Journal of Natural Gas Science and Engineering 57 (2018) 266–283

Contents lists available at ScienceDirect

Journal of Natural Gas Science and Engineering

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

Characteristics of gas hydrate reservoirs and their effect on petrophysical properties in the Muli area, Qinghai-Tibetan plateau permafrost

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ARTICLE INFO

Keywords:
Gas hydrate
Muli area
Permafrost
Geophysical logs

ABSTRACT

Gas hydrates occur in the pores of sandstones with low porosity and high clay mineral content and in the fractures of mudstones in the Muli area. This leads to difficulties in the evaluation of gas hydrates using geophysical logs. Understanding the characteristics of gas hydrate reservoirs and the generation mechanisms for geophysical log responses is the basis for log interpretation. In this study, core experiments including scanning electron microscopy, thin section observation, nuclear magnetic resonance, and porosity and permeability measurements were performed to understand the pore structure of gas hydrate reservoirs. X-ray diffraction, X-ray fluorescence, cation exchange, total organic content, and natural gamma spectrometry measurements were conducted to understand the rock composition and its effect on the petrophysical properties of the reservoirs. Reservoir log responses were analyzed and combined with core experimental data. The results showed that pore-type reservoirs with low porosity (0.6%–10.7%) and low permeability (0.005 mD-0.603 mD) belong to tight sandstones and fracture-type reservoirs contain relatively high TOC (0.133%–8.377%). A high resistivity log value is the most significant feature of gas hydrate-bearing reservoirs. An increase in clay mineral content, which is related to more bound water and a higher cation exchange capacity in sandstones, can remarkably reduce resistivity, which results in poor correlation between the resistivity of water-saturated sandstone and porosity. Fractures in mudstone are important storage spaces for gas hydrates. Calcite veins frequently occur in mudstones in the Muli area. If fractures are filled by calcites, the density, resistivity, and velocity of mudstone increase significantly. The velocity log values between gas hydrate-bearing reservoirs and other formations show no significant difference, which is caused by narrow and complex storage spaces, fracture-filling constituents, and poor velocity measurement results related to borehole collapse. This study is helpful to improve the accuracy of evaluation of gas hydrates in the Muli area.

1. Introduction

Gas hydrates are ice-like crystalline solids consisting of water and gas molecules. They are formed under low temperature and high-pressure conditions. Due to the vast amount of gas hydrate reserves, gas hydrates are considered a possible future energy source (Makogon, 2010; Vedachalam et al., 2015; Merey, 2016). At present, natural gas hydrates have been found both in permafrost regions and in marine and lacustrine sediments. The permafrost regions in which gas hydrates have accumulated are mainly distributed in high-latitude regions around the Arctic, such as western Siberia, Russia (Makogon et al., 2007); the Alaska North Slope, USA (Collett et al., 2011); and the Mackenzie Delta, Canada (Bily and Dick, 1974). In 2008, gas hydrates were found in the Muli area of the Qilian Mountains of the Qinghai-Tibet plateau, a mid-latitude permafrost region (Zhu et al., 2010). In recent years, gas hydrate investigation in the Qiangtang Basin and Tuotuohe area of the Qinghai-Tibet plateau has been conducted to understand the potential of gas hydrate resources (Fu et al., 2013; Liu et al., 2016). As the only area in the Qinghai-Tibet plateau where gas hydrate samples have been obtained, the Muli area of the Qilian Mountains, is the focus of research related to enrichment, evaluation, and exploitation of gas hydrates.

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https://doi.org/10.1016/j.jngse.2018.07.013
Received 7 March 2018; Received in revised form 7 June 2018; Accepted 16 July 2018

Drilling results have revealed that gas hydrates and their associated anomalies in the Muli area are distributed discontinuously between 130 m and 400 m in the vertical profile and that gas hydrate-bearing reservoirs are limited in horizontal extent (Lu et al., 2011; Wang et al., 2014a, 2014b; Hou et al., 2015). Numerous studies have been conducted to understand the geological controlling factors affecting gas hydrates and the formation mechanism of gas hydrates in the Muli area. Lu et al. (2013) analyzed the gas and isotope composition of gas hydrate and its associated gases in wells DK-1 and DK-2 and proposed that the gas source for gas hydrates in this area is mainly from deep source rocks. The research results from Zuo et al. (2016) and Cheng et al. (2018) also support this view. Wang et al. (2014b, 2015) carried out a study on fracture-filling pyrites and proposed that episodes of mineralization are related to the shrinkage of the gas hydrate stability zone. Sun et al. (2015) and Li et al. (2017a) investigated the synthesis of gas hydrate in rocks from the Muli area and found that gas hydrate is more likely to form in fractures in mudstone. By analyzing geochemical and geological data from well DK-9, Lu et al. (2016) found that gas hydrate and its related anomalies are closely related to faults or fracture zones. They proposed that faults or fracture zones control the distribution of gas hydrates by serving as migration paths for gases at deep and providing storage space in the shallow formation. However, these studies were mainly based on drilling results and core observation. Because gas hydrates dissociate under surface conditions, these data do not truly reflect actual gas hydrate-bearing reservoirs. Some scholars carried out numerical simulations based on limited geological data to understand gas production potential (Sun et al., 2014; Li et al., 2014, 2015). The accuracy of the simulation results depends on the selection of reservoir parameters. In fact, in situ gas hydrate saturation is still unknown and the physical properties of reservoirs have not been adequately studied in the Muli area. This has become a key factor restricting further research in the Muli area.

Geophysical logging can record in situ physical parameters of formations related to resistivity, magnetism, acoustics, thermology, and radioactivity, and is an important tool for the identification of gas hydrate-bearing reservoirs and evaluation of the gas hydrate content (Lee and Collett, 2006; Cook et al., 2010; Collett, 2013; Satyavani et al., 2015). Gas hydrates have higher acoustic velocity and resistivity than pore water. When gas hydrates replace pore water and occupy pore spaces in rocks, the acoustic velocity and resistivity of the rocks will increase. Therefore, an increase in acoustic velocity and resistivity is usually used as a marker of gas hydrate-bearing reservoirs, and the values of acoustic velocity and resistivity can be used to estimate gas hydrate saturation using petrophysical models of marine and permafrost regions around the Arctic (Hyndman et al., 1999; Kim et al., 2011; Lee and Collett, 2011; Shankar and Riedel, 2011; Wang et al., 2011). In the Muli area, gas hydrates occur in the pores and fractures of consolidated rocks (Fang et al., 2017; Qu et al., 2017). Some scholars directly used evaluation models of non-consolidated sedimentary strata to calculate gas hydrate saturation in the Muli area (Guo, 2011; Guo and Zhu, 2011; Lin et al., 2013; Liu et al., 2017). The accuracy of these calculation results is unknown. Although Zhu et al. (2010) found that gas hydrate-bearing rocks in well DK-1 have high resistivity and velocity log values, similar to gas hydrate-bearing sediments in marine and permafrost regions around the Arctic, Fang et al. (2017) indicated that log data from the Muli area cannot be directly interpreted based on the geophysical characteristics and models of marine and Arctic gas hydrates. The petrophysical characteristics of reservoirs in the Muli area are significantly different from those of unconsolidated sediments. It is impossible to establish a reliable model for log interpretation without an understanding of the factors affecting log response. Fang et al. (2017) compared the geophysical response characteristics of different formations based on geophysical logs in the Muli area. However, they did not deeply analyze the mechanism of log response due to a lack of core data. In marine and permafrost regions around the Arctic, analysis of physical properties based on cores is an important basic study to understand the mechanisms of geophysical response and to establish or enhance petrophysical models (Rose et al., 2011; Winters et al., 2011; Bahk et al., 2013; Horozal et al., 2015; Chatterjee et al., 2016). To date, only a few studies have been published involving petrophysical experiments from gas hydrate reservoirs in the Muli area (Lu et al., 2010; Guo, 2011; Lin et al., 2013). These studies only measured the porosity, permeability, and density of cores to establish porosity log evaluation models and estimate gas hydrate resources. At present, the analysis of geophysical log and core data is insufficient in the Muli area. This is an important factor restricting the development of a log interpretation model for this area.

It has been 10 years since gas hydrates were initially found in the Muli area. Due to the lack of petrophysical models for this area, geophysical logs have not been fully utilized in previous research. Differing from other regions, gas hydrate-bearing reservoirs in the Muli area are Middle Jurassic consolidated rocks. This means that analysis methods for unconsolidated sediments cannot be used for interpreting reservoirs from the Muli area. Therefore, for log interpretation of reservoirs from the Muli area, new methods must be established based on the mechanisms of log response in consolidated rocks. This study provides the first detailed and extensive analysis of petrophysical properties from gas hydrate reservoirs in the Muli area based on geophysical log and core data. Through this study, we intend to understand the characteristics of gas hydrate reservoirs and determine the dominant factors affecting log responses. This study will guide the quantitative evaluation of gas hydrates in the Muli area and will be helpful for the exploration of gas hydrates in other, similar permafrost regions.

2. Geological setting

The Sanlutian coalfield, the main area, studied in the Scientific Drilling Project of Gas Hydrates, is located in the Juhugeng mine area of the Muli coalfield, Qilian Mountains (Fig. 1). The Qilian Mountains consists of three structural units: The North Qilian structural zone, the Middle Qilian block, and the South Qilian structural zone (Feng, 1997). The Muli coalfield belongs to the Middle Qilian block. Since the Sinian, there have been three major geological stages in the tectonic evolution of the area: continental rift (Sinian to Middle Cambrian), ocean expansion and trench-arc-basin formation (Late Cambrian to Middle Ordovician), and the orogenic stage (after the Middle Ordovician). During the orogenic stage, the area experienced thrust-down orogeny, collision orogeny, and intra-land orogeny (Feng, 1997). During the early Paleozoic, the Qilian Mountains area was a small ocean basin. At the end of the Late Triassic, the old Tethyan Ocean completely closed and the whole Qilian Mountains area was uplifted and eroded due to Indosinian movement. A series of inter-mountain faulted depression basins occurred due to faulting and rifting of the Qilian Mountains area caused by Early Yanshan movement. These basins deposited a series of Jurassic age fluviolacustrine coal-bearing marsh facies and other clastic sediments (Fu and Zhou, 1998, 2000).

The Juhugeng mine area consists of a central anticline and two synclines in the north and south. The Sanlutian coalfield is located in the southern syncline. The strata in the study area mainly consist of Carboniferous, Permian, Triassic, and Jurassic formations. The Upper Jurassic, Middle Jurassic, and Triassic are the main exposed strata, in addition to Quaternary strata (Zhu et al., 2010). The Middle Jurassic formations include the Muli Formation (J_2m) and Jiangcang Formation (J_2j). The depositional environment was delta to lacustrine in the Lower Jiangcang (J_2j^1), and shallow lake to semi-deep lake in the Upper Jiangcang (J_2j^2). The J_2j^1 formation consists of mudstone, siltstone, fine sandstone, and a thin coal seam. The J_2j^2 formation consists of mudstone and oil shale. The Lower Muli (J_2m^1) formed in a braided river sedimentary environment and is composed of coarse sandstone and medium sandstone. The Upper Muli (J_2m^2) formed in a lacustrine to deltaic sedimentary environment and is composed of mudstone, siltstone, fine sandstone, and a coal seam.