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Giant gas discovery in the Precambrian deeply buried reservoirs in the Sichuan Basin, China: Implications for gas exploration in old cratonic basins

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ABSTRACT

An estimated trillions of cubic meters of natural gas have recently been discovered in the Sinian dolomite reservoirs in the Sichuan Basin, China. The 20–26 m thick reservoirs were found in deep structural–lithologic traps of 5000–5500 m deep. The Sinian gas is thought to have been derived mainly from the Sinian source rocks, and partly from the Cambrian source rocks. The gas is thermally matured, with a dryness ratio ($C_1/\sum C_{1-4}$) of 0.997–0.9998, C_2H_6 content <0.2%, and H_2S content of 0.5–2.75%. The stable carbon isotope compositions ($\delta^{13}C$) of CH_4 and C_2H_6 are similar in all the reservoirs, with values of −33.5‰ to −31.5‰ and −36.0‰ to −27.0‰ (PDB), respectively. The Sinian gas reservoirs are believed to have been accumulated by the following processes: initial paleo-oil accumulated during the Silurian–Devonian; gas accumulation after oil cracking of the paleo-oil accumulations during the Jurassic–Early Cretaceous; and the current gas accumulations formed by paleo-gas remigration and adjustment since the Late Cretaceous. This new gas accumulation model is consistent with large-scale gas accumulations for deeply buried paleocratonic basins worldwide, in which the source rocks initially underwent thermal oil generation from kerogen, followed by gas generation via oil cracking. The gas discovery in the Sinian dolomite reservoirs has led to a new wave of hydrocarbon gas exploration in the ancient cratonic basin containing the mostly thermally matured source rocks in China. We conducted a series of geochemical analyses of the H_2S in the gases. The sulfur isotope compositions ($\delta^{34}S$) of gypsum, H_2S, and secondary pyrite sampled from the Sinian Dengying Formation showed that H_2S was generated by a moderate thermochemical sulfate reduction (TSR) during the Jurassic–Early Cretaceous periods. TSR was terminated by the depletion of SO_4^{2-} in the formation water, resulting in a modest H_2S content of 5–10% in the natural gases. Because the dolomites are rich in cations, a large quantity of H_2S may have been bound to form metal sulfides. We infer that H_2S contents of 0.8–10% are present widely in the deeply buried Sinian reservoirs. Therefore, measures should be taken to prevent H_2S-related accidents during gas exploration in the deep strata.

1. Introduction

Precambrian sediments are of great interest to geoscientists in China (Zhao and Guo, 2012; Zhao et al., 2012). Before 1950, no Precambrian organic fossils had been found anywhere in the world (Dickas, 1986a; Kontorovich et al., 2005; Wang and Han, 2011) and no primary hydrocarbons were found in the Precambrian strata. Since then, geological exploration in the Precambrian, especially in the Mesoproterozoic and Neoproterozoic, has revealed not only many fossils, but also hydrocarbon source rocks and reservoirs (Murray et al., 1980; Klemme and Ulmishek, 1991; Bazhenova and Apefyev, 1996; Galushktn et al., 2004; Dutkiewicz et al., 2004; Kontorovich et al., 2005). Although the source rocks are quite old, the thermal maturity of their organic matter ranges widely, from immature to over mature (Wang and Simoneit, 1995). This led to the discovery of primary oil and gas accumulations in Precambrian rocks.

Precambrian sediments were distributed on many continents throughout the world, including East Europe, Western Siberian, North America, Africa, Australia, North China, South China, and

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India (Dickas, 1986b), and were predominantly deposited in rift basins. Presently, they are embedded in very complex geological structures and have complex lithologies. Due to limited exploration, the hydrocarbon accumulations in the Precambrian strata are not well understood (Zhu et al., 2013a). For the past 20 years, although dozens of primary oil and gas fields or oil and gas shows have been discovered in Precambrian reservoirs (Parfenov et al., 1995; Kuznetsov, 1995, 1997; Migurskiy, 1997), only a few commercial primary oil and gas accumulations (source rocks and reservoir rocks, all Precambrian) have been found on the Siberian Platform (Meyerhoff, 1980; Fowler and Douglas, 1987). Large condensate and gas accumulations have been discovered in Riphean carbonate rocks (geological age, 1600–680 Ma) and Vendian clastic rocks (about 680–570 Ma, equivalent to the Sinian in the Sichuan Basin) of the Upper Proterozoic on the Siberian Platform. Oil has also been discovered in Proterozoic carbonates in the Haweel Cluster region of southern Oman (Terken and Frewin, 2000; Al-Riyami et al., 2005), and in the Sinian in India–Pakistan, but these are only in small reserves. Until now, our knowledge of the great reserves of the Proterozoic primary gas accumulations throughout the world has been very limited.

Proterozoic sedimentary rocks are widely distributed in North China, South China (Sichuan Basin), and the Tarim Basin (Zhou et al., 2006; Zhao et al., 2011; Zhao and Cawood, 2012; Wang et al., 2012, 2013; Xu et al., 2013). The Sinian and Nanhua deposits in the Mesoproterozoic and Neoproterozoic (800–543 Ma) are mainly distributed on the Yangtze Platform in South China. The Qingbaikou System, Jixian System, and Changcheng System (1800–800 Ma) are only found on the North China platform. So far, oil and gas have been discovered in the Mesoproterozoic reservoirs on the North China Platform, but oil–source correlations show that the oil and gas were derived mainly from source rocks in the Cenozoic Shahejie Formation (Zhu et al., 2013b; Jin et al., 2014a), which belongs to a petroleum system of young source rocks and ancient reservoir rocks. There is no commercial primary oil or gas discoveries in North China, but some oil and gas shows have been reported (Wang and Han, 2011). In South China, the Weiyuan Gas Field was discovered in dolomite reservoirs in the Sinian Dengying Formation of the Upper Proterozoic in the Sichuan Basin, but the gas predominantly comes from the Cambrian source rocks (Dai et al., 2003). Primary oil and gas have not yet been found in the Sinian strata, and it is currently a research focus for petroleum geologists in China.

Recently, important gas discoveries have been made in the Precambrian reservoirs in the central part of the Sichuan Basin, in which the geological gas reserves are over trillions of cubic meters. This is the largest gas reserve to have developed from the oldest marine source rocks in China, and is also the first commercial discovery of primary gas accumulations in the Precambrian anywhere in the world. We conducted a series of geochemical analyses on the gases, and undertook geological investigations of the reservoirs. The gas generation, H_2S origins, oil cracking in the ancient reservoirs, and the gas accumulation process were examined in details. These data will be useful for gas exploration in the Precambrian deposits of China and throughout the world.

2. Geological setting

The Sichuan Basin is one of China's most tectonically stable sedimentary basins. It is a northeasterly diamond-shaped oil- and gas-bearing sedimentary basin in the upper Yangtze Platform and has an area of about 180×10^3 km^2 (Zhai, 1992) (Fig. 1). The Sichuan Basin is a superimposed basin that developed on the Yangtze Craton during three important stages of basin evolution: rifting at the cratonic margin in the Nanhua Period of the Neoproterozoic; internal rifting of the craton and the depression of the craton during the Sinian to the late Middle Triassic; and the development of foreland basins in the Late Triassic–Cretaceous. The basin as deposited with marine strata during the Sinian–Middle Triassic, and terrestrial clastic sedimentary rocks during the Late Triassic–Eocene, with a total thickness of about 8000–12,000 m.

The Sinian–Middle Triassic marine strata are mainly composed of carbonate rocks with a cumulative thickness of 6000–7000 m. These marine strata have undergone several phases of tectonic movement, including the Tongwan Movement, Caledonian Movement, and Indosinian Movement. As a result, multiple paleo-uplifting and several regional unconformities were developed. These structures significantly influenced the formation of the carbonate reservoirs and hydrocarbon accumulations.

In the central part of the Sichuan Basin, the Sinian System consists mainly of the Doushantuo Formation and the Dengying Formation (Fig. 1), with a thickness of 300–1200 m. The Dengying Formation is dominated by algal dolomite and crystallite dolomite, whereas the Doushantuo Formation is dominated by interbedded sandstone and mudstone. A large-scale Sinian gas field was recently discovered in the Moxi (MX well)–Gaoshiti (GS well) area in central Sichuan Basin (Fig. 1). The major gas-bearing intervals are the fourth and second members of the Sinian Dengying Formation (Z_2dn_4, Z_2dn_2). In the Cambrian Longwangmiao Formation, another giant gas field has also been discovered in the granular beach-facies dolomite.

The GS1 well was drilled in a paleo-uplift in the central Sichuan Basin in 2011. The yield from well testing was 1.38×10^6 m^3/d in the 5130–5196 m reservoir interval in the Sinian Dengying Formation (Du et al., 2014), confirming the presence of a large-scale Sinian gas field. The MX8 well was drilled in 2012. The well testing yield was 1.91×10^6 m^3/d in the Cambrian Longwangmiao Formation overlying the Sinian System, indicating the presence of a large-scale gas field in the Cambrian Longwangmiao Formation.

The gas reservoir in the Sinian Dengying Formation is buried at 5000–5500 m, and the gas reservoir interval is 20–60 m thick. The reservoir is composed of algal mound-facies dolomite. The reservoir storage space is composed of residual pores, cavities, and caverns. The average porosity is 3–4% and the permeability is $(1–6) \times 10^{-3}$ μm^2. The temperature of the gas reservoir is 140–160 °C. The pressure coefficient is 1.01–1.15. The gross gas column height is 180–200 m and the average single-well gas yield is 0.7×10^6 m^3/d. The natural gas is a highly mature dry gas containing H_2S. The reservoir is a structural–lithologic reservoir. The area of the Sinian gas-bearing stratum exceeds 7000 km^2, and the geological reserve is estimated to be over 700×10^9 m^3 (Zou et al., 2014).

The proven geological reserve of natural gas in the Cambrian Longwangmiao Formation is 440.38×10^9 m^3, with an area of 800 km^2 and the geological reserve of natural gas is expected to exceed 600×10^9 m^3 (Du et al., 2014). The thickness of the gas reservoir is 12–65 m, with an average thickness of 40 m. The reservoir storage space is dominated by intergranular cavities and intercrystalline cavities. The porosity is 4–5%; the permeability is $1–5 \times 10^{-3}$ μm^2. The temperature of gas reservoir is 135–145 °C. The pressure coefficient is 1.65. The average single-well gas yield is 1.1×10^6 m^3/d. It is a structural–lithologic reservoir.

3. Sample collection and analysis

A number of gas samples were collected and chemically analyzed based on chemical analyses and production data collected systematically in the fields over the years. At the well site, gas samples were collected from the production wells, and H_2S samples were collected from the coring interval. The chemical analyses were as follows.