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Research paper

Deterministic estimation of gas-hydrate resource volume in a small area of the Ulleung Basin, East Sea (Japan Sea) from rock physics modeling and pre-stack inversion

Bo Y. Yi[a], Gwang H. Lee[b,*], Nyeon K. Kang[a], Dong G. Yoo[a], Joo Y. Lee[a]

[a] *Korea Institute of Geoscience and Mineral Resources, Daejon 34132, South Korea*
[b] *Department of Energy Resources Engineering, Pukyong National University, Busan 48513, South Korea*

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ABSTRACT

We made deterministic estimations of the gas-hydrate and in-place gas resource volumes in a small area in the northwestern Ulleung Basin, East Sea (Japan Sea) from 3-D pre-stack seismic data and well-log and core data from the UBGH2-6 well. We modeled the P-impedance (I_p) logs at the well for 0%–100% pore-space gas-hydrate saturation from the P-wave velocity (V_p) and density logs modeled by the simplified three-phase Biot-type equation (STPBE). Then, the I_p volume for the gas-hydrate-bearing zone (GHBZ) was constructed by pre-stack inversion and divided into 28 layers. The porosity and mineralogy along these layers were assumed to be uniform, respectively, to the porosity log upscaled to the layers and the sediment constituents at the well determined from the core samples. Next, the pore-space gas-hydrate saturation at every time sample of each layer was found by matching the I_p value of the time sample to the modeled I_p logs upscaled to the layers. The gas-hydrate saturation volume with a cell size of 25 m × 6.25 m × 1 ms was obtained from the product of the pore-space gas-hydrate saturation volume and the porosity volume. The gas-hydrate saturation volume was converted into the depth volume based on the V_p value at each cell found by matching the pore-space gas-hydrate saturation of the cell to the modeled V_p logs. The estimated total gas-hydrate and gas resource volumes are about 8.43×10^8 m^3 and about 1.38×10^{11} m^3, respectively.

1. Introduction

Natural gas hydrate is considered a potential energy source as it contains an enormous volume of gas (Kvenvolden, 1993; Sloan and Koh, 2008). Gas hydrate forms under temperature and pressure conditions common in marine sediments below about 500 m of water depth and in onshore permafrost regions (Kvenvolden, 1993). The subsea depth of the gas-hydrate stability zone (GHSZ) can be inferred from the bottom-simulating reflector (BSR) that corresponds approximately to the boundary between the GHSZ and free gas below. The early model in the 1980s for gas-hydrate distribution was simple, depicting gas hydrate as an almost uniformly distributed component in the GHSZ (Boswell and Collett, 2006). The occurrence of gas hydrate in the GHSZ is now known to be very complicated with significant lateral and vertical variability (Boswell and Collett, 2006). The complex interaction of many factors (e.g., temperature, pressure, gas chemistry, salinity, availability of gas and water, lithology, etc.) controls the gas-hydrate occurrence in the GHSZ (Collett, 1995; Boswell and Collett, 2006).

Seismic and well-log data have been used to assess gas-hydrate saturation for various scales. Lu and McMechan (2002) and Wang et al. (2011) estimated gas-hydrate saturation in the Blake Ridge area off the east coast of North America and in the Shenhu area, South China Sea, respectively, based on empirical relationships between P-impedance (I_p) (the product of density and P-wave velocity, V_p) and porosity. McConnell and Kendall (2004) interpreted gas-hydrate deposits by mapping the high I_p zone in northwest Walker Ridge in the Gulf of Mexico. I_p was also used in the determination of the extent of gas hydrate near the Mallik research wells, Mackenzie Delta, Canada (Bellefleur et al., 2006).

Dai et al. (2008a) estimated the gas-hydrate saturation in the Keathley Canyon area, northwestern Gulf of Mexico from 3-D pre-stack inversion and rock-property models. Their pre-drill estimates agree with the gas-hydrate occurrence and saturation estimated from well-log data (Dai et al., 2008b). Gas-hydrate saturation in the Gulf of Mexico Gas Hydrate Joint Industry Project Leg II area, predicted from pre-stack inversion, is comparable to that calculated from well-log data especially in areas of moderate to high concentrations of gas hydrate (Shelander et al., 2012). Shankar et al. (2013) used various rock physics models to

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[*] Corresponding author.
E-mail addresses: byyi@kigam.re.kr (B.Y. Yi), gwanglee@pknu.ac.kr (G.H. Lee), nkkang@kigam.re.kr (N.K. Kang), dgyoo@kigam.re.kr (D.G. Yoo), jyl@kigam.re.kr (J.Y. Lee).

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model the V_p logs for different values of gas-hydrate and free-gas saturations at sites NGHP-01 and 07 in the Krishna-Godavari Basin, eastern margin of India. They matched the actual V_p logs to the modeled V_p logs to estimate the gas-hydrate and free-gas saturations at the drilling sites.

Kang et al. (2012), Lee et al. (2013), and Riedel et al. (2013) made volumetric estimations of gas-hydrate resources in the Ulleung Basin, East Sea (Japan Sea) using seismic and various well-log data acquired by the Korea Institute of Geoscience and Mineral Resources (KIGAM). Kang et al. (2012) interpreted five seismic facies in the GHSZ of the basinal area and estimated the gas-hydrate and in-place gas resource volumes by Monte Carlo simulation for each facies. Their estimates of gas-hydrate and gas volumes in the basinal area range from about 2.5×10^9 m^3 to about 9.2×10^9 m^3 with a mean of about 5.4×10^9 m^3 and from about 4.1×10^{11} m^3 to about 1.5×10^{12} m^3 with a mean of 8.8×10^{11} m^3, respectively. Riedel et al. (2013) applied Monte Carlo simulation and multi-attribute transform (MAT) to estimate the gas-hydrate resource volume in a small area (16 km × 25 km) in the southern part of the Ulleung Basin. Riedel et al.'s (2013) estimates range from 4.4×10^6 m^3 to 6.4×10^8 m^3 with a mean of about 1.9×10^8 m^3. Lee et al. (2013) estimated the volumes of gas-hydrate and in-place gas in a small (37 km × 58 km) area of the northern central part of the basin from a dense grid of 2-D seismic and logging-while-drilling (LWD) data, using the seismic inversion and MAT techniques. Their estimated gas-hydrate and in-place gas volumes are about 3.03×10^9 m^3 and about 3.97×10^{11} m^3, respectively.

In this study, we made deterministic estimations of the gas-hydrate and in-place gas volumes of a small area (12 km × 21 km) in the northwestern Ulleung Basin (Fig. 1) from pre-stack 3-D seismic data and LWD and core data from the UBGH2-6 well which was drilled in 2010 during the Second Gas Hydrate Drilling Expedition carried out by KIGAM. The water depth of the study area is about 2150 m. The UBGH2-6 well penetrated the gas-hydrate-bearing zone (GHBZ) from 110 mbsf (meters below seafloor) to 155 mbsf, identified from the well logs and core samples (Bahk et al., 2013). The GHBZ consists of hemipelagic mud and turbidite; gas hydrate occurs in the turbidite beds. The base of the GHSZ in the well is about 167 mbsf (Ryu et al., 2013). The BSR can be interpreted locally in the study area (Kim et al., 2015).

2. Geologic setting

The East Sea is a back-arc basin lying between the Eurasian plate and the Japanese Island arc (Fig. 1). The opening of the East Sea began in the Early Oligocene, forming three deep basins: the Japan, Yamato, and Ulleung basins, separated by submerged continental remnants (Tamaki et al., 1992). The Ulleung Basin is bounded to the west by the steep continental slope of the Korean Peninsula and to the north by the rugged Korea Plateau. The gentle slopes of the southwestern Japanese arc and the Oki Bank form the southern and eastern basin margins, respectively. The basin floor of the Ulleung Basin is fairly smooth and dips gently to the northeast. The water depths in the basin range from less than 1500 m in the south to over 2300 m in the northeast.

During the latest Neogene, margin-wide slope failures, caused by the regional tectonic deformation related to the closure of the East Sea, resulted in basinwide deposition of mass-transport complexes in the Ulleung Basin (Lee and Suk, 1998). The mass-transport complexes, consisting mostly of debris-flow deposits sourced from the south, reached the northernmost part of the basin (Horozal et al., 2015). The first few hundred meters of the sedimentary section in the study area is dominated by turbidite and hemipelagic sediments with thin debris-flow deposits (Kang et al., 2012; Horozal et al., 2015). The sedimentary section penetrated by the UBGH2-6 well can be divided into three lithofacies: (1) hemipelagic muds (0–110 mbsf), (2) hemipelagic mud-turbidite interbeds (110–209 mbsf), and (3) muddy debris-flow deposits (209–230 mbsf) (Bahk et al., 2013). The base of the GHSZ occurs in the hemipelagic mud-turbidite interbeds. Hemipelagic muds contain up to about 50% of biogenic silica (opal-A). Sand beds in the GHBZ at the UBGH2-6 well are usually more than 30 cm thick (Bahk et al., 2013).

3. Data

The data used in this study consist of 3-D pre-stack seismic data (Fig. 1) and LWD and X-ray powder diffraction (XRD) data of the core samples from the UBGH2-6 well which is the only well drilled in the 3-D seismic coverage (Fig. 2). The seismic data were acquired by Korea National Oil Corporation as part of a pre-test-production survey for the UBGH2-6 well. Four lines of 324-channel (4000-m long) streamers recorded flip-flop shots from two sets of 1060-in^3 (2000 psi) eight air-gun array. The hydrophone group interval and shot spacing were 12.5 m and 25 m, respectively. The bin size is 25 m × 6.25 m. The data were recorded to 6.144 s with a sampling interval of 1 ms. The standard pre-stack time-migration processing was applied to the data; the data were processed by WesternGeco.

The LWD data include gamma-ray, resistivity, P-wave acoustic (Fig. 2a) and density logs (Fig. 2b). The seafloor to 227-mbsf interval was cored with about 70% recovery (Ryu et al., 2012). The matrix density (i.e., grain density) log (Fig. 2c) was constructed from the densities of the 171 dry sediment samples from the cores. The porosity log (Fig. 2d) was computed from the density log using the following formula:

$$\varphi = \frac{\rho_{ma} - \rho_{\log}}{\rho_{ma} - \rho_f} \tag{1}$$

where ρ_{log}, ρ_{ma} and ρ_f are the well-log bulk density, matrix density, and fluid density, respectively. ρ_f was assumed to be 1.02 g/cm^3. ρ_{ma} was read from the matrix density log. Density porosity is known to better predict the porosity of gas-hydrate-bearing sediments than neutron porosity (Riedel et al., 2006; Collett et al., 2008).

Mineral compositions (Fig. 2e) of the core samples were analyzed by XRD and software program (SIROQUANT) based on Rietveld quantification method (Bahk et al., 2013). The Philips X'pert MPD diffractometer was used with Cu anode in conditions of 40 kV and 20 mA. The sediment constituents include quartz, opal-A, clay, feldspars, muscovite, calcite, pyrite, and dolomite.

Petrel® (version 2015) was used for seismic data interpretation and mapping and Hampson-Russell® (version 9) for well-log data analysis and inversion.

4. Data analysis and results

The gas-hydrate and gas resource volumes in the GHBZ were estimated by matching the values of I_p computed from pre-stack inversion at each time sample to the I_p logs for the full range of pore-space gas-hydrate saturations computed by rock physics modeling based on the simplified three-phase Biot-type equation (STPBE) of Lee (2008). The theory of the STPBE is given in Appendix A. The STPBE is based on a pore-filling model which treats gas hydrate as a solid-phase component in gas-hydrate-bearing sediments; sediment grains, gas hydrate, and pore fluid form three homogeneous, interwoven frameworks. The data analysis workflow is shown in Fig. 3.

4.1. Rock physics modeling: the simplified three-phase Biot-type equation (STPBE)

First, we modeled the I_p logs at the UBGH2-6 well for 0%–100% pore-space gas-hydrate saturation at 0.1% interval from the V_p and density modeled by the STPBE, based on the porosity from the density-porosity log and the elastic moduli (Table 1) of the sediment constituents. As a result, a total of 1001 I_p curves were obtained. Fig. 4 shows the porosity log and the modeled curves for V_p, density, and I_p for