Marine and Petroleum Geology 47 (2013) 30–42

Contents lists available at SciVerse ScienceDirect

Marine and Petroleum Geology

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

Characterization of gas hydrate reservoirs by integration of core and log data in the Ulleung Basin, East Sea

J.-J. Bahk[a,*], G.-Y. Kim[a], J.-H. Chun[a], J.-H. Kim[a], J.Y. Lee[a], B.-J. Ryu[a], J.-H. Lee[a], B.-K. Son[a], T.S. Collett[b]

[a] *Petroleum and Marine Research Division, Korea Institute of Geoscience and Mineral Resources, Daejeon 305-350, Republic of Korea*
[b] *US Geological Survey, Denver Federal Center, Denver, CO 80225, USA*

A R T I C L E I N F O

Article history:
Received 18 January 2013
Received in revised form
8 May 2013
Accepted 9 May 2013
Available online 25 May 2013

Keywords:
Gas hydrate
Sedimentary facies
Logging-while-drilling
Ulleung Basin
East Sea

A B S T R A C T

Examinations of core and well-log data from the Second Ulleung Basin Gas Hydrate Drilling Expedition (UBGH2) drill sites suggest that Sites UBGH2-2_2 and UBGH2-6 have relatively good gas hydrate reservoir quality in terms of individual and total cumulative thicknesses of gas-hydrate-bearing sand (HYBS) beds. In both of the sites, core sediments are generally dominated by hemipelagic muds which are intercalated with turbidite sands. The turbidite sands are usually thin-to-medium bedded and mainly consist of well sorted coarse silt to fine sand. Anomalies in infrared core temperatures and porewater chlorinity data and pressure core measurements indicate that "gas hydrate occurrence zones" (GHOZ) are present about 68–155 mbsf at Site UBGH2-2_2 and 110–155 mbsf at Site UBGH2-6. In both the GHOZ, gas hydrates are preferentially associated with many of the turbidite sands as "pore-filling" type hydrates. The HYBS identified in the cores from Site UBGH2-6 are medium-to-thick bedded particularly in the lower part of the GHOZ and well coincident with significant high excursions in all of the resistivity, density, and velocity logs. Gas-hydrate saturations in the HYBS range from 12% to 79% with an average of 52% based on pore-water chlorinity. In contrast, the HYBS from Site UBGH2-2_2 are usually thin-bedded and show poor correlations with both of the resistivity and velocity logs owing to volume averaging effects of the logging tools on the thin HYBS beds. Gas-hydrate saturations in the HYBS range from 15% to 65% with an average of 37% based on pore-water chlorinity. In both of the sites, large fluctuations in biogenic opal contents have significant effects on the sediment physical properties, resulting in limited usage of gamma ray and density logs in discriminating sand reservoirs.

1. Introduction

Occurrence and distribution of natural gas hydrate are largely controlled by an interplay between the factors such as pressure and temperature conditions which restrict gas-hydrate stability zone (GHSZ), sufficient supplies of methane into the GHSZ over the solubility in water, and characteristics of host sediments (Boswell et al., 2012; Collett et al., 2009; Xu and Ruppel, 1999). In particular, grain-size distribution of the host sediments, which determines pore size and permeability, has been suggested to have a primary role in control of gas-hydrate morphology and saturation leading to the three distinct types of gas-hydrate occurrences: (1) pore-filling gas hydrate in coarse-grained sediments (coarse silt and sand) with generally high saturation (>50% of pore volume), (2) pore-filling gas hydrate in fine-grained sediments with usually low saturation, and (3) grain-displacing gas hydrate which occurs as discreet veins or nodules in fine-grained sediments with variable saturations (Bahk et al., 2011; Boswell et al., 2012; Ginsburg et al., 2000; Holland et al., 2008; Lee and Collett, 2009; Torres et al., 2008; Tréhu et al., 2004). Among these types, the first one has been considered most promising as a potential resource and chosen as target reservoirs of onshore and offshore gas-hydrate explorations and production tests (Boswell et al., 2006; Collett et al., 2009).

Discrimination of sand reservoirs or estimation of sand to shale ratios in conventional exploration well logs commonly rely on gamma-ray logs where cleaner sand beds tend to exhibit relatively lower gamma radiation API values (Rider, 1995). Such behaviors in gamma-ray logs have been also successfully applied to locating sand reservoirs in GHSZ, particularly in sand-prone successions where thicknesses of sand beds are generally more than a meter, significantly greater than vertical resolutions of gamma ray logging-while-drilling (LWD) tools (e.g., 45 cm for GeoVision, Mrozewski et al., 2010) (Boswell et al., 2011, 2012). In addition to

---

* Corresponding author. Tel.: +82 42 868 3380; fax: +82 42 868 3417.
E-mail address: jjbahk@kigam.re.kr (J.-J. Bahk).

0264-8172/$ – see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.marpetgeo.2013.05.007

the gamma-ray logs, resistivity and sonic logs which tend to show higher resistivity and velocity with higher gas-hydrate saturation, have been often used for further differentiation between gas-hydrate-bearing and water-bearing sand reservoirs (Collett et al., 2012; Goldberg et al., 2010). However, in case of mud-prone successions within GHSZ where sand beds are usually thin- to medium-bedded (<30 cm thick), gamma-ray logs fail to resolve individual sand beds. Instead, high resolution resistivity, such as button and ring resistivity of GeoVision with vertical resolution of ~7 cm (Mrozewski et al., 2010), better discriminates individual thin gas-hydrate-bearing sand layers incased in mud (Fujii et al., 2009; Tsuji et al., 2009). The deployment of resistivity criteria has been verified by the coring results which show preferential enrichments of gas hydrate in the sand layers interbedded with mud (Fujii et al., 2009; Tsuji et al., 2009).

The First Ulleung Basin Gas Hydrate Drilling Expedition (UBGH1) in 2007 revealed gas hydrates with significant saturations either in fractured mud or in thin-bedded turbidite sand layers from the three coring sites (Bahk et al., 2011; Chun et al., 2011; Kim et al., 2011). The Second Ulleung Basin Gas Hydrate Drilling Expedition (UBGH2) in 2010 conducted LWD and coring at 13 sites to better identify the overall distribution of gas hydrate in the Ulleung Basin and locate gas-hydrate reservoirs that could be potential targets of future production tests (Ryu et al., 2012). This paper focuses on logging and coring results from Sites UBGH2-2_2 and UBGH2-6 which have relatively good gas-hydrate reservoir quality in terms of individual and total cumulative thicknesses of gas-hydrate-bearing sand beds. By integration of detailed onboard and post-cruise analyses of well logs and cores, we intend to demonstrate characteristic responses of various kinds of well logs to the occurrences of gas-hydrate-bearing sand beds in a mud-prone succession in the Ulleung Basin and how they can be applied to evaluation of gas-hydrate sand reservoirs. Besides the resolutions of logging tools, roles of biogenic opal were addressed in the interpretation of well-log characteristics.

2. Geological setting

The Ulleung Basin is a deep, bowl-shaped, back-arc basin bounded by the steep continental slope of the eastern Korean Peninsula to the west and the South Korea Plateau to the north (Fig. 1). The northern and western margins of the basin are relatively steep with gradients of up to 10°. In the south and east, the basin is bordered by rather gentle slope (1°–2°) and broad shelf (30–50 km wide) of the Japanese Arc and the Oki Bank (Fig. 1). The basin floor lies at water depths of 2000–2300 m and gradually deepens northeastward.

The Ulleung Basin was opened in the Late Oligocene to Early Miocene by crustal extension accompanied with southward movement of SW Japanese Islands (Tamaki et al., 1992; Yoon and Chough, 1995). At the end of the Middle Miocene (11–12 Ma), basin closure was caused by the northward collision of the Bonnic Arc with central Japan (Chough and Barg, 1987). The basin closure led to uplift of the southern margin and basin-wide deposition of mass transport deposits (MTDs) which were evolved from frequent slope failures along the southern slope during the latest Neogene (Lee and Suk, 1988; Lee et al., 2001). Since the Pleistocene, the deeper parts of the basin have been dominated by distal turbidites and hemipelagites as the depocenter of the MTDs rapidly retreated to the southern margin (Lee and Suk, 1988; Lee et al., 2001).

The presence of gas hydrates in the Ulleung Basin was predicted based on geophysical evidences, such as bottom simulating reflectors (BSR), columnar seismic blank zones associated with velocity pull-up structures (seismic chimneys), and seafloor pockmarks and mounds (Gardner et al., 1998; Horozal et al., 2009; Ryu et al., 2009; Yoo et al., 2008). Depths of the BSR from the seafloor range from about 200 ms to 250 ms in two-way travel time (TWT) (Horozal et al., 2009). In particular, the deeper parts of the Ulleung Basin are characterized by numerous seismic chimneys, which are up to 2 km in width and often reach to the seafloor (Horozal et al., 2009; Ryu et al., 2009).

During the UBGH1, two of the seismic chimneys in the basin plain (Sites UBGH1-09 and UBGH1-10) and MTD-dominated sequences underlain by a strong BSR in the southern lower slope (Site UBGH1-04) were selected for LWD and coring (Park et al., 2008). Sites UBGH1-09 and UBGH1-10 are generally characterized by significantly elevated electrical resistivity (>80 Ω-m) and P-wave velocity (>2000 m/s) which are associated with abundant hydrate veins and nodules in hemipelagic mud (Bahk et al., 2011; Chun et al., 2011; Kim et al., 2011). In contrast, at Site UBGH1-4, gas hydrate was only recovered from thin sandy turbidites interbedded with hemipelagic mud just above the BSR (Riedel et al., 2012).

Following the UBGH1, the UBGH2 was established on 13 sites which encompass four seismic chimney sites, one MTD-dominated site, and eight sites of turbidite and hemipelagite sequences, with the aims of both understanding overall distribution of gas hydrates in the Ulleung Basin and delineation of gas-hydrate reservoirs that could be potential targets of future production tests (Fig. 1; Ryu et al., 2012). Sites UBGH2-2_2 and UBGH2-6, which are focused on in this paper, were chosen from the turbidite and hemipelagite sequences in the basin plain which are generally characterized by well stratified, seafloor-parallel reflectors with variable amplitudes above the BSR in multi-channel seismic profiles (Ryu et al., 2012). Site UBGH2-6 is located near the northwestern end of the basin plain with the water depth of ~2153 m (Fig. 1), where the depths of BSR and the base of gas hydrate stability zone (BGHSZ) were predicted pre-drilling and estimated at 175 mbsf and 167 mbsf, respectively (Table 1). The estimation of the BGHSZ was based on the geothermal gradient from formation temperature measurements, assuming Structure I gas hydrate. This site was selected to test a series of high amplitude seismic reflectors potentially representing gas-hydrate-bearing sand layers overlying MTD. Site UBGH2-2_2 is located near the seismic chimney sites of UBGH1-09 and UBGH2-2_1 with water depths of ~2093 m (Fig. 1; Table 1). It was selected to test lateral extent of the gas hydrate occurrences outside of the seismic chimneys. The BSR and BGHSZ at the site were predicted pre-drilling and estimated at 165 mbsf and 180.5 mbsf, respectively (Table 1). The difference between the depths of BSR and BGHSZ is not clearly understood yet.

3. Methods

3.1. LWD and coring operations

The UBGH2 consisted of a LWD phase followed by a coring phase including wireline logging for two selected sites (Ryu et al., 2012). The LWD phase was conducted using the Schlumberger's logging tools of the GeoVision, TeleScope, EcoScope and SonicVision (Ryu et al., 2012), down to the termination depths more than 100 m below the predicted BSR depths at Sites UBGH2-2_2 and UBGH2-6 (Table 1). Based on the LWD results, coring was performed at nearby holes ~10 m apart using Fugro Hydraulic Piston Corer (FHPC), Fugro Corer (FC), and Fugro Rotary Corer (FRC) for non-pressurized cores and Fugro Pressure Corer (FPC) and Fugro Rotary Pressure Corer (FRPC) for pressurized cores. The coring intervals are discontinuous, interrupted by significant drilling intervals at Site UBGH2-2_2, but nearly continuous at Site UBGH2-6. At Site UBGH2-6, the second coring hole (UBGH2-6C) was attempted to increase core recovery in the gas hydrate occurrence zone (GHOZ), which was very poor in the first coring hole (UBGH2-6B) (Table 1).