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Research paper

Major factors affecting the closure of marine carbonate caprock and their quantitative evaluation: A case study of Ordovician rocks on the northern slope of the Tazhong uplift in the Tarim Basin, western China

Xiuxiang Lü [a, b, *], Yafang Wang [a, b], Hongfeng Yu [c], Zhongkai Bai [d]

[a] College of Geosciences, China University of Petroleum, Beijing 102249, China
[b] State Key Laboratory of Petroleum Resource and Prospecting, China University of Petroleum, Beijing 102249, China
[c] Research Institute of Exploration and Development, Tarim Oilfield Company, Petro China, Korla, Xinjiang 841000, China
[d] Oil and Gas Survey, CGS, Beijing 100029, China

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ABSTRACT

There are many examples of oil and gas reservoirs throughout the world that have tight carbonate rock as the caprock. These oil and gas reservoirs are often vertically overlapped (with multiple oil and gas sections) and laterally connected (to many oil and gas reservoirs). The closure of carbonate caprock is affected by many factors, such as the clay content, differential diagenesis and layer thickness. As evaluation parameters, the clay content can be determined by a gamma ray well-logging curve; the differential diagenesis is reflected in filling effects, rupture effects, cement composition and content and can be measured through the displacement pressure; the layer thickness can be obtained from drilling and well-logging data. In different regions or different members, the factors and parameters to be considered or evaluated for the closure are dependent on actual geological conditions. In this study, the clay content, displacement pressure and layer thickness were analysed, determined, calculated and normalized to generate an overall closure evaluation index (λ) for the caprock in wells on Ordovician Liang 3–5 mud-bearing limestone members on the northern slope of the Tazhong uplift. On the plane distribution map, the area with $\lambda \geq 1$ was effectively sealed. The tight carbonate in the inner Yingshan Formation (with high-resistivity, referred to as a high-resistivity layer) was also effectively caprock. Regardless of whether it can seal oil and gas, the sealing capacity mainly depends on the displacement pressure difference between the high-resistivity layer and the underlying carbonate reservoir. Based on drilling results and the comparison of the displacement pressure difference between the two layers (by actual measurements and calculations), we observed that when the pressure difference is more than 1.95 MPa, it is an effective caprock.

1. Introduction

The caprock is one of the key and indispensable elements in the formation of oil and gas reservoirs. Gypsum salt rock (evaporite) and shale (fine clastic rock) are recognized as regional caprocks that control the formation of large oil and gas fields (Lash, 2006; Van Geet et al., 2008; Zhou et al., 2012; Li and Tong, 2012; Amann-Hildenbrand et al., 2013; Snedden, 2014). Statistical data show that in the sedimentary caprocks of the world, oil and gas fields with gypsum salt rock as the caprock account for only 8% of the oil and gas fields that have been evaluated but account for 55% of the total oil and gas reserves (Jin et al., 2010). Considering the fact that the marine carbonate rock in some of the large gas- and oil-bearing basins in China was formed in earlier times and destruction or strong modification occurred after the formation of the oil and gas reservoirs, the excellent closure of the gypsum salt caprock has attracted much attention (Jin et al., 2006; Jin, 2011; Zhao et al., 2007; Lü et al., 2009; Du et al., 2013). Oil and gas reservoirs with tight carbonate as an effective caprock (Wu et al., 2011; Lü et al., 2014; Zhou, 2015) are widely distributed under the background of ancient uplifts or unconformity karsts. The effectiveness and quality of the tight carbonate caprock are affected by many factors,

* Corresponding author. College of Geosciences, China University of Petroleum, Beijing 102249, China.
E-mail address: luxx@cup.edu.cn (X. Lü).

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such as thickness, clay content, diagenesis, and tectonic movement (Yang and Liu, 1991; Tang et al., 2008; Tonnet et al., 2011; Ellis et al., 2013). In petroliferous areas, there are often multiple oil and gas reservoirs, resulting in the poor continuity of a single tight carbonate caprock but in vertically stacked and laterally distributed reservoirs. These can be combined with fractured vuggy reservoirs to form a less contiguous distribution of oil and gas reservoirs (Zhou et al., 2006; Miao et al., 2007; Lü et al., 2012). For example, the Liang 3–5 members (O_3l^{3-5}) of the Lianglitag Formation contain mud and are in a patchy distribution longitudinally in the Tazhong uplift of the Tarim Basin (Fig. 1c). They overlap vertically to form an effective caprock for the underlying karst reservoirs (Zhao et al., 2011; Qian et al., 2012). Based on the existing exploration results, there are many examples of tight carbonate rock that act caprocks for gas and oil reservoirs, confirming that tight carbonate caprock is the key factor in determining if a carbonate reservoir will contain oil and gas (Chen and Yin, 1981; Zhai and Wang, 1999; He et al., 2002; Lambert, 2006; Liu et al., 2011).

The majority of the literature related to carbonate caprock focuses on reservoirs (Lazaratos et al., 1995; Nadeau and Ehrenberg, 2006; Aguilera, 2006; Feng et al., 2008; Liu and Lü, 2010; Zhou et al., 2011; Ji et al., 2012; Tang et al., 2013; Menke et al., 2014; Ronchi and Cruciani, 2015). The marine carbonate rocks in the Pechora Basin in the former Soviet Union were mainly developed in the Ordovician-Permian periods; the mudstone on the top of the lower Permian is regional caprock, and the inner mudstone in the Carboniferous-Permian layer is not developed. However, a number of oil- and gas-bearing strata have been found in huge Permian and Carboniferous limestone formations. They form vertically stacked carbonate reservoirs with mud-bearing limestone and tight limestone caprocks that are 10–100 m thick (Gan, 1991).

Compared with conventional caprocks such as gypsum salt rock and shale, tight carbonate is a special type of caprock. For regional gypsum salt rock and shale caprocks, their closure is mainly evaluated based on the thickness and spatial distribution on a macro scale or on displacement pressure, porosity, permeability, specific surface area and micropore structure on a micro scale (You, 1991; Fu and Xu, 2003; Zhen et al., 1996; Zhou, 1997; Schlömer and Krooss, 1997; Lü et al., 2000, 2005; Fu et al., 2015). Because carbonate rock is highly heterogeneous, can easily form fractures and has poor lateral continuity with many factors that affect its closure, we attempted to analyse the major factors that affect the closure of tight carbonate caprock. In this study, the Ordovician marine carbonate rock on the northern slope of the Tazhong uplift in the Tarim Basin was investigated. Data from drilling, well-logging and the measurement of displacement pressure from two direct caprocks of the Liang 3–5 mud-bearing limestone members of the Lianglitag Formation (O_3l) and inner tight carbonate (pure lithology and high-resistivity) of the Yingshan Formation (O_1y) in the Ordovician were combined and analysed to evaluate the effectiveness of tight carbonate rock in different cover members. The results were used to define the methods for the evaluation of tight carbonate caprock.

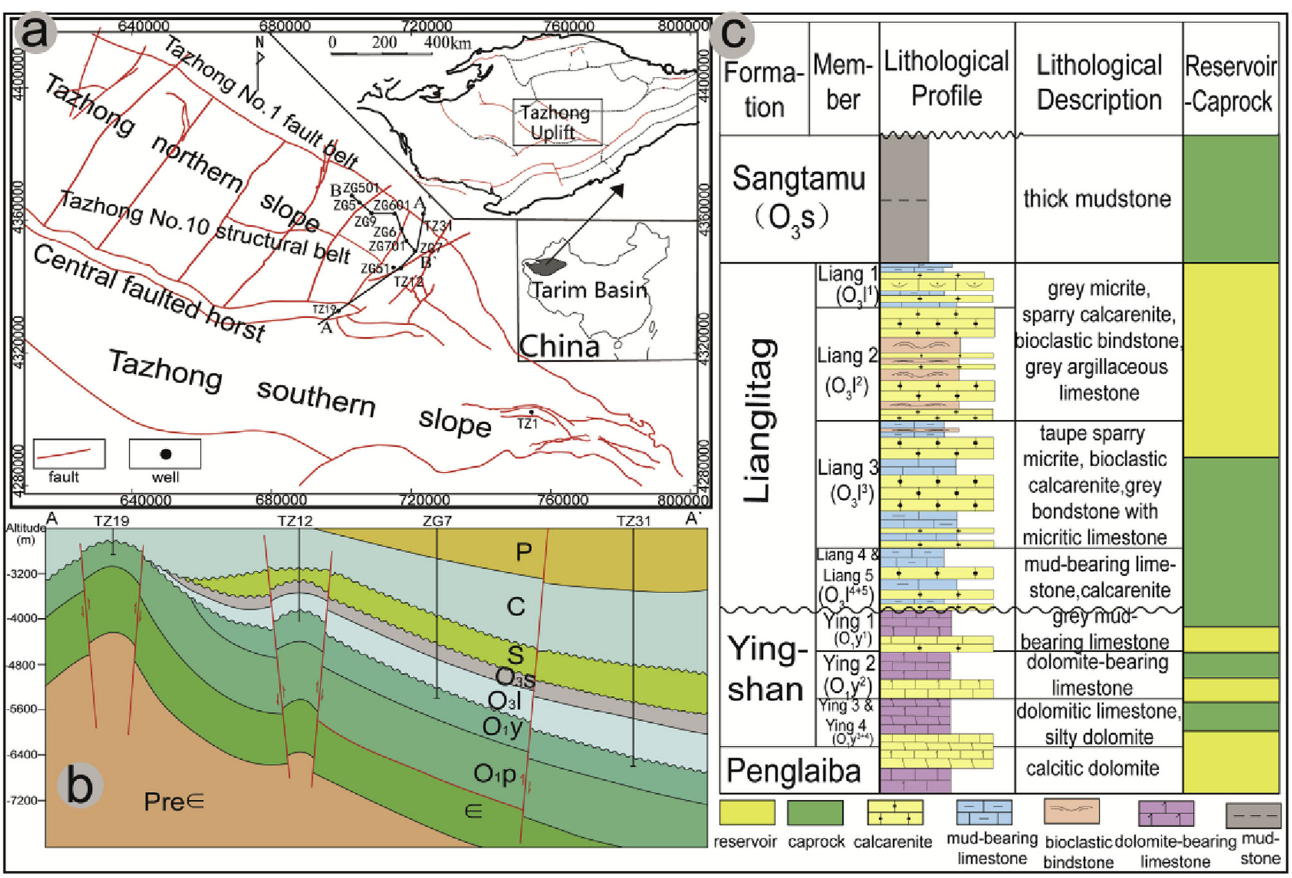

Fig. 1. (a) Geologic map of the northern slope in the Tazhong uplift, Tarim Basin. (b) Stratigraphic profile A-A′ through the northern slope in the Tazhong uplift. (c) Stratigraphic column during the Ordovician with reservoir and caprock. Pre ∊ indicates Precambrian; ∊ indicates Cambrian; O_1p indicates the Penglaiba Formation, Lower Ordovician; O_1y indicates the Yingshan Formation, Lower Ordovician; O_3l indicates the Lianglitag Formation, Upper Ordovician; O_3s indicates the Sangtamu Formation, Upper Ordovician; S indicates Silurian; C indicates Carboniferous; P indicates Permian.