Marine and Petroleum Geology 59 (2015) 150–165

Contents lists available at ScienceDirect

Marine and Petroleum Geology

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

Research paper

Processes involved in the origin and accumulation of hydrocarbon gases in the Yuanba gas field, Sichuan Basin, southwest China

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ARTICLE INFO

Article history:
Received 28 June 2014
Accepted 5 August 2014
Available online 20 August 2014

Keywords:
Gas origin
Oil cracking
Solid bitumen
Fluid potential
Gas remigration and accumulation
Sichuan Basin

ABSTRACT

Natural gases in the superimposed Sichuan Basin commonly experienced a history of remigration in marine carbonate reservoirs since the late Cretaceous. The reservoir in the Changxing Formation (P_2c) in the Yuanba gas field in the Sichuan Basin is characterized by a great burial depth of 6200–7000 m and a high temperature about 165 °C. The gas dryness is 99.73–99.99%, and $\delta^{13}C$ values of methane and ethane are −31.0 to −28.9‰ and −29.9 to −25.6‰, respectively. The chemical and isotopic compositions of natural gases, abundant reservoir solid bitumen, and high reservoir temperature (maximum to 240 °C) indicate that the P_2c gases are of sapropelic origin and are derived from oil cracking. The paleo-oil layers, recognized by solid bitumen distribution, were mainly developed in high position traps when the paleo-oil accumulated during the early Jurassic. Reconstructed structural evolution shows the northwest was uplifted sharply and southern part dipped gently to the north in the gas field after oil cracking. Fluid potential analyses based on changes in the structural configuration imply that gas should re-migrate mainly to the northwest. The observations that paleo-oil-water contacts are mainly above the present day gas-water contacts in the northwest traps, and are below present day gas-water contacts in the middle and eastern traps also confirm the gas remigration trend. Currently, high gas production wells are mainly located in northwest traps and in high positions in the middle and eastern traps. Systematic analyses on early paleo-oil accumulation and late gas remigration processes can reduce the economic risks associated with natural gas exploration in the northeastern Sichuan Basin.

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1. Introduction

The petroliferous basins in western China (such as the Sichuan, Junggar, and Tarim) are typical superimposed basins, and commonly experienced multiple tectonic cycles and movements (Zhai, 1989; Tong, 1992; Jin and Wang, 2004; He et al., 2005). The petroleum in these superimposed basins are also commonly experienced complex migration and accumulation processes (Jin and Wang, 2004; Li et al., 2005, 2008; Ma et al., 2008; Hao et al., 2009, 2011; Pang et al., 2010). The complexity of petroleum migration and accumulation includes: multiple sources, origins, and charging history (Jin and Wang, 2004; Ma et al., 2008; Liu et al., 2013) as well as chemical alteration, remigration and accumulation, and loss of prior accumulated oil and gases (Cai et al., 2004; Li et al., 2005; Hao et al., 2008, 2009, 2011; Li et al., 2008; Ma et al., 2008; Pang et al., 2010; Liu et al., 2013). As a result, investigating the sources, origins, and accumulation processes is vital to reducing the economic risks associated with petroleum exploration in these superimposed basins.

In recent years, many medium to large gas fields, such as the Dukouhe, Luojiazhai, Puguang, Yuanba, and Longgang gas fields, have been found in the Upper Permian Changxing Formation (P_2c) and Lower Triassic Feixianguan Formation (T_1f) in the northeastern and northern Sichuan Basin (Ma et al., 2007, 2010; Du et al., 2010; Guo, 2011a). The Upper Permian source rocks had been confirmed to have made a major contribution to these gas fields (Li et al., 2005; Hao et al., 2008, 2009; Zou et al., 2008; Zhao et al., 2011), and the Lower Cambrian and Silurian source rocks may also have contribution to the Puguang gas field (Ma et al., 2008). The origins of natural gases include: oil cracking gases from sapropelic source

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http://dx.doi.org/10.1016/j.marpetgeo.2014.08.003
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rocks (Li et al., 2005; Hao et al., 2008), and gases from coal-sourced rocks (Zhao et al., 2011). Prior accumulated natural gases usually remigrated resulting from the changes in the gas field's structural configuration during the late Yanshanian and Himalayan movement (Li et al., 2005, 2008; Hao et al., 2008, 2009; Ma et al., 2008; Duan et al., 2013). However, it is hard to trace the process from the paleo-oil reservoir to the present day gas reservoir using the correlation of chemical and isotopic composition data, because the gases experienced high thermal maturity (burial depth is generally larger than 4500 m) and gas dryness is high (generally above 99.0%).

The Yuanba gas field is a large gas field found by SINOPEC Exploration Southern Company in marine carbonate strata in the Sichuan Basin after the discovery of the Puguang gas field (Guo, 2011a). Burial depth of the Yuanba gas field is 6200–7000 m, which is 1000 m deeper than the Puguang gas field (Guo, 2011a; Duan, 2013). The broad reservoir solid bitumen in the Yuanba gas field implies that natural gases are probably derived from oil cracking. In addition, present day gas-water contacts and gas production is complex because the structural configuration also changed during the Yanshanian and Himalayan movement (Duan et al., 2013). As a result, this gas field provides a good geological example of how to investigate the paleo-oil accumulation, oil cracking and gas remigration processes, and supply implications for marine carbonate natural gas exploration in the Sichuan Basin.

Based on natural gas chemical and isotopic compositions, structure evolution, solid bitumen distribution, present gas-water contacts, and gas production data, the purpose of this paper is to discuss: (1) origin of hydrocarbon gas (oil-typed gas or coal-typed gas?); (2) factors controlling the distribution of paleo-oil accumulation; (3) the process of gas remigration; and (4) factors controlling the distribution of highly productive gas wells.

2. Geological setting

2.1. Structural units and traps distribution

The Yuanba gas field is located in the northern Sichuan Basin, southwestern China (Fig. 1A). Five secondary structural units make up the front of the Micangshan uplift: the Cangxi-Bazhong gentle slope in the south, Jiulongshan anticline and Chixi depression in the north, and Tongnanba anticline and Tongjiang depression in the east. The Yuanba gas field is mainly located in the Cangxi-Bazhong gentle slope (Fig. 1A).

The Yuanba gas field, discovered in 2007, has the main gas production interval in the dolostone reservoir of P_2c (Guo, 2011a). Based on more than thirty wells that were drilled and three-dimensional seismic interpretation results, reef and shoal stratigraphic traps mainly developed in the platform margin from a northwesterly to southeasterly direction (Fig. 1B). The northeastern part of the platform margin was sloped and with an open shelf, and the southwest part was an open platform. The stratigraphic traps in the northwest are higher than those in the southeast (Fig. 1B).

2.2. Tectonic cycle, movements, and basin evolution

The Sichuan Basin, situated in the western region of the Yangtze craton, is a rhombic basin trending from northeast to southwest, with an area of 180,000 km^2. The basin is a late Mesozoic foreland basin overlying a Sinian-middle Mesozoic passive margin, and experienced six tectonic cycles (Fig. 2): Yangtze (pre-Sinian-early Sinian), Caledonian (late Sinian-Silurian), Hercynian (Devonian-Permian), Indosinian (Triassic), Yanshanian (Jurassic-Cretaceous), and Himalayan (Tertiary-Quaternary) (Zhai, 1989; Tong, 1992). The basin was mainly characterized by subsidence and uplift before the Indosinian movement, and large scale lateral compression has been occurring since late Indosinian movement (Ma et al., 2007). Specific tectonic movements and basin evolution are as follows.

The Jinning movement consolidated the basement of the Yangtze craton at the end of the pre-Sinian. Then subsidence and regional elevations occurred several times, and a mainly marine carbonate platform was deposited in the middle Triassic. The Tongwan movement, at the end of Sinian, caused uplift and erosion, and resulted in the unconformity between the Upper Sinian and Lower Cambrian. The Caledonian movement caused the northeast trending Leshan-Longnvsi uplift that formed in the central Sichuan Basin at the end of the Silurian (Zhai, 1989). The Yunnan movement at the end of Carboniferous and Dongwu movement at the end of early Permian led to uplift and erosion, respectively. The Early Indosinian movement led to uplift and erosion caused by lateral compression from the Tethys Ocean plate to the southwest and the Pacific Ocean plate to the southeast during the end of the middle Triassic, and the rhomboid shape of the Sichuan Basin began to form. Then continental deposits developed up until the present. The Late Indosinian movement caused rapid uplift in the western basin boundary at the end of Triassic, and the late Yanshanian movement caused the northeast to southwest trending fold to begin to form in the eastern part of the basin. Strong lateral compression occurred during the Himalayan movement, the western, eastern, and northern boundaries of the Sichuan Basin uplifted rapidly, and the complete bruchfalten in the east of the basin finally formed.

2.3. Stratigraphy and paleo-environments

The total thickness from the Sinian to Quaternary is 6000–12,000 m in the Sichuan Basin (Fig. 2). The thickness of marine deposits (Upper Sinian to Middle Triassic) is 6000–12,000 m, and that of continental deposits (Upper Triassic to Quaternary) is 2000–6000 m.

Sinian is the first deposit developed on the Yangtze basement. The Lower Sinian consists of piedmont and fluvial deposits in the southwest, eruptive materials in the west, and fluvial, offshore, and shallow sea deposits in the southeast. The Upper Sinian consists of offshore-shallow sea deposits. The Cambrian-Silurian was deposited in an open and constricted platform. The Lower Cambrian consists of black shale, siltstone and muddy limestone; the Upper Cambrian consists of dolostone interbedded with thin anhydrite. The Ordovician consists of limestone, muddy limestone and siltstone. The Lower Silurian consists of black shale, and the Middle Silurian consists of black siltstone and mudstone. Devonian deposits can only be discovered in the western part of the basin, and consist of mainly quartz sandstone. Carboniferous deposits can be found in the eastern part of the basin, and consist of dolostone developed in a constricted platform and tidal flats. The Lower Permian was deposited in an open platform, and consists of limestone interbedded with thin shale and muddy limestone. The Upper Permian Longtan Formation (P_2l) was developed in continental to a marine transitional environment in the southwestern part of the basin, and consists of mudstone interbedded with coal; simultaneously, the Wujiaping Formation (P_2w) was developed in constricted embayment in the northeast basin, and consists of marine mudstone and muddy limestone. The Upper Permian Changxing Formation (P_2c) developed in a platform that consists of limestone and dolostone; meanwhile, the Dalong Formation (P_2d) was developed in an open shelf that consists of mudstone and muddy limestone. The Lower Triassic Feixianguan Formation (T_1f) was developed in a shallow platform, and consists of limestone and dolostone. The Lower Triassic Jialingjiang (T_1j) and Leikoupo (T_2l) Formations were developed in constricted and evaporated platforms, and consist of limestone and anhydrite.

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