Marine and Petroleum Geology 95 (2018) 67–81

Contents lists available at ScienceDirect

Marine and Petroleum Geology

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

Research paper

Paleogeography and shale development characteristics of the Late Permian Longtan Formation in southeastern Sichuan Basin, China

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ARTICLE INFO

Keywords:
Sequence stratigraphy
Paleogeography
Shale development characteristics
The Late Permian
Sichuan Basin

ABSTRACT

The Late Permian Longtan Formation is extensively developed within the southeastern Sichuan basin which lies on the western margin of the Yangtze Plate in southwestern China. The stratigraphy and sequence boundaries of the Longtan Formation were interpreted from a combined study of field data, well log data and various data analysis in order to determine the extent and thickness of shale sequences. This interpretation defined the broad sequence stratigraphic framework and separated the Longtan Formation into three 3rd-order sequences. In addition, the formation was divided into five sedimentary facies using sedimentary, paleontological, geophysical and other data. The facies identified were fluvial, low energy shore, tidal flat, melanged accumulated shelf and platform basin. Three paleogeographic maps were created based on the 3rd-order sequences: SQ1, SQ2 and SQ3. The study shows that SQ1- SQ3 sedimentary environment of the study area, which extends from the southwest to northeast, was developed followed by fluvial, shore, tide, shallow water melanged accumulation shelf, deep water melanged accumulation shelf and platform basin.

The mud shale rock types of the Longtan Formation that were identified are carbonaceous mud shale, silty mudstone and lime mudstone. According to the divided standard of mud shale effective thickness, there are three mud shale assemblages present in the sequences SQ1, SQ2, SQ3, namely, mud shale with sandstone, mud shale with limestone, and mud shale. SQ1 has the thickest mud shale identified on well logs. Mud shale with sandstone was well developed in the southwest of the study area and was interpreted to have been deposited in a shore or tidal flat sedimentary environment. This rock assemblage has a large effective thickness and extensive lateral distribution. In contrast, the assemblage of mud shale with limestone was mainly developed in the northeast of the study area and was interpreted to have formed in a melanged accumulation shelf sedimentary environment. The effective thickness of the mud shale with limestone is small and the distribution is limited. There is developed mud shale in above two type's sedimentary environment, but the distribution is also limited. The Longtan Formation's mud shale reached stage B diagenesis and is principally composed of quartz and clay minerals. The average quartz content is 43.40% and the average clay mineral content, which is mainly composed of illite, mixed illite/smectite, chlorite and kaolinite, is 39.58%. The sedimentary environment has controlled the distribution of minerals within the sequences. The clay mineral content gradually decreases as the sedimentary environment changes from shore-tidal flat in the southwest to deep water melanged accumulation shelf in the northeast. Therefore this comprehensive analysis shows that the southwest of the study area is the key area for shale gas exploration in the Longtan Formation.

1. Introduction

Sequence stratigraphy and paleogeography are both the key and fundamental components of oil and gas exploration. Sequence stratigraphy was proposed by Vail et al. (1977), and has been widely used to reveal source-reservoir-seal and evolutional history of sedimentary basins (Posamentier and Allen, 1993, 1999; Lin et al., 2009; Barbier et al., 2012; Timms et al., 2015; Khila et al., 2016; Zhao et al., 2016). Sedimentary facies exert a primary control on the characteristics of sediments (Timms et al., 2015).

There have been a number of significant shale gas exploration breakthroughs in the Sichuan basin focusing on the Lower Cambrian

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https://doi.org/10.1016/j.marpetgeo.2018.04.016
Received 18 October 2017; Received in revised form 29 March 2018; Accepted 22 April 2018
Available online 24 April 2018
0264-8172/

(Qiongzhusi Formation) and the Upper Ordovician – the Lower Silurian (Wufeng Formation and Longmaxi Formation, respectively) (Huang et al., 2012; Fan et al., 2013; Luo et al., 2016; Li et al., 2016). Since the 1990s there have also been several studies on one of the three Paleozoic mud shales intersected in the southeastern Sichuan basin, the Longtan Formation of the Upper Permian (Lopingian) (Zhang et al., 1993; Lin et al., 2009; Ten et al., 2010; Cao et al., 2013; Liu et al., 2015; Borjigen et al., 2014; Zhang et al., 2017a, 2017b; Luo et al., 2018). However, a detailed understanding of the sequence stratigraphy and the paleogeography of the Longtan Formation has yet to be developed until this study. Xu et al. (2004) discussed the sequence stratigraphy of the Longtan Formation and identified two transgression-regression cycles, therefore identifying two 3rd-order sequences. Lin et al. (2009) and Li et al. (2009) later revised this interpretation divided the formation into three 3rd-order sequences.

As sequence stratigraphy has advanced an increasing number of geologists have valued interpreting the finer 4th-6th order sequences which provides further resolution on sea level change and climate (Wu et al., 2012; Zhang et al., 2011; van den Belt et al., 2015). Wavelet analysis of the well log curve is used to obtain this high-frequency sequence stratigraphic interpretation in this study.

The subject of this paper is the Longtan Formation shale in the southeastern Sichuan basin, which has been studied by detailed field outcrop observation, well log curve interpretation, sequence stratigraphy and sedimentary facies analysis. The stratigraphic framework and division of sequence stratigraphy are mainly based on interpretation of the well log curves in the study area. In addition, depositional environments and sedimentary facies types are based on the well log sequence divisions and sedimentary sign, including types of sedimentary rocks, sedimentary structure and so on. The petrology and mineralogy characteristics of the Longtan Formation shale has been studied in detail through thin sections, SEM, and X-ray diffraction analyses to provide reliable data.

2. Geological background

The study area is located in the southeastern Sichuan Basin which covers more than 180,000 km^2, and is considered one of most important gas-producing basins in West China (Fig. 1). Sichuan basin is a multicycle sedimentary basin surrounded by thrust belts and bounded to the north by the Daba Mountain and Micang Mountain, the Daliang Mountain to the south, the Qiyue Mountain to the east, and Longmen Mountain to the west. The Sichuan Basin can be divided into six tectonic units (Tong, 1992, Fig. 1): western Sichuan low and steep structural area (I), central Sichuan low and flat structural area (II), northern Sichuan low and flat structural area (III), southwestern low and slow structural area (IV), southeastern Sichuan low and steep structural area (V) and eastern Sichuan high and steep structural area (VI). The main study area includes the eastern Sichuan high and steep structural area (VI) and the southeastern Sichuan low and steep structural area (V).

Sichuan Basin is in the Upper Yangtze Region, tectonically, and was dominated by marine sediments from late Proterozoic to Middle Triassic (BGMRSP, 1991). The Permian period is associated with strong volcanic activity in South China. Volcanic activity began during the late Maokou stage of the Middle Permian and ceased at the end of the Late Permian. Volcanic activity peaked at the turn of the Middle Permian and at the beginning of the Late Permian in the Upper Yangzi area (Wang, 1994), where the 'Emeishan basalt' erupted. In the southwestern Sichuan Basin at the end of the Middle Permian, the Kangdian ancient land, lying to the southwest, was uplifted by the Dongwu orogenic movement and became the main provenance of Sichuan Basin which showed a paleogeography of the southwest high and the northeast low (BGMRSP, 1991). Directly east of the uplifted Kangdian ancient land, a set of sediments containing deep gray-gray black shale, tuffaceous sandstone with coal seams were developed, which were called Longtan Formation (P_3l, Fig. 2A, B, C). Further away in the northern and eastern Sichuan basin, the Longtan Formation is called the Wujiaping Formation which developed a set of shallow marine carbonate sediments with limestone, flint-bearing nodal limestone, chert and shale (P_3w, Fig. 2B and C). They were simultaneously heterogeneous deposition products. The Upper Permian Changxing Formation (P_3c) overlies the P_3l with conformity while the P_3l overlies the Middle Permian Maokou Formation (P_2m) with an unconformity (Fig. 2A, B, C).

3. Database and methods

3.1. Sequence stratigraphic analysis

The Longtan Formation only outcrops at limited locations in the study area. Therefore, for accuracy, this study is mainly based on interpretation from well log data and 2D seismic. The GR curve, which is more sensitive to the argillaceous content, was chosen for well log analysis. The reasoning for this is that mud shale particles are small relative to the larger surface area of the host sandstone and carbonate rocks, and their more easily adsorbed radioactive elements, such as K, Th, U, have a higher gamma value which is clearly observed on the GR logs. The wavelet toolbox within Matlab software was used to preprocess GR data for wells that were suspected to have been crossed by faults or to contain volcanic rocks. Initially the GR well log data was sampled at 0.125 m intervals, which means eight data points were collected over 1 m. The original GR data was then denoised (D-noised) in the wavelet toolbox to avoid data that was not related to the geology, and to avoid human and environmental factors. Furthermore, Wang (2009) and Peng et al. (2013) recommend that GR data is processed in the wavelet toolbox for the db*N* wavelet transform after it is D-noised. This can effectively decompose complex signals with multiple frequency components (Wang, 2009), and a continuous wavelet with morl wavelet is obtained with a corresponding two-dimensional energy spectrum.

3.2. Paleogeography, petrography and mineralogy analysis

Field outcrops, thin sections, scanning electron microscope (SEM) and mineral analysis from XRD were comprehensively applied in this study. Three paleogeographic maps of the Longtan Formation based on the sequence stratigraphic divisions were identified and the sedimentological evidence obtained (including lithofacies, sedimentary structures, log curve patterns). Thin sections and SEM were made from the samples selected from field outcrops of the Longtan Formation and both were used to interpret for shale minerals. Thin sections were interpreted to identify carbonate minerals and one-third of the sections were stained with alizarin red S. Thin sections were examined using a Leica polarizing microscope and SEM by Quanta250 FEG in the State Key Laboratory of Oil and Gas Reservoir Geology and Exploitation (Chengdu University of Technology). To understand the mineral composition and content and to aid microscopic observation, 45 samples were selected from field outcrops and examined by X' Pert Powder in the Sichuan Coalfield Geology Bureau. 19 samples selected from three outcrops for the TOC test and were measured using a Leco CS-2300 carbon/sulfur analyzer. 5% HCl was used to remove inorganic carbon in samples at 80 °C, after eliminating residual HCl with pure water and drying, the de-carbonate samples were put into the apparatus to measure TOC value.

4. Results

4.1. Sequence stratigraphic divisions

The identification of the sequence boundaries (SB) is key to establishing the correct sequence (Khila et al., 2016; Zhao et al., 2016; Zahid et al., 2016). Based on field outcrops, well logs and 2D seismic profiles,