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Reservoir characterization of Chang 7 member shale: A case study of lacustrine shale in the Yanchang Formation, Ordos Basin, China☆

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ABSTRACT

The shale portion of Chang 7 member (C7M) can be divided into two sub-members (SM): the Chang 7-2 sub-member (C7-2SM) and Chang 7-3 sub-member (C7-3SM). An analysis of trace elements shows that C7M shale developed under a freshwater sedimentary environment. C7-3SM shale was formed under conditions of comparatively higher salinity and a much deeper waterbody than C7-2SM shale.

C7-3SM shale exhibits a larger content of an illite/smectite mixed layer (70.35%) and reducing minerals (12.94%), but less quartz content (22.31%). Although C7-3SM shale has lower Ro values, it displays much higher S_1 values and productivity of hydrocarbon per gram of total organic carbon (TOC) due to Type II_1 kerogen, which are mainly Type II_2 and possibly Type III in C7-2SM shale.

Samples with a drilling orientation perpendicular to sedimentary stratification ("vertical" samples) display relatively lower porosity and permeability. Although no apparent difference of permeability occurs between the two shale sections, C7-2SM shale exhibits higher porosity for both "vertical" and "parallel" samples. Moreover, C7-3SM shale displays lower values of specific surface area and adsorption quantity.

The composition of minerals, together with residual hydrocarbon, leads to the lower porosity and adsorption quantity for C7-3SM shale. Compared with C7-2SM shale, C7-3SM shale is not good at generating and storing natural gas. Overpressure may be the reason for the increase in acoustic travel time (AC) values with progressive burial depth for C7-3SM shale.

1. Introduction

Successful exploration of shale gas in the USA has led to a profound paradigm shift in our understanding of source rocks and reservoirs in the oil and gas industry, and it has greatly encouraged investigations into shale reservoir characterization, such as the composition (both organic and inorganic), pore networks, and gas potential of shale all over the world during the past ten years (Chalmers and Bustin, 2007a,b, 2008a,b; Curtis, 2002; Jarvie et al., 2007; Ross and Bustin, 2007, 2008, 2009; Strapoc et al., 2010; Kuila and Prasad, 2012). Global shale gas exploration and exploitation focus on marine shale at present, and shale gas research in China has mainly concentrated on the Paleozoic marine shale of the Upper Yangtze region (Zhang et al., 2009; Editorial Committee of Shale Gas Geology and E&D Applications Series, 2011). In recent years, major breakthroughs have been made in lacustrine shale gas exploration in the Mesozoic Yanchang formation of the Ordos basin. In April 2011, well LP177 tested a daily gas production of 2350 m^3 at Chang7 Member after fracturing (Wang et al., 2012), making it the first lacustrine shale gas well in China. Later, other shale gas wells were successfully tested for shale gas after fracturing, among which wells YYP1 and YYP3 produced more than 7800 m^3/d, and 16,000 m^3/d in Chang 7 Member, respectively, showing that Mesozoic lacustrine shale also has bright shale gas exploration prospects (Wang et al., 2014). The Chinese government has already permitted the establishment of a pioneering test area of lacustrine shale in the Ordos basin. In the past few years, more and

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more Chinese geologists have shown interest (Wang et al., 2012; Chen et al., 2011; Han et al., 2013).

However, most researchers considered C7M shale as a whole in view of reservoir characterization (Wang et al., 2014; Guo et al., 2014), and compared it with marine shale. The content of quartz varies from 15% to 30%, and the illite-smectite mixed layers vary from 30% to 70% (Er et al., 2013). The kerogen in C7M shale mainly contains Type II organic matter, and the TOC ranges from 0.49% to 6.08% (Yang et al., 2012; Jiang et al., 2013). According to the calculation on the basis of field desorption experiments, the gas capacity of whole C7M shale could be above 3.71 m^3/t on average (Zeng et al., 2014). C7M shale differs in many ways from marine shale, in terms of structural setting, sedimentary environment, shale gas genetic types, pore networks, geochemical characteristics, shale reservoir characterization, fracture developments, and accumulation model (Loucks et al., 2009; Gale et al., 2007; Yang et al., 2013). C7M shale is generally less mature than marine shale and possesses relatively large amounts of clay minerals, which affects methane sorption under dry conditions and contributes to the shale anisotropy (Song et al., 2013; Yang et al., 2013; Bi et al., 2014; Guo et al., 2014).

The nuances in C7M shale are neglected. Moreover, we realize that C7-3SM shale displays a much lower content of natural gas than that of C7-2SM shale in the process of field desorption experiments. Hence, the conclusions of previous researchers from the perspective of the whole C7M shale are not detailed enough to characterize C7M shale and guide C7M shale exploration and exploitation in China. A comprehensive study is much necessary.

2. Geological setting

The Ordos Basin is an important hydrocarbon-containing basin situated in the central part of the North China Plate. It is a multi-cycle cratonic basin developed on the Archean granulites and lower Proterozoic greenschists of the North China block (Hanson et al., 2007). Subsidence began in the Paleozoic era, and the sedimentary center changed in the Mesozoic era (Yang, 2000, 2002; Cao, 2008). The development of the Ordos basin during the Paleozoic–Mesozoic can be divided into three evolutionary stages: the Cambrian–Early Ordovician cratonic basin with divergent margins; Middle Ordovician–Middle Triassic cratonic basin with convergent margins; and Late Triassic–Early Cretaceous intraplate remnant cratonic basin (Yang et al., 2005, 2013; Ji et al., 2012).

Because of the wrenching movement around the basin in the Cenozoic era, the Ordos Basin is now a large asymmetric north-south syncline. The Ordos Basin can be divided into six tectonic units: the Northern Yimeng uplift, south Weibei uplift, eastern Jinxi flexural zone, western Xiyuan obduction zone with the Tianhuan hollow zone in close proximity, and Yishan ramp region in the center. The Yishan ramp region is the main part of the wide-gentle east limb. The research area is located in the southeast of the Yishan ramp region and is a western-leaning monocline with a lower stratigraphic dip ($<1^\circ$), gentle average slope (7–8 m/km) and simple internal structure (Fig. 1).

The Triassic strata in the Ordos basin consist of fluvial and lacustrine deposits (Li et al., 1995; Liu, 1998). The Yanchang formation is deposited in the late Triassic age and has been divided into 10 members from top to bottom by researchers according to the marker beds and sedimentary cycles. Shale layers, the main source rock in the area, are primarily deposited in C7M (Fig. 2). C7M developed in the period of flooding lakes in the Ordos Basin. Shale layers, as the main body of C7M, mostly consist of black shale and oil shale (commonly known as “Zhangjiatan” black shale in China) (Zhang et al., 2007; Yang et al., 2010). Oil shale includes organic matter lamina, pyrite framboids and nano-fossils (Chen et al., 2007; Zhang et al., 2008). C7M shale strata are approximately 196.9 ft (approximately 60 m) thick on average, and its thickest point is approximately 262.5 ft (approximately 80 m). It is buried at a depth ranging from 3289.8 to 5413.3 ft (1000 m–1650 m), with an average of 4225.7 ft (approximately 1288 m).

The whole C7M can be divided into three SMs according to the sedimentary cycle (Yang et al., 2010; Yang and Zhang, 2005). The lithology of Chang 7-1SM mainly consists of sandstone and siltstone, which does not belong to the C7M shale reservoir. C7M shale can be divided into C7-2SM and C7-3SM (Fig. 2), of which the upper parts of both display higher gamma readings because they contain volcanic debris with radioactive substances (Zuo et al., 2008; Qiu et al., 2009, 2011). They show significant differences in their acoustic time data, with C7-2SM presenting low frustration in the AC data and C7-3SM displaying an increase in AC values with progressive burial depth.

To determine the subtle differences in the causes of changes in their acoustic time data and the reason for the lower natural gas content in C7-3SM shale, a total of 325 samples have been used in a series of integrated and repeatable methods, including X-ray diffraction (XRD), trace element analysis, TOC and ROCK-EVAL.II methodology, vitrinite reflectance analysis, maceral composition analysis, N_2 adsorption analysis, CH_4 adsorption analysis, and porosity and permeability analyses. The experimental data provide a more comprehensive understanding of the reservoir characterization of C7M shale.

3. Sample preparation and experimental methods

A total of 325 measurements were conducted in this research. The sample numbers for each experiment are presented in detail in Table 1. The preparation process for each experimental method is described as follows.

3.1. Lithology analysis

Mineral composition, as the basic characteristic of a shale reservoir, affects the shale property in all aspects. For example, Kuila and Prasad (2012) presented the influence of mineral composition on specific surface area, pore-size character and distribution in detail. Guo et al. (2014) proposed that clay minerals affected the methane sorption of bulk rocks.

A commonly used and statistically valid method to evaluate minerals in shale reservoirs is X-ray diffraction. Forty-two shale samples from C7M shale were analyzed for whole-bulk and clay fraction mineralogy by quantitative X-ray diffraction following two independent processes of the CPSC procedure (China Petroleum Standardization Committee, 2010). First, the bulk mineral composition of the powder sample was determined at this stage to only include the total clay content. Second, the individual clay mineral content of the clay fractions separated from the rock powder sample was determined.

3.2. Analysis of geochemical characteristics

Rock-Eval pyrolysis is an established method for characterizing the type and thermal maturity of organic matter in sedimentary rocks, as well as their petroleum generation potential (Espitalie et al., 1977). The TOC content, a basic geochemical characteristic of the shale reservoir, was calculated from the amount of CO_2 evolved during hydrocarbon generation and also during oxidation at 650 °C (Stasiuk et al., 2006).

One-hundred-twenty-five samples were used in the TOC and Rock-Eval analyses, which were conducted at the State Key Laboratory of Petroleum Resources and Prospecting, China University of