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Original research paper

Pore formation and occurrence in the organic-rich shales of the Triassic Chang-7 Member, Yanchang Formation, Ordos Basin, China☆

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Abstract

Shale-reservoir appraisal depends greatly on its pore characteristics (e.g., diameter, geometry, connectivity). Using a new pore-classification scheme based on the matrix type and occurrence state, four types of pores are identified in the organic-rich shales of the Triassic Chang-7 Member: intergranular, intragranular, organic pore, and microfracture. The intergranular pores are subdivided into primary pores between clastic grains, clay-mineral aggregates, and secondary dissolution pores between clastic grains or clay-mineral aggregates based on their origins, respectively. The intragranular pores are subdivided into secondary dissolved pores in feldspars, intra-clay-mineral aggregates and inter-pyrite. Organic pores include primarily microfractures in the organic matter and isolated organic pores. Microfracture is mainly developed along sandy and muddy laminations. Analysis by integration of data from pore imaging, low-temperature liquid nitrogen absorption, relationships between pore geometry and mineral components and between TOC and maturity of organic matter indicates that depositional environment, diagenesis, and thermal evolution of organic matter controlled the formation and preservation of pores. Organic-rich shales deposited in a deep and semi-deep lake environment contains thinly bedded turbidite sandstones, which are characterized by high content of clastic particles and thus favor the development of primary intergranular and intragranular pores, as well as microfractures along sandy laminations. During the early diagenesis process, precipitation of pyrite favors the development of inter-pyrite pores. However, compaction reduced the diameter and bulk pore volume. Organic pore has been greatly reduced under compaction. Dissolution led to formation of both inter and intra-feldspar pores, which has improved reservoir quality to some extent. Organic pore started to develop after shale maturity reaches a threshold ($R_O = 0.75\%$). Consequently, low organic pores could have been caused by the combination effect of low maturity and compaction. In addition, hydrocarbon is adsorbed on the surface of the organic matter, which could have caused the expansion of kerogen and then the reduction of organic pore.

Keywords: Matrix pore; Organic pore; Depositional environment; Diagenesis; Organic maturity

1. Introduction

Organic rich shale is originally studied as source rock and seal. Along with the success in shale-gas development, its importance in serving as hydrocarbon reservoirs has been recognized. Argon ion polishing technology (AIP), Field emission scanning electron microscopy (FESEM), Focusing Ion Beam (FIB), Nano-CT, and Nuclear Magnetic Resonance Imaging (NMRI) has been extensively applied in the

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characterization of shale pore geometry, diameter, and connectivity, leading to detailed, micro-scale, and quantitative shale-pore characterization [1−9]. The Triassic Chang-7 Member of the Yanchang Formation contains abundant organic-rich shale and is the key exploration target for unconventional hydrocarbon in the Ordos Basin, China [10−12]. Since the shale in the Chang-7 Member was deposited in lacustrine environment, its mineral compositions, kerogen type and maturity of organic matters are greatly different from marine shales. Consequently, the study on the pore types and their controlling factors will help understand the mechanism in reservoir formation and hydrocarbon occurrence and accumulation in the organic-rich Chang-7 Member.

2. Pore types and characteristics

Different from conventional reservoirs, shale reservoir consists of not only clastic grains, pores, matrix, and cement, but also organic matter. In recent years, characterization of shale pores has been greatly improved due to the development of technology. Due to variation in measuring methods, samples conditions, and geological backgrounds, many different classification schemes for shale pores have been proposed based on matrix types, pore occurrence state, pore geometry, origin, and connectivity [1,7,8,13−23].

Geometry, diameter, and connectivity can only be used to characterize pores qualitatively or semi-quantitatively and the results are affected by sample conditions, measuring methods, and accuracy. Pore origin requires systematic analysis on the geological background, which is difficult to achieve. Consequently, a new method that is simple, practical and easy to operate is called for the classification of pores in shale reservoirs.

2.1. Pore classification

Pore origin and occurrence state are the two most important criteria for conventional pore classification for clastic and carbonate reservoirs [24−26], which can be adopted in classification of shale pores.

Organic matter is fundamentally different from matrix. The formation mechanism of organic pores and matrix pores are also different. Consequently, organic pore is defined as a separate pore type. Organic matter includes kerogen and bitumen, which both contain pores [4,15,16,18,27−29].

Pores in the shale reservoirs are commonly very small due to the small-scale grains and high clay content. They have very low preservation potential and tend to be greatly reduced by compaction. It is comparatively easier to characterize the occurrence state than to judging the origin of pores in shale reservoir. Consequently, we classified the matrix-related pores into intergranular and intragranular based on their occurrence state and then subdivided them based on their origins (Table 1).

2.2. Pore types of the Chang-7 shale

Matrix pores in the Change-7 shale includes intergranular, intragranular, organic pore and microfracture.

2.2.1. Intergranular pores

Intergranular pores include primary pores between grains, clay mineral aggregates, and dissolution pores between grains.

Primary intergranular pores are formed during the depositional process by the support of clastic grains, which are not filled by matrix, cement and organic matters. The boundary of pores is commonly in regular geometry, including triangular (Fig. 1a), polygonal (Fig. 1b and c), close to round (Fig. 1a) and fractures. Pore diameter ranges from 10 nm to 2 μm. Quartz and feldspars are the two main clastic grains. Clastic grains and clay minerals are in contact with each other in the form of point or lines, without concave and convex contact relationship and deformed clay minerals (Fig. 1a−c). The clastic grains and organic matter are in the concave and convex contact with each other. In some cases, the clastic grains are embedded into the organic matters. The near

Table 1
Classification of pore types for the Chang-7 shale reservoir.

Matrix	Pore occurrence state	Origin	Description
Mineral matrix	Intergranular	Primary intergranular	Occur in between primary clastic grains or in between clastic grains and clay minerals
		Intergranular dissolution pores	Occur in between primary clastic grains due to dissolution
		Pores in between layers	Occur along the muddy laminations. In the geometry of strip
		Pores between clay-mineral	Occur in between irregularly arranged clay mineral
		Pores between clay-mineral aggregates	Occur in aggregates that are formed by clay minerals with electrostatic charges
	Intragranular	In organism's body cavity	Relates to fossils, unfilled organism bodies
		Pellets	Excreta of various marine organisms
		Intragranular dissolution pores	Dissolution of the internal part of clastic grains (e.g., feldspar)
		Pores in between clay-mineral	Occur in between irregularly arranged clay mineral
		Pores in between pyrite cluster	In between clustered pyrite mineral
		Cement dissolution pores	Dissolution of cements (e.g., carbonate minerals)
Organic matter		Kerogen	Pores formed during kerogen biodegradation
		Bituman	Pores formed during bituman hydrocarbon fractionation
Microfracture			Affected by structural, depositional and diagenesis processes. Could cut through clastic grains, muddy laminations and lithologic interface.