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REVIEW ARTICLE

Influence of sedimentary environment on the properties of organic-rich shales in China: a review

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Abstract The sedimentary environment is inextricably linked to the macroscopic and microscopic characteristics of shale reservoirs, which influences shale gas accumulation significantly. This study discusses how the sedimentary environment affects the organic-matter-rich shale reservoirs that have been deposited in typical marine, marine-continental transitional, and continental basins in China. The following four aspects were analyzed including shale rock type and thickness distribution, organic matter abundance and distribution, mineral composition and pore structure, and kerogen type and hydrocarbon generation potential. From continental to marine facies, the sedimentary setting of shales with high organic content generally ranges from shore-shallow lakes to deep lakes, deltas, tidal flat lagoons, shallow sea shelves, and deep or semi-deep seas. In deeper water, the clay mineral content decreases, but the brittleness index and siliceous content increase with darker shale color. Thick shales mostly were deposited in deep or semi-deep lakes, delta fronts, prodeltas, tidal flat lagoons, and deep or semi-deep seas from continental to marine basins. The primary factors influencing organic matter enrichment in deep-sea and deep-lake shales are redox conditions and high biological productivity under favorable sedimentary environments, whereas favorable factors for organic matter enrichment in transitional facies include warm-humid palaeoclimates and abundant debris inputs. Continental shale is characterized by the presence of intergranular and intragranular pores, a low pore volume and specific surface area, and a high average pore size and hydrocarbon potential. The kerogen types are complex in continental shales, with type I in deep lake shales and type III in lakeshore shales. Transitional shales occur mostly in coal-bearing strata with type III organic content, medium pore sizes, and hydrocarbon generation potential. The high specific surface area and pore volume, small pore size, and high brittle mineral content of marine shale facilitate the production of dissolution pores. Marine shales are mainly kerogen type I–II_1 with relatively high maturity and low hydrocarbon production potential. By constructing an intrinsic link between the sedimentary environment and reservoir parameters, a sedimentary model of organic-rich shale under different depositional context should be summarized in the future, which can provide a foundation to analyze the geological circumstances of shale gas accumulation.

Keywords organic-rich shale, sedimentary environment, shale gas, pore structure, shale gas distribution

1 Introduction

Shale is a fine-grained sedimentary rock comprised of clay minerals and silty quartz, which are formed by clastic materials and biomass during physical processes such as transport, compaction, deposition, and a series of biochemical processes in a specific sedimentary environment. Based on the three end-members including sand grade (> 62.5 μm), coarse mud grade (32–62.5 μm), and fine mud grade (< 8 μm), fine-grained sedimentary rocks can be divided into six types: fine-grained mudstone (clay rock), medium-grained mudstone (mudstone), coarse-grained mudstone (siltstone), sandy mudstone, argillaceous sandstone, and sandstone. This classification considers mudstone to be fine-grained sedimentary rocks with silt and mud grades below 62.5 μm and particle content greater than 50% (Lazar et al., 2015), whereas the laminated rock is called shale (Shao and Zhang, 2023). The distribution and development of mudstones are directly correlated with the variations in different depositional environments (Zhang et al., 2019; Hou et al., 2022). Except for possessing significant gas reserves (Ross and Bustin, 2008; Mendhe et al., 2017), organic-rich shales are exceptional

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geological carriers for recording palaeoclimatic and palaeoenvironmental information (Murphy et al., 2000; Wang et al., 2017b). As different sedimentary zones affect the development of mudstone and the distribution of excellent source rocks, this study focuses on the effect of the depositional setting on organic-rich shales' properties, which is essential for shale gas production and exploration.

Palaeoclimate, palaeosalinity, palaeoproductivity, sea-level fluctuations, and redox conditions are all the factors that can affect the formation of sedimentary environments (Li et al., 2015; Peng, 2017). Differences in sedimentary environments can significantly impact terrigenous debris input, deposition rate, water redox conditions, and ancient productivity during the shale formation process (Doebbert et al., 2010; Norsted et al., 2015), which further affects shale properties such as thickness, lithofacies type, organic matter type, mineral composition, organic matter abundance, pore fracture structure, and hydrocarbon generation potential (Song et al., 2019). Generally, the sedimentary environment analysis is the basis of seeking organic-rich shales and successful exploiting shale gas. However, a systemic and deep characterization of depositional settings is difficult to match the fast growing of shale gas industry in China, especially continental and marine-continental transitional basins. Therefore, the influence of sedimentary environment on the properties of organic-rich shales should be enhanced. According to previous studies, the sedimentary environment has the following effects on shale reservoirs.

1) Sedimentary petrology, sequence stratigraphy, and palaeontological stratigraphy were analyzed based on investigations of traditional field outcrops and borehole profiles. Combined with geophysical or geochemical testing methods, the sedimentary environment of shale can be recovered under a sequence framework. The Triassic terrestrial depositional environment in the Ordos Basin includes delta and lacustrine facies (Yang et al., 2010), whereas a model of Permian marine-continental transitional shales can be classified into barrier coastal facies and delta facies in China (Li, 2014). For the Lower Cambrian Qiongzhusi Formation, marine organic-rich shales in the Middle-Lower Yangtze areas primarily formed on the continental shelf and in stagnant semi-deep or deep sea (Wang et al., 2013).

2) The sedimentary structures of the research horizons were identified, and the variation characteristics of the shale rock type and thickness under different depositional environments were determined. Continental shale, often mixed with silty or sandy mudstone, was found in deep or semi-deep lakes, and its development was greatly influenced by terrigenous clastic sediments that were thicker, darker, and more widely distributed toward the lake center (Zeng, 2013a). Transitional shales with a small single-layer thickness and fast-changing lithology were usually interbedded with thin layers such as siltstones, mudstones, and coals. Marine shale was mostly developed on shallow to deep sea shelves with a larger single-layer thickness and fewer interlayers and was not easily affected by terrigenous detritus (Liang, 2014).

3) Quantify the variations in the total organic carbon (TOC) content distribution across different sedimentary environments and propose the key regulating variables and models of organic carbon enrichment in shales. Generally, anoxic environments regulate organic matter enrichment. When transitional shale is present in oxygen-rich water, abundant organic matter can also form under specific geological conditions of high biological productivity and high deposition rate. The quartz content and clay mineral abundance are positively linked to high organic carbon content in marine and continental shales (Bustin et al., 2009; Liang, 2014). Except for carbonaceous mudstone, transitional shales have low TOC levels (Ding et al., 2021; Guo et al., 2021).

4) Quantity the physical properties of shale reservoirs and discuss the effects of the depositional environment on mineral composition, fracturability, and pore structure. Although clay minerals do not promote pore development, brittle minerals are advantageous for it (Zeng, 2013a; Liu et al., 2021). Inorganic mineral pores were predominant in the continental and marine shales, followed by organic matter pores. The higher clay mineral content in continental and transitional shales easily influences fracture, whereas the highly brittle minerals in marine shale can give rise to more organic matter pores (Zeng, 2013a; Liang, 2014; Song et al., 2020). The pores in transitional shales present an unbalanced multi-peak distribution, and the proportion of mesopores is the largest, signifying more inorganic pores and microfractures and fewer organic pores (Yang and Guo, 2020; Guo et al., 2021; Li et al., 2022).

5) The impact of the sedimentary setting on shale kerogen types and hydrocarbon generation potential can be examined using the methods such as rock pyrolysis, the kerogen type index (TI), and carbon isotopes. The organic matter in marine shale is too mature and the type of organic matter is mainly I-II. Continental shale with low maturity has complex organic matter types, including type I-III (Liang, 2014; Song et al., 2020). Type III kerogen is predominant in transitional shale, which has a low hydrocarbon generation potential (Wei et al., 2020; Guo et al., 2021).

This study examines the following aspects based on numerous domestic and foreign investigations: 1) the distribution of organic-rich shale in China, 2) the shale sedimentary environment and its impacting elements, 3) shale rock type and thickness distribution, 4) shale organic matter abundance and distribution, 5) shale mineral composition and pore structure, and 6) shale organic type and hydrocarbon generation potential. The controlling mechanism of various sedimentary environments on organic-rich shales is discussed, which is conducive to the orderly advancement of China’s shale gas exploration and lays the foundation for the early realization of peak carbon and carbon neutrality targets.

2 Distribution of organic-rich shale in China

The organic-rich shales cover Precambrian-Cenozoic strata in China and are widely dispersed throughout a variety of geological times and spaces (Fig. 1). Specifically, organic-rich shales were mainly developed in the Cambrian, Ordovician, and Silurian during the Lower Palaeozoic era; the Devonian, Carboniferous, and Permian during the Upper Palaeozoic era; the Triassic, Jurassic, and Cretaceous during the Mesozoic era; and the Palaeogene during the Cenozoic era. In terms of sedimentary environments, China’s organic-rich shales can be categorised into three types: marine, marine-continental transitional, and continental shales (Shao et al., 2014; Li et al., 2016; Zou et al., 2022).

Precambrian to Early Palaeozoic marine shales are mostly distributed in the Tarim Basin, Sichuan Basin, Yangtze Plate, and a few areas on the southern edge of the North China Basin. Transitional shales were widespread in the north-east, north-west, north, and south of China during the Late Palaeozoic. The Tarim Basin, Bohai Bay Basin, Junggar Basin, Qaidam Basin, Sichuan Basin, Turpan-Hami Basin, Ordos Basin, Songliao Basin, and a tiny piece of the Yangtze Plate are the principal locations for Late Palaeozoic to Cenozoic continental shales (Fig. 2).

2.1 Marine shale

Marine organic-rich shales are developed as an excellent source rock around the world. North American shale gas is primarily derived from marine organic-matter-rich shales formed in the Late Palaeozoic Devonian, Permian, Jurassic-Cretaceous, and Carboniferous cratons and foreland basins (Zou et al., 2011). Marine organic-rich shales favorable for shale gas exploration and production

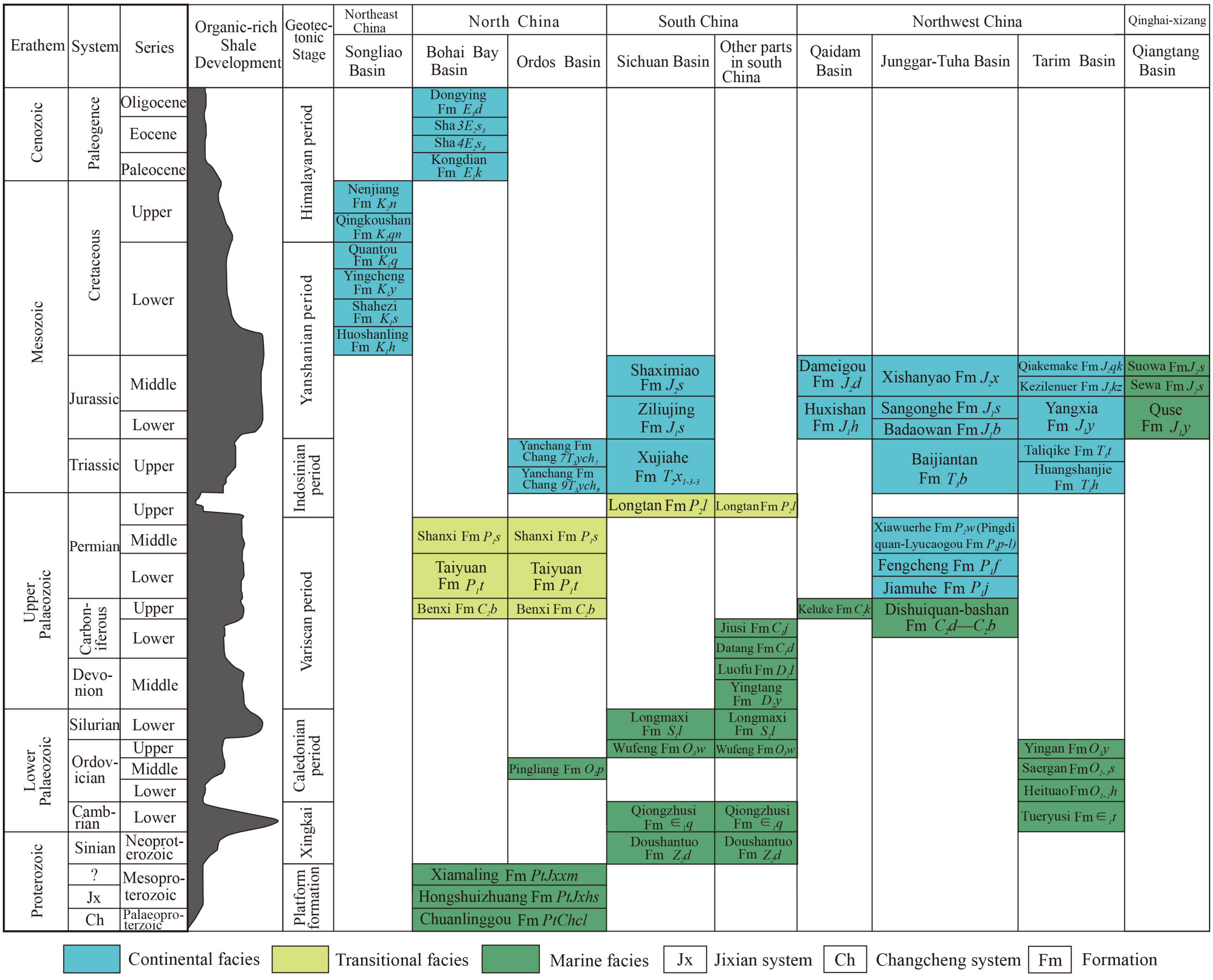

Fig. 1 Organic-rich shale distribution of major onshore oil and gas-bearing basins in China (modified from Dong et al., 2016).

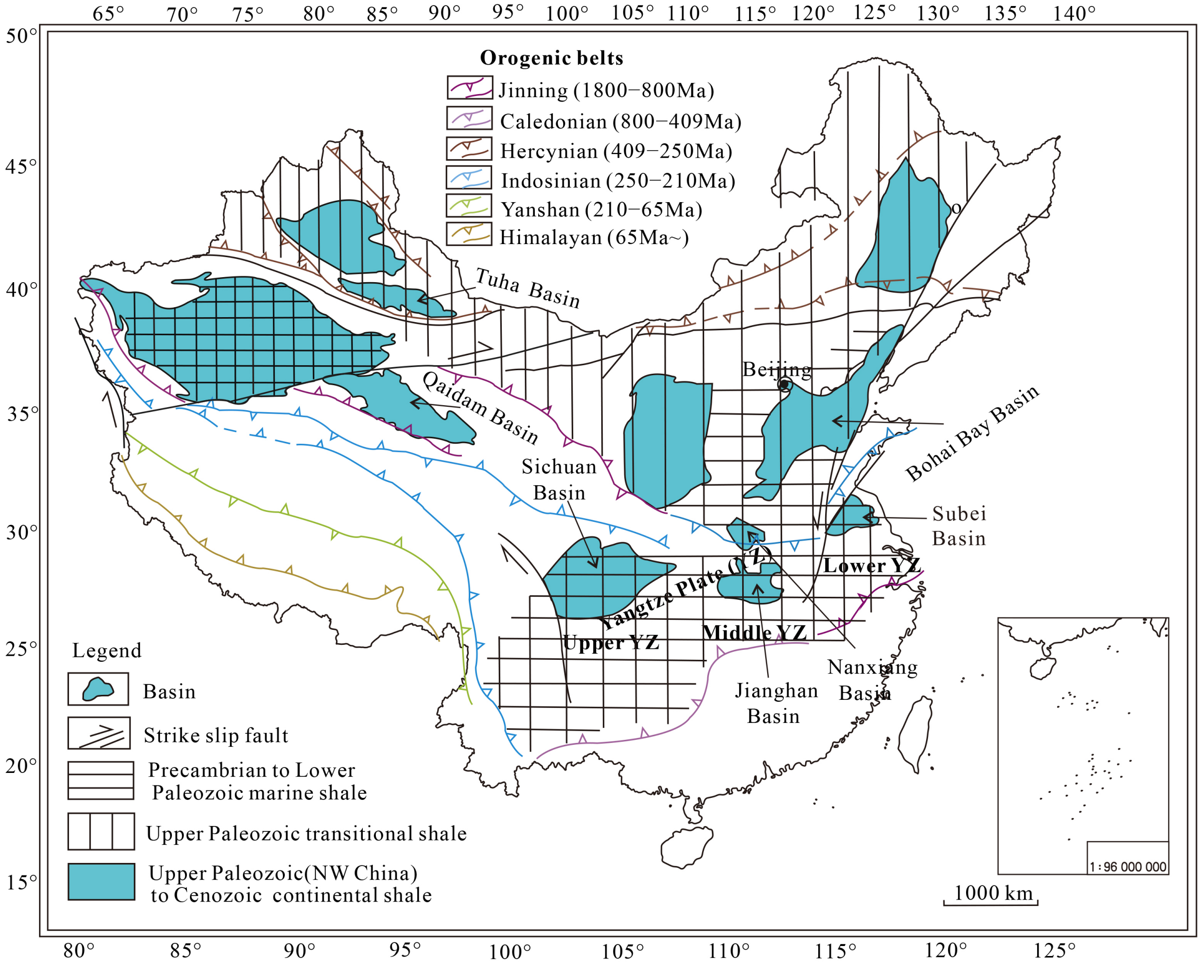

Fig. 2 Distribution of organic-rich shales in marine, transitional, and continental facies in China (modified from Jiang et al., 2016; Wang and Li, 2004; Zou et al., 2010).

in southern China are distributed in the Palaeozoic strata (Figs. 1, 2), which were mainly formed in deep and semi-deep shelf facies in intercratonic or marginal depressions. The Precambrian-Early Palaeozoic marine shales are primarily found in the Yangtze Plateau, Sichuan Basin, Tarim Basin, and a few locations near the southern boundary of the North China Basin (Fig. 2). Specific shale strata in the southern region include the Lower Cambrian Qiongzhusi Formation (Shuijingtuo, Hetang, Niutitang Formation, etc.), Upper Ordovician Wufeng Formation, Lower Carboniferous Jiusi Formation, and Lower Silurian Longmaxi Formation, as well as their equivalent strata. In the northern region, these strata include the Upper Proterozoic Chuanlinggou Formation, Hongshuizhuang Formation, Xiamaling Formation, and Middle Ordovician Pingliang Formation. In the Tarim Basin, marine shales are found in the Middle-Upper Ordovician Saergan-Yingan Formation. Currently, shale gas exploration in China is mainly focused on the southern marine strata, such as the Qiongzhusi, Niutitang, Wufeng, and Longmaxi formations (Zhang et al., 2013; Zeng et al., 2014; Wang et al., 2017a; Jiang et al., 2018).

2.2 Marine-continental transitional shale

The transitional organic-rich shales were mainly formed in the Carboniferous-Permian coal-bearing clastic rocks, and the Late Palaeozoic shales were developed in north-east, north-west, north, and south China (Figs. 1, 2). Organic matter in transitional shale is dominated by terrestrial higher plants, which is frequently interbedded with sandstone and coal seams. Therefore, the transitional facies' lithology is unstable in the horizontal direction and has a quite large total thickness in the longitudinal direction (Li et al., 2018; Luo et al., 2018; Zhao et al., 2020). Transitional organic-rich shales are commonly found in the Carboniferous-Permian, including the Longtan, Liangshan, and their equivalents in southern China, and the Benxi, Shanxi, and Taiyuan formations in northern China. The Carboniferous-Permian transitional shale has a distribution area of 10.7 × 10^4 km^2 in north China, with favorable shale thicknesses ranging from 10 to 60 m, whereas it has a distribution area of 8.6 × 10^4 km^2 in south China, with favorable shale thicknesses ranging from 7 to 150 m. Currently, transitional shale gas is mostly focused on the Taiyuan, Xiashihezi, and Shanxi formations in north China (Li et al., 2016), as well as the Longtan Formation in the Lower Yangtze area (Yan et al., 2016; Liu, 2018).

2.3 Continental shale

The Tarim Basin, Bohai Bay Basin, Junggar Basin, Ordos Basin, Turpan-Hami Basin, Qaidam Basin, Songliao Basin, Sichuan Basin, and a small part of the Yangtze Plate are the principal locations for Late Palaeozoic to Cenozoic continental shales (Figs. 1, 2). In the Junggar Basin, several sets of Permian shale, such as the Jiamuhe, Fengcheng, Wuerhe, Pingdiquan, and Lyucaogou formations, developed. The shales of members 7 and 9 of the Yanchang Formation were formed during the Late Triassic in the Ordos Basin. In the Late Triassic of the Sichuan Basin, three sets of shales from members 1, 3, and 5 were developed in the Xujiahe Formation. Several groups of shales in the central-western Jurassic strata were associated with coal measures, including the Shimengou, Huxishan, and Dameigou formations in the Qaidam Basin; the Xishanyao, Badaowan, and Sangonghe formations in the Turpan-Hami and Junggar basins; the Shahezi, Yingcheng, Qingshankou, and Nenjiang formations in the Songliao Basin; the Kongdian Formation in the Bohai Bay Basin; and the Yangxia, Kezilenuer, and Qiakemake formations in the Tarim Basin. At present, continental shale gas is mainly explored in Mesozoic strata in north-western and north-eastern China, including the Ordos Basin in the Yanchang Formation (Wang et al., 2014), the Qaidam Basin in the Dameigou and Shimengou formations (Hou et al., 2017; Qin et al., 2018), and the Fuxin Basin in the Jiufotang and Shahai formations (Chen et al., 2018).

3 Overview of the sedimentary environment of shale formation in China

3.1 Marine shale

In China, marine shales are widely produced and distributed. Eight sets of black marine shales from the Upper Ordovician and Lower Cambrian have been grown in the Southern Yangtze region (Ma et al., 2004; Zhang et al., 2017). In the Upper Yangtze region of the Lower Palaeozoic, marine organic-rich shale had a high abundance, significant thickness, and favorable organic matter type, rendering it suitable for investigation and development (Li et al., 2012b; Zhu et al., 2013; Zou et al., 2017). These shales were deposited mostly in deep, semi-deep, and shallow seas with fast deposition rates, sufficient debris, and closed geological conditions (Kang, 2007; Wang et al., 2018).

The Cambrian Niutitang Formation of the Upper Yangtze region and the Qiongzhusi Formation of the Sichuan Basin contain black shales, which were deposited in deep shelf facies controlled by continental margin depression (Dong et al., 2010; Zou et al., 2010; Jiu et al., 2012; Jiang et al., 2013; Li et al., 2013; Zhu et al., 2017). The southern Sichuan Basin experienced a large transgression and was on a semi-open deep-water shelf connected to western Hubei during the Early Cambrian. Therefore, from west to east in the Upper Yangtze area, the Early Cambrian sedimentary environments include the Kangdian Palaeoland, Shoreland, shallow-water shelf, deep-water shelf in southern Sichuan, shallow shelf, deep shelf in eastern Sichuan-western Hubei, slope, and deep-sea basin (Liang et al., 2008; Ma et al., 2009; Jia et al., 2017). In the southern Sichuan Basin of the Qiongzhusi period, the depositional environment was a shelf face that can be subdivided into the six major depositional microfacies including beach bar, sandy-muddy shallow shelf, muddy shallow shelf, turbidite sand, sandy-muddy deep shelf, and muddy deep shelf (Li et al., 2013). During the Lower Silurian Longmaxi Formation, the shales comprise a suite of organic-rich carbonaceous shales, dark gray-black silty shales, and siliceous shales deposited in anoxic environments in the deep sea, semi-deep sea, and shelves (Guo et al., 2004). The depositional environment from the lower to the upper section was generally changed from a deep-water to a shallow-water shelf (Zhang et al., 2013).

The Cambrian shales were formed mainly in marine strata and were rich in carbonate rocks in the Tarim Basin and the dark shales developed in the shelf zones were distributed in the margins of the terraces during the early stages of marine intrusion. The Ordovician Saergan and Yingan shales were developed mainly in deep-shelf basins under more favorable reducing conditions (Zhang et al., 2003; Gao et al., 2010; Zeng et al., 2013b). Additionally, for shallow shelf areas of the continental margin and platform margin slope, Cambrian black shales with carbonate interlayers were formed on the North China Platform (Liao et al., 2010). Black shale interbedded with dark gray carbonate rocks was also formed in the western Ordos area, which belongs to the restricted sea (Liu, 2018).

3.2 Marine-continental transitional shale

The transitional shale was represented by organic-rich dark mudstones in the coal measures. The North China Platform (Shao et al., 2006; Hu et al., 2012; Fu et al., 2018), Tarim Basin (Niu et al., 2010), and Junggar Basin developed transitional dark mudstones/shales during the Carboniferous-Permian, forming marine-continental clastic rocks and shallow marine carbonate rocks with coal-bearing strata. Dark mudstone and shale are dispersed in tidal flats, delta distributary bays, swamps, and floodplain sedimentary settings during the Taiyuan, Benxi, and

Shanxi periods in the Ordos Basin (Shen et al., 2018; Dong et al., 2021). Many layers of dark mudstones (carbonaceous shales) associated with coal seams developed in the carbonate tidal flats, lagoons, and shallow delta facies during the Taiyuan and Shanxi periods in the Qinshui Basin. In the South Yangtze Platform during the Upper Permian Longtan Formation, the shale was mostly formed in the lagoon of the bay and the swamp of the deltaic plain and is mostly made of black mudstone, coal seams, silty mudstone, and argillaceous siltstone (Li et al., 2012a; Wu et al., 2013; Zhang et al., 2015; Yan et al., 2016).

3.3 Continental shale

Organic-rich continental shale formed mostly in lacustrine deposits of the Mesozoic-Cenozoic (Liu et al., 2006), and is found in regions of the Sichuan Basin (south China) and the Ordos, Songliao, Junggar, Bohai Bay, and Tarim basins (north China).

In the Ordos Basin, the Upper Triassic shales form terrigenous clastic rocks dominated by river and lacustrine facies, and the Ordos Basin has undergone a complete lake transgression-regression process in the Yanchang Formation (Yang et al., 2010; Liu et al., 2018). The Member 7 of the Yanchang Formation developed into shallow-deep lake facies, which includes the largest lake region and an abundance of aquatic organisms, plankton, and stably distributed mudstone/shale (Yang et al., 2012; Wang et al., 2014; Ma, 2017). In the Upper Triassic Xujiahe Formation of the Sichuan Basin, members 3 and 5 formed during the expansion period (Ye and Zeng, 2008; Huang, 2009). Furthermore, dark mudstones are widely distributed, thick, and abundant in organic matter, with the potential to form shale gas. Lower Jurassic mudstones are mostly found in shallow and semi-deep lakes and are typically interbedded with siltstone and limestone (Li et al., 2010; Nie et al., 2017).

4 Relationships between sedimentary environment and rock type, thickness distribution of shales

The main criteria for investigating shale gas formation and storage are the shale rock type and thickness distribution characteristics. The lithology and thickness of shales are crucial for evaluating shale gas reservoirs, whereas the sedimentary setting affects the shale rock type and shale thickness distribution. Take the marine shale from the Lower Cambrian Qiongzhusi Formation in the Middle-Lower Yangtze region, the Carboniferous-Permian transitional shale in Qinshui Basin, and the Jurassic continental shale at the Qaidam Basin's northern margin as examples to illustrate the influence of depositional environments on shale rock types and thickness distribution. With an increase in the water level, the shale color gradually darkened, and the silicon content continuously increased for most rock types, from gray sandy mudstone to black siliceous shale. Shallow, deep, and semi-deep basins are beneficial for the formation of thick marine shale, and the effective thickness increases with deeper seawater (Wang et al., 2013). The interdistributary bay, interbay swamp, and tidal flat-lagoon in the lower deltaic plain are ideal for the production of dark transitional mudstone, and thick mudstone is mostly dispersed in the delta front, prodelta, and tidal flat-lagoon belts (Li, 2014; Li et al., 2016; Liu, 2018). Continental shale is well-developed in deep or semi-deep lakes with a thick single layer. Generally, shale thickness increases from shallow to deep lakes, and the maximum thickness is located at the center of deep lacustrine environments (Hou et al., 2017). However, the excessive space available in deep water has led to a lack of sediment supply (Li, 2017; Shi et al., 2023), and dark-thick shales are more frequent in semi-deep lakes and seas.

4.1 Effect of marine sedimentary environment on rock type and shale thickness

During the Early Cambrian Qiongzhusi Formation, seawater invaded from the south-west into the Middle-Lower Yangtze area, depositing shallow to deep marine environments (Fig. 3). Black carbonaceous and sandy shales coexist with anthracite in the central and south-western regions of the Jiangsu Province. The seawater gradually deepens toward the south-east, and the transgression area expands from south-west to north-east, forming euxinic basins and gentle slope belts in the Jiangshan-Shaoxing and Hangzhou-Jiaxing areas (Fig. 3). The Jiangshan-Yuhang region of Zhejiang Province is a stagnant basin with highly developed black carbonaceous shale, stone coal, siliceous shale, and thin limestone. Huangshan, Hefei, and Anqing are siliciclastic deep-water basin deposits, and the developed dark gray rocks represent a strong reducing environment. In Hubei Province and north-west Hunan Province, the lower section is composed of carbonaceous shale with limestone or dolomitic limestone, and gray-green shale with calcareous shale makes up the upper part, indicating a semi-deep sea and a shallow sea shelf. Under the conditions of strong reduction and slow subsidence, many algae are well-developed (Feng et al., 2001). Four sedimentary facies, including gentle slopes, shelves, deep or semi-deep-sea basins, and continental slopes, were developed primarily in the Early Cambrian Qiongzhusi of the Middle-Lower Yangtze area, with organic-rich shale developing primarily in the semi-deep or deep-sea stagnant basin and continental shelf.

The Middle-Lower Yangtze contains the following sedimentary centers of organic-rich shale: Zhangjiajie–Huaihua in Hunan Province, Yangzhou-Yancheng in

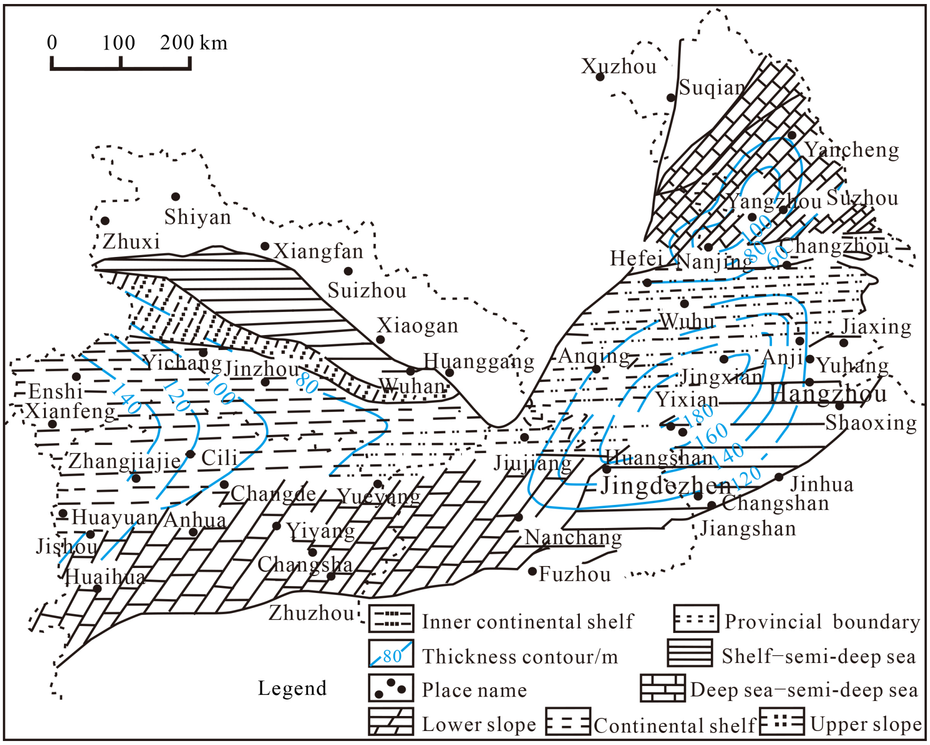

Fig. 3 Lithofacies palaeogeography and shale distribution of Lower Cambrian Qiongzhusi Formation in the Middle-Lower Yangtze area (modified from Wang et al., 2013; Chen, 2002; Feng et al., 2001; Zhang, 1993).

Jiangsu Province, and Yixian-Huangshan in Anhui Province. These sedimentary centers basically spread in a north-east direction, and the organic-rich shale ranges in thickness from 100 to 180 m. Generally, the distribution of shale thickness is strongly connected to the sedimentary facies belt. The effective shale thickness tends to increase as the seawater deepens from the north-west to the south-east. Organic matter is more easily enriched and preserved in deep-water areas, and the high TOC value areas overlap with the thick areas (Fig. 3). Therefore, shallow shelves and deep- or semi-deep-sea environments are beneficial for the formation of thick marine shales.

The Qiongzhusi shale is classified into four rock groups based on outcrops, core observations, and laboratory tests: siliceous shale, calcareous shale, carbonaceous shale, and silty shale (Wang et al., 2013). 1) The TOC concentration of black carbonaceous shale ranges from 3% to 15% and was usually deposited in semi-deep seas. 2) Layered black silty shale was primarily formed on the shelf and showed a relatively low carbonaceous content. 3) Dark gray calcareous shale was mainly deposited in shallow sea and sea-land transition environments. Limestone fractures were found in hand specimens with lamellar and massive calcareous shales. 4) With a gray-black color and great hardness, gray-black siliceous shale was primarily formed in deep and semi-deep marine environments with abundant fine-grained cryptocrystalline silicon. Therefore, from the shelf to the deep sea, the shale color gradually changes from gray to black, and silty shale usually develops on the shallow shelf owing to the influence of terrigenous debris.

4.2 Impact of transitional sedimentary environment on rock type and shale thickness

The transitional coal-bearing strata of the Carboniferous-Permian were mainly deposited in northern China. In the Late Carboniferous, Early Permian, and Late Permian, the depositional environments were dominated by carbonate platforms and barrier lagoons, deltas and alluvial plains, and rivers and lakes (Shao et al., 2008; Song, 2009; Yang et al., 2015)

In this research, the Carboniferous-Permian strata in Qinshui Basin was studied to reveal the impact of transitional sedimentary environment on rock type and shale thickness. From the Late Carboniferous to the Early Permian, the Qinshui Basin formed a typical transitional environment, mainly consisting of interbedded sandstone, shale, and coal seams. The Carboniferous-Permian Qinshui Basin includes the Benxi, Taiyuan, Shanxi, Xiashihezi, Shangshihezi, and Shiqianfeng formations from bottom to top, of which the Taiyuan and Shanxi formations are the main coal-bearing strata, forming several sets of hydrocarbon source rocks such as coal seams and shales (Hou et al., 2019; Shao et al., 2021). The depositional environment of the Taiyuan Formation consists of carbonate platform, barrier island, lagoon, and delta from south to north, and the depositional environment of the Shanxi Formation is generally characterized by the depositional system of delta front, lower delta plain upper delta plain from south to north (Fig. 4).

Through the observation of drill cores and field outcrops, four shale rock types were identified in the Qinshui Basin based on the color and sedimentary structure of the shale, which are gray-black shale, gray shale, carbonaceous shale, and sandy shale (Shao et al., 2014; Hou, 2021). 1) The gray-black shale contains fossilized plant roots and leaves, and was mainly formed in the delta plain, delta front, and lagoon environments. 2) Gray shale developed horizontal bedding and massive structure, and can be formed in a variety of environments. 3) Carbonaceous shales are rich in fossilized plants and generally developed at the base of coal seams, which were mainly deposited in deltaic plains, peat bogs, lagoons and tidal flat. 4) The sandy shale is mostly gray to gray black in color with a few horizontal laminations, which was mainly formed in the tidal flat with a strong hydrodynamic force.

The Taiyuan Formation in the Qinshui Basin was continuously deposited on top of the Benxi Formation, with sandstones, mudstones, carbonate rocks and coal seams of the main lithologies. The Taiyuan Formation is one of the major coal-bearing segments in the Upper Palaeozoic, and its top and bottom boundaries are marked by developed Jinci and Beichagou sandstones (Li et al., 2005). The Shanxi Formation consists of gray-black carbonaceous mudstone, sandy mudstone, siltstone, sandstone, and coal seams, and is conformably distributed above the Taiyuan Formation and is rich in plant fossils (Jia, 2007). In the Taiyuan Formation, mudstones and shales were formed in lagoon-tidal flats and deltaic plain marshes with more primary organic matters. In the Shanxi Formation, a river system developed in the northern Qinshui Basin, with more sandstone and less mudstones and shales. The central and southern parts were in a deeper-water interdelta bay environment, which was conducive to the formation of large-scale dark organic-rich shale, whereas the northern part was in a shallower-water environment and formed mudstone and shales with relatively small thickness (Yu, 2020).

The shale of the Taiyuan Formation in the Qinshui Basin has a maximum thickness of 30 m. For the Shouyang-Songta-Heshun areas in the northern basin, the shale thickness ranges from 7 m to 30 m, with an average of 19 m, which increases gradually from Shouyang to Heshun. For the southern part, the mudstone thickness ranges from 5 m to 23 m, increasing gradually from south-west to north-east. In general, the thick shale in the Taiyuan Formation is mainly distributed in the delta front and tidal flat, and the relatively deep-water environment is conducive to the generation of dark shale (Fig. 4(a)).

There are two favorable zones for the shale distribution in the Shanxi Formation. The first favorable zone is from Qinxian to Jiexiu area, where effective shale thickness ranges from 21.75 to 31 m, with an average value of 24.9 m. The second favorable zone is from Zhangzi to Anze area, where effective mudstone thickness ranges from 11.7 to 30.58 m, with an average value of 21.9 m. For the southern part, the shale thickness in the Duanshi-Mabi area can be up to 20 m, and the lithology is dominated by carbonaceous mudstone, which is rich in organic matter. The depositional period of the Shanxi Formation was dominated by a deltaic depositional

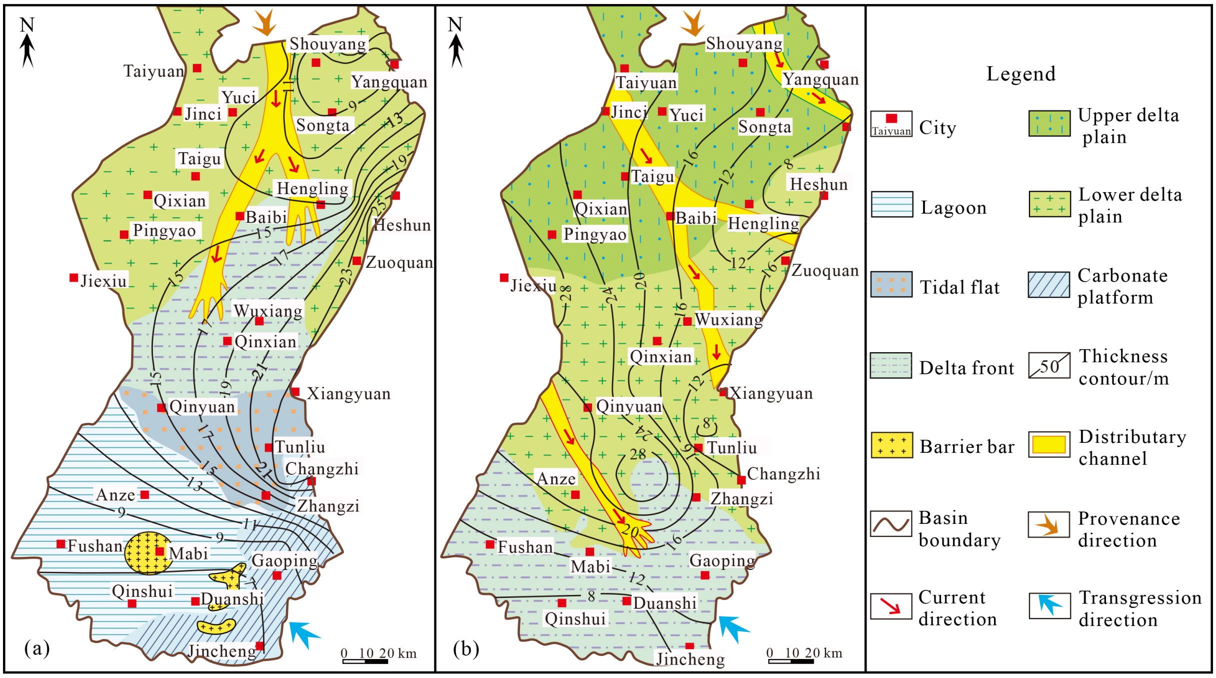

Fig. 4 The shale thickness and palaeogeographic maps of Taiyuan Formation (a), and Shanxi Formation (b) in the Qinshui Basin (modified from Shao et al., 2015).

system, and the thickness of shale developed in the lower delta plain and delta front is greater than that in the upper delta plain (Fig. 4(b)).

4.3 Impact of continental sedimentary environment on rock type and shale thickness

The role of the continental depositional setting in controlling shale rock types and thicknesses was analyzed using the Middle Jurassic shales of the Yuqia Coalfield in the Qaidam Basin as an example. The Middle Jurassic in the northern Qaidam Basin consists of the Dameigou and Shimengou formations, which include three distinct dark mudstones: the upper Dameigou, upper Shimengou, and lower Shimengou formations (Li et al., 2014).

During the Dameigou Formation, the depositional provenances were shifted from the north-west and south-east in the Yuqia Coalfield, and the sedimentary environments included lower delta plain, upper delta plain, alluvial plain, delta front, and shore-shallow lake. Among them, the range of the shore-shallow lake was relatively small, whereas the delta sedimentary system developed rapidly during the Dameigou period (Fig. 5(a)). Compared with the Dameigou Formation, the lower Shimengou Formation has a finer grain size, a smaller extent of the alluvial plain, and a larger delta front and shore-shallow lake area (Fig. 5(b)). The upper Shimengou Formation is mostly composed of lacustrine deposits, and a variety of shore-shallow lakes along the deep and semi-deep lakes foster ideal circumstances for the production of organic-rich mud shale.

For the Middle Jurassic period, organic matter shale in the Yuqia Coalfield can be classified into four types based on hand specimen observations, test analyses, and mud shale characteristics: gray-black shale, oil shale, dark gray mudstone, and carbonaceous mudstone (Hou et al., 2022). The mud shale in the lower part of the Shimengou Formation and the upper part of the Dameigou Formation are thinly bedded and contain more interbedded layers, which are typically carbonaceous mudstone and dark gray mudstone developed in the delta plain. Gray-black shale and brown oil shale, which were formed under lacustrine conditions, developed well in the upper part of the Shimengou Formation, with only a few interlayers and a thick single layer.

In the Shimengou Formation, the shale in the upper section was well developed in shallow or deep lakes. The lower part is made up of gray, dark gray, black, and carbonaceous mudstone, with several layers of siltstone and fine sandstone in shallow lake facies, whereas the upper part is thick yellow-brown oil shale in semi-deep or deep lake facies. In this part, the cumulative shale

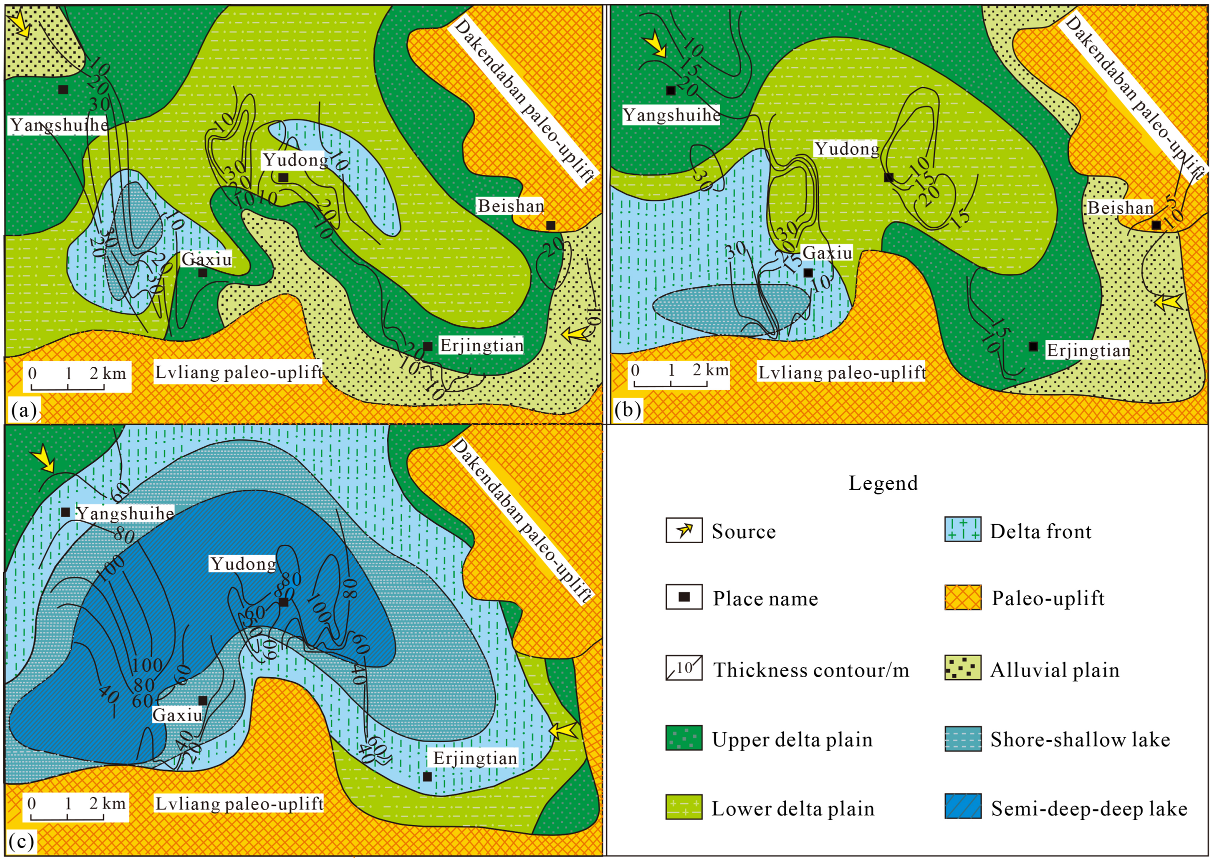

Fig. 5 Lithofacies palaeogeography and shale thickness distribution of Dameigou Formation (a), Lower Shimengou Formation (b), and Upper Shimengou Formation (c) in Yuqia Coalfield.

thickness is 40.62 m, and the single-layer thickness is relatively substantial, with an oil shale thickness greater than 20 m. The largest oil shale thickness was found in the center of the deep lake environment, and it gradually grew from shore-shallow lacustrine facies to deep lacustrine facies (Fig. 5(c)).

The Lower Shimengou shale was distributed in an interdistributary bay influenced by the braided river delta plain with abundant clastic materials and coarse deposits, which is composed of carbonaceous, gray, and gray-black mudstone. The lithology of this section consists of gravel-bearing coarse sandstone, gray siltstone, coarse sandstone, fine sandstone, and a thin coal seam. The dark shale in this area has a total thickness of 16.5 m, with individual layers thicker than 5 m. For the shore-shallow lake and delta sedimentary environments, the shales developed in the delta front and lower delta plain are thicker than those developed in the upper delta plain (Fig. 5(b)).

The Dameigou Formation's upper-middle part comprises a set of interdistributary bay swamps and lacustrine deposits in the braided river delta plain. This section contains several siltstone interlayers with a thin single layer and a cumulative thickness of 97.92 m. The lithology includes black, dark-gray, and carbonaceous mudstones. Generally, the shale thickness in this section gradually increases from the delta plain to the delta front (Fig. 5(a)).

5 Relationships between sedimentary environment and organic matter abundance and distribution

According to Chen et al. (2006), the parameters affecting the organic matter enrichment in shales can be summarized based on the conditions of organic matter formation and preservation. 1) Biological productivity: a previous study suggested that the growth and distribution of marine organic-rich sediments were not primarily affected by the reductive environment (Calvert, 1987). High productivity is the primary reason of the large amount of organic material in marine sedimentary rocks. Sufficient organic matter can also form marine deposits with high organic carbon content in non-reducing environments, because an abundance of organic materials can significantly reduce oxygen levels during their decomposition, causing hypoxia at the bottom of the water and forming a reducing environment. 2) Redox conditions: Demaison and Moore (1980) and Tyson and Pearson (1991) suggested that the sedimentary environment or underwater anaerobic conditions would be the key factors in the production of organic-rich sedimentary strata. Although high organic matter productivity can be achieved in many environments, the preservation of organic materials and the creation of organic-rich sedimentary rocks require anoxic conditions underwater. 3) Deposition rate: the enrichment of organic matter in sediments is correlated with both biological productivity and sediment accumulation rate. In general, rapidly accumulating strata have low organic matter content. 4) Sedimentary environment: sedimentary environments are fundamental factors influencing the development of organic-rich shale because diverse sedimentary settings affect biological productivity, redox conditions, and deposition rate. Biomass is abundant in marine and lacustrine shales, and a hypoxic environment is the primary cause of high TOC. Compared with marine shale, the relatively small amount of sedimentary water in the continental lake basin, palaeoclimate, salinity, and tectonic background further control the enrichment of organic matter in continental shale by affecting productivity and preservation conditions (Sageman et al., 2003; Ma et al., 2022; Zhang et al., 2023). In the shallow lakes, large amounts of plant debris and other nutrients are brought in by terrestrially derived detritus, which results in a high TOC content in the sediments. As the sedimentation rate increases, a large amount of organic matter is gathered quickly, resulting in the increase the shale's TOC content (Hou et al., 2022). The water level of shale in a transitional environment is shallower and is more affected by continental sources; thus, shale TOC accumulation is closely related to the original production and preservation conditions. Due to different geological factors controlling organic matter abundance and distribution in marine, transitional and continental basins, it's necessary to summarize various sedimentary models of organic-rich shale under different depositional context in the future, which can provide a foundation to analyze the geological circumstances of shale gas accumulation.

5.1 Effect of marine environment on organic matter abundance and distribution

Undercompensated shallow-deep basins, platform marginal slopes, undercompensated bays, and evaporative lagoons are the main depositional locations for marine organic-rich shale (Li et al., 2008). More research has revealed that the deep-water shelf in the Sichuan Basin of the Ordovician Wufeng-Silurian Longmaxi shales has changed to a shallow-water shelf (Zhang et al., 2013; Zhao et al., 2018). Specifically, the Sichuan Basin is an undercompensated deep-water sediment containing sapropelic organic matter from the early Longmaxi and Wufeng periods, during which the slow depositional rate and reducing environment promoted organic matter enrichment (Zhang et al. 2012). For the upper part of the Longmaxi Formation, with a decline in sea level, the supply of terrestrial materials increased, and the deposition rate accelerated, resulting in a significant decrease in organic carbon content.

For the Shizhu section and Changxin 1 well in the eastern Sichuan Basin and the YS112 well in the southern Sichuan Basin, organic-rich shales of the Wufeng and Longmaxi formations formed, and the TOC content of the shale increased significantly from the shallow to the deep-water shelf (Fig. 6). Specifically, the mean TOC content in YS112 well of the Longmaxi Formation (shallow-water environment) is 1.47%, whereas that is 4.32% for the Wufeng Formation (deep-water environment) (Fig. 6(a); Yan et al., 2022). The average TOC content of shales in the Shizhu section and Changxin 1 well in Longmaxi Formation is 2.41% and 1.5%, whereas it in Wufeng Formation shale the average TOC level is 3.80% and 3.29%, respectively (Fig. 6(b); Zhang et al., 2013). A comparative analysis of different profiles and well locations showed that the sedimentary geographical location and facies zone contributed significantly to the composition and growth of marine organic-rich shale. Through the analysis of elemental geochemistry, the original productivity of the Wufeng-Longmaxi Formation shales was not high, and the real controlling factor for their enrichment was the redox conditions in an advantageous depositional environment (Chen et al., 2016).

5.2 Effect of transitional environments on organic matter abundance and distribution

Transitional sediments are subject to the dual influence of terrigenous rivers and oceans, and the enrichment of organic matter is affected by palaeoclimatic, redox, terrigenous debris input, palaeoproductivity, and sedimentation rate. The Longtan Formation mudstone was formed in a typical transitional environment in Guizhou Province, with the upper part of the Longtan Formation being mostly a delta, and the lower part being a barrier sand bar-tidal flat-lagoon environment (Liu, 2018).

5.2.1 Barrier sand bar-tidal flat-lagoon environment

A lagoon is a closed, low-energy environment with deep water levels that are suitable for organic matter build-up and burial owing to anoxic reduction. Therefore, the shale developed in this lagoon model is relatively thick (3.08 m) and has high organic carbon content (11.42%). The tidal flat was closer to the provenance than the lagoon; thus, the accumulation of shale was affected more by terrigenous debris input. Mixed flats and peat flats can generate shale with high organic carbon content during tidal flat sedimentation, with mixed flats forming thicker mudstone and shale. Due to the short water coverage period, the organic-rich shale tends to be thinner than 2 m in the peat flat. In the Longtan Formation, climatic conditions changed from damp and hot to wet and warm when the mud shale had been deposited in an anoxic flat-lagoon environment. Furthermore, the TOC content was found to have a significant positive association with the redox indicators U, V, and V/Cr but a modest negative correlation with the palaeo-productivity indices P/Ti and Ba/Al, indicating that the primary cause of organic matter enrichment in the tidal flat-lagoon habitat is anoxic conditions (Liu, 2018).

5.2.2 Delta facies

Organic-rich shale has developed into two lithofacies assemblage types in the delta including interdistributary bays and peat swamps. The delta sedimentary stage had a high chemical index of alteration, making it suitable for the growth of terrestrial plants. As the delta environment is close to the source area, shale deposition, including organic matter and mineral composition, is directly affected by terrigenous debris from rivers. At this time, sedimentary water in an oxidising environment is no longer suitable for organic matter accumulation, whereas a high deposition rate and considerable amount of terrestrial organic matter input are important factors in organic matter enrichment. In delta sediments, interdistributary bays can produce thick, organic-rich shales, whereas the shale created in peat swamps is rather thin (Liu, 2018).

5.3 Effect of continental sedimentary environment on organic matter abundance and distribution

In the northern Qaidam Basin of the Middle Jurassic Shimengou Formation, two sections of organic-rich shale

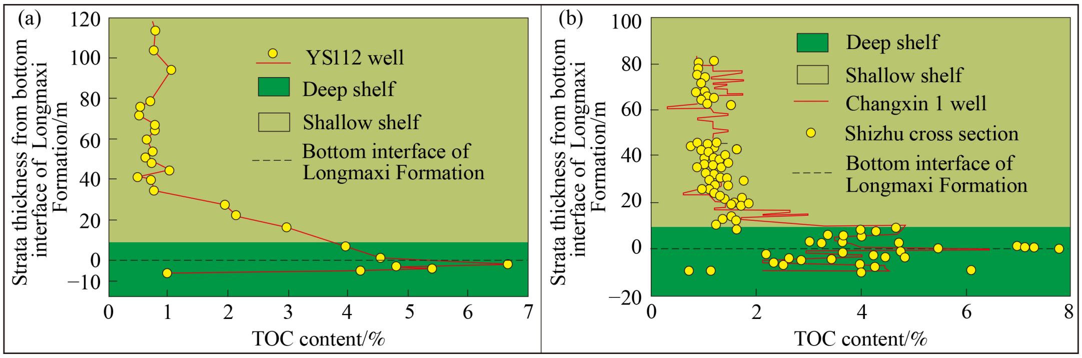

Fig. 6 Total organic carbon (TOC) content variation in the shales linked to the strata thickness from the bottom of Longmaxi Formation in YS112 well (a) and Shizhu cross section, Changxin 1 well (b) (modified from Zhang et al., 2013; Yan et al., 2022).

developed: the second (H2) and third (H3) members. The H3 shale in the upper part was deposited in a semi-seep or deep lake, in contrast to the H2 shale in the lower part, which was deposited in a shore-shallow lacustrine. The H3 shale's TOC ranges from 0.18% to 17.4%, and the distribution of organic matter increases gradually from bottom to top (Fig. 7). The H2 shale's TOC samples ranges from 0.27% to 9.78% and has an average of 3.02%. Compared to the mudstone in H3, the organic matter abundance in H2 is significantly lower. Therefore, shale in shore-shallow lakes has a lower TOC content than that in deep or semi-deep lakes.

The TOC content is horizontally higher in H3 in the Yuqia Coalfield, showing an increasing trend from west to east (Fig. 8(a)). The H3 shale in an anoxic deep or semi-deep lake is accompanied by a low deposition rate and good preservation conditions, causing the TOC content to rise as lake depth increases (Hou et al., 2022). H2 has a significantly lower shale TOC content than H3, ranging from 1% to 2% (Fig. 8(b)). The H2 shale formed during a strong terrigenous debris input period, resulting in a low TOC content due to limited organic matter productivity (Hou et al., 2022).

In general, the processes that govern organic matter enrichment in continental shales are much more complicated than those that influence marine shales. In addition to productivity and redox conditions, the local tectonic context, salinity, and palaeoclimate may also have an effect. For shales of the Jurassic Ziliujing Formation in the north-eastern Sichuan Basin, lacustrine productivity showes an upward trend with an increase in climatic humidity because abundant rainfall and sufficient surface rivers brought large amounts of organic matter, such as terrigenous plant debris. For continental saline lake basins, such as the felsic/mixed shale of the Palaeogene Sha 1 member in the Qikou Sag of the Bohai Bay Basin, it is difficult for oxygen and water flow to reach the lake bottom owing to different salinities, which is helpful for forming an anoxic environment and promoting organic matter enrichment and preservation. However, extremely high-water salinity would prevent plankton from growing, causing productivity to fall and making it difficult to enrich organic matter in places such as the Kong 2 member of the Palaeogene in the Qikou Sag and the upper Es4 member of the Palaeogene in the Dongying Sag (Zhang et al., 2023). The Xu3 and Xu5 members in Western Sichuan of the Upper Triassic Xujiahe Formation were formed in a stable subsidence stage, which offered favorable circumstances for organic matter preservation and enrichment (Zuo, 2019).

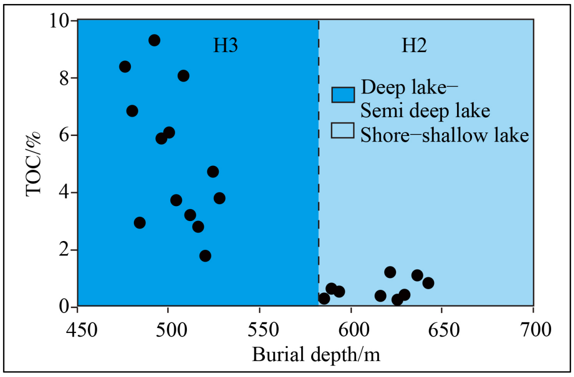

Fig. 7 Total organic carbon (TOC) content distribution of shale in the third (H3) and the second member (H2) of Shimengou Formation in YQ-1 well, northern Qaidam Basin.

6 Relationships between sedimentary environment and organic types, hydrocarbon generation potential

Kerogen, which constitutes 80%–90% of sedimentary organic matter and serves as the material basis for the production of oil and gas, can be classified into several types according to different classification standards and research purposes (Dai et al., 2008; Xiong et al., 2014; Hou et al., 2017). The sedimentary environment affects kerogen in two ways: 1) it affects the input and degradation of biological species to form different

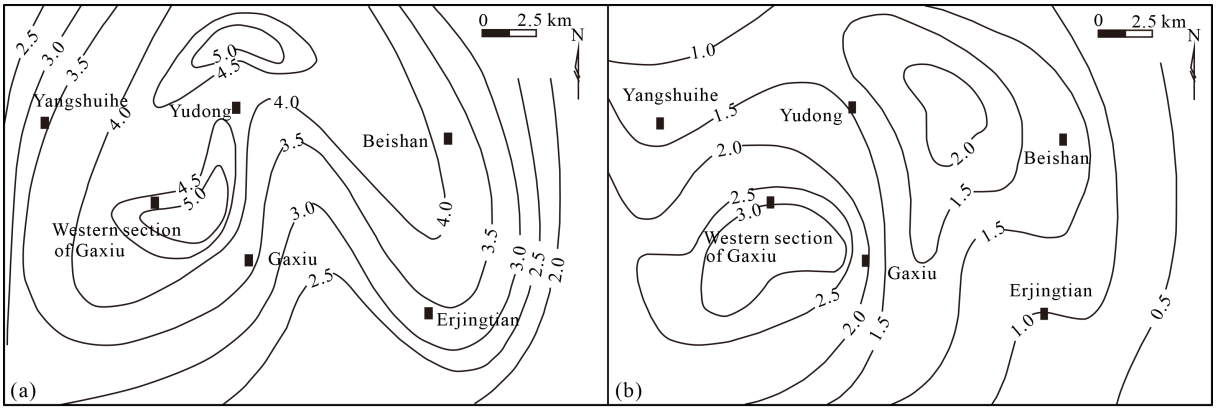

Fig. 8 Total organic carbon (TOC) isolines of the third (a) and the second member (b) of Shimengou Formation in Yuqia Coalfield, Northern Qaidam Basin.

kerogen types and 2) it affects the input of terrigenous detritus by oxidising organic matter and destroying kerogen. Marine deep shelves are rarely affected by terrestrial sources and organic matter is primarily sourced from plankton. Meanwhile, the kerogen in marine shale is mainly type I-II$_1$, which is high in hydrogen and low in oxygen, with plenty of hydrocarbons and organic pores. Under the influence of terrigenous sources, continental shale provides a large amount of plant debris, resulting in complex organic matter types, primarily II$_1$-III. A total of 109 shale samples from continental, transitional, and marine facies in China revealed a positive correlation between the hydrocarbon generation potential and TOC content (Fig. 9). Marine shale is highly mature and shale gas is a typical dry gas with little potential to produce hydrocarbons. However, the remaining TOC content of marine shale is still high (2%–10%), indicating that marine shale may provide a considerable amount of gas and serve as an effective shale reservoir in China (Fig. 9). In terms of hydrocarbon generation potential, the Carboniferous-Permian transitional shale has developed from poor to good. Similar to continental shale, many kerogen types are known owing to the influence of terrigenous debris, and shale gas can vary from wet to dry. Lacustrine shale is frequently near the oil-generating window and has low maturity but significant hydrocarbon generation potential. The hydrocarbon production potential of China's transitional and continental shales is substantial; however, the development area of marine shale still holds the greatest promise for shale gas extraction.

6.1 Effect of marine sedimentary environment on organic matter types and hydrocarbon generation potential

The kerogen types and hydrocarbon generation potential of marine shales were analyzed in the Guizhou Niutitang and Longmaxi formations based on kerogen carbon isotopes ($\delta^{13}C$) values. The Niutitang Formation is rich in plankton, and its kerogen macerals differ from those of the Longmaxi Formation, in which the former is composed of sapropelic and humic amorphous substances, and the latter is dominated by humic amorphous substances (Sun et al., 2017). During the Niutitang Formation, the shale kerogen belongs to type I-II$_1$ with −34.7‰ to −28.6‰ $\delta^{13}C$ and a 64–96 type index with a good hydrocarbon generation. The distribution range of $\delta^{13}C$ is −28‰ to −29.15‰ in the Longmaxi Formation, with a type index of 28–58; thus, the kerogen is mostly type II$_1$. The Niutitang Formation has a lower $\delta^{13}C$ than the Longmaxi Formation due to the high algae content, enrichment of lipids, and weak decomposition of bacteria in the reductive environment (Teng et al., 2004). In terms of biological fossils, graptolites and trilobites are abundant in the shales of Niutitang Formation. In the Longmaxi Formation, graptolite fossils are replaced by benthic organisms such as trilobites and brachiopods with abundant bioturbation structures. The bioturbation structures are developed mainly in an environment with sufficient sunlight and rich oxygen content, indicating that the water body becomes shallow in the Longmaxi Formation. According to the relationship between hydrocarbon generation potential and kerogen type (Jiang et al., 2016), the shales of the Niutitang Formation are mainly deep-water shelf facies, and they have larger hydrocarbon generation potential than the Longmaxi Formation, which is predominantly shallow-water shelf.

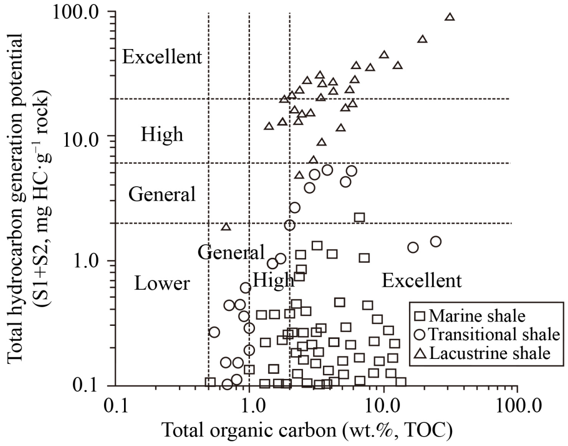

Fig. 9 Relationship between organic matter content and hydrocarbon generation potential of marine, marine-continental transitional, and continental shales in China (modified from Jiang et al., 2016).

6.2 Effect of transitional sedimentary environment on organic matter types and hydrocarbon generation potential

Compared to marine shale, transitional shale has a greater supply of terrigenous debris, and its sedimentary background is closely related to delta and tidal flat-lagoon coal-forming environments (Cao et al., 2014). In contrast to marine and deep or semi-deep lacustrine shales, organic material in transitional shales is mainly sourced from terrestrial higher plants. Therefore, kerogen macerals are dominated by vitrinite and fusinite, and the organic matter is primarily of type III. This kerogen begins to generate gas at a relatively low maturity; thus, the exploration target for transitional shale is shale gas. Barrier lagoon shale is found in the Lower Yangtze of the Upper Longtan Formation, corresponding to a high single-layer thickness. The kerogen is mainly type II and III, and its hydrocarbon potential (S1 + S2) is relatively high (11.56 mg/g on average) (Yan et al., 2016). The shale in the coastal plain facies is 12–25 m thick with 0.41%–9.24% TOC content, and the kerogen is a typical type III gas-generating organic matter. For the delta front environment, the kerogen is mainly of types II and III, with a shale thickness (2–90 m), a TOC content (0.25–1.91%), and a hydrocarbon generation potential (4.46–

19.93 mg/g). Based on the calculating the kerogen TI of transitional shales in the Ordos Basin, Bohai Bay Basin, and Qianbei Platform, the results show that the organic matter types of mud shales are all type III (Li, 2014).

The organic matter type changes from III to II for shale deposits migrating toward the marine environment (shallow shelf direction), whereas the organic matter type changes from II to III for shale deposits migrating toward the continental environment (shore plains). Both forms of organic material were found in the shales deposited in the barrier lagoon and delta front. In addition, if shale overburden develops in coal seams, type III kerogen appears in most cases and the shale hydrocarbon generation potential is reduced.

6.3 Effect of continental sedimentary environment on organic matter types and hydrocarbon generation potential

Various types of continental shale deposits exist, and organic-rich shales are mostly situated in shore-shallow, deep, or semi-deep lakes. Due to the generally low maturity of continental shale, exploration targets include shale gas and oil (Panno et al., 2013). The shale's hydrogen index (HI) in the northern Qaidam Basin changes greatly (42.17–1167.88 mg/g) in the Shimengou Formation. For the average HI, the value (747.17 mg/g) of the Upper Shimengou deep or semi-deep lacustrine shales is significantly higher than that (186.02 mg/g) of the Lower Shimengou shallow lake shales (Hou et al., 2017). Considering the maximum pyrolysis temperature and HI, most Shimengou shales are identified at the low-maturity stage, and a few shales are at the immature stage. The majority of the Upper Shimengou shales have kerogen types I and II_1, whereas the majority of shales in the lower section belong to type II_2 and III. Therefore, the kerogen of deep or semi-deep lakes tends to generate oil with high hydrocarbon generation potential, whereas the kerogen of shallow lakes tends to generate gas with low hydrocarbon generation potential. The shale kerogens close to the lake margin in Jiyang Depression are mainly type II_2 with limited type III, and the shale kerogens near the lake center are mainly type I and II_1 (Li et al., 2022).

7 Relationships between sedimentary environment and mineral composition, pore structure

The physical features of the shale reservoir are determined by different rock types and mineral compositions (Liu et al., 2013), which in turn affect shale gas accumulation. In China, shales from various sedimentary environments are composed of brittle quartz, feldspar, clay (kaolinite, chlorite, illite, and montmorillonite), organic matter (kerogen), carbonate rocks (calcite and dolomite), pyrite, and siderite (Jiang et al., 2016). Marine shales of the Early Palaeozoic contain numerous brittle minerals in the Yangtze region, and their mineral compositions are quite similar to the Barnett shales in the United States (Loucks and Ruppel, 2007; Martin et al., 2008). Transitional shale in the Yangtze region has far less brittle mineral content than marine shale, but significantly more clay mineral content, making it unsuitable for shale gas exploration and development (Liu, 2018). Lacustrine shale contains more clay minerals than marine shale, with some areas reaching more than 50% (Yuan et al., 2015; Zhou et al., 2020). However, for deep or semi-deep lakes, where the supply of terrigenous detritus is interrupted, the black shales with high TOC contents, large thicknesses, and highly brittle minerals also have good exploration potential (Wang et al., 2014). Therefore, the lacustrine shale's mineral composition is closely tied to its sedimentary facies; however, its use as a favorable reservoir for shale gas exploration must be analyzed in light of the specific situation (Boyer et al., 2011; Zou et al., 2011; Ju et al., 2014). The transitional and continental environments are relatively weak for shale gas development because of the high clay minerals. It is important to emphasize the influence of the depositional environment on the type of clay minerals, supporting shale gas exploration and development.

Different sedimentary environments results in different shale mineral compositions and pore types. Marine shale is characterized by brittle mineral compositions accounting for 50%–70%, such as quartz and feldspar. These minerals have an anti-compaction effect that can effectively protect the intergranular pores and then form residual intergranular pores. This effect can also lead to the development of carbonate minerals, which can easily form dissolution pores. The pores of transition shales are dominated by matrix pores (clay mineral intergranular pores, intergranular pores, dissolution pores, etc.), with fewer organic matter pores. Continental shale reservoirs are enriched with 55%–68% clay minerals owing to dilution by terrigenous debris, and the pore structure of shale is dominated by clay mineral pores and organic matter pores. With an increase in burial depth and continuous diagenesis, clay minerals are transformed from montmorillonite to more stable minerals such as illite and chlorite, forming intergranular and intragranular pores.

7.1 Control of marine sedimentary environment on mineral composition and pore structure

In the Middle-Lower Yangtze area of the Lower Cambrian Qiongzhusi Formation, organic-rich shale primarily formed on the shelf and in deep or semi-deep seas. The shale contains quartz and clay as the main constituent minerals in the Qiongzhusi Formation, with trace amounts of feldspar, dolomite, calcite, and authigenic minerals. Clay minerals in shallow shelf environments range from 7.1% to 55.2%, whereas they range from 8.8% to 26.4% in deep and semi-deep seas (Wang et al., 2013). Therefore, the shale's clay content is much higher on shallow shelves than that in deep or semi-deep-sea environments, although the opposite is true for the brittleness index (Fig. 10).

Different mineral compositions affect the pore type and structural properties (Wang et al., 2013; Hou et al., 2018). In the Middle-Lower Yangtze region, the shale mainly formed in retained basin facies during the Early Cambrian, depositing a set of carbonaceous and siliceous shales. Fine-grained or strawberry-like pyrite deposited in a closed or semi-closed anoxic reduction environment is scattered or laminated and filled with several pyrite intergranular pores. The lamellations found in shales deposited in the deep or semi-deep sea retention basin are well developed, which results in many fractures at the bottom of the Qiongzhusi Formation that demonstrates good connectivity to form a reservoir space. The Qiongzhusi Formation in north-western Hunan Province generates carbonaceous shale and siliceous rocks of shelf facies with substantial clay minerals, many organic matter pores, and abundant intercrystalline pores. The pore distribution in the marine shales is mainly concentrated at 6–8 nm, with a relatively large pore volume of 1–2 μL/g and a high specific surface area of 10–20 m^2/g (Fig. 11).

7.2 Influence of transitional sedimentary environment on mineral composition and pore structure

In western Guizhou Province, the lower section of the Longtan Formation formed in a tidal flat lagoon. The shale's average quartz content is 48.9%, making it the most abundant carbonate mineral component. The clay mineral content is the second highest at 29.1% followed by feldspar at 8.9%. The upper Longtan Formation formed in a delta sedimentary environment, and the shale's quartz content is higher than the lower section, averaging 54%, whereas the clay mineral content is lower, averaging 23.1% (Liu, 2018). Therefore, in the Longtan Formation, the tidal flat-lagoon depositional setting of the lower section exhibits lower levels of quartz and higher levels of carbonate, pyrite, and clay minerals than the upper deltaic section, and proving that the water body has a significant influence on mineral composition. From the lower tidal flat lagoon to the upper delta environment, the brittleness index shows a fluctuating increase, reflecting frequent transgression and regression during the development of the Longtan Formation. However, the influence of terrestrial debris from rivers increases, resulting in the increasing brittleness index. In terms of pore types, intercrystalline and solution pores in clay minerals predominate in tidal flat lagoons, whereas intercrystalline and intergranular pores predominate in delta environments (Li, 2014). Owing to the various sedimentary types and rapidly replacing lithofacies in the transitional strata, the pore structure changes significantly according to the sedimentary environment. The average pore size is 4–10 nm, the total pore volume is 2–4 μL/g, and the specific surface area is 9–20 m^2/g (Li, 2014). Although there are notable variations in various regions, the transitional shale's pore parameters are typically between those of continental and marine shales (Fig. 11).

7.3 Effect of continental sedimentary environment on mineral composition and pore structure

The H2 shale in the Yuqia Coalfield of the Shimengou Formation is dominated by clay minerals and quartz, with the highest clay mineral content of 28%–82% and an average content of 61.95%, followed by quartz content of 17%–67% and an average content of 33.50%. The H3 shale of the Shimengou Formation has an average brittle mineral content of 49.74%, which is higher than that of H2. However, carbonate minerals, pyrite, and other authigenic minerals account for a larger proportion of

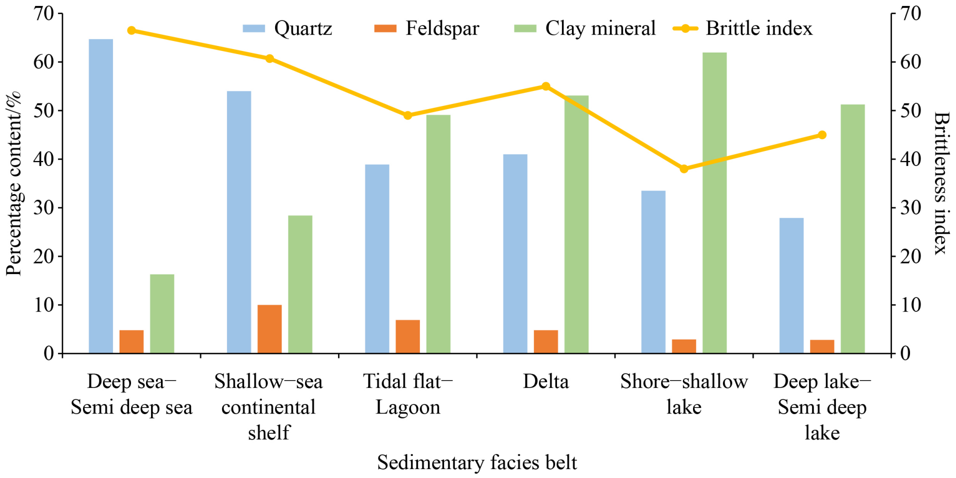

Fig. 10 Variation of brittleness index and shale mineral composition according to sedimentary environment (data from Hou et al., 2017; Liu, 2018; Wang et al., 2013; Li, 2014).

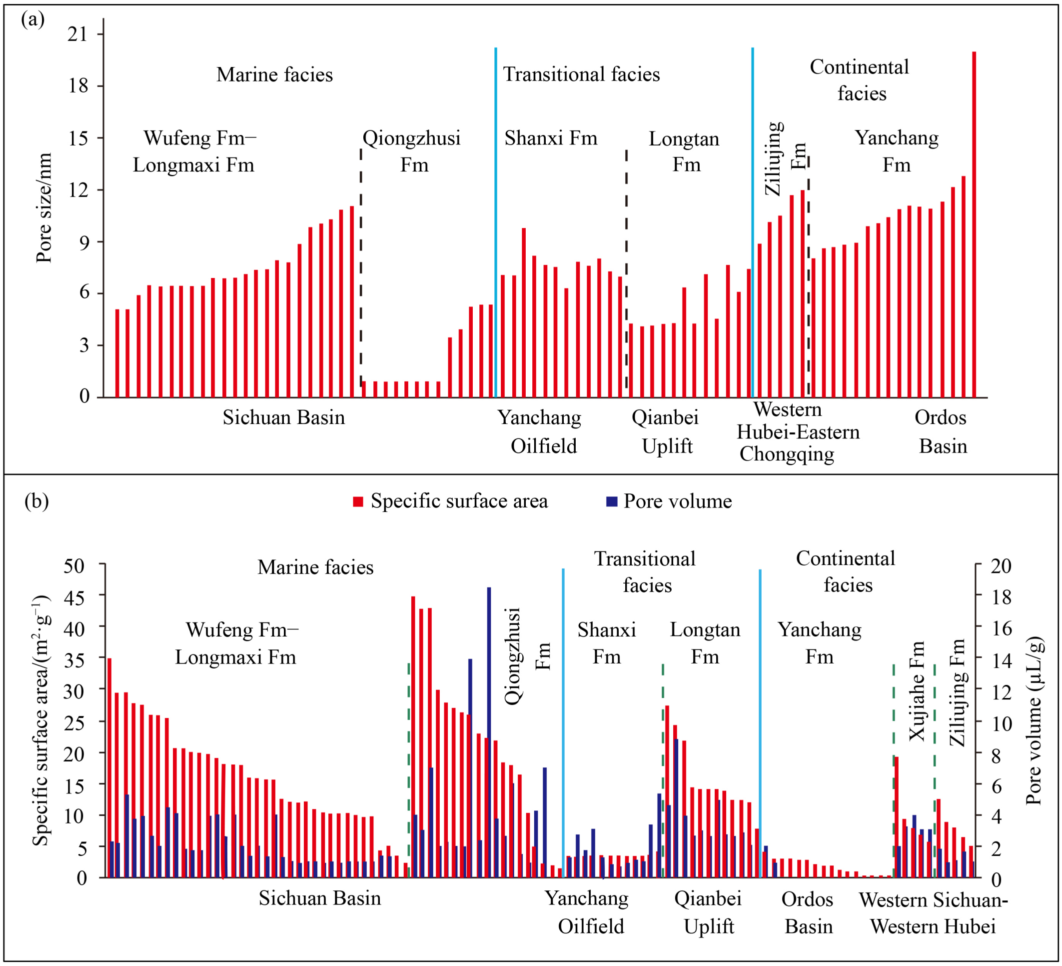

Fig. 11 Variations in shale pore structure parameters according to different sedimentary environments for average pore size (a) and specific surface area and pore volume (b) (data from Er et al., 2013, 2015; Liu et al., 2014; Xin and Luo, 2009; Guan et al., 2016; Li, 2014).

brittle minerals in H3, with an average value of 30.67% for total quartz and feldspar, which is lower than the H2 of 36.41% (Shao et al., 2016; Hou et al., 2017). The H3 shale was formed in a semi-deep or deep lake setting and was less affected by terrigenous clastic matter, thus having a lower quartz and feldspar content than shallow lakes. However, owing to the strong reduction conditions in deep or semi-deep lakes, other brittle mineral contents including siderite and pyrite clearly increase, resulting in a lower total brittleness index in shore-shallow lakes than in deep or semi-deep lakes (Fig. 10).

As the TOC content increases in the northern Qaidam Basin, the true and apparent densities of shales decrease (Hou et al., 2017), indicating that inorganic minerals and organic matter in shale are inversely correlated (Ross and Bustin, 2008). Continental shales have a higher porosity than marine and transitional shales, ranging between 4.3% and 25.1% (Ross and Bustin, 2009; Pan et al., 2015). Except for several distinct discrete points, the porosity and TOC content are positively correlated (Hou et al., 2017). By analyzing the mineral composition of the shale at these anomalies, a correspondence between shale with low quartz content and lower porosity is found, which should be closely related to the strong support of quartz. Therefore, shale porosity is affected by both inorganic mineral porosity and organic matter. Inorganic mineral matrix pores are regulated by mineral content (Cander, 2012; Pan et al., 2015), whereas Organic porosity is closely related to TOC content (Loucks et al., 2012; Mastalerz et al., 2013). Although continental shale's pore size is typically bigger than that of marine shale (between 10 and 12 nm), it has a smaller pore surface area and volume (5–8 m^2/g and 0.3–0.6 μL/g, respectively) than marine shales (Fig. 11).

8 Influence of different sedimentary environments on the properties of organic-rich shale

The sedimentary environments of organic-rich shales include deep sea, semi-deep sea, shallow shelf, tidal flat-lagoon, delta, shore-shallow lacustrine, and semi-deep or deep lacustrine (Table 1). The typical lithology of deep or semi-deep lakes is gray-black siliceous shale and black organic-rich carbonaceous shale. The main factors responsible for TOC enrichment are redox conditions and biological productivity. Marine shale has highly brittle minerals and low clay content with abundant intergranular, dissolution, and residual intergranular pores. Marine shale with a higher pore volume and specific surface area has a smaller pore size, and the organic matter is mainly type I-II$_1$ with low hydrocarbon potentials.

For shallow shelves, the typical rock types are dark-gray calcareous shale and black silty shale with low organic matter content, and TOC enrichment is determined by terrigenous debris input and deposition rate. Shale on shallow shelves is characterized by medium-sized clays and highly brittle minerals with well-developed intergranular, residual intergranular, and intergranular pores. These pores have a small size but a high pore volume and specific surface area, and the organic matter is mainly type I-II$_1$ with a low hydrocarbon potential.

The typical rock types in tidal flat-lagoon environments are black shale, gray-black rock, and carbonaceous mudstone with variable organic matter content. The enrichment of shale organic matter is affected by redox conditions, and the mineral content is characterized by medium brittle minerals and high clays. The pore types mainly consists of dissolution and intergranular pores with relatively average pore diameters, pore volumes, and specific surface areas. The organic matter is mainly type III with a medium hydrocarbon potential.

Typical rock types in delta environments are dark-gray sandy mudstone and carbonaceous mudstone with variable organic matter contents, where organic matter enrichment is controlled by terrestrial inputs and deposition rates. The delta, which has developed numerous intergranular and intragranular pores, is characterized by high clay and medium brittle minerals with medium pore size, pore volume, and specific surface area. The kerogen is mainly type III, with medium hydrocarbon potential.

For shore-shallow lakes, the typical rock types are carbonaceous mudstone and dark-gray mudstone with low organic content, and deposition rate and terrigenous debris input jointly affect organic matter enrichment. The shallow lake contains low brittle mineral and high clay content, and generally has developed intergranular and intragranular pores with large pore sizes and small pore volumes and specific surface areas. The kerogen is mainly of type II$_2$-III with a high hydrocarbon potential.

For deep or semi-deep lakes, the typical rock types are gray-black shale and oil shale with high organic content, and the biological productivity and redox conditions jointly determine the organic matter enrichment. The mineral content is characterized by medium brittle mineral and high clay content, and intergranular and intragranular pores with large pore sizes and low specific surface areas and pore volumes. The kerogen is mainly

Table 1 Comparison characteristics of organic-rich shales in different depositional settings

Sedimentary facies	Sedimentary subfacies	Typical rock type	Organic matter abundance	Main control factors of TOC enrichment	Mineral content	Brittle index	Pore type*	Pore structure	Organic matter	Hydrocarbon potential
Marine facies	Deep sea-Semi deep sea	Black carbon shale, Gray black siliceous shale	High	Redox condition, Biologic productivity	Low clay, High brittle minerals	High	Intercrystalline pore, Residual intergranular pore, Solution pores	Small pore size, High surface area and pore volume	I-II$_1$	Low
	Shallow-sea continental shelf	Black silty shale, Dark gray calcareous shale	Low	Terrestrial input, Deposition rate	Middle clay, High brittle minerals	High	Intercrystalline pore, Residual intergranular pore, Intergranular pore	Small pore size, High surface area and pore volume	I-II$_1$	Low
Transitional facies	Tidal flat - Lagoon	Black shale, Gray black shale, Carbon mudstone	Changes greatly	Redox condition	High clay, Middle brittle minerals	Middle	Intercrystalline pore, Solution pores	Middle pore size, surface area and pore volume	III	Middle
	Delta	Dark gray sandy shale, Carbon mudstone	Changes greatly	Terrestrial input, Deposition rate	High clay, Low brittle minerals	Middle	Intercrystalline pore, Intergranular pore	Middle pore size, surface area and pore volume	III	Middle
Continental facies	Shore-shallow lake	Dark gray mudstone, Carbon mudstone	Low	Terrestrial input, Deposition rate	Low clay, High brittle minerals	Low	Intergranular pore, Intra-granular pore	Large pore size, Low surface area and pore volume	II$_2$-III	High
	Deep lake-Semi deep lake	Gray black mudshale, Oil shale	High	Redox condition, Biologic productivity	High clay, Middle brittle minerals	Middle	Intergranular pore, Intra-granular pore	Large pore size, Low surface area and pore volume	I-II$_1$	High

Note: *, Pore types except organic matter pores.

type I–II$_1$ with a high hydrocarbon potential.

In marine, transitional, and continental environments, shale color gradually darkens from shallow to deep waters. There are many sedimentary types with rapid changes in transitional facies, suggesting a multicycle lithology. Carbonaceous mudstone associated with coal seams is a critical factor contributing to the high TOC content in the transitional facies. Shales in deep or semi-deep seas and deep or semi-deep lakes are rich in biomass, and the TOC content increases nearer sea, which is influenced by redox conditions and biological productivity. The clay content is higher in continental and transitional shales than in marine shale. Many minerals, such as carbonate, pyrite, and siderite, are present in deep or semi-deep seas and lakes, which increase the shale brittleness index. In addition to organic matter pores, marine shale has more residual intergranular and dissolution pores, whereas continental shale tends to contain more intergranular and intragranular pores. Considering the pore parameters, marine and continental shales are more stable than marine-continental transitional shales in that marine shales have smaller pore sizes but higher pore volumes and specific surface areas, whereas continental shales have larger pore sizes but lower pore volumes and specific surface areas. Marine shale has low hydrocarbon generating potential and high maturity, and the main kerogen type is I-II$_1$. Terrestrial shale has a low maturity, high hydrocarbon content, and various organic types. Transitional shale has medium hydrocarbon potential, and the majority of organic matter comes from higher plants with type III kerogen. As the depositional environment has many direct and indirect influences on the properties of shales, the systematic research should be strengthened in the future.

9 Conclusions

1) From shallow to deep water, shale color gradually changes from light gray to gray, deep gray, gray-black, and black. Owing to the influence of terrigenous clastic input, silty shale usually occurs near provenances with high brittleness. Carbonaceous shale is a special type of rock that typically appears in swamp environments of any sedimentary system. The thicknesses of the continental and marine dark shales gradually increase from the provenance to the deposition center, with thicker shales mostly occurring in semi-deep lake (lacustrine facies) and sea (marine facies) zones, whereas thick shales of transitional facies mostly occur in areas with high accommodation.

2) Marine shale is rich in biomass, and its TOC content increases gradually toward sea. The major factor influencing organic matter enrichment is the redox conditions in favorable sedimentary environments, which is consistently associated with variations in TOC in semi-deep lacustrine shales. The TOC content of shallow lacustrine shales is generally affected by the deposition and rate of terrigenous debris input. The influence of transitional shale depositional environments on TOC content can be summarized in two aspects. 1) In sedimentary areas, such as barrier island-tidal flat-lagoon environments, the preservation conditions of low-oxidation bottom water are key factors affecting organic matter enrichment. 2) In delta facies zones, the original productivity and terrigenous clastic input, which are controlled by climatic conditions, can largely determine the TOC distribution. It's suggested to summarize various sedimentary models of organic-rich shale under different depositional environment to well analyze the TOC content and distribution.

3) The mineral components and corresponding pore types of shales are different in various depositional environments. 1) Clay minerals are distinctly higher in terrigenous shales than in marine shales. 2) The brittle minerals in the semi-deep and deep sea shales are mainly attributed to authigenic quartz, whereas the quartz in the terrigenous and marine-terrigenous transitional facies is mainly controlled by terrigenous input. Owing to the strong reduction conditions in deep and semi-deep lakes, the content of other brittle minerals (siderite and pyrite) increases significantly. As a result, the total brittle mineral content of shale in shore-shallow lake environments is lower than that in deep or semi-deep lacustrine environments. 3) In addition to organic matter pores, marine shale has more residual intergranular and dissolution pores, whereas continental shale tends to have more intergranular and intragranular pores. 4) Organic matter and inorganic mineral matrix pores both influence shale porosity, with organic pores directly tied to TOC content and inorganic pores determined by mineral content and their various associations.

4) Marine deep-water shelves are seldom affected by land sources and organic substances are originated from plankton with kerogen type I-II$_1$. Except for semi-deep or deep lacustrine facies, continental and transitional environments bring in ample plant clastic components, resulting in more complex organic matter of type II$_1$-III. Marine shale is in a stage of high-maturity evolution with an extremely low hydrocarbon generation potential, indicating that marine shale in China has produced a significant amount of gas. Similar to continental shale, the hydrocarbon generation potential of transitional shale varies greatly, and there are many kerogen types owing to the influence of terrigenous detritus. Lacustrine shale with low maturity has high hydrocarbon generation potential, making it suitable for oil shale exploitation.

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