reservoir porosity, as well as weakening the connectivity of pore structures and increasing the compactness of reservoirs</td></tr>
<tr><td>Chemical pressure solution</td><td>Quartz particles dissolve at contact points or interfaces and the dissolved silica precipitates again</td></tr>
<tr><td rowspan="3">Cementation</td><td>Carbonate cementation</td><td>There are three types of carbonate cements: calcite, dolomite and trace siderite, which widely occupy pore space in the form of pore filling or the selective replacement of framework particles</td><td>Carbonate cement in early stages consolidates rock skeletons and increases the rock's resistance to compaction; in later stages, it blocks throats, resulting in reductions in reservoir porosity</td></tr>
<tr><td>Silica cementation</td><td>Mainly manifested by the secondary enlargement of authigenic quartz and the filling of pores and fracture spaces, and dust rings can also be seen between clastic particles</td><td>Generally reduces pore throat radius and reservoir porosity</td></tr>
<tr><td>Mud cementation</td><td>Mainly cemented with chlorite and illite: chlorite mostly appears in the form of particle coating and pore lining, while illite often fills the inside of pores or wraps around the surfaces of particles</td><td>Mainly reduces reservoir porosity, but chlorite cementation also plays a certain positive role in the preservation of pores</td></tr>
<tr><td colspan="2">Dissolution</td><td>Feldspar, rock debris, and other particles are dissolved, creating more storage space</td><td>Dissolution pores in early diagenetic processes are affected by compaction or cementation and are difficult to preserve; dissolution in late diagenetic processes greatly increase reservoir porosity</td></tr>
</table>

(1) Compaction and pressure solution are the main factors leading to reductions in primary pores in tight gas reservoirs

The original porosity created during the deposition processes of tight gas sandstone reservoirs diminishes due to diagenetic transformation. Mechanical compaction and chemical pressure solution are the primary factors that obliterate original pores and intensify the densification of reservoirs [29,38,42–44,46,50,53]. In the Western Sichuan Depression, the reservoirs in the Xujiahe Formation were significantly impacted by mechanical compaction, particularly during the early stages of diagenesis. This not only reduces reservoir porosity but also alters pore throat morphology and disrupts pore structure, thereby weakening pore connectivity. With increasing burial depths and temperatures, diagenesis progresses to the intermediate stage. Previously mechanically compacted quartz particles are tightly arranged, while chemical pressure dissolution occurs at boundaries or particle contact points, causing silica to precipitate, further compressing pore spaces [48]. As a result of mechanical compaction and chemical pressure solution, reservoir rock skeleton particles exhibit concave–convex or sutured contacts and some feldspar and quartz particles even undergo fragmentation and deformation under high lithostatic pressure [34]. Burial depth and time are pivotal in determining the strength of the compaction effect. Greater burial depths exert higher static pressure on reservoirs, while longer burial times lead to more extensive compaction. Consequently, T_3x^2 reservoirs underwent more intense compaction compared to those in T_3x^4, explaining why the overall porosity of T_3x^2 reservoirs is lower [40].

(2) Cementation has a dual impact on the pore spaces of tight gas reservoirs

The impact of cementation on reservoirs is indeed complex. Different types of cementation that developed during various diagenetic periods can lead to diverse transformation effects on reservoirs. During early stages, certain cements can fortify original pore frameworks, bolstering resistance to compaction within the pores and protecting them. However, as diagenesis progresses into later stages, cement begins to obstruct pore throats and fill secondary pores, contributing significantly to reservoir densification. In the T_3x^2 and T_3x^4 reservoirs in the Xujiahe Formation in the Western Sichuan Depression, a variety of cementation types, such as carbonate, siliceous, and muddy cementation, are widely prevalent, further adding to the complexity of their diagenetic history.

Carbonate cement primarily consists of calcite and dolomite, with a small proportion of siderite. Calcite cement is predominantly found in T_3x^4, while T_3x^2 is characterized by dolomite and siderite [42,46]. Carbonate cementation tends to occur in weakly compacted environments, generally preceding siliceous cementation and dissolution. Early carbonate cements, primarily composed of calcite, can selectively replace sandstone skeleton particles, thereby reinforcing their structures. This process prevents further reductions in primary pores during compaction, thereby mitigating decreases in porosity caused by compaction to some extent [31,34,40,50]. The quantity of carbonate cement is inversely related to reservoir porosity and permeability, indicating that while carbonate cement initially aids in preserving porosity, its subsequent filling of pore spaces and obstruction of pore throats play more dominant roles in later stages [29,43].

The predominant silica cement in tight gas reservoirs in the Xujiahe Formation is quartz cement. Feldspar dissolution, clay mineral transformation, and pressure dissolution are the primary sources of siliceous material for quartz cement [37]. The main expression of siliceous cementation is the secondary enlargement of quartz. While this enlargement can close intergranular pores and reduce throat spaces, leading to declines in reservoir porosity and permeability, it sometimes also provides support to pores, thereby resisting compaction [31,33]. Furthermore, another manifestation is the development of authigenic quartz in pores and fractures, which tends to have a detrimental effect on the physical properties of reservoirs [44,46,49,50]. In conclusion, due to its multiple manifestations, the relationship between siliceous cement and reservoir quality is relatively complex, but overall, as the content of siliceous cement increases, the physical properties of reservoirs tend to deteriorate.

The Western Sichuan Depression's Xujiahe Formation features a variety of clay minerals, with chlorite, illite, and kaolinite cementation being the primary types. Chlorite, the dominant argillaceous cement and the most prevalent clay mineral in T_3x^2, typically forms flaky films on particle surfaces or adheres to pore interiors, creating particle coatings and pore linings [34]. In contrast to carbonate and siliceous cementation, early chlorite cementation exerts a relatively robust protective effect on reservoir pores. It not only enhances resistance to pore compaction and pressure solution but also inhibits the secondary enlargement of quartz [40,56]. As diagenesis progresses, additional chlorite cement develops in the intergranular pores of reservoirs, leading to reductions in reservoir porosity. Illite is present in both T_3x^2 and T_3x^4, although its overall abundance is not high. It assumes various forms, primarily appearing as flakes, needles, bundles, etc. developing on particle surfaces or within pores. Kaolinite, though poorly developed in T_3x^2, is primarily present in T_3x^2 in worm-like and book-sheet shapes, occupying intragranular or intergranular pore spaces [46]. In summary, while mud cement can offer a degree of pore protection, its pore-filling capacity is more significant.

(3) Dissolution is the main factor improving the porosity of tight gas reservoirs

Given that the tight gas reservoirs and source rocks of the Xujiahe Formation in the Western Sichuan Depression are interbedded, fluids can readily permeate the sandstone reservoirs, leading to dissolution. As previously noted, the majority of pores in T_3x^2 and T_3x^4 are secondary pores resulting from dissolution. In essence, dissolution augments reservoir porosity and enhances reservoir quality, making it the most direct contributing factor.

During the early to middle stages of diagenesis, fluids within pores dissolve mineral particles and fragments, such as feldspar. These dissolved minerals subsequently reprecipitate within diagenetic systems in the form of authigenic minerals, such as authigenic quartz, thus creating secondary pores. However, preservation becomes challenging under the influence of compaction and cementation [32,47,51]. In late diagenesis phases, dissolution becomes the primary process enhancing the physical properties of reservoirs. Organic acids, generated by organic matter, infiltrate reservoir sandstone, utilizing pores and fractures as pathways, and interact with unstable mineral components or cuttings. This interaction results in the generation of a significant number of intergranular and intragranular dissolution pores. Secondary pores formed during this process can be well preserved, effectively improving reservoir quality [29,34,50,53]. In addition to dissolving mineral particles or rock debris, fluids also react with various cements, primarily forming intergranular pores and expanding intergranular pores. Feldspar, an essential dissolution mineral in the sandstone of the Xujiahe Formation in the Western Sichuan Depression, exhibits relatively high content in T_3x^2, leading to more developed feldspar dissolution pores in this section [43,48]. Nonetheless, overall, the development and preservation of dissolution pores in T_3x^4 are superior to those in T_3x^2, indicating that dissolution in T_3x^4 was more intensive in optimizing reservoirs [40]. Furthermore, some studies have suggested that while dissolution can increase reservoir porosity, it may also complicate pore structures and deteriorate reservoir permeability [45].

5.4.3. Tectonic Action Is an Important Factor in Improving Tight Gas Reservoirs

Since the Late Triassic, the Western Sichuan Depression has been influenced by multiple periods of regional tectonic activity, leading to the formation of the Longmenshan Structural Belt. The compression and subsequent deformations caused by this structural belt have resulted in continuous flexural deformations, creating complex geological structures within the Western Sichuan Depression. Evolutionary processes have played crucial roles in shaping the distributions of sedimentary facies and sand bodies within the Xujiahe Formation by altering sedimentary systems. The Indosinian movement during the Triassic period transformed the Sichuan Basin's sedimentary system from marine carbonate rocks into continental clastic rocks. As a result, the Xujiahe Formation strata in the Western Sichuan Depression were influenced by the interaction of sea and land, leading to the deposition of littoral shallow marine facies (T_3x^1, T_3x^3, and T_3x^5) and continental facies (T_3x^2 and T_3x^4). Consequently, the Xujiahe Formation possesses the necessary conditions for the development of tight gas sandstone reservoirs.

After the Yanshan and Himalayan movements, tectonic activity in the Western Sichuan Depression increased in frequency. This led to significant changes in the structural morphology of the area, resulting in the development of numerous faults, folds, and related structural cracks. These cracks have had a profound impact on the Xujiahe Formation. The presence of sandstone has significantly enhanced the reservoirs in the Xujiahe Formation, not only by increasing their storage capacity but also by providing effective pathways for natural gas migration, rendering it a "sweet spot" with substantial exploration and development value [30,57,58]. To better understand the relationship between fractures and tight gas reservoirs in the Xujiahe Formation in the Western Sichuan Depression, previous researchers have introduced the concept of fault–fracture bodies. They have combined the fracture characteristics of the area with the proposed fault–fold–fracture body (FFFB) concept, which represents fracture–pore connected units formed after modification by folds or faults [28]. One study classified effective fractures into fault–fold bodies, fold–fracture bodies, and fault–fracture bodies and highlighted the presence of good matrix reservoirs in the Xujiahe Formation in the Western Sichuan Depression (as introduced in the chapter on the physical properties of reservoirs). The connectivity provided by effective fractures significantly increases permeability, suggesting that two FFFBs with network fractures and single structural fractures can serve as primary "sweet spot" types.

6. Discussion

This review aims to summarize the characteristics and primary controlling factors of tight gas reservoirs in the Xujiahe Formation in the Western Sichuan Depression. It provides a systematic review and analysis of relevant research from 2008 to 2023. This chapter focuses on discussing the research findings to explore the limitations of previous studies and identify potential directions for future research.

Based on the results of the literature screening and classification, over the past 15 years, there has been a gradual increase in articles focusing on the tight gas reservoirs in the T_3x^2 and T_3x^4 sections in the Western Sichuan Depression, with the majority of these articles focusing on diagenesis research. Traditionally, the impact of diagenesis on reservoir quality has been the primary research focus in this field, particularly concerning development mechanisms and the production of various cementation types. However, limited studies have been conducted on reservoir pore space, sedimentary microfacies, faults, and other tectonic processes in the study area. Unlike conventional reservoirs, tight gas sandstone reservoirs possess more intricate microstructures, requiring the careful characterization of pore volume, throat size, microfracture development, and even mineral particle and debris contents [59]. As exploration and development processes for tight gas sandstone reservoirs have advanced, more sophisticated requirements for characterizing and describing the microstructures of tight gas reservoirs in the Xujiahe Formation in the Western Sichuan Depression have emerged. Consequently, future research needs to place greater emphasis on the influence of sedimentation and tectonic processes on reservoir pore structures [60,61].

6.1. Research on Sedimentary Systems

The T_3x^2 and T_3x^4 sections in the Western Sichuan Depression primarily represent shallow water delta sedimentary systems. These systems feature extensive underwater distributary channels and mouth bar microfacies sand bodies, which exhibit favorable physical properties and serve as the foundational elements for their classification as tight gas reservoirs. Nevertheless, current research remains deficient in terms of understanding delta sedimentation processes, including the genetic types of sand bodies, the spatial configurations of sand bodies and structural locations, and correlations between sedimentary structures formed in high hydrodynamic environments and reservoir quality. Comprehensive analyses of the shallow water delta depositional systems in the Western Sichuan Depression could not only enhance our comprehension of the reservoirs in the Xujiahe Formation but also contribute to a more comprehensive understanding of delta formation and development mechanisms [62]. The Xujiahe Formation exhibits distinctive strata characteristics, with the T_3x^2, T_3x^4, and T_3x^6 sections serving as reservoirs, while the T_3x^1, T_3x^3, and T_3x^5 sections act as hydrocarbon source rock layers. However, empirical exploration cases have demonstrated the occurrence of self-generation and self-reservoir phenomena within hydrocarbon source rock layers, as evidenced by the tight gas reservoirs in the Dayi Structure in T_3x^3 within the Western Sichuan Depression [29]. Therefore, we believe that enhanced focus on the study of fine-grained sedimentary systems in future research would likely lead to the discovery of "sweet spots".

6.2. Research on Microfractures and Fractures

The low porosity and permeability characteristics of tight gas sandstone reservoirs necessitate the involvement of effective fractures in the reservoir formation process. Previous research has highlighted that the development of fractures is the primary factor influencing the gas-bearing properties of tight gas sandstone reservoirs [63]. In the Sichuan Basin, fractures are notably well developed, with a significant presence of microfractures in reservoirs within the Xujiahe Formation in the Western Sichuan Depression, particularly in the T_3x^2 section. This abundance of microfractures has formed high-quality tight gas reservoirs, despite their poor porosity and permeability [40]. Consequently, the assessment and forecasting of fractures within tight gas sandstone reservoirs are of paramount importance. By identifying and defining effective fractures, understanding the varying impacts of fractures of different scales on reservoir modifications, and advancing fracture body theory, we can further propel the exploration of tight gas reservoirs in the future.

6.3. Research on Cementation

The influence of cementation on reservoirs has a dual effect, wherein clay minerals, particularly chlorite, can either positively or negatively alter reservoir quality during different diagenetic stages. The type, distribution, and transformation of clay minerals are intricately linked to fluid–rock interactions within the basin. Therefore, delving deeper into the attachment mechanisms and growth processes of clay minerals is crucial for a more comprehensive analysis of the impact of cementation on reservoir quality.

6.4. Research on the Relationships between Reservoirs and Fluids

In the current era of energy structure adjustment and transformation, the simulation and prediction of high-quality tight gas reservoirs has significantly influenced the discovery and exploration outcomes of tight gas reservoirs. The detailed characterization of reservoir porosity and permeability aids in understanding fluid behaviors and distributions within reservoirs. The reservoirs in the Xujiahe Formation in the Western Sichuan Depression exhibit strong fluid–rock interactions. Therefore, accurately simulating multiphase and multicomponent fluid behaviors within complex and dense environments is vital for unconventional oil and gas reservoir production. Utilizing advanced imaging technology, numerical simulation methods, deep learning, big data analysis, and other technologies to establish more precise models of pore structures and fluid behaviors in tight gas sandstone reservoirs is crucial. Scientific research endeavors in this area could significantly enhance resource extraction efficiency [64,65].

6.5. Research on Reservoir Characteristics of Different Tight Gas Fields

Influenced by the distinctive and intricate geological features of the Western Sichuan Depression, the characteristics of the tight gas sandstone reservoirs within the study area have been compared to those of other significant tight gas reservoirs, such as the Daniudi and Sulige gas fields in the northern Ordos Basin. Notably, there are discernible differences. The tight gas sandstone reservoirs in the northern Ordos Basin exhibit variations in lithology, physical properties, and pore type compared to those in the study area. Taking the reservoirs in the Shanxi Formation as an example, the average quartz content in the sandstone is notably high, reaching up to 92%, in contrast to the reservoirs in the Xujiahe Formation in the Western Sichuan Depression. Despite both formations possessing tight gas sandstone reservoirs, the quartz sandstone reservoirs prevalent in the Shanxi Formation surpass the lithic sandstone reservoirs in the study area in terms of porosity and permeability [66,67]. Furthermore, owing to the relatively gentle overall tectonic activity in the Ordos Basin, microfractures play a pivotal role in its reservoirs, with their impact being less pronounced than that of microfractures in the study area [68]. These distinctions underscore the unique characteristics of the tight gas sandstone reservoirs within the Xujiahe Formation in the Western Sichuan Depression.

In comparison to tight gas reservoirs situated in different structural locations within the Sichuan Basin, the findings from the reservoir characteristics research in the study area can offer valuable insights. For instance, in the Tongnanba gas field on the northeastern edge of the basin, tight gas reservoirs are predominantly located in the T_3x^2 and T_3x^4 underwater distributary channels, mouth bar microfacies, and delta plain subfacies. These reservoirs exhibit a notable presence of microfractures, which contribute to the development of pore spaces. Concerning physical properties, the porosity and permeability of the two gas fields demonstrate a degree of similarity, both falling within the category of extremely low porosity–low permeability to extremely low porosity–extra low permeability type. These parallels underscore potential correlations in reservoir characteristics between reservoirs in the study area and those in the Tongnanba gas field, offering a useful reference for further analysis [69,70].

6.6. Impact of Tight Gas Reservoir Characteristics Research on Actual Exploration and Development of Tight Gas Reservoirs

The study of tight gas sandstone reservoir characteristics has had a profound and guiding influence on the exploration and development of oil and gas reservoirs. This has been particularly significant in regions with extremely complex underground geologies, such as the Western Sichuan Depression. Only by continuously improving our understanding of tight gas reservoir characteristics can we achieve efficient exploration approaches. Early tight gas exploration studies in the country began in the Sichuan Basin. Moving into the 21st century, gas fields such as Xiaoquan, Hexing, and Xinchang have been successively discovered in the Western Sichuan Depression. Various oilfield companies, universities, and scientific research institutions have conducted tight gas exploration studies in the Xujiahe Formation. Through in-depth research on reservoir characteristics and more detailed investigations on the lithology, physical properties, pore structure, and other features of reservoirs, oil and gas exploration in the Xujiahe Formation in the Western Sichuan Depression has moved into the stage of large-scale production.

Using the tight gas reservoirs in T_3x^2 section of the Xinchang structural belt in the Western Sichuan Depression as a case study, the development of numerous microfractures is a significant feature, allowing the reservoirs to remain viable despite having extremely low porosity [15,40,46,63]. Scholars have extensively researched microfractures developed in reservoirs using various methods, such as imaging logging, geophysical detection, core identification, and others. They have characterized their morphology, predicted their distributions, and identified high- and stable-yielding oil and gas reservoirs, such as Hexing, Fenggu, and Xinchang, where microfractures are widely developed. The prediction of "sweet spots" has been a focal point in recent tight gas reservoir exploration [4,71]. Furthermore, previous researchers have combined effective matrix reservoirs in the Xinchang structural belt with effective fracture characteristics within the context of sedimentary facies and identified fracture, bedding, and pore sweet spots in the tight gas reservoirs in the T_3x^2 section of the Xinchang structural belt [72,73]. This advancement has greatly improved tight gas production in the Xujiahe Formation in the Western Sichuan Depression and provided directional guidance for future exploration and development.

7. Conclusions

Although previous researchers have conducted numerous studies on the characteristics of tight gas sandstone reservoirs within the Xujiahe Formation in the Western Sichuan Depression, there has been no systematic review to integrate and summarize their findings. This review adopted the PRISMA method, selecting 26 articles published within the last 15 years from Web of Science and Scopus, two mainstream databases. The discussion focused on reservoir characteristics, including lithology, physical properties, reservoir space, and main controlling factors. The findings indicate that the reservoirs in the Xujiahe Formation in the Western Sichuan Depression primarily consist of fine-grained to medium-grained lithic sandstone, feldspathic lithic sandstone, and lithic quartz sandstone, all of which demonstrate poor physical properties and pore structures. Consequently, they fall within the categories of extra-low-porosity–low-permeability or extra-low-porosity–extra-low-permeability reservoirs, with secondary pores serving as their main storage spaces. Additionally, sedimentation, diagenesis, and tectonic processes collectively play both positive and negative roles in shaping the quality of tight gas reservoirs within the Xujiahe Formation in the Western Sichuan Depression.

This systematic literature review has provided a relatively comprehensive framework for research within this field, particularly in terms of guiding future exploration and development research in the study area. The established reservoir characteristics offer a starting point for further research, focusing on sedimentary systems, fracture development, and cementation. Primary research directions for the future include the prediction and characterization of high-quality tight gas reservoirs and the identification of additional "sweet spots" for tight gas, ultimately contributing to the increased and stable production of tight gas in the Xujiahe Formation in the Western Sichuan Depression.

Author Contributions: Conceptualization, J.W. and J.Z.; methodology, J.W.; software, J.W. and Z.Y.; validation, J.W., J.Z., and Z.Y.; formal analysis, J.W.; investigation, J.W. and Z.Y.; data curation, Z.Y.; writing—original draft preparation, J.W.; writing—review and editing, J.Z. and Z.Y.; supervision, J.Z.; project administration, J.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This study was supported by The "14th Five Year Plan" Prospective Basic Science and Technology Project, China National Petroleum Corporation (Grant Nos. 2021DJ2101).

Data Availability Statement: Data sharing is not applicable to this article.

Acknowledgments: We would like to thank the reviewers for their professional review work, constructive comments, and valuable suggestions on our manuscript.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Li, D. Brief introduction to low-permeability oilfield development. *Pet. Geol. Oilfield Dev. Daqing* **1997**, *3*, 36–40.
2. Holditch, S.A. Tight gas sands. *J. Pet. Technol.* **2006**, *58*, 86–93. [CrossRef]
3. Zou, C.; Tao, S.; Yuan, X.; Zhu, R.; Dong, D.; Wei, L.; Lan, W.; Gao, X.; Gong, Y.; Jia, J. Global importance of "continuous" petroleum reservoirs: Accumulation, distribution and evaluation. *Pet. Explor. Dev.* **2009**, *36*, 669–682.
4. Dai, J.; Ni, Y.; Wu, X. Tight gas in China and its significance in exploration and exploitation. *Pet. Explor. Dev.* **2012**, *39*, 277–284. [CrossRef]
5. Li, J.; Guo, B.; Zheng, M.; Yang, T. Main types, geological features and resource potential of tight sandstone gas in China. *Nat. Gas Geosci.* **2012**, *23*, 607–615.
6. Tong, X.; Guo, B.; Li, J.; Huang, F. Comparison study on accumulation & distribution of tight sandstone gas between China and the United States and its significance. *Eng. Sci.* **2012**, 6. [CrossRef]
7. Li, J.; Wei, G.; Xie, Z.; Liu, R.; Hao, A. Accumulation mechanism and main controlling factors of large tight sandstone gas fields in China: Cases study on Ordos Basin and Sichuan Basin. *Acta Pet. Sin.* **2013**, *34*, 14.
8. Zhang, D. Development prospect of natural gas industry in the Sichuan Basin in the next decade. *Nat. Gas Ind. B* **2022**, *9*, 119–131. [CrossRef]
9. Yang, Y.; Wen, L.; Zhou, G.; Zhan, W.; Li, H.; Song, Z.; Zhang, J.; Tao, J.; Tian, X.; Yuan, J.; et al. New fields, new types and resource potentials of hydrocarbon exploration in Sichuan Basin. *Acta Pet. Sin.* **2023**, *44*, 2045.
10. Surdam, R.C.; Jiao, Z.S.; Martinsen, R.S. The regional pressure regime in Cretaceous sandstones and shales in the Powder River Basin. In *Basin Compartments and Seals*; American Association of Petroleum Geologists: Tulsa, OK, USA, 1994.
11. Liu, H.; Liang, H.; Cai, L.; Shen, F. Structural styles of the Longmenshan thrust belt and evolution of the foreland basin in western Sichuan Province, China. *Acta Geol. Sin.* **1994**, *68*, 101–118.
12. Jia, D.; Chen, Z.; Jia, C.; Wei, G.; Li, B.; Zhang, X.; Wei, D.; Shen, Y. Structural features of the Longmen Shan fold and thrust belt and development of the western Sichuan foreland basin, central China. *Geol. J. China Univ.* **2003**, *9*, 402.
13. Li, Z.; Liu, S.; Lin, J.; Tang, C.; Deng, B.; Sun, W. Structural configuration and its genetic mechanism of the West Sichuan Depression in China. *J. Chengdu Univ. Technol.* **2009**, *36*, 645–653.
14. Liu, S.; Yang, Y.; Deng, B.; Zhong, Y.; Wen, L.; Sun, W.; Li, Z.; Jansa, L.; Li, J.; Song, J.; et al. Tectonic evolution of the Sichuan basin, southwest China. *Earth-Sci. Rev.* **2021**, *213*, 103470. [CrossRef]
15. Liu, S.; Ren, X.; Yao, S.; Liu, Z.; Ning, M.; Wang, X.; Huang, X. Relationship between gas reservoir distribution and structural system of Upper Triassic Xujiahe Fm in the Sichuan Basin. *Nat. Gas Ind. B* **2019**, *6*, 220–235. [CrossRef]
16. Zheng, H. New advances in petroleum geology and exploration techniques of clastic reservoirs in the four large-sized basins in central-western China. *Oil Gas Geol.* **2012**, *33*, 497–505.
17. Zhao, M.; Yang, W.; Wang, Y.; Lu, J.; Xu, L.; Li, L.; Li, X.; Yao, L. Distribution and genetic mechanisms of connected pore systems in continental shale reservoirs: A case study of Xujiahe Formation of Upper Triassic, Western Sichuan Depression. *Pet. Geol. Exp.* **2022**, *44*, 170–179.
18. Wu, X.; Zhou, X.; Chen, Y.; Wang, P.; Wang, Y.; Yang, J.; Zeng, H. Molecular characteristics of source rocks in Upper Triassic Xujiahe Formation, Western Sichuan Depression, Sichuan Basin. *Pet. Geol. Exp.* **2022**, *44*, 854–865.
19. Mahjour, S.K.; Faroughi, S.A. Risks and uncertainties in carbon capture, transport, and storage projects: A comprehensive review. *Gas Sci. Eng.* **2023**, *119*, 205117. [CrossRef]

20. Mahjour, S.K.; Santos, A.A.S.; Correia, M.G.; Schiozer, D.J. Scenario reduction methodologies under uncertainties for reservoir development purposes: Distance-based clustering and metaheuristic algorithm. *J. Pet. Explor. Prod. Technol.* **2021**, *11*, 3079–3102. [CrossRef]
21. Chapman, A.L.; Morgan, L.C.; Gartlehner, G. Semi-automating the manual literature search for systematic reviews increases efficiency. *Health Inf. Libr. J.* **2010**, *27*, 22–27. [CrossRef]
22. Haddaway, N.R.; Pullin, A.S. The Policy Role of Systematic Reviews: Past, Present and Future. *Springer Sci. Rev.* **2014**, *2*, 179–183. [CrossRef]
23. Haddaway, N.R.; Woodcock, P.; Macura, B.; Collins, A. Making literature reviews more reliable through application of lessons from systematic reviews. *Conserv. Biol.* **2015**, *29*, 1596–1605. [CrossRef] [PubMed]
24. Sriganesh, K.; Shanthanna, H.; Busse, J.W. A brief overview of systematic reviews and meta-analyses. *Indian J. Anaesth.* **2016**, *60*, 689–694. [CrossRef]
25. Moher, D.; Liberati, A.; Tetzlaff, J.; Altman, D.G.; The PRISMA Group. Preferred Reporting Items for Systematic Reviews and Meta-Analyses: The PRISMA Statement. *J. Clin. Epidemiol.* **2009**, *62*, 1006–1012. [CrossRef] [PubMed]
26. Page, M.J.; McKenzie, J.E.; Bossuyt, P.M.; Boutron, I.; Hoffmann, T.C.; Mulrow, C.D.; Shamseer, L.; Tetzlaff, J.M.; Akl, E.A.; Brennan, S.E.; et al. The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. *J. Clin. Epidemiol.* **2021**, *134*, 178–189. [CrossRef]
27. Ouzzani, M.; Hammady, H.; Fedorowicz, Z.; Elmagarmid, A. Rayyan—A web and mobile app for systematic reviews. *Syst. Rev.* **2016**, *5*, 210. [CrossRef]
28. Liu, J.; Liu, Z.; Liu, Z.; Liu, Y.; Shen, B.; Xiao, K.; Bi, Y.; Wang, X.; Wang, A.; Fan, L.; et al. Geological characteristics and models of fault-fold-fracture body in deep tight sandstone of the second member of Upper Triassic Xujiahe Formation in Xinchang structural belt of Sichuan Basin, SW China. *Pet. Explor. Dev.* **2023**, *50*, 603–614. [CrossRef]
29. Guo, Y.; Sima, L.; Wang, L.; Miao, X.; Li, A.; Su, S. Saturation evaluation of tight sandstone in the Dayi structure, West Sichuan Depression. *Front. Earth Sci.* **2023**, *11*, 1223997. [CrossRef]
30. Duan, Z.; Liu, Y.; Lou, Z.; Liu, Z.; Xu, S.; Wu, Y. Tight gas accumulation caused by overpressure: Insights from three-dimensional seismic data in the western Sichuan Basin, Southwest China. *Geoenergy Sci. Eng.* **2023**, *223*, 211589. [CrossRef]
31. Yu, Y.; Lin, L.; Li, Z.; Rankenburg, K.; Evans, N.J.; McInnes, B.I.A. LA-ICP-MS U–Pb dating of calcite cement in Upper Triassic tight-gas sandstone reservoirs, western Sichuan Basin, SW China. *Terra Nova* **2022**, *34*, 359–368. [CrossRef]
32. Ma, J.; Ma, Z.; Miao, J.; Zheng, L.; Wang, Q.; He, C. Co-evolution simulation experiment of source rock fluid and reservoir rock and its geological implications: A case study of Upper Triassic Xujiahe Formation, Western Sichuan Basin. *Pet. Geol. Exp.* **2022**, *44*, 698–704.
33. Yu, Y.; Lin, L.; Li, Z.; Chen, H. Source of quartz cement in tight gas sandstone: Evidence from the Upper Triassic Xujiahe Formation in the western Sichuan Basin, SW China. *J. Pet. Sci. Eng.* **2022**, *212*, 110299. [CrossRef]
34. Pan, B.; Chen, H.; Lin, L.; Yu, Y.; Wu, D.; Dong, Y. Diagenesis and reservoir quality of the second member of the Upper Triassic Xujiahe Formation tight gas sandstones in the Western Sichuan Depression, southwest China. *Geol. J.* **2021**, *56*, 3187–3206. [CrossRef]
35. Feng, D.; Xiao, K. Constant velocity mercury injection and nuclear magnetic resonance in evaluation of tight sandstone reservoirs in Western Sichuan Basin. *Pet. Geol. Exp.* **2021**, *43*, 368–376.
36. Cheng, W.; Ba, J.; Carcione, J.M.; Pang, M.; Wu, C. Estimation of the Pore Microstructure of Tight-Gas Sandstone Reservoirs with Seismic Data. *Front. Earth Sci.* **2021**, *9*, 646372. [CrossRef]
37. Ren, J.; Lv, Z.; Wang, H.; Wu, J.; Zhang, S. The Origin of Quartz Cement in the Upper Triassic Second Member of the Xujiahe Formation Sandstones, Western Sichuan Basin, China. *Water* **2021**, *13*, 1890. [CrossRef]
38. Yang, P.; Zhang, L.; Liu, K.; Cao, B.; Gao, J.; Qiu, G. Diagenetic history and reservoir evolution of tight sandstones in the second member of the Upper Triassic Xujiahe Formation, Western Sichuan Basin, China. *J. Pet. Sci. Eng.* **2021**, *201*, 108451. [CrossRef]
39. Huang, Y.; Liu, Z.; Li, P.; Liu, J.; Liao, C.; Xu, S. Analysis of lithofacies and evaluation of effective reservoirs of member 2 of Xujiahe Formation in the Xinchang area in Western Sichuan. *Pet. Res.* **2020**, *5*, 244–253. [CrossRef]
40. Wang, Q.; Chen, D.; Gao, X.; Wang, F.; Li, J.; Liao, W.; Wang, Z.; Xie, G. Microscopic pore structures of tight sandstone reservoirs and their diagenetic controls: A case study of the Upper Triassic Xujiahe Formation of the Western Sichuan Depression, China. *Mar. Pet. Geol.* **2020**, *113*, 104119. [CrossRef]
41. Wu, F.; Wen, Z.; Yao, C.; Wang, X.; Xi, Y.; Cong, L. Numerical Simulation of the Influence of Pore Structure on Resistivity, Formation Factor and Cementation Index in Tight Sandstone. *Acta Geol. Sin. Engl. Ed.* **2020**, *94*, 290–304. [CrossRef]
42. Zhong, Y.-J.; Huang, K.-K.; Ye, L.-M.; Lan, Y.-F.; Liu, L. Diagenesis of tight sandstone reservoirs of Xujiahe Formation (Upper Triassic), the Xinchang Gas Field, western Sichuan Basin, China. *Geol. J.* **2020**, *55*, 4604–4624. [CrossRef]
43. Yu, Y.; Lin, L.; Zhai, C.; Chen, H.; Wang, Y.; Li, Y.; Deng, X. Impacts of lithologic characteristics and diagenesis on reservoir quality of the 4th member of the Upper Triassic Xujiahe Formation tight gas sandstones in the western Sichuan Basin, Southwest China. *Mar. Pet. Geol.* **2019**, *107*, 1–19. [CrossRef]
44. Li, M.; Zhu, R.; Lou, Z.; Yin, W.; Hu, Z.; Zhu, H.; Jin, A. Diagenesis and its impact on the reservoir quality of the fourth member of Xujiahe Formation, Western Sichuan Depression, China. *Mar. Pet. Geol.* **2019**, *103*, 485–498. [CrossRef]
45. Li, M.; Lou, Z.; Gong, Y.; Jin, A.; Zhu, R. Diagenesis factor that effect the reservoir properties and gas accumulation in the 4th member of Xujiahe formation, Western Sichuan Basin, China. *Pet. Sci. Technol.* **2019**, *37*, 551–558. [CrossRef]

46. Yue, D.; Wu, S.; Xu, Z.; Xiong, L.; Chen, D.; Ji, Y.; Zhou, Y. Reservoir quality, natural fractures, and gas productivity of upper Triassic Xujiahe tight gas sandstones in Western Sichuan Basin, China. *Mar. Pet. Geol.* **2018**, *89*, 370–386. [CrossRef]
47. Liu, S.; Chen, A.; Shen, Z.; Lv, Z.; Zhang, X. Fluid-rock interaction and dissolution of feldspar in the Upper Triassic Xujiahe tight sandstone, western Sichuan Basin, China. *Open Geosci.* **2018**, *10*, 234–249. [CrossRef]
48. Gong, L.; Zeng, L.; Gao, Z.; Zhu, R.; Zhang, B. Reservoir characterization and origin of tight gas sandstones in the Upper Triassic Xujiahe formation, Western Sichuan Basin, China. *J. Pet. Explor. Prod. Technol.* **2016**, *6*, 319–329. [CrossRef]
49. Song, H.; Ji, Y.; Zhou, Y.; Chen, X.; Zhao, C.; Dong, R.; Yang, Y. Reservoir Characteristics and Control Factors of the 4th Member of Xujiahe Formation in The Middle Part of Western Sichuan Depression. *Acta Geol. Sin.* **2015**, *89*, 77–78. [CrossRef]
50. Chen, D.; Pang, X.; Xiong, L.; Wang, L.; Xie, M. Porosity evolution in tight gas sands of the Upper Triassic Xujiahe Formation, western Sichuan basin, China. *Rev. Mex. Cienc. Geol.* **2014**, *31*, 361–375.
51. Liu, S.; Huang, S.; Shen, Z.; Lu, Z.; Song, R. Diagenetic fluid evolution and water-rock interaction model of carbonate cements in sandstone: An example from the reservoir sandstone of the Fourth Member of the Xujiahe Formation of the Xiaoquan-Fenggu area, Sichuan Province, China. *Sci. China-Earth Sci.* **2014**, *57*, 1077–1092. [CrossRef]
52. Zeng, L. Microfracturing in the Upper Triassic Sichuan Basin tight-gas sandstones: Tectonic, overpressure, and diagenetic origins. *AAPG Bull.* **2010**, *94*, 1811–1825. [CrossRef]
53. Xu, Z.; Zhang, X.; Wu, S.; Zhao, Y. Genesis of the low-permeability reservoir bed of upper Triassic Xujiahe Formation in Xinchang gas field, Western Sichuan Depression. *Pet. Sci.* **2008**, *5*, 230–237. [CrossRef]
54. Folk, R.L. *Petrology of Sedimentary Rocks*; Hemphill's The University of Texas: Austin, TX, USA, 1968.
55. Jianfeng, S.; Chunsong, S.; Xin, W. Genesis Types and Diagenesis Compaction Mechanisms of Sandstone Rreservoirs in Dynamic Environments in Oil/Gas Basins in China. *Pet. Sci.* **2006**, *3*, 23–31.
56. Rong, L.; Di, Z.; Zhu, L. Densification of Upper Triassic Xujiahe tight sandstones, Western Sichuan, China. *Pet. Geol. Exp.* **2011**, *33*, 274–281.
57. Zhu, H.; Liu, L.; Huang, Z.; Fan, X.; Zhang, J. Reservoir engineering geological characteristics and stimulation in Xujiahe Formation, Xinchang gas field, Western Sichuan Depression, Sichuan Basin. *Oil Gas Geol.* **2021**, *42*, 1002–1010.
58. He, F.; Liang, C.; Lu, C.; Yuan, C.; Li, X. Identification and description of fault-fracture bodies in tight and low permeability reservoirs in transitional zone at the south margin of Ordos Basin. *Oil Gas Geol.* **2020**, *41*, 710–718.
59. Zhu, X.; Pan, R.; Zhu, S.; Wei, W.; Lei, Y.E. Research progress and core issues in tight reservoir exploration. *Earth Sci. Front.* **2018**, *25*, 141.
60. Mustafa, A.; Mahmoud, M.A.; Abdulraheem, A. A review of pore structure characterization of unconventional tight reservoirs. In Proceedings of the Abu Dhabi International Petroleum Exhibition and Conference, Abu Dhabi, United Arab Emirates, 11–13 November 2019; p. D031S098R001.
61. Lai, J.; Wang, G.; Wang, Z.; Chen, J.; Pang, X.; Wang, S.; Zhou, Z.; He, Z.; Qin, Z.; Fan, X. A review on pore structure characterization in tight sandstones. *Earth-Sci. Rev.* **2018**, *177*, 436–457. [CrossRef]
62. Shi, Z.; Zhu, X.; Zhang, Y.; Jin, H. Advances and trending topics in sedimentary reservoir research of the Upper Triassic Xujiahe Formation, Sichuan Basin. *Oil Gas Geol.* **2021**, *42*, 784–800.
63. Ding, W.; Wang, X.; Hu, Q.; Shuai, Y.; Cao, X.; Liu, J. Progress in tight sandstone reservoir fractures research. *Adv. Earth Sci.* **2015**, *30*, 737.
64. Zhang, T.; Li, Y.; Li, Y.; Sun, S.; Gao, X. A self-adaptive deep learning algorithm for accelerating multi-component flash calculation. *Comput. Methods Appl. Mech. Eng.* **2020**, *369*, 113207. [CrossRef]
65. Zhang, T.; Zhang, Y.; Katterbauer, K.; Al Shehri, A.; Sun, S.; Hoteit, I. Deep learning–assisted phase equilibrium analysis for producing natural hydrogen. *Int. J. Hydrogen Energy* **2024**, *50*, 473–486. [CrossRef]
66. Li, G.; Chen, Y.; Jia, H.; Zhao, Y.; Xie, R.; Liu, S.; Li, L. Occurrence and distribution characteristics of fluids in tight sandstone reservoirs in the Shilijiahan zone, Northern Ordos Basin. *Nat. Gas Ind. B* **2017**, *4*, 174–181. [CrossRef]
67. Xu, J.; Yu, C.; Qi, D.; Yang, R.; Yu, H.; Zhang, W.; Wang, T. Characteristics and Controlling Factors of Tight Gas Sandstones from the Upper Shanxi and Lower Shihezi Formations in the Northern Sulige Area, Ordos Basin, China. *Energy Fuels* **2023**, *37*, 15712–15729. [CrossRef]
68. Hao, S.; Li, L.; Zhang, W.; Qi, R.; Chen, J. Forming conditions of large-scale gas fields in Permo-Carboniferous in the northern Ordos Basin. *Oil Gas Geol.* **2016**, *37*, 149–154.
69. Li, W.; Zhang, Z.; Zhang, H.; Zhao, S.; Yan, H.; Liu, X. Hydrocarbon source and accumulation in Upper Triassic to Lower Jurassic in the Tongnanba area, Northeastern Sichuan Basin. *Arab. J. Geosci.* **2015**, *8*, 2515–2525. [CrossRef]
70. Cao, H.; Wang, W.; Liu, M. Characteristics of fractures in Xujiahe Formation of Tongnanba structural belt, Northeastern Sichuan Basin. *Xinjiang Pet. Geol.* **2018**, *4*, 424–429.
71. Zou, C.; Yang, Z.; He, D.; Wei, Y.; Li, J.; Jia, A.; Chen, J.; Zhao, Q.; Li, Y.; Li, J.; et al. Theory, technology and prospects of conventional and unconventional natural gas. *Pet. Explor. Dev.* **2018**, *45*, 604–618. [CrossRef]

72. Liu, J.; Hu, Z.; Liu, Z.; Jin, Q.; Xiao, K.; Bi, Y.; Li, J. Gas pool sweet spot models and their forming mechanism in the xu 2 member in Xinchang area, Western Sichuan Depression, Sichuan Basin. *Oil Gas Geol.* **2021**, *42*, 852–862.
73. Zheng, R.; Ye, T.; Zhai, W.; Dai, C.; Gao, H. Prediction of sandbody distribution in the upper triassic Xujiahe Formation, the West Sichuan depression. *Oil Gas Geol.* **2008**, *29*, 405–411.