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Research paper

The natural-gas hydrate exploration prospects of the Nayixiong Formation in the Kaixinling-Wuli Permafrost, Qinghai-Tibet Plateau

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A B S T R A C T

Critical components of the Qinghai-Tibet Plateau natural-gas hydrate (NGH) petroleum system has been examined in this study. The results demonstrate that the Kaixinling-Wuli permafrost region contains viable prospects for gas hydrate exploration within favorable temperature and pressure stability conditions. In the study area, the average annual temperature of ground surface is −4.2 °C, the thickness of permafrost ranges from 40 to 150 m (average 84 m), and the geothermal gradient beneath the permafrost is between 1.54 °C/100 m and 2.67 °C/100 m (average 2.03 °C/100 m). The thickness of the methane-gas hydrate stability zone (GHSZ) is approximately 240–450 m. The Upper Permian Nayixiong Formation is dominated by braided delta and shallow shelf facies under mostly reducing conditions. The potential swamp deposited source rocks have a high total organic carbon (TOC) content that features a mixture of kerogen types II or III and an average vitrinite reflectance (R_o) of 2.04%. Overall, the thick sedimentary column in this region, its abundance of organic matter and its high thermal maturity suggest that the Nayixiong Formation source rocks have a high gas-generation potential. An effective fault-fracture-pore system also provides migration channels for deeper gas and also act as a reservoir for vein-type gas hydrate occurrences. The Kaixinling-Wuli area, when compared to other regions in the Qinghai-Tibet Plateau, exhibits greater gas hydrate petroleum system exploration potential as a result of the favorable temperature/pressure stability conditions and effective gas and gas-hydrate migration-storage system.

1. Introduction

A natural-gas hydrate (NGH) is an ice-like solid substance composed of natural gas and water at appropriate temperature and pressure and is widely distributed within and beneath the permafrost and within seafloor sediments of continental margins (Makogon, 2010; Makogon et al., 2007; Sloan, 1998). It has been estimated that natural-gas hydrates resources are 10 times larger than global conventional gas reserves (Zou, 2013) and for that reason, many countries have considered it a potential energy source for the 21st century (Kvenvolden, 1993; Makogon et al., 2007; National Research Council, 2000, 2010; Zou, 2013). Hydrate Energy International (HEI) has released a new evaluation of world gas hydrate resource potential that the calculated total median gas volumes in-place in hydrate-bearing sands may reach 44,311 tcf (Johnson, 2011). Permafrost gas hydrates have received considerable attention and have been widely researched worldwide, such as in Canada's Mackenzie Delta (Majorowicz and Hannigan, 2000a, 2000b), Russia's Messoyakha Gas Field (Makogon and Omelchenko, 2013), Alaska's North Slope (Collett et al., 2011; Patil et al., 2013) and China's Muli Coalfield, which is located in the Qilian Mountain permafrost region (Lu et al., 2011; Zhu et al., 2010a, 2009).

Permafrost gas-hydrate exploration activities are commonly concentrated in Arctic region, whereas China focuses mainly in high-altitude permafrost regions of the Qinghai-Tibet Plateau in mid-latitude areas with favorable pressure/temperature stability conditions and prospects for gas hydrates (Chen et al., 2005; Fu et al., 2013; He et al., 2012; Lu et al., 2007; Wu et al., 2010). In

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2008, China Geological Survey succeeded in collecting gas hydrates in well DK-1 at Qilian Mountain permafrost region (Zhu et al., 2009, 2010a,b). These discovered hydrates are mainly described as vein-type NGH, which is unlike larger permafrost hydrate deposits concentrated in conventional geological traps (Max et al., 2006). Vein-type NGH has raised a new geological proposition, which can be used to suggest similar but unrecognized gas hydrate on the earth, even on Mars (Max and Johnson, 2011; Max et al., 2013). The study area of this research is the Kaixinling-Wuli permafrost region, which is considered to be a very promising target (Lu et al., 2007; Tang et al., 2015; Zhu et al., 2011a,b). Recently, the Upper Permian Nayixiong Formation has been identified as the key gas hydrate-bearing layer in the region (Chen et al., 2014; Li, 2013; Li et al., 2013). Nayixiong Formation is dominated by transitional sedimentary facies, interbedded with several minable coal seams and considerable dark mudstone, which might be favorable source rocks (Li et al., 2013; Tang et al., 2015). Gong et al. (2014, 2015) studied the hydrocarbon-generation potential of the Nayixiong Formation's source rocks and suggested that tectonic movements and deep fault systems might control gas-hydrate formation.

Similar to conventional petroleum systems, the NGH petroleum system comprises the gas hydrate stability zone (GHSZ), gas source, migration, and reservoir (Collett et al., 2011; Max and Johnson, 2014). The NGH petroleum system concept is used to document our understanding of how NGH is formed and the nature of host sediments and how concentrated NGH accumulations are, and the identification of diagenetic methane hydrate in fractures (vein-type hydrate) can greatly extend the geographic area in which NGH concentrations could occur (Max and Johnson, 2011). The major objective of this study is to apply the NGH petroleum system approach to evaluate the primary elements for NGH formation in the Kaixinling-Wui permafrost region. Compared with the Muli area and the Qiangtang Basin (Fu et al., 2013; He et al., 2012; Lu et al., 2011; Zhu et al., 2010a,b, 2009, 2006), the results of this study can facilitate NGH exploration in the Kaixinling-Wuli area and throughout the Qinghai-Tibet Plateau.

2. Geological setting

2.1. Tectonic setting

The Kaixinling-Wuli area is located in Southern Qinghai province, in the middle of the Qinghai-Tibet Plateau. Tectonically, the study area marks the collisional margin between North Qiangtang Basin to the south and Hoh Xil-Jinsha River suture zone to the north (Fig. 1A) that was active from the Paleozoic to Mesozoic and subsequently it experienced tectonic uplift along with Indo-Asia collision since the Cenozoic (Dewey et al., 1988; Zhang et al., 2012). Therefore, the entire plateau remains in a longitudinal compressive state (Pan, 1999; Zhang et al., 2013). Against this background, the regional structure pattern shows WNW or near EW orientation, and regional strata experienced multi-period fold deformation, which led to the formation of the Kaixinling-Wuli anticlinorium (Fig. 1B). Simultaneously, the area also developed many thrust and transpressional faults, severely disrupting the continuity of the regional strata. Corresponding to the complex structure, the stratigraphic dip varies greatly from horizontal to vertical. As a result, the strata burial depth varies greatly in region, from the observed outcrop to a predicted depth greater than 3000 m.

2.2. Stratigraphy

The thick stratigraphic section is composed of Carboniferous, Permian, Triassic, Cretaceous, Paleogene, Neogene and Quaternary sediments (Fig. 1C). In the Late Carboniferous, the Kaixinling-Wuli area was a widespread epeiric sea environment, in which thick Zharigen Formation (C_3z) carbonates were deposited with a thickness of more than 875 m. From the Late Carboniferous to Permian, a tethys oceanic crust subducted in both the southeast and northeast directions, resulting in the formation of a series of sedimentary basins and magmatic arcs associated with the active continental margin (Kong et al., 2014; Niu et al., 2011). The Lower Permian deposition of the Nuoribagaribao Formation (P_1nr, >1683 m) sandstones with limestone and volcanic rocks, and the Jiushidaoban Formation (P_2j, >1103 m) limestone filled the developing basins. In the Late Permian, the area became warm and wet, and the Nayixiong Formation (P_3n, >1159 m) was deposited as a coal-bearing clastic rock stratum. Unconformity on the Labuzhari Formation (P_3lb, >475 m) are the Jiapila, Bolila and Bagong formations (T_3jp, T_3b and T_3bg), which are Upper Triassic in origin; and the tectonic environment became a retro-arc foreland basin. Jiapila Formation is mainly filled with clastic rocks and volcanic rocks, Bolila Formation is limestone interbedded with sandstones while Bagong Formation consists of coal-bearing terrigenous rocks, with column thickness of >1372 m, >2431 m and >3277 m, respectively.

The Nayixiong Formation is widely distributed in the study area; it has a minimum thickness of 1159 m. It is primarily composed of marine–continental transitional sediments, periodically influenced by carbonaceous terrestrial source influx (Deng et al., 2014). Frequent marine transgressions and regressions have contributed to the burial and preservation of organic matter: mudstone and shale comprise approximately 32% of the stratum (Li, 2013). Because of the high TOC, high-maturity organic matter of type III and strong gas generation capability, the mudstone has been considered an important source rock for gas hydrate petroleum system in this region (Li, 2013; Li et al., 2013; Tang et al., 2015). In addition, the Nayixiong Formation contains 5 to 10 layers of coal, of which the thickest layer is up to 10 m (Wu, 2011); thus, coal-derived gas might contribute to the accumulation of gas in the region.

3. Samples and methods

All of the Nayixiong Formation samples were collected from the TK1 well drilled in the study area. Overall, 36 rock samples were collected and analyzed, including trace elements of 19 samples, total organic carbon (TOC), Rock-Eval pyrolysis, chloroform extraction and vitrinite reflectance (R_o) of 13 samples, gas chromatography (GC) and GC-mass spectrometry (MS) analyses of 7 samples, reservoir rock data (porosity and permeability) of 8 samples, and 25 rock thin sections cut from 10 samples (Table 1).

The trace elements were measured by a Perkin Elmer Elan DCR-e analyzer using pressurized airtight digestion and inductively coupled plasma mass spectrometry (ICP-MS). The measured elements include Sr, Ba, Th, U and others. Total organic carbon was tested using a Leco CS-230 carbon and sulfur analyzer. Samples needed to be pretreated with diluted hydrochloric acid and then programmed for complete combustion in a nearly pure oxygen flow; simultaneously, the total sulfur content was measured. Rock-Eval pyrolysis experiments were performed on an OGE-VI Hydrocarbon Evaluation Workstation instrument in which samples were programmatically heated to 600 °C in a helium atmosphere. The measured parameters included volatile organic hydrocarbon (VOHC) content, mg HC/g rock (S_1), which was measured in an oven at a constant temperature of 300 °C for 3 min; pyrolysis HC generation yield, mg HC/g rock (S_2), which was measured when samples were heated from 300 to 600 °C at a rate of 25 °C/min; carbon oxide yield, mg CO_2/g rock (S_3), which was measured from a process