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Formation mechanisms of deeply buried marine dolostone reservoirs: A review

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Abstract

Deeply buried dolostone reservoirs have become a key exploration focus in recent years. However, there are debates regarding reservoir classification and dissolution mechanisms. This paper conducts a statistical analysis of deep dolostone reservoirs, summarizing aspects such as reservoir classification, dissolution mechanisms, and microbialite reservoirs. Based on depositional environments, deep to ultra-deep dolostone reservoirs worldwide are classified into ramp and platform facies. According to dolomitization mechanisms, deep to ultra-deep dolostone reservoirs are divided into three types: near-surface evaporation-reflux dolomitization, hydrothermal dolomitization, and multiphase dolomitization reservoirs. Key factors controlling the development of deep dolostone reservoirs include depositional environments, diagenesis (e.g., meteoric water dissolution, hydrocarbon emplacement, and deep dissolution processes) and tectonic activities. Clotted structures formed in high-energy depositional environments exhibit better physical properties, while stromatolites and laminates formed in low-energy depositional environments have poorer physical properties. Microbialite structures significantly influence pore types and structures. Deep dissolution mechanisms include hydrothermal activity, thermochemical sulfate reduction, and dedolomitization. This study is of great significance for those concerned with the exploration potential of deep dolostone reservoirs.

Key words: **Deep burial, dolostone reservoir, sedimentary environment, diagenesis, microbialite**

1 Introduction

Deep to ultra-deep (>4500 m) carbonate reservoirs represent a frontier domain in hydrocarbon exploration, with significant resource potential. Globally, deep carbonate sequences primarily occur in the Paleozoic–Mesozoic, with some in the Precambrian, and are predominantly composed of dolostone.

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Notably, over 90% of hydrocarbon reservoirs in 46 pre-Silurian carbonate oil fields are hosted within dolostone formations (Sun, 1995). Even so, the genesis of deep dolostone reservoirs remains a subject of ongoing debate. Conventional carbonate diagenetic models suggest a progressive reduction in porosity with increasing burial depth, with median values approximating 5% at 5000–6000 m (Halley and Schmoker, 1983). However, deeply buried dolostone reservoirs from the Tarim and Sichuan Basins can maintain porosities of 10–20% (Cai et al., 2014; Jiang et al., 2019), challenging classical paradigms of carbonate reservoir evolution. While extensive research has been conducted on the formation mechanisms of shallow and intermediate depth dolostones (Machel, 2004), systematic investigations on the origin and preservation of deep dolostone reservoirs on a global scale remain insufficient. Existing classifications of marine carbonate reservoirs in China (Zhao et al., 2012)—comprising depositional, diagenetic, and reworked types—have not comprehensively address the unique characteristics of ultra-deep dolostone reservoirs.

The formation mechanisms of high-quality deep carbonate reservoirs remain a subject of debate. On the one hand, reservoir development is primarily related to early-stage processes, including depositional facies, dolomitization, and meteoric water dissolution, with deep burial environments relatively closed and carbonate minerals in equilibrium with pore fluids, thereby limiting large-scale dissolution while promoting cementation and porosity reduction (Ehrenberg et al., 2007; Machel and Buschkuehle, 2008; Bjørlykke and Jahren, 2012; Hao et al., 2015). But, on the other hand, an alternative hypothesis suggests that deep burial conditions facilitate the influx of organic acids from hydrocarbon source rocks, deep hydrothermal fluids, or hydrocarbons, which destabilize carbonate minerals and induce secondary porosity formation, contributing to the development of high-quality reservoirs (Heydari and Moore, 1989; Jiang et al., 2014, 2017; Biehl et al., 2016; Jia et al., 2016; Hu et al., 2020a, 2020b, 2022, 2023a, 2023b). Furthermore, experimental and numerical modeling studies indicate that thermochemical sulfate reduction (TSR) may generate additional reservoir space under deep burial conditions (Fu et al., 2016; Jiang et al., 2018). The key unresolved question remains whether deep dolostone reservoirs primarily inherit and preserve their porosity from early diagenesis or whether late-stage fluid activity plays a dominant role in generating secondary porosity within initially dense dolostones.

Microbial dolostone is a distinct type of biogenic rock formed through interactions between benthic microbial communities and their surrounding environment (Burne and Moore, 1987). Microbial carbonates are widely distributed throughout geological history and can serve as high-quality hydrocarbon reservoirs (Luo et al., 2013). Globally, several oil fields have identified microbial carbonate reservoir intervals with significant hydrocarbon potential, including the Little Cedar Creek and Appleton oil fields in Alabama, USA, as well as the pre-salt oil fields in the Santos Basin, Brazil. Most microbial carbonates are developed within relatively old stratigraphic units. With advancements in deep exploration technologies, deeply buried and geologically ancient microbial carbonates are increasingly becoming a key target for hydrocarbon exploration.

To address these issues, this study integrates global case studies of deep dolostone reservoirs and reclassifies them based on their petrophysical characteristics. Furthermore, it systematically analyzes the evolution of deep dolostone reservoir properties with burial depth and identifies the primary controlling factors. In addition, by examining typical microbial carbonate hydrocarbon fields, this study evaluates the impact of microbial carbonate structures on reservoir quality. Finally, the exploration potential of deep to ultra-deep carbonate hydrocarbon reservoirs is discussed.

2 Classification of deep-burial dolostone reservoirs

Deep to ultra-deep dolostone reservoirs can be classified into two main types based on depositional environments. Ramp-type reservoirs include examples such as the Ediacaran in South Oman

Basin (Grotzinger and Al-Rawahi, 2014), the Cambrian Longwangmiao Formation in the Sichuan Basin, China, and the Carboniferous Smackover Formation in the Gulf of Mexico, USA. Platform-type reservoirs are more widespread and include the Precambrian dolostones of the Siberia Basin, Russia (Frolov et al., 2015); the Ediacaran Dengying Formation in the Sichuan Basin, China (Hu et al., 2020a, 2020b); the Cambrian Bonneterre Formation in Missouri, USA (Greg and Shelton, 1993); the Cambrian–Ordovician reservoirs in the Tarim Basin, China; the Ordovician Ellenburger Formation in West Texas, USA (Amthor and Friedman, 1991); the Permian reservoirs of the Lower Saxony Basin, Germany (Biehl et al., 2016); and the Permian–Triassic reservoirs in the Sichuan Basin, China (Jiang et al., 2014). Additionally, a limited number of dolostone reservoirs have been identified in deep-water slope settings.

Deep to ultra-deep dolostone reservoirs can be classified into three types based on dolomitization mechanisms (Table 1). Evaporative-reflux dolostone reservoirs form near the surface due to evaporation-driven reflux, with examples including the Precambrian dolostones of the Siberia Basin, Russia; the Ediacaran in South Oman Basin; the Permian–Triassic reservoirs in the Sichuan Basin, China; the Permian and Carboniferous reservoirs in the Gulf of Mexico, USA (Heydari, 1997, 2003); and the Jurassic in Abenaki Basin in Canada (Wierzbicki et al., 2006). Hydrothermal dolostone reservoirs result from high-temperature fluid circulation and are represented by the Cambrian Bonneterre Formation in southeastern Missouri, USA, and the Permian reservoirs of the Lower Saxony Basin, Germany. Multiphase dolostone reservoirs undergo multiple dolomitization events over geological time and include the Ediacaran Dengying Formation in the Sichuan Basin, China; the Cambrian Longwangmiao Formation in the Sichuan Basin, China (Fu et al., 2020); the Cambrian–Ordovician reservoirs in the Tarim Basin, China (Jiang et al., 2018); and the Ordovician Ellenburger Formation in West Texas, USA (Kerans, 1988).

In terms of genesis, considering the influence of depositional environment and diagenesis on reservoir modification, deep dolostone reservoirs can be classified into several types (Table 2), including clotted microbial reef-shoal reservoirs, thick-cycle grain shoal reservoirs, platform-margin fault zone reservoirs, dolostone interlayers within limestone, and evaporite-associated dolostone reservoirs.

3 The evolution and mechanisms of dolostone reservoirs during burial

The classic model of porosity evolution in dolostone reservoirs with increasing burial depth suggests that the initial sediment porosity is approximately 40–50%. As burial depth increases, porosity continuously decreases due to destructive processes such as cementation and compaction. When the burial depth reaches 5,000–6,000 m, porosity typically falls below 10%. However, geological case studies indicate that some deeply buried dolostone reservoirs can retain porosity levels of 10–20%. Based on relevant examples, the key controlling factors in the evolution of high-quality deep dolostone reservoir properties include:

(I) Depositional Environment: High-energy depositional settings, such as reef-shoal facies, tend to have relatively high initial porosity and high permeability. In contrast, low-energy environments, such as lagoonal subfacies, may also exhibit high initial porosity but significantly lower permeability (Saller and Vijaya, 2002; Rezende et al., 2013). The latter is more susceptible to compaction and pressure dissolution during burial, leading to a rapid decline in porosity and permeability, which is unfavorable for reservoir development.

(II) During the syndepositional or early diagenetic stage, meteoric water dissolution plays a crucial role in modifying reservoir properties by creating secondary pore space. Petrographic evidence, such as intraparticle dissolution pores, interparticle pores, crescent-shaped cement, and percolation sand deposits, has been observed in formations like the Triassic reservoirs of the Sichuan Basin and the Khuff Formation in the Middle East (Ehrenberg et al., 2006). Extended subaerial exposure can lead to the formation of dissolution caves, which may later collapse, resulting in brecciated carbonates (Loucks, 1999). Geochemical indicators, including negative carbon isotope excursions and decreased strontium concentrations at the tops of fourth- to fifth-order cycles (e.g., Latemar Platform, Triassic (Christ et al., 2012)), further support the influence of meteoric diagenesis. These isotopic shifts are attributed to terrestrial vegetation-derived CO_2 input and reduced organic matter burial, allowing ^{12}C-enriched CO_2 to enter the inorganic carbon pool. Meanwhile, Sr depletion is linked to the lower Sr concentration in meteoric water compared to seawater, as well as the transformation of unstable aragonite to calcite, leading to Sr loss from the sediment.

(III) Dolomitization plays a critical role in enhancing deep carbonate reservoir quality by increasing porosity and improving mechanical stability. Statistical analyses demonstrate that deep-buried dolostone generally retains higher porosity than limestone due to isovolumetric dolomitization, which can increase porosity by up to 13% (Machel, 2004). Evidence from the Lower Saxony Basin, Germany, suggests that dolomitizing fluids significantly enhance rock porosity when passing through limestone (Biehl et al., 2016). Additionally, experimental studies indicate that acidic fluids improve the reservoir properties of dolostone more effectively than limestone. Dolomitization has been a key process in formation of high-quality reservoirs, such as the Cambrian dolostone reservoirs in the Tarim Basin (Jiang et al., 2018) and the Ediacaran microbial dolostone reservoirs in Oman (Grotzinger and Al-Rawahi, 2014). Moreover, dolostone's greater resistance to compaction and pressure solution reduces cementation effects, whereas limestone is more susceptible to pressure dissolution, which negatively impacts reservoir quality.

(IV) Hydrocarbon Migration: When hydrocarbons charge into carbonate reservoirs, the original pore water is displaced by oil and gas. This hydrocarbon-dominated environment inhibits the nucleation of hydrophilic minerals, thereby preserving pore spaces (Cox et al., 2010). The relatively high porosity (approximately 4%) of dolostone above the oil-water contact in Well Lin-1 and the Liaojiapo section (Deng-4 Member) indicates that hydrocarbon migration has played a crucial role in the development of high-quality reservoirs in the Dengying Formation (Liu et al., 2016).

(V) Organic Acid Dissolution: Organic acids generated during the maturation of source rocks were once considered a major driver of secondary porosity formation during the middle to late diagenetic stage (Cai et al., 1997). However, given the limited production of organic acids and their potential depletion during migration, it is unlikely that a significant volume of carbonate minerals could be dissolved solely due to the influence of organic acids entering the reservoir.

(VI) Deep burial dissolution in carbonate rocks: It remains a controversial issue in reservoir studies. On the one hand, in a closed deep burial environment, the low water-rock ratio is not conducive to dissolution but rather favors precipitation (Halley and Schmoker, 1983). For example, in the Sichuan Basin, deep burial dissolution of Permian-Triassic carbonates primarily formed in near-surface depositional-diagenetic settings, whereas deeper burial environments mainly preserved existing porosity (Hao et al., 2015). Conversely, previous studies (Ma et al., 2008) proposed that under acidic conditions, $MgSO_4$ ion pairs and HSO_4^- react with ethane with relatively low free energy. Based on this, and that deeply buried dolostone often forms high-quality reservoirs while coeval deeply buried limestone exhibits poor reservoir properties, it has been suggested that dolomite and anhydrite undergo thermochemical sulfate reduction (TSR) reactions with hydrocarbons in aqueous environments, leading to dissolution and calcite replacement. This mechanism has been attributed to the formation of up to 25% porosity in the Changxing and Feixianguan formations in eastern Sichuan Basin. In-situ Raman analyses (Wang et al., 2013) further demonstrated that at high temperatures, SO_4^{2-} and Mg^{2+} extensively complex, resulting in liquid phase separation, confirming the formation of sulfate-magnesium complex-

Table 1 The classification of sedimentary facies for the deep-burial dolostone reservoirs

Type	Case study	Details
Ramp-type	Ediacaran microbialites in the South Oman Basin, Oman	The Ediacaran reservoirs in the South Oman Basin, Oman, are buried at depths ranging from 3,000 to 7,000 m and are primarily composed of microbialites. The dominant reservoir spaces include microbial framework pores, intercrystalline pores, and intergranular pores. The porosity of these reservoirs ranges from 0.4% to 23%, while permeability varies from 0.01 to 313 × $10^{-3}\mu m^2$.
	Cambrian Longwangmiao Formation in the Sichuan Basin, China	In the deeply buried carbonate strata (4,500–8,600 m) of the Cambrian Longwangmiao Formation in the Sichuan Basin, large-scale oil and gas fields have been continuously discovered. The porosity of the Longwangmiao Formation reaches up to 18%, with an average of approximately 6–8%, while permeability can reach 180 × $10^{-3}\mu m^2$.
	Carboniferous Smackover Formation in the Gulf of Mexico, USA	In the Gulf of Mexico Basin, the Carboniferous Smackover Formation was deposited in a carbonate ramp setting and is primarily composed of oolitic dolostone. The reservoir porosity is generally less than 20%, with a maximum permeability of 100 × $10^{-3}\mu m^2$. The formation is buried at depths of up to 6,000 m, with a burial temperature of approximately 200 °C.
Platform-type	Precambrian in Siberia Basin, Russia	The Precambrian dolostone reservoirs in the Siberia Basin, Russia, are buried at depths reaching 11,000 m. The primary reservoir spaces consist of fractures and dissolution pores, with porosity and permeability reaching 14% and 1000 mD, respectively. The proven hydrocarbon reserves currently amount to 250 million tons of crude oil and 100 million cubic meters of natural gas.
	Ediacaran Dengying Formation, Sichuan Basin, China	The Dengying Formation in the Sichuan Basin is a dolostone reservoir buried at a depth of approximately 5–6 km. The primary reservoir spaces consist of secondary dissolution pores and fractures, with well-developed intercrystalline and interparticle pores. The dominant porosity range is between 2% and 5%.
	Cambrian–Ordovician, Tarim Basin, China	The Cambrian–Ordovician interval in the Tarim Basin hosts thick dolostone reservoirs buried at depths of up to 8 km. The primary reservoir spaces consist of secondary dissolution vugs and fractures, with porosity and permeability exhibiting significant variability.
	Permian–Triassic, Sichuan Basin, China	The Lower Triassic Feixianguan Formation in the eastern Sichuan region contains a large natural gas reservoir buried at depths of up to 7,000 m, with high H_2S content. The reservoir consists of high-quality oolitic dolostone, residual oolitic dolostone, and crystalline dolostone. In northeastern Sichuan, the Feixianguan Formation reservoir has an average permeability of 180 × $10^{-3}\mu m^2$.
	Ordovician Ellenburger Formation, West Texas, USA	The Ordovician Ellenburger Formation in West Texas was deposited in a carbonate platform setting, with a maximum burial depth of up to 7,000 m. The primary reservoir spaces consist of moldic pores, dissolution vugs, and intercrystalline pores. The maximum effective porosity can reach 12%, with an average porosity of 3.4%.
	Cambrian Bonneterre Formation, Southeastern Missouri, USA	The Cambrian Bonneterre Formation in Missouri was deposited in a carbonate platform setting, with lithologies primarily consisting of microbialites and oolitic dolostone. The porosity is 3.5% ± 3.1%, with an average permeability of 2 × $10^{-3}\mu m^2$. The maximum reservoir burial temperature reaches 235°C.
	Permian Lower Saxony Basin, Germany	The Permian in the Lower Saxony Basin in Germany has a present-day burial depth of approximately 7,100 m. High-quality reservoirs are mainly distributed in the intertidal to subtidal zones, with oolitic dolostone as the dominant lithology. The natural gas reservoirs contain high concentrations of H_2S and CO_2. The primary reservoir space is pore-fracture type, with porosity ranging from 0% to 24% and permeability reaching 100 × $10^{-3}\mu m^2$.

Table 2 The classification of controlling factors of deep-burial dolostone reservoirs

Primary Controlling Factors	Secondary Controlling Factors	Typical Examples
Clotted Microbial Reef-Shoal	Platform-margin meteoric water/thermal fluid alteration	Dengying Formation, Sichuan Basin; Xiaoerbulake Formation, Tarim Basin
Thick-Cycle Grain Shoal		Longwangmiao Formation, Sichuan Basin
Platform-Margin Fault Zone	Thermal fluid/ thermochemical sulfate reduction (TSR)/ organic acid alteration	Dengying Formation, Sichuan Basin; Longwangmiao Formation, Sichuan Basin
Dolostone Interlayers within Limestone		Penglaiba Formation, Tarim Basin; Yingshan Formation, Tarim Basin
Evaporite-Associated Dolostone		Xiaoerbulake Formation, Tarim Basin; Wusonggeer Formation, Tarim Basin

es under high-temperature conditions. This process disrupts Mg^{2+}-H_2O complexes and enhances dolomite dissolution. Case studies support the presence of deep burial dissolution in carbonate reservoirs (Karouse et al., 1988; Qing and Mountjoy, 1994), which facilitates reservoir development. The deep burial dissolution characteristics of the Dengying Formation dolostone reservoirs in the Sichuan Basin can be summarized as follows (Fig. 1): (1) Sulfate minerals, coarse-crystalline dolomite, and saddle dolomite exhibit significant dissolution features, forming intra-crystalline pores, inter-crystalline pores, and dissolution vugs. (2) Dissolution cavities develop near stylolites. (3) Bitumen is distributed centrally within dissolution cavities, with surrounding minerals showing evidence of dissolution. The types of pores formed by deep burial dissolution include inter-crystalline pores, intra-crystalline pores, and dissolution vugs.

The dissolution mechanisms include: (1) One or multiple phases of hydrothermal fluid alteration of the reservoir. Dissolved dolomite is often associated with hydrothermal minerals such as quartz and fluorite. Furthermore, organic matter maturation releases organic acids, which promote carbonate dissolution. Previous studies (Song et al., 2009) show that hydrothermal dolostone in Well Lin-1 of the Sichuan Basin has higher porosity (3.4% vs. 2.3%) and permeability (1.43×10^{-3} vs. 0.02×10^{-3} μm^2) compared to non-hydrothermal dolostone.

(2) Thermochemical sulfate reduction (TSR) produces H_2S, CO_2, and water (Worden and Smalley, 1996; Worden et al., 1996, 2000; Cai et al., 2001, 2013; Machel, 2001), with the reaction equation typically represented as:

$$\text{Hydrocarbon} + CaSO_4 \rightarrow CaCO_3 + H_2S \pm CO_2 \pm S \pm H_2O \pm \text{altered hydrocarbon} \quad (1.2)$$

Additionally, both one-dimensional and three-dimensional numerical simulations indicate that TSR improves reservoir properties. A one-dimensional EQ3/6 simulation of methane reacting with anhydrite to form calcite suggests a 1% increase in porosity (Hutcheon et al., 1995). A one-dimensional PHREEQC simulation, from a petrological perspective, shows that TSR enhances reservoir porosity by 1.6% while also increasing permeability (Jiang et al., 2018). Furthermore, a three-dimensional PHAST simulation demonstrates that reactions between anhydrite and calcite are accompanied by dolomite dissolution (Fu et al., 2016).

(3) Dolomite dissolution and dedolomitization. Calcite replacing dolomite typically occurs in near-surface environments (Fu et al., 2008). If the reaction involves only the calcite replacement of dolo-

mite, the process follows an "isomolar exchange," which increases mineral volume and reduces porosity. However, recent studies (Cai et al., 2014) have found that dolostone readily forms $MgSO_4$ ion pairs, which react with hydrocarbons through thermochemical sulfate reduction (TSR), leading to dolomite dissolution, calcite replacement of dolomite (dedolomitization), and calcite replacement of anhydrite. When sulfate minerals participate in this reaction, differences in dissolution kinetics between sulfates and carbonate minerals, or the reaction of one mole of sulfate with one mole of dolomite to form one mole of calcite, can enhance reservoir properties.

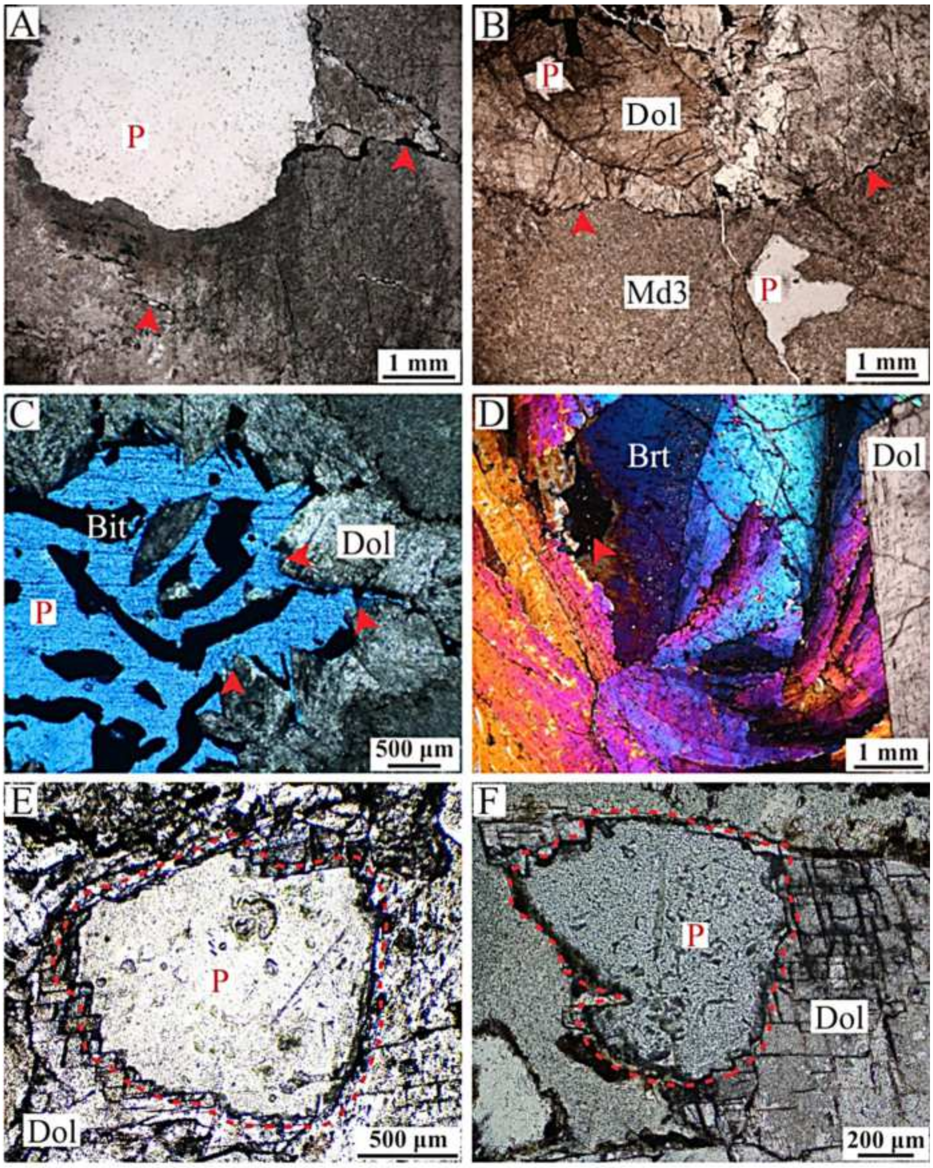

Fig. 1 Microphotographs of late-stage diagenetic pores (Hu et al., 2020a). **(A):** Pores developed near stylolites (red arrow), Sichuan Basin GS 32 well, Dengying Formation, depth 5433.89 m. **(B):** Intercrystalline dissolution pores on both sides of stylolites (red arrow), Sichuan Basin GS 7 well, Dengying Formation, depth 5348.2 m. **(C):** Bitumen distributed in intercrystalline dissolution pores within medium-coarse crystalline dolomite cement (red arrow), Sichuan Basin GK 1 well, Dengying Formation, depth 5151.74 m. **(D):** Corroded barite (red arrow) crosscut by saddle dolomite, Sichuan Basin GS 103 well, Dengying Formation, depth 5176.41 m. **(E):** Intragranular dissolution pores of saddle dolomite, Sichuan Basin GS 7 well, depth 5333.3 m, and **(F):** GS 103 well, depth 5305.43 m. The red dashed lines indicate pore boundaries.

4 Microbialites

Microbial carbonate rocks contain vast hydrocarbon resources. In recent years, several oil and gas fields have been discovered worldwide, including the Upper Jurassic Smackover Formation in the Appleton Oil Field of the Gulf of Mexico, USA (Mancini et al., 2004; Ahr, 2011), the Lower Cretaceous Pre-Salt reservoirs in Brazil (Freire et al., 2011; Muniz and Bosence, 2015), and the Cambrian reservoirs in the Tarim Basin (Fig. 2; Li et al., 2024). Porosity is a key factor in microbial carbonate reservoir studies. The formation and modification of porosity in microbial carbonates are influenced by biological activity, sedimentary processes, and diagenesis (Parcell, 2002; Ahr, 2008). These three factors affect and alter the fabric of microbial carbonate rocks, which in turn influences pore characteristics such as pore shape and throat radius (Lønøy, 2006; Lucia, 2007; Verwer et al., 2011). A distinguishing feature of microbial carbonates compared to abiotic carbonates is their microbialite structure, which is closely related to reservoir quality. Different microbialite structures in microbial carbonates often result in varying reservoir properties.

The pore development of microbial carbonate reservoirs is closely related to the structure of microbialites themselves. The original porosity and pore structure of different types of microbialites are preserved under deep burial conditions, demonstrating the control of microbialite type and structure on pore development. Due to the influence of various depositional environments, biological activities, and abiotic processes, microbial carbonates exhibit strong heterogeneity in their structural characteristics. Certain microbial types often possess distinctive structural features, such as *Girvanella*, kidney-shaped bacteria, and attached bacteria (Monty, 1976; Riding, 2000, 2011). More importantly, microbial carbonates with different microbialite structures often show significant variations in porosity and permeability. The microbialite reservoirs in the Upper Permian (Zechstein) Main Dolomite Formation of northwestern and central Poland display strong heterogeneity in pore distribution (Słowakiewicz et al., 2013). Laminated biomicrites from slope and basin facies, as well as microbial boundstones from lagoonal facies, generally have low porosity. In contrast, oolitic-oncolitic grainstones, thrombolitic microbialites, and stromatolitic microbialites from intertidal to subtidal settings exhibit better porosity (>8%). Additionally, oil fields in the Upper Permian Zechstein Formation indicate that stromatolites and thrombolites in intertidal-subtidal settings form more favorable reservoirs, whereas microbial micrites and grainy micrites from lagoonal and slope facies are associated with poorer reservoir quality (Słowakiewicz et al., 2013).

The structure of microbialites influences the types, characteristics, and quality of reservoir spaces. In the Xiaoerbulake Formation of the Tarim Basin, microbialite structures are controlled by microbial types, with different structures corresponding to different pore types. For example, thrombolites are dominated by inter-thrombolite dissolution pores, whereas *Renalcis*-dominated microbialites correspond to *Renalcis* framework dissolution pores (Li et al., 2015). In the Upper Jurassic Smackover Formation of the Gulf of Mexico, thrombolites in the inner ramp are classified into three structural types: laminated, chaotic, and fingered (Parcell, 2002). Under the same diagenetic conditions, these microbialite structures experienced varying degrees of diagenetic modification, with differences in pore heterogeneity significantly impacting reservoir quality (Mancini et al., 2004). Due to better lateral and vertical connectivity, fingered and chaotic thrombolites exhibit superior reservoir properties compared to laminated thrombolites. Previous studies (Tonietto and Pope, 2013) further suggest that although marine cementation, meteoric water dissolution, and burial dissolution modified the pores, these modifications occurred based on the pre-existing pore structure. Similarly, microbialites from the Jurassic Smackover Formation (Tonietto and Pope, 2013) and Brazilian microbialite reservoirs (Bourdet et al., 2010) indicate that thrombolites, due to their irregular structure and resistance to compaction, generally retain higher porosity. In contrast, stromatolites, characterized by their directional growth structure and weaker compaction resistance, tend to have poorer reservoir properties. Microbialites from the Sinian-Cambrian systems in the Sichuan and Tarim Basins (Fig. 2) demonstrate that *Renalcis*-dominated microbialites and thrombolitic dolomites, which develop abundant dissolution pores, exhibit better reservoir quality. In contrast, stromatolites tend to have relatively lower porosity.

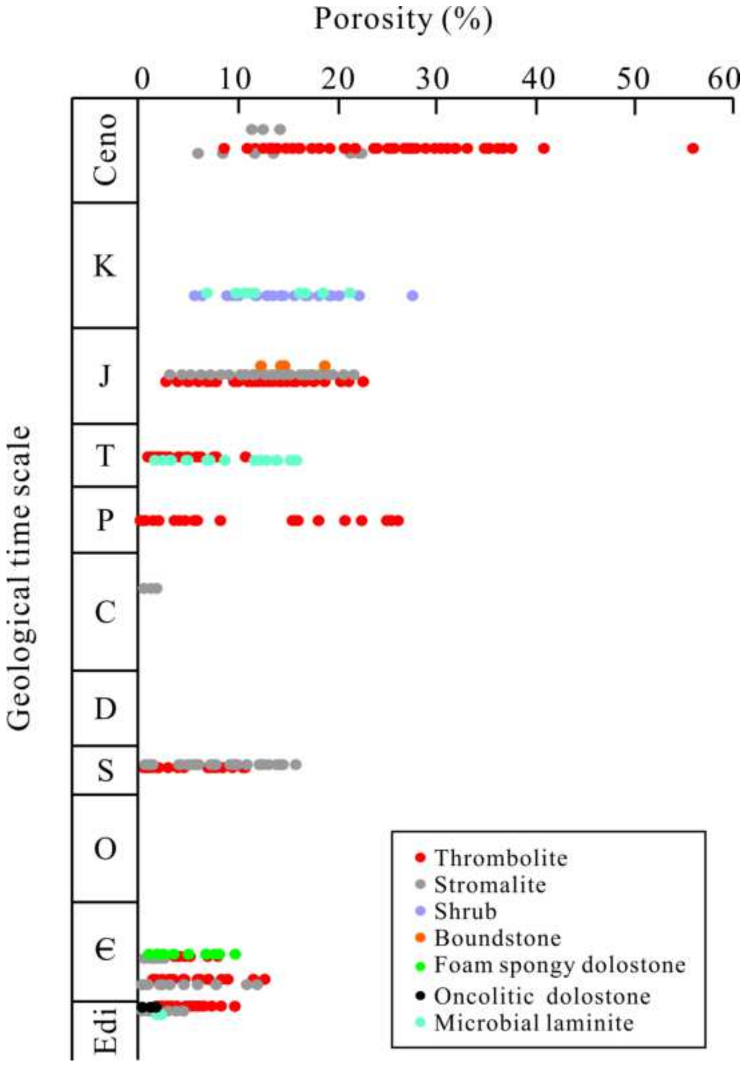

Fig. 2 The plot of microbialite reservoir porosity, modified from reference (Li et al., 2004)

5 The implications for deep-burial dolostone reservoirs

Comprehensive analysis indicates that the formation of high-quality deep to ultra-deep carbonate reservoirs is primarily controlled by factors such as depositional environment, microbialite type, tectonic activity, and various diagenetic processes. These processes include meteoric water influence, dolomitization, faulting and hydrothermal activity, and thermochemical sulfate reduction (TSR), all of which play a crucial role in deep-buried reservoir development. Specifically, the impact of depositional environment, microbialite type, and tectonic activity varies depending on reservoir type, while mete-

Table 3 Controlling factors of typical deep-burial carbonate reservoirs
Sed. Envir.= Sedimentary Environment. Mic. R. Type= Microbial Rock Type. Met. Wat.= Meteoric Water. Dol.= Dolomitization. Hyd. Act.= Fault & Hydrothermal Activity.

No.	Field	Sed. Envir.	Mic. R. Type	Met. Wat.	Dol.	Hyd. Act.	TSR	References
1	South Oman Basin, Precambrian, Oman	√	√		√			Grotzinger and Al-Rawahi, 2014
2	Siberia Basin, Precambrian, Russia	√		√				Frolov et al., 2015
3	Tarim Basin, Cambrian-Ordovician, China	√		√	√	√	√	Jiang et al., 2018
4	Longwangmiao Formation, Cambrian, Sichuan Basin, China	√		√	√		√	Fu et al., 2020
5	Bonneterre Formation, Cambrian, Southeast Missouri, USA			√		√		Greg and Shelton, 1993
6	Ellenburger Formation, Ordovician, West Texas, USA			√	√	√		Amthor and Friedman, 1991
7	Upper Jurassic, Gulf of Mexico Basin, USA			√	√		√	Heydari and Moore, 1989
8	Abenaki Platform, Upper Jurassic, Canada				√	√		Wierzbicki et al., 2006
9	Lower Cretaceous, Gulf of Mexico Basin, USA				√	√		Bourdet et al., 2010
10	South Florida Basin, Cretaceous, USA				√			Halley, and Schmoker, 1983
11	Permian-Triassic, Sichuan Basin, China	√		√	√		√	Cai et al., 2014
12	Upper Permian, Lower Saxony Basin, Germany				√	√	√	Biehl et al., 2016
13	Upper Permian-Lower Triassic, Khuff Formation, Middle East						√	Ehrenberg et al., 2006
14	Leikoupo Formation, Triassic, Sichuan Basin, China				√		√	Jiang et al., 2019

oric water leaching, dolomitization, hydrothermal activity, and TSR significantly contribute to most deep-buried reservoirs (Table 3). Additionally, some high-quality deep reservoirs are influenced by other factors, such as the Sabkha process. For example, in the Cambrian reservoirs of the Yaha area in the Tarim Basin, the lithology is mainly gypsum-bearing micritic dolomite. The dissolution of gypsum can create mold pores, greatly enhancing reservoir quality. Understanding these controlling factors provides a crucial geological basis for the exploration and development of deep to ultra-deep high-quality carbonate reservoirs.

6 Conclusions

(1) Based on depositional environments, deep to ultra-deep dolomite reservoirs worldwide can be classified into ramp-type dolomite reservoirs and platform-type dolomite reservoirs. According to dolomitization mechanisms, they can be further categorized into three types: evaporative reflux dolomitization, hydrothermal dolomitization, and multi-stage dolomitization reservoirs.

(2) Depositional environment, tectonic activity, and diagenetic processes—including meteoric water dissolution, hydrocarbon emplacement, and deep burial dissolution—are key factors controlling the development of deep dolomite reservoirs. Among them, the mechanisms of deep burial dissolution include hydrothermal activity, thermochemical sulfate reduction (TSR), and dedolomitization.

(3) Microbialite structures influence pore types and pore structures. Clotted microbialites formed in high-energy depositional environments exhibit better reservoir properties, whereas stromatolites and laminated microbialites formed in low-energy settings generally have poorer reservoir quality.

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