International Journal of Mining Science and Technology 24 (2014) 425–431

Contents lists available at ScienceDirect

International Journal of Mining Science and Technology

journal homepage: www.elsevier.com/locate/ijmst

Reservoir space of the Es_3^3–Es_4^1 shale in Dongying sag

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ARTICLE INFO

Article history:
Received 5 September 2013
Received in revised form 10 November 2013
Accepted 9 February 2014
Available online 11 June 2014

Keywords:
Shale
Oil
Gas
Reservoir space
Dongying sag

ABSTRACT

The Es_3^3–Es_4^1 shales in Dongying sag are source rocks with large reserves of shale oil and gas. For the identification of development characteristics and geological significance of the reservoir space, FMI logging, core observation, thin section analysis, X-ray diffraction, fluorescence microscopy, scanning electron microscopy, mercury porosimetry, low-temperature nitrogen adsorption, atomic force microscopy, and conventional physical property testing were used to study the petrology and reservoir space of the Es_3^3–Es_4^1 shale in Dongying sag. The results suggest that the shale is rich in carbonate minerals. Phanerocrystalline stratiform and lamellar argillaceous limestone and calcareous claystone are the oil- and gas-bearing lithofacies. The oil in the micropores is mainly present as membranes and clots. The shale reservoir space has a network structure with veins, carbonate and clay minerals, and micropores among pyrite and the matrix. The results provide the geological framework for future shale oil and gas exploration in Dongying sag.

1. Introduction

Presently, shale oil and gas are important targets of hydrocarbon exploration globally. China has great shale oil and gas exploration and development potential. Dongying sag is located in the southeast of Jiyang Depression. It is a small secondary fault-sag basin of area 5850 km^2. Dongying sag is a dustpan-like structure with faults in the north and overlapping in the south. The Es_3^3 and Es_4^1 submembers are the major hydrocarbon source rocks in Dongying sag [1–4]. Es_3^3 and Es_4^1 are mainly dark shale with thickness of 100–400 m and 100–300 m, respectively. The Es_3^3 and Es_4^1 submembers are the product of intensive faulting and their thickness increases near the basin margins. By the end of 2012, tests and well loggings were completed in 25 wells. Among the 25, 15 wells had industrial grade oil and gas, 9 wells had low oil yield, 6 wells had shale oil and gas yield of 4–10 t/d, 6 well had shale oil and gas yield of 10–25 t/d, and 3 wells had shale oil and gas yield of 46–99 t/d. Thus, the production efforts in these 25 wells are mainly concentrated on the Es_3^3 and Es_4^1 submembers.

Based on existing work, we took shale samples from five wells (Fan 120 well, Wang 31 well, Wang 57 well, Niu 38 well, and Li 673 well) and collected cores of three new coring wells (Niuye 1 well, Fanye 1 well, and Liye 1 well) [5–12]. We used core and thin section analysis, X-ray diffraction, clay analysis, scanning electron microscopy (SEM), and physical property testing to study the petrology and reservoir space of Es_3^3–Es_4^1 shale in Dongying sag.

2. Petrology

2.1. Mineralogy

The mineralogy of the Es_3^3–Es_4^1 shale in Dongying sag is highly variable. According to the X-ray diffraction data from 1000 core samples of 26 wells (Table 1), clays (27%), quartz (25%), and calcite (34%) are the primary minerals, followed by dolomite (6%), pyrite (3%), alkali feldspars (3%), and siderite (<1%). Anhydrite is present in several samples. The sand and shale content (clays, quartz, and feldspars) is 20–97% with an average of 56%, and the clay minerals are roughly equal to the amount of terrigenous clastic material. The endogenous and epigenetic components (calcite, dolomite, and pyrite) range between 3% and 80% with an average of 44%. The Liye 1 well has the highest content of sand and shale components among the three coring wells with shale lithology. The average content of clay minerals, quartz, and calcite in the Es_4^1 submember is 20%, 23%, and 37%, respectively, and the average content of feldspars is 5%, dolomite 11%, and pyrite 3%. The sand and shale components vary between 3% and 96% with an average of 49%, and the content of clay minerals is lower than the terrigenous

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http://dx.doi.org/10.1016/j.ijmst.2014.05.002
2095-2686/

Table 1
Mineralogy of the Es_4^1 and Es_4^1 submember in Dongying sag (1000 core samples of 26 wells).

Mineral composition		Mineralogy										Clay minerals			
		Clay minerals	Quartz	Potassium feldspar	Anorthoclase	Calcite	Dolomite	Siderite	Pyrite	Anhydrite	Terrigenous compositions	Endogenous compositions	Mixed-layer illite and smectite	Illite	Kaolinite	Chlorite
Es_3^3	Maximum	62	49	6	16	71	72	11	14	1	97	80	64	100	29	13
	Minimum	6	6	0	0	1	0	0	0	0	20	3	4	36	0	0
	Average	27	25	<1	3	34	6	<1	3	≤||	56	44	22	74	2	1
Es_4^1	Maximum	59	68	8	35	76	97	4	34	1	96	97	77	100	9	7
	Minimum	1	1	0	0	0	0	0	0	0	3	4	0	23	0	0
	Average	20	23	<1	5	37	11	≤||	3	≤||	49	51	13	85	3	1

clastic material. The endogenous and epigenetic components are 4–97% with an average of 51%. The Fanye 1 well has the highest content of carbonates among the three coring wells with argillaceous limestone lithology. Overall, the shale in the area is rich in carbonate minerals (Fig. 1). The carbonates content of the samples is 30% in Es_3^3 and 57% in Es_4^1. Clearly, they are carbonate rocks. Relative to Es_3^3, Es_4^1 is richer in carbonate minerals with higher dolomite content, and low in sand and shale components.

According to the X-ray diffraction data from 189 core samples of 3 coring wells (Table 1), illite is the dominant clay mineral, followed by mixed-layer illite and smectite. There is little kaolinite and chlorite. The average content of the abovementioned four clay minerals in the Es_3^3 submember is 74%, 22%, 2%, and 1%, respectively. The average content of the mixed-layer illite and smectite is 18%. The average contents of the four clay minerals in the Es_4^1 submember is 85%, 13%, 1%, and 1% and the average content of the mixed-layer illite and smectite is 12%.

2.2. Rock classification

According to the thin section analysis of 1043 samples from 67 wells (Table 1), the shale in this area consists of clay minerals, calcite, and silt-sized clastic material. Dolomite, pyrite, and organics are also present. The rock lithologies are complex as well as variable because of the variable mineral content and texture. The rocks are mainly mudstone and limestone, and to a lesser extent dolomite and siltstone-sandstone.

According to the data in Table 2 and Fig. 2, mudstone is dominant in the Es_3^3 submember, followed by limestone. Dolomite and siltstone-sandstone are minor. The main lithological type is that of calcareous claystone and argillaceous limestone, followed by mudstone, dolomite-bearing mudstone, and silt-bearing mudstone. The limestone in the Es_4^1 submember is about 50%; the content of mudstone is about 40%. There is also little dolomite and siltstone-sandstone. The main lithological type is that of argillaceous limestone, followed by calcareous claystone and argillaceous-bearing limestone, mudstone, dolomitic limestone, and dolomite-bearing mudstone.

Primarily, the Es_3^3 submember contains mudstone. Limestone accounts for half the Es_4^1 submember, mudstone is lesser than limestone. Dolomite and siltstone-sandstone in the Es_4^1 submember are more abundant than the Es_3^3 submember.

2.3. Typical lithofacies and organic matter

The sedimentary facies of the Es_3^3–Es_4^1 shale in Dongying sag are mainly deep and semideep lacustrine and are not readily divided to sedimentary microfacies. The shale facies are divided according to structure, rock types, and calcite characteristics and are used to analyze the sedimentation features, and oil and gas potential.

According to the data for the 35 wells with industrial grade shale oil and gas in the Jiyang depression, the shale strata are mainly lamellar argillaceous limestone and calcareous claystone. According to the core data, horizontal bedding is observed. Microscopic observations show that the minimum thickness of the lamellae is less than 0.01 mm (Fig. 3). The lamellae are mainly argillaceous, calcareous, argillocalcareous, and organic-rich (Fig. 3a). The main component is that of argillaceous-calcareous lamellae (Fig. 3b). The argillaceous lamellae are rich in organic matter, and the calcite is typically larger because of recrystallization (Fig. 3c). There are also columnar fibrous calcite crystals perpendicular to the bedding plane

Lamellar argillaceous limestone and calcareous claystone favor the enrichment and high-production of shale oil and gas, and are relatively rich in organic matter. Sapropelite is the major maceral of the lamellar argillaceous limestone and calcareous claystone