Petroleum Research 2 (2017) 222–232

Contents lists available at ScienceDirect

Petroleum Research

journal homepage: http://www.keaipublishing.com/en/journals/petroleum-research/

Full Length Article

Significance of gypsum-salt rock series for marine hydrocarbon accumulation

Wenhui Liu [a, b, c, *], Heng Zhao [d, e], Quanyou Liu [a, b], Bing Zhou [a, b], Dianwei Zhang [a, b], Jie Wang [a, b], Longfei Lu [a, b], Houyong Luo [a, b], Qingqiang Meng [a, b], Xiaoqi Wu [a, b]

[a] State Key Laboratory of Shale Oil and Gas Enrichment Mechanisms and Effective Development, SINOPEC, Beijing 100083, China
[b] Petroleum Exploration & Production Research Institute, SINOPEC, Beijing 100083, China
[c] Northwest University, Shaanxi 710069, China
[d] Lanzhou Center for Oil and Gas Resources, Institute of Geology and Geophysics, Chinese Academy of Sciences, Gansu 730000, China
[e] University of Chinese Academy of Sciences, Beijing 100049, China

ARTICLE INFO

Article history:
Received 25 November 2016
Received in revised form
21 April 2017
Accepted 26 April 2017

Keywords:
Gypsum-salt rock series
Hydrocarbon generation
Source rock
Sedimentary environment
Reservoir
Caprock

ABSTRACT

With further exploration and research, the gypsum-salts rock series as good caprocks attracted a lot of attention. The gypsum-salt rock series played an important role during migration, preservation and trapping of hydrocarbons. Recently, major breakthroughs have been continuously made in marine petroleum exploration of gypsum-salt rock series in the eastern Ordos Basin, the central Tarim Basin and the western Sichuan Basin in China, and the high-evolution and low-abundance gypsum-salt rock series as hydrocarbon source rocks become possible. Besides research advances in the reservoir–caprock assemblage of gypsum-salt rock series, development and hydrocarbon-generation potential of source rocks in the gypsum-salt rock series were well studied in terms of source-rock development environment and hydrocarbon generation mechanism. Results showed that the gypsum-salt rock series, including high-evolution and low-TOC gypsum-salt rock series in China, could be regarded as good source rocks. This understanding was a breakthrough to previous traditional viewpoint that low-TOC gypsum-salt rock series could not act as effective hydrocarbon sources. The key to understand hydrocarbon-generation mechanism was that abundant and high-quality hydrocarbon-generation materials, large amount of hydrocarbon generation and conversion in geological history, and hydrocarbon-generation materials occurred in the form of carboxylates, were developed in the high-evolution and low-TOC gypsum-salt rock series.

1. Introduction

Gypsum-salt rock was a kind of evaporate which primarily consisted of gypsum, anhydrite and gypsum metahydrate with a certain amount of saline minerals, clay minerals, organic matter and iron oxides (Shen et al., 2000; Zhang et al., 2014; Zhuo et al., 2014). The gypsum-salt rock series occurred spatially with gypsum-salt rock, was developed during the gypsum salt deposition period, pre-salt and post-salt depositional periods, and the epigenetic modification period posterior to formation of the gypsum-salt rock series. Basically, it referred to sedimentary series influenced by gypsum salt geochemical environment, and included marine gypsum-salt rocks, marine carbonate rocks and minor amount of clastic rocks. Besides controlling development of high-quality hydrocarbon caprocks, the gypsum-salt rock series played some special roles in development and modification of source rocks and carbonate rock reservoirs. Around the world, formations of many large hydrocarbon reservoirs were closely associated with the gypsum-salt rock series, and the gypsum-salt rock–carbonate rock association was an important hydrocarbon accumulation assemblage in the world. Numerous gypsum-salt rock sedimentary basins were developed in China, among which the Tarim Basin, Ordos Basin and Sichuan Basin were marine basins. As continuous breakthroughs made in the exploration of oil and gas in Leikoupo Formation in the western Sichuan Basin, the Ordovician pre-salt hydrocarbon reservoirs in the eastern Ordos Basin, and Well Zhongshen 1 and Well Zhongshen C1 in Tazhong area of Tarim

* Corresponding author. State Key Laboratory of Shale Oil and Gas Enrichment Mechanisms and Effective Development, SINOPEC, Beijing 100083, China.
E-mail address: whliu@nwu.edu.cn (W. Liu).
Peer review under responsibility of Petroleum Research.

https://doi.org/10.1016/j.ptlrs.2017.04.002

Basin, potential roles of the gypsum-salt rock series in marine hydrocarbon accumulation had drawn high attention. Because the gypsum-salt rock was a core factor for formation and evolution of the gypsum-salt rock series, only the gypsum-salt rock was discussed in this paper in detail.

The gypsum-salt rocks had tight, plastic and mobile features, and were long regarded as good caprocks. However, researches on oil–salt paragenetic basins showed that 46% of pay beds was below salt-bearing strata, 41% was above salt-bearing strata and 13% was within salt-bearing strata (Zhang and Tian, 1998). Therefore, it was speculated that besides as good caprocks, the gypsum-salt rocks might play an important role in hydrocarbon accumulation. Further studies in recent years showed that the gypsum-salt rock series played important roles in the generation, migration, preservation and trapping processes of oil and gas (Busson, 1992; Jin et al., 2006, 2010; Hao et al., 2015). Nonetheless, researches on potential and mechanism of hydrocarbon generation from the gypsum-salt rock series was still very insufficient at present, that directly influenced hydrocarbon exploration and resource assessment of marine gypsum-salt rock series. In this paper, relevance of the gypsum-salt rock series with hydrocarbon formation and accumulation was studied, and research advances in reservoir–caprock assemblage of the gypsum-salt rock series were summarized; but importantly, development and hydrocarbon-generating potential of source rocks in the gypsum-salt rock series were well investigated from perspectives of source rock development environment and hydrocarbon generation mechanism.

2. Formation environment and depositional model of the gypsum salt

Theories on the origin of gypsum salts had been developed for a long time, and genetic models such as sand bar, desert, subkha salification, deepwater and deep basin, dried deep basin and high mountain deep basin had been established successively, and promoted development of gypsum salt genesis theory (Yuan and Xie, 1963; Yuan et al., 1983; Zhang, 1992). According to current studies, the gypsum salt has two genesis types, such as the evaporation genesis, the deep brine genesis, of which the evaporation-derived gypsum salts was formed from evaporation and deposition of paleo-seawater in the closed to semi-closed arid environments (e.g., marine tidal flat, lagoon, bay and coastal subkha), this type of gypsum salts were widely distributed with small thickness. The deep brine-derived gypsum salts were formed from precipitation of mantle fluids which intruded upward along large deep fractures and then directly formed without undergoing large-scale evaporation process; hence, formation of this type of gypsum salt was not related with the arid climate, and its depositional range controlled by active tectonic zones was restricted, but thickness was often extremely large (Zhang et al., 1999; Zhao et al., 2007); thus, this type of gypsum salts derived from deep brine could be regarded as good caprocks and main source materials of late salt tectonic transformation, and it also might contain relative high content of organic matter under certain conditions and had good hydrocarbon-generation potential (Yuan and Qin, 2001). But the deep brine-derived gypsum salts greatly differed from typical evaporite in sedimentary cycle, lithologic sequence and distribution characteristics, and it not belonged to the marine gypsum-salt rock series. In this paper, the evaporation-genetic gypsum-salt rocks, including some gypsum-salt rocks which were formed from deep brine and underwent large-scale evaporation process, would be focused in this study.

2.1. Sedimentary environment of gypsum salts

Evaporation-derived gypsum-salt rocks were formed from evaporation, concentration and crystallization of brine during the middle and late periods of basin development, its origin was generally related to restricted basin, subsidence rate, deposition rate and extreme arid climate (Yuan et al., 1983; Jin et al., 2006), and source materials of the gypsum-salt rock mainly included seawater, deep brine and overland runoff (Gao et al., 2009). The gypsum-salt rocks were mostly formed during the basin transformation period. From perspective of sequence stratigraphy, the gypsum-salt rocks mostly occurred in the highstand systems tracts of the second-order sequence of fast transgression or slow regression, and mainly were distributed in the late period of the highstand systems tracts (Zhou et al., 2011). The restricted basin caused continuous salt accumulation without free communication with external water, and the water in the basin was thus fully evaporated. The gypsum-salt rocks were primarily developed in the basins with subsidence rate less than deposition rate; under such condition, the sedimentary environment of lacustrine/sea basin would change from the semi-closed lagoons to the closed saline lake environment, resulting in abrupt increase of salt concentration of basin water and massive gypsum-salt rock deposition (Kirkland and Evans, 1981). The climate condition was also a main constraint for gypsum-salt rock deposition, and arid climate condition made evaporation effect greater than recharging effect, so that the salt concentration kept increasing and the gypsum-salt rocks deposited; but in a transient humid climate, the clastic sediments were developed. The gypsum-salt rocks deposited under the reduction or oxidation condition with a high water salinity (greater than 140‰) and a pH value greater than 7.8 (Gao et al., 2009).

In the stable deepwater environment, the surface water was evaporated to form high-density brine which would settle down under gravity and displace lower-density deep brine, then the stratified brine was formed. The surface water had the low salinity, the deep water had the very high salinity which was up to the saturation concentration of the gypsum-salt rock, while the middle halocline had the very variable water salinity. With high dissolved oxygen and low salinity, the surface water was suitable for survival of euryhaline and halophilic plankton. The deep water was relatively tranquil, and basically did not exchange with the surface water, thus lack of free oxygen kept the deep water in the reduced state (Degens and Stoffers, 1976). The stratified brine led to high biomass yield in the surface water and anoxic reduction environment in the deep water, that were favorable for formation of high-quality source rocks (Jin et al., 2008). As continuous evaporation, the water salinity kept increasing and precipitated carbonate minerals, gypsum minerals and salt rock minerals in an ascending order of solubility. Such the gypsum-salt rocks had the stable developed horizons and lack of exposure markers, its horizontal distribution exhibited the planar zone, i.e., of mudstone, carbonate rock and gypsum-salt rock occurrence sequentially from margins to the center (Bao et al., 2004). Due to flood water and decrease of salt source materials induced by climate change, the stratified brine would be damaged to form clastic sediments, and poor anoxic condition was not favorable for preservation of organic matter (Fig. 1).

Greatly influenced by external factors, the shallow-water environment could not form the stratified water in general, but would also precipitate saline minerals due to intense evaporation. Such type of gypsum-salt rocks was poorly stratified, mainly occurred in nodular, ptygmatic or scattered shapes with exposure markers and onshore purple-red muddy sediments; horizontally, it was developed in the land side and exhibited the banded distribution which was parallel with shoreline (Li et al., 2012).