Marine and Petroleum Geology 88 (2017) 268–281

Contents lists available at ScienceDirect

Marine and Petroleum Geology

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

Research paper

Sedimentary control on the formation of a multi-superimposed gas system in the development of key layers in the sequence framework

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A R T I C L E   I N F O

Article history:
Received 28 April 2017
Received in revised form
24 July 2017
Accepted 21 August 2017
Available online 24 August 2017

Keywords:
Key layers
Multi-superimposed gas system
Sedimentary control
Marine flooding surface
Linxing block

A B S T R A C T

Based on core observations, well logs and test results of siderite-bearing mudstone from the Benxi Formation to the Member 2 of the Shanxi Formations in the Linxing block, northeastern Ordos Basin, a logging identification model for siderite-bearing mudstone (key layer) was established. The porosity characteristics and sealing property were quantitatively evaluated by logging data. Sedimentary control on the formation of multi-superimposed gas-bearing system in the development of key layers in the sequence framework was also discussed. The results showed that the siderite-bearing mudstone has obvious logging response characteristics, e.g., high photoelectric absorption cross-section index (PE), high density (DEN), high amplitude natural gamma ray (GR), low acoustic (AC), low resistivity (M2RX) and low neutron porosity (CNCF). The quantitatively evaluated results of the porosity characteristics and sealing property for the key layer showed that the key layer has the characteristics of low porosity (with an average of 1.20 percent), low permeability (with an average of $2.29 \times 10^{-8} \mu m^2$), and high breakthrough pressure (with an average of 12.32 MPa) in the study area. This layer acts as an impermeable gas barrier in a multi-superimposed gas system. The results also indicated that the material composition of the multi-superimposed gas-bearing system can be established by the sequence stratigraphic framework. The sedimentary evolution results in a cyclic rhythm of material composition vertically. The spatial distribution of the corresponding transgressive event layer near the maximum flooding surface (MFS) in the sequence framework restricts the spatial distribution of the key layer with high breakthrough pressure and low porosity, which constitutes the gas-bearing system boundary. The siderite-bearing mudstone formed near the MFS in the second-order sequence and constitutes a stable comparison of the first-order gas-bearing system boundary, which has a wide range of regional distribution and stable thickness. The siderite-bearing mudstone formed near the MFS in the third-order sequence is often incompletely preserved due to the late (underwater) diversion channel erosion and cutting. This layer forms the coal-bearing reservoirs, which we termed as a second-order gas-bearing system in adjacent third-order sequences to form a uniform gas-bearing system.

1. Introduction

Three types of natural gas in coal series forming a potential, considerable, and unconventional natural gas resource, have attracted geologists' attention, both in research and in exploration and extraction (Cao et al., 2015; Qin et al., 2016). The government has created a major 13th Five-Year science and technology project

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http://dx.doi.org/10.1016/j.marpetgeo.2017.08.024
0264-8172/

for demonstration, and to achieve large scale extraction (Qin et al., 2016). There has been successful precedent for gas in coal series comprehensive exploration and extraction in the world. For example, the depth of the target coal seam is 1560–2560 m, which is the per-piloted in the coalbed methane and tight sandstone gas co-exploitation in the White River uplift of the Pisens Basin, United States. The direct roof of the coal seam is tight sandstone. The average daily gas production of a single well is 1.09×10^4 m^3, and up to 1.44×10^4 m^3 and 60% gas production from a coal seam (Oison et al., 2002; Nelson, 2003). Recently, China has carried out coalbed methane, tight sandstone gas and shale gas comprehensive exploration and attempted development at the eastern margin of the Ordos Basin (Liang et al., 2011, 2014, 2016; Qin et al., 2014, 2016; Wang et al., 2015; Dong et al., 2016; Guo et al., 2015; Li et al., 2016; Xie et al., 2016), where the depth of coal seams range from 700 m to 2100 m in Linxing block. The single well gas production is $0.48–5.28 \times 10^4$ m^3/d, an average of seven wells in the early stage, and it is objective to make tight sandstone as the main target layer of the production test wells (Qin et al., 2016). However, the current coal series comprehensive exploration has not been very successful, and large scale extraction has not yet been achieved.

The characteristic differences of multi-coal seams and fluid pressure systems of the strata are not considered in the extraction process, which is the key factor leading to the low production of multi-layer coal seams and the production capacity of coalbed methane (Lambert et al., 1990; McDaniel, 2005; Moore, 2012; Guo et al., 2014; Fu et al., 2013; Jiang et al., 2013; Vishal et al., 2013; Qin et al., 2014; Belushko et al., 2014; Moore et al., 2015; Zhang et al., 2015; Wang et al., 2015; Shen et al., 2016). The gas reservoirs of the Upper Paleozoic are not one pressure system at the eastern margin of the Ordos Basin (Liu, 2015; Yang et al., 2015; Zhang et al., 2015; Wang et al., 2015). There are multiple independent gas-bearing systems vertically through the strata. Results showed that there were multi-independent gas systems vertically in the coal series; essentially, the strata fluid pressure systems are independent (Qin et al., 2008). However, the fundamental geological causes of the fluid pressure systems are relatively independent as the siderite-bearing mudstone in the coal series is a conventional water barrier layer which acted as a key layer defining the upper and lower boundaries of the superimposed gas system (Shen et al., 2012, 2016; Yuan, 2014; Qin et al., 2016). Based on the study of the Upper Paleozoic coal-series sedimentary and sequence stratigraphy, this paper discussed the sedimentary characteristics of key layers and sedimentary control mechanisms of multi-superimposed gas-bearing systems and was expected to provide a valuable reference for the efficient exploitation of three type of natural gas in coal series in the Linxing Block.

2. Geological background

The Linxing Block is located at the eastern margin of Ordos Basin, which is situated on the western margin of the Sino-Korean paraplatform, the oldest craton in China (Dai et al., 2002, 2006; Liu et al., 2008; Zhao et al., 2008). It covers the Shannbei slope and the western Shanxi flexural fold belt of the present tectonic framework (Fig. 1). The coal-bearing strata of the Linxing block consist of the Upper Carboniferous series Benxi (C_2b) and Jinci Formations (C_2j) as well as the Permian Taiyuan (P_1t) and Shanxi (P1*s*) Formations.

The thickness of the Benxi Formation ranges from 22 to 49 m with an average of 30 m. It formed in a seashore environment. The thickness of the Jinci Formation is in the range of 20–36 m with an average of 28 m. This formation also formed in a seashore environment. The Taiyuan Formation is 32–90 m thick with an average of 56 m and is the main coal-bearing stratum. It consists of sandstones (such as the Qiaotou sandstone, Malan sandstone, and Qiligou sandstone), mudstone, siltstone, limestone (from the bottom to the top including the Miaogou limestone, marked L_1; Maoergou limestone, marked L_{2-3}; Xiedao limestone, marked L_4; and Dongdayao limestone, marked L_5) and coal seams, and formed in a seashore-delta environment. The Nos. 8 and 9 coal seams are the main minable seams. The thickness of the Shanxi Formation ranges between 87 and 130 m, with an average of 100 m. It was deposited in a delta front environment. There are several main minable coal seams, such as Nos. 2, 3, 4 and 5. Table 1 shows the major marker horizons in the stratigraphic correlation of the study area.

3. Properties

3.1. Fluid pressure system

The essence of a gas-bearing system is the development of a unified fluid pressure system in the interior (Qin et al., 2016; Yi et al., 2016). Many factors can result in an increase of fluid pressure in the deep layer, e.g., less compaction, fluid volume increasing (including hydrothermal expansion, mineral conversion, and hydrocarbon generation), fluid motion, transfer of buoyancy and pressure, and tectonism (Osborne and Swarbrick, 1997; Hao et al., 2005; Zhang et al., 2009; Yang et al., 2014). The system shows fluctuations in the fluid pressure vertically. The gas reservoirs of the Upper Paleozoic are not in a uniform pressure system in the Ordos Basin (Liu, 2015; Yang et al., 2015; Zhang et al., 2015; Wang et al., 2015). There are several fluctuations in the pressure coefficient.

In this work, the Eaton formula method (Eaton, 1975) is used to calculate the pressure coefficient of sand and shale reservoirs by logging parameters, which were constrained by the measured pressure. The study area is rich in logging data and has more than one exploration well with measured pressure (Table 2). The relative error of the prediction results is less than 10 percent, with higher reliability.

$$\ln(\Delta t_n) = \ln(\Delta t_0) - kH \quad (1)$$

$$\rho_p = \rho_0 - (\rho_0 - \rho_w)(\Delta t_n / \Delta t)^C \quad (2)$$

The pressure of the target reservoirs ranges from 0.68 to 1.08, mainly in the interval of 0.75–0.95, which is categorized as an under-pressure reservoir. The pressure coefficient increased from the Benxi Formation to the Jinci Formation vertically (Fig. 2), then with little fluctuations from the Jinci Formation to the Basal Member 2 of the Taiyuan Formation. The pressure coefficient displays initially decreased, increased later on from the Member 2 of the Taiyuan Formation to the Shanxi Formation. The lowest point of the pressure coefficient lies at the bottom of Member 1 of the Shanxi Formation.

3.2. Vertical gas content distribution

There is no obvious variation law of gas content for coal-bearing reservoirs, such as tight sandstone and coal seams, in Wells A1 and A2. Data shows volatility changes with depth for the gas content. There are four gas content peaks in coal seams Nos. 02, 4 and 5, 8 and 9, and the K_1 sandstone from the top to the bottom. Four gas-bearing units could be divided at least vertically in Well A1, in accordance with the principle of air content fluctuation (Fig. 2). The gas content of Well A2 ranges from 1.62 to 72.34 ml/g, and that of well A1 ranges from 1.41 to 62.06 ml/g (Fig. 3). At least three or four gas-bearing units can be divided, based on the variations in gas content, which appeared wavy.