Marine and Petroleum Geology xxx (2016) 1–12

Contents lists available at ScienceDirect

Marine and Petroleum Geology

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

Research paper

# Elastic-wave velocity characterization of gas hydrate-bearing fractured reservoirs in a permafrost area of the Qilian Mountain, Northwest China

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A R T I C L E I N F O

*Article history:*
Received 20 December 2015
Received in revised form
20 August 2016
Accepted 21 August 2016
Available online xxx

*Keywords:*
Gas hydrate
Permafrost area of Qilian Mountain
Fracture occurrence models
Pore shapes of reservoirs
Effective medium theory

A B S T R A C T

There are two types of gas hydrate-bearing reservoirs in the permafrost area of Qilian Mountain. Most of the gas hydrates occur mainly in the fractured mudstone reservoirs and rarely in the pores of the sandstone reservoirs. In this study, for the acoustic velocity characterization of the fractured gas hydrate reservoirs of the Qilian Mountain permafrost area, some mudstone core samples were collected for physical rock experiments, such as the acoustic experiment and the porosity and permeability experiment. An acoustic velocity numerical simulation of gas hydrate reservoirs was performed according to the Biot theory and the differential effective medium theory, with the conditions of multiple gas hydrate occurrence models, including the suspension model, the semi-cementation model and the cementation model, and considering both infinite and penny-shaped cracks. Fracture porosity was added to the core samples that only contain matrix porosity. With fracture porosity ranging from 0.01% to 5%, the variation laws between acoustic velocity with fractured porosity and hydrate saturation are obtained: (1) In the case of an infinite crack, if the fractured porosity is 0.01%–1%, the P-wave velocity decreases rapidly in the case of the three occurrence models. If the fractured porosity is higher than 1%, the acoustic velocity decreases gradually. If the crack shape is a penny-shaped crack, the P-wave velocity decreases almost linearly with increasing fracture porosity. (2) If the hydrate occurrence model is the suspension model, the P-wave velocity increases slightly with increasing hydrate saturation. If the occurrence model is the semi-cementation model or the cementation model, when the gas hydrate saturation of the infinite crack ranges from 0 to 80%, the acoustic velocity increases approximately linearly, whereas when the gas hydrate saturation ranges from 80% to 100%, the velocity increases rapidly. If the crack is a penny-shaped crack, the velocity increases almost linearly with increasing gas hydrate saturation from 0 to 100%. (3) It is found that the fractured gas hydrate reservoirs of the Qilian Mountain permafrost area contain both penny-shaped and infinite cracks, of which the infinite crack is the main crack shape. The gas hydrate occurrence in the Qilian Mountain permafrost area mainly follows the suspension model. This has significance for the seismic exploration and log evaluation of gas hydrate-bearing fractured reservoirs in the permafrost area of the Qilian Mountain in studying the acoustic velocity characterization, the crack shapes and occurrence models of gas hydrate reservoirs in the study area.



## 1. Introduction

Gas hydrates, also known as gas clathrates, are rigid clathrate lattices of water molecules and gas molecules that are formed in low-temperature and high-pressure environments. The occurrence status of gas hydrates can be categorized as either I-type structures

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http://dx.doi.org/10.1016/j.marpetgeo.2016.08.017
0264-8172/

or II-type structures (Kvenvolden, 1988a, b; Pan, 1986). Under standard conditions, 1 $m^3$ of I-type gas hydrates contains, at most, 164 $m^3$ of natural gas (Sloan, 1998; Liu et al., 2015; G. Zhang et al., 2015; Yang et al., 2008). It is estimated that the organic carbon content of proven gas hydrates worldwide is twice the total amount of organic carbon content of proven coal, oil, natural gas and other fossil fuels (Kvenvolden, 1999; X.H. Zhang et al., 2015). Gas hydrates are widely distributed, have large-scale reserves and produce less pollution upon combustion than other fuels; thus, gas hydrates are viewed as a new clean energy source for the future (Macdonald, 1990; Nisbet, 1990). Natural gas hydrates are mainly distributed in the deep ocean and in permafrost areas (Collett et al., 2011a,b; Dang et al., 2008). Gas hydrates have been found in many regions of the world, including the Gulf of Mexico in the Atlantic Ocean, the Blake Ridge of the east coast of the United States, the Nankai Trough of Japan, the Oman Gulf of the Indian Ocean and others (Bouriak et al., 2000; Collett et al., 2011a,b; Paull et al., 1991; Maslin et al., 1998). Gas hydrates in the Shenhu area of the South China Sea and in some permafrost areas in China, such as the Qinghai-Tibet permafrost, were discovered in recent years. The exploration prospect of natural gas hydrates in permafrost areas of China is promising (Zhao et al., 2012; Wang et al., 2015, 2015a). Among these permafrost areas, the discovery of gas hydrates in the Qilian Mountain permafrost area of the Qinghai-Tibet Plateau is the first discovery of gas hydrates in the mid-latitude plateau permafrost area, and it has important scientific significance and economic value (Lu et al., 2013; Zhu et al., 2010). Gas hydrates of the Qilian Mountain permafrost area can be developed in shallow layers, and the maximal depth of gas hydrate occurrence is approximately 400 m (Lu et al., 2011; Zhu et al., 2010). The Qilian Mountain permafrost is relatively thin, with a maximum thickness of 120 m. The strata bearing the gas hydrates are consolidated in the Middle Jurassic sequence and have a complex gas composition; in addition to methane, ethane, propane, propylene and isobutene are present.

Geophysical methods are important in the evaluation of gas hydrates. In seismic sections, the bottom simulating reflection (BSR) and other seismic characteristics are used to identify gas hydrates (Mackenzie, 1960). The log response characteristics, such as high resistivity and high acoustic velocity, can also be used to identify gas hydrates (Tamaki et al., 2016). In addition, other methods, such as acoustic, optic and biochemistry methods, play an important role in the identification and evaluation of gas hydrates. Gas hydrates in the Qilian Mountain permafrost area have various occurrence models and complex pore shapes. Gas hydrates in the research area mainly exist in the fractures of mudstone reservoirs. In this paper, the Biot theory and differential effective medium theory are employed to calculate the theoretical acoustic velocity for the study of the acoustic velocity characteristics of gas hydrates under three occurrence models: the suspension model, the semi-cementation model and the cementation model. Two pore shapes involving infinite and penny-shaped cracks are considered. The relationships between the acoustic velocity, fractured porosity and hydrate saturation are obtained.

## 2. Geological setting

The research area is in the Qilian Mountain permafrost area, which is located in the Juhugeng mining area, Muli coal field, Tianjun town, Qinghai province (Fig. 1, Wen et al., 2011; Zhu et al., 2006). The Qilian Mountain permafrost area is located in the north of the Qinghai-Tibet Plateau. It is 4100–4300 m above sea level and is approximately one hundred thousand square kilometers in area (Zhu et al., 2010). The region is covered by snow all year and the average temperature is approximately −5.1 °C. The stratigraphic thickness of the permafrost area is approximately 60–120 m (Zhou et al., 2000).

The structural units in the Qilian Mountain include three parts: the North Qilian tectonic belt, the mid-Qilian continental block and the southern Qilian tectonic belt. Among them, the North Qilian tectonic belt is subdivided into the Hexi Corridor and Nanshan Corridor, and the mid-Qilian continental block is mainly Tuolaishan. The Qilian Mountain area attained the current tectonic properties after a long period of tectonic evolution (Zhang and Yang, 2007). The Juhugeng mining area consists of a large anticline and two small synclines. The large anticline includes the southern margin of Datong Mountain and the northern margin of Tuolaishan. The northern syncline includes three well fields: the Sanjing field, the Erjing field and the Yilutian field. The southern syncline includes the Sijing field, the Yijing field, the Erlutian field and the Sanlutian field (Fu and Zhou, 1998, 2000). The gas hydrate drilling area is mainly located within Sanlutian field. Since 2008, ten small aperture holes for gas hydrate scientific experiments have been drilled by the Oil and Gas Survey of the China Geological Survey in the Qilian Mountain permafrost area, including DK-1, DK-2, DK-3 and so on. Gas hydrate samples were drilled from six holes: DK-1, DK-2, DK-3, DK-8, DK-9 and DK-12. Gas hydrates were not directly drilled from the other four holes, but gas hydrate relative anomalies were observed. In 2013, thirteen gas hydrate holes were designed and drilled by the Qinghai No. 105 Coal Geological Exploration Team, including DK13-11, DK12-13, DK11-14 and so on. Four small aperture holes were completed in 2013; of these, gas hydrate samples were drilled from the DK13-11, DK12-13 and DK11-14 holes. Ten small aperture holes were completed in 2014; of these, gas hydrate samples or suspected samples were drilled from the DK8-19 and DK10-17 holes. Acoustic logging, resistivity logging, gamma logging, neutron logging, density logging and other logging series were taken in the drilling holes. The drilling depths are all between 0 and 600 m (Feng, 1997).

The strata at the drilling depths in this research area are mainly of Sinian, Cambrian, Ordovician, Carboniferous, Permian, Triassic, Jurassic and Quaternary age. Triassic strata are largely exposed in the research area and are in unconformable contact with Middle Jurassic rocks. Most of the gas hydrates exist in Middle Jurassic strata. Middle Jurassic strata are divided into two groups, the Jiangcang group and the Muli group. The lower segment of the Jiangcang group was formed in a delta-lacustrine sedimentary environment and the upper segment was formed in a shallow lake-semi-deep lake sedimentary environment. The lower segment of the Muli group was formed in a braided river alluvial plain sedimentary environment and the upper segment was formed in a lake-swamp sedimentary environment, where a coal seam developed (Wen et al., 2011). The lithology in the research area includes sandstone, siltstone and silty mudstone, muddy siltstone, shale, oil shale and coal. Gas hydrate reservoirs are mainly found in the upper segment of the Jiangcang group of Middle Jurassic age, followed by the lower segment of the Jiangcang group. The lithology is mainly siltstone, oil shale, mudstone and fine sandstone, all of which are mostly dense rock. The upper segment of the Jiangcang group mainly contains oil shale, whereas the lower segment of the Jiangcang group mainly contains fine sandstone, muddy siltstone, mudstone and oil shale. The boring samples show that the Muli group has better physical properties for the deposition of gas hydrates because the sandstone has a high porosity structure, whereas mudstone and oil shale are well-developed in the Jiangcang group (Zhu et al., 2006). In our research, the Jiangcang group is our target reservoir, and the occurrence depth of gas hydrates is approximately 100–400 m. Fractures in the reservoir rock in the study area are well developed due to multiple tectonic movements and the fault system. The occurrence of gas hydrates is complex. Field drilled core samples containing gas hydrates were observed.

Please cite this article in press as: Qu, L., et al., Elastic-wave velocity characterization of gas hydrate-bearing fractured reservoirs in a permafrost area of the Qilian Mountain, Northwest China, Marine and Petroleum Geology (2016), http://dx.doi.org/10.1016/j.marpetgeo.2016.08.017