Precambrian Research 313 (2018) 91–108

Contents lists available at ScienceDirect

Precambrian Research

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

Precambrian temperature and pressure system of Gaoshiti-Moxi block in the central paleo-uplift of Sichuan Basin, southwest China

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ARTICLE INFO

Keywords:
Thermal history
Pore pressure evolution
Low temperature thermochronology
Basin modeling
Fluid inclusions
Sichuan Basin

ABSTRACT

Recently, trillions of cubic meters gas resources have been found in Sinian reservoirs of Gaoshiti-Moxi region in the central uplift of Sichuan Basin, which is the first commercial discovery of primary gas field in Precambrian anywhere in the world. To obtain a great breakthrough in Precambrian hydrocarbon exploration, it is necessary to find out the evolution process of temperature and pressure. Reconstructing the thermal history and pore pressure evolution in carbonate reservoirs are challenging problems, especially in deep-old layers without available samples and methods. To study the temperature and pressure system, we conducted a comprehensive analysis combining the paleo-thermal indicators and inclusions Pressure-Volume-Temperature (PVT) simulation with basin modeling. The results showed that the thermal history of the Gaoshiti-Moxi area could be divided into three stages. From the Late Sinian to Late Paleozoic, the thermal regime was stable with low heat flow value ($< 65\,mW/m^2$). During the Early Paleozoic, the heat flow increased rapidly to the peak value ($75–100\,mW/m^2$). From Mesozoic to present, the thermal subsidence occurred in the basin with the heat flow decreasing to the present value ($60–70\,mW/m^2$). With the boundary condition of above thermal history, the simulated pressure of Dengying Formation in Gaoshiti-Moxi area could be divided into four stages. The excess pressure began to form during the Triassic. From the end of Triassic to Middle Jurassic, the excess pressure increased steadily and slowly. From Middle Jurassic to the end of Early Cretaceous, the strata subsided rapidly while the excess pressure increased significantly. Since the Late Cretaceous, the Dengying Formation suffered from rapid uplifting and gas lateral migrating with the excess pressure decreasing, until the Late Neogene, the excess pressure in reservoirs declined to zero.

1. Introduction

Precambrian sediments were distributed on many sedimentary basins throughout the world, but the hydrocarbon accumulations in the Precambrian strata have not been understood. Due to limited exploration, although dozens of oil or gas fields have been discovered in Precambrian reservoirs (Kuznetsov, 1997; Craig et al., 2009), only a few commercial hydrocarbon accumulations have been found in the East Siberian Basin (Meyerhoff, 1980; Fowler and Douglas, 1987), the South Oman Salt Basin (O'Dell and Lamers, 2003; Ghori et al., 2009) and Bikaner-Nagaur Basin (Ghori et al., 2009; Sheikh et al., 2003; Peters et al., 1995). Generally, these deep-old reservoirs always suffered from high temperature and high pressure, which would affect the thermal maturity of source rocks, the diagenesis degree of reservoir layers and the driving force of migration. However, the evolution of temperature and pressure in deep-old reservoirs is a complicated problem often controlled by many factors and its detailed study is constrained by limited drilling data and methods. For instance, in the South Oman Salt Basin, the Late Neoproterozoic to Early Cambrian contains a unique self-charging system with respect to hydrocarbon and overpressure generation and dissipation, which are controlled by salt tectonic, microstructural and thermo-kinetic (Kukla et al., 2011).

In China, the Proterozoic sedimentary rocks are also widely distributed in North China Platform, Yangtze Platform and Tarim Platform. Restricted by exploration technology, only a few of oil and gas shows have been found. In the north of Tarim Basin, the oil and gas in Sinian (541–580 Ma) migrated along the direction of overpressure reduction. In the center of Sichuan Basin, the top of Sinian in Weiyuan area buried as deep as 6000 m during Cretaceous with the paleo-temperature over 200 °C, which made oil cracking totally into natural gas and asphalt (Zhu et al., 2015; Liu et al., 2015). It is obvious that the temperature and pressure have a great influence on deep hydrocarbon

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https://doi.org/10.1016/j.precamres.2018.05.028
Received 5 January 2018; Received in revised form 27 April 2018; Accepted 20 May 2018
Available online 21 May 2018

accumulation. Recently, on the same structural unit with Weiyuan field, trillions of cubic meters gas accumulations have been found in Sinian reservoirs of Gaoshiti-Moxi block, which is the first commercial discovery of primary gas field in Precambrian anywhere in the world. To obtain a great breakthrough in Precambrian hydrocarbon exploration, it is necessary to find out the evolution process of temperature and pressure.

The limited drilling data show that, the gas accumulated in the fourth member (Z_2dn^4) and second member (Z_2dn^2) of Dengying Formation (Z_2dn) which are two sets of marine carbonate sediments (Zou et al., 2014a,b; Liu et al., 2015; Jiang et al., 2016). The burial depth of Dengying Formation is more than 5000 m with high temperature 148–152 °C and normal pressure. However, a large amount of residual bitumen in the core show the oil cracking has occurred, which will easily produce overpressure (Wang et al., 2017; Zhu et al., 2015). Even the overlying Longwangmiao Formaiton in Cambrian ($Є_1l$), also the main oil-gas accumulation layer, which has the same tectonic background and source rock with Z_2dn shows a strong overpressure (Du et al., 2014; Zou et al., 2014a,b; Wei et al., 2015). Therefore, the evolution of temperature and pressure in Sinian need to be reconstructed to illustrate the gas accumulation mechanism. But for marine strata, there are many limitations on temperature and pressure study, such as lack of effective thermal indicators and exact porosity model for limestone and dolomite. This paper will show the comprehensive analysis on the temperature and pressure system in deep-marine reservoirs. Based on present temperature-pressure field distribution, combining the paleo-thermal indicators and fluid inclusions thermodynamics simulation with basin modeling to reconstruct the temperature and pressure of the Dengying Formation in geological time scale, respectively. Finally, make a comprehensive discussion about the controlling action of temperature and pressure on source rocks, reservoirs and accumulation dynamics.

2. Geological setting

The Sichuan basin is in the northwest of the Upper Yangtze Craton, southwest of China. The central unit located between the Longquan Mountain and the Huaying Mountain is an inherited uplift which can be divided into three tectonic zones, Weiyuan, Gaoshiti-Moxi and Longnüsi (Fig. 1). In the gentle zone of the central paleo-uplift, a giant gas field of Precambrian was discovered in the Gaoshiti-Moxi block which was also the target area of this study. The central paleo-uplift had been already in shape at the end of Sinian (about 541 Ma) and fully formed during the Caledonian movement. From the end of the Silurian to the Early Permian, the paleo-uplift suffered from weathering and erosion, leading to the absence of Devonian and Carboniferous and the small residual thickness of the Ordovician and the Silurian. And then the paleo-uplift accepted continuous deposition and stable development from the Hercynian to the Early Yanshan movement. Influenced by the Late-Yanshan and Himalayan tectonic movements, the Yangtze plate generally uplifted (Du et al., 2016; Mei et al., 2014; Xu et al., 2012). By the compression from western Longmen Mountain, the tectonic high formed in Weiyuan area while the secondary tectonic high formed in Gaoshiti-Moxi block, making favorable conditions for hydrocarbon accumulation.

Since the central paleo-uplift experienced several tectonic movements from the Sinian to the Middle-Triassic, including the Tongwan movement, the Caledonian movement, the Dongwu movement and the Indosinian movement, multiple unconformities have developed (Fig. 2). The top of the Dengying Formation (Z_2dn) suffered from prolonged weathering and denudation during the period of the Tongwan movement. The erosion thickness was recovered by the trend method (Mu et al., 2002; Li et al., 2015). The results showed that the erosion was less than 100 m in Moxi, but the erosion was approximately 160–200 m in the Gaoshiti (Mei et al., 2014). Influenced by the Caledonian movement, the unconformity between the bottom of the Permian and the underlying strata developed continuously from the end of the Silurian to the Early Permian when the paleo-uplift was flattened. The erosion thickness was 1200–1400 m in the Gaoshiti-Moxi. The Dongwu movement between Middle and Late Permian was the rapid differential uplift caused by the rises of Mount Emei mantle plume. The uplift was fast result in a temporary erosion of the Maokou formation (P_2m). Due to the Gaoshiti-Moxi area was located in the outer zone of the Mount Emei mantle plume, the uplift at the end of Middle Permian was not obvious and the erosion thickness was less than 100 m (He et al., 2011). Affected by the uplift of the southeast region in the Indosinian period, the Leikoupo formation (T_2l) suffered severe erosion. The amount of denudation of the Gaoshiti was 110–160 m, and less than 100 m in the Moxi. From the Late Triassic to the end of the Early Cretaceous, the Sichuan basin accepted continental clastic deposition. Then, the central paleo-uplift, even the whole basin, uplifted and was subjected to severe denudation, which exposed the Jurassic to the surface. The results of the apatite fission tack showed that the erosion of the gentle region in the central uplift was 2500–3000 m (Mei et al., 2014; Xu et al., 2012; Deng et al., 2013). The rate of uplifting increased gradually from the Late Cretaceous to the Neogene. Especially in the Neogene, the extent of denudation accounted for approximately half of the total erosion.

A giant gas field was recently discovered in Dengying Formation of the Upper Sinian in Gaoshiti-Moxi area (Fig. 1 and Fig. 2). The Sichuan Basin was a confined carbonate platform during the period of Late Proterozoic, mainly developed algal mounds, tidal-flat deposits and grain beach (Zou et al., 2014a,b; Jiang et al., 2016). The xerothermic sedimentary environment caused the slow water-rock interaction and the existence of abundant high-magnesium calcite, which would protect the primary matrix porosity. According to the lithology and algae content, the Dengying Formation could be divided into four members from the bottom up. The second member (Z_2dn^2) and fourth member (Z_2dn^4) are algal dolomites, the first member (Z_2dn^1) is poor algal dolomites and the third member (Z_2dn^3) is poor algal mudstones. Affected by the episodic Tongwan Movement, two sets of karst weathering crusts were formed at the top of Z_2dn^2 and Z_2dn^4, which developed large number of pores, fissures and caves by the dissolution of atmospheric fresh water during syngenetic period. After the late uplift movements, the connectivity of original pores and fissures in the weathering crust was greatly improved by tectonic fractures. Therefore, the Z_2dn^2 and Z_2dn^4 become high quality reservoirs with large area distribution. And the black mudstones in Z_2dn^3 were known as the source rocks as well as the overlying Qiongzhusi Formaiton of the Lower Cambrian ($Є_1q$). The gas reservoirs of Dengying Formation are tectonic-stratigraphic compound reservoirs filling with oil cracking gas (see Table 1).

3. Methods

The main task of this study was to reconstruct the thermal history and pressure evolution of the Z_2dn in Gaoshiti-Moxi area by comprehensive analysis, combining the paleo-thermal indicators and inclusions simulation with basin modeling. The information of samples for thermal history and pressure evolution reconstruction have been listed in Section 5.1.1 (Table 2 and Table 3) and Section 5.2.1 (Table 6), respectively.

3.1. Thermal history reconstruction by paleo-thermal indicators

Considering the Upper Sinian in the central Sichuan Basin was buried deeply, we preferred to select the thermal indicators with higher annealing temperature and partial retention zone (PRZ) to avoid the early thermal information being reset, such as zircon fission track (ZFT) and zircon He age (ZHe). The ZFT dating is a well-established low-temperature thermochronology method. The closure temperature is approximately 240 ± 20 °C (Bernet, 2009) and PAZ is 170–350 °C (Yamada et al., 1995, 2007). However, the (U-Th)/He thermochronology of zircon is an emerging method based on the production of