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Occurrence and seismic characteristics of gas hydrate in the Ulleung Basin, East Sea

Dong G. Yoo[a,*], Nyeon K. Kang[a], Bo Y. Yi[a], Gil Y. Kim[a], Byong J. Ryu[a], Keumsuk Lee[b], Gwang H. Lee[c], M. Riedel[d]

[a] Petroleum & Marine Research Division, Korea Institute of Geoscience and Mineral Resources (KIGAM), 124 Gwahang-no, Yuseong-gu, Daejeon 305-350, Republic of Korea
[b] Korea National Oil Corporation (KNOC), Anyang 431-711, Republic of Korea
[c] Department of Energy Resources Engineering, Pukyoung National University, Busan 608-737, Republic of Korea
[d] National Resources Canada, Geological Survey of Canada, 9860 West Saanich Road 16, Sidney, BC V8L 4B2, Canada

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ABSTRACT

Multi-channel seismic reflection and well-log data from the Ulleung Basin, East Sea reveal several seismic signatures indicative of gas-hydrate occurrence in the Ulleung Basin that are associated with vertically and/or laterally stacked mass-transport complexes. The seismic indicators include (a) a bottom simulating reflector (BSR), (b) a seismic chimney, (c) high amplitude reflections within the gas hydrate stability zone (GHSZ), (d) acoustic blanking, (e) enhanced reflections below the BSR, and (f) seafloor gas-escape features. The BSR, associated with enhanced reflections below, is most commonly found over much of the basin indicating a physiochemical boundary of gas hydrates overlying free gas. Seismic chimneys are characterized by velocity pull-up and reduced reflectivity on the seismic sections, which appear to be caused by active migration of fluid gas vertically into the GHSZ. The logging data retrieved from the seismic chimneys showed elevated electrical resistivity (>80 Ohm-m) and P-wave velocity (>2000 m/s), indicating the presence of gas hydrate. Another seismic characteristic observed in gas hydrate bearing sediments is the strong amplitude reflections, defined by the relatively high reflectivity within the GHSZ. Acoustic blanking is likely to be the result of hydrate accumulation in the sediments causing a significant reduction of acoustic impedance contrast between sedimentary layers. Where the upward migrating gas seeps into the deep water column, seafloor pockmarks and mud mounds may be formed.

Gas hydrate was recovered from the Ulleung Basin, East Sea in 2010 during the Second Ulleung Basin Gas Hydrate Drilling Expedition (UBGH2) under the Korean National Gas Hydrate Program. Based on the results, gas-fluids migrate into the GHSZ through two distinct pathways: (1) structural conduits which include fault and fracture systems associated with seismic chimneys and (2) stratigraphic conduits associated with inclined turbidite/hemipelagic layers. Two types of gas-hydrate occurrence were identified in the basin: (1) a stratally-bound type (pore filling) within turbidite sand layers and (2) a locally concentrated type (massive, nodule or fracture filling) within upward-growing chimneys associated with near vertical faults. Relatively high concentrations of gas hydrate, however, tend to occur in localized seismic chimneys, rather than in the strata-related features. The successful recovery indicates that the Ulleung Basin provides favorable conditions for gas-hydrate formation.

1. Introduction

Occurrences of marine gas hydrates are well known from numerous geophysical and geological studies (e.g. Hyndman and Spence, 1992; Kvenvolden, 1993; Lee et al., 1993; Xu and Ruppel, 1999). In seismic sections, the presence of gas hydrate can be identified by the existence of Bottom Simulating Reflectors (BSRs), which have high amplitude and reverse polarity and tend to be parallel to the seafloor topographic surface (Shipley et al., 1979). Therefore, a BSR remains perhaps the most common indicator of gas hydrates, although it may not be essential for gas hydrate recovery (Kvenvolden and Barnard, 1983; Shipley et al., 1979; Hyndman and Spence, 1992; Holbrook et al., 1996). The existence of gas hydrate within sediment pore space may reduce the acoustic impedance contrasts of sedimentary layers, leading to a decrease in

* Corresponding author. Tel.: +82 42 86 3324; fax: +82 42 868 3417.
E-mail address: dgyoo@kigam.re.kr (D.G. Yoo).

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seismic reflectivity (i.e., acoustic blanking) above a BSR (Shipley et al., 1979; Hovland et al., 1997; Wood and Ruppel, 2000; Diaconescu et al., 2001). Seismic chimneys or near vertical wipe-outs associated with seismic blanking are also seen in seismic data as a gas hydrate indicator, together with pockmarks or mounds on the seafloor in many areas (Ginsburg, 1998; Hyndman et al., 2001; Riedel et al., 2006). The presence of free gas below the BSR also may be inferred from the observation of enhanced reflections, which show high-acoustic impedance contrast in seismic profiles (Holbrook et al., 1996; Wood and Ruppel, 2000; Bünz et al., 2003; Hustoft et al., 2007).

The probable existence of gas hydrates in the Ulleung Basin has been suggested by several seismic indicators including BSR, the acoustic blanking zone, and seismic chimneys (Gardner et al., 1998; Lee et al., 2005; KIGAM, 2007; Ryu et al., 2009; Bahk et al., 2013a). Horozal et al. (2009) identified various seismic indicators of gas hydrate and free gas in the Ulleung Basin. Haacke et al. (2009) attempted to relate the seismic images of chimney structures in the deep-water basin to the concentration of gas hydrates. Mass-transport deposits associated with gas hydrate occurrence in the basin were documented by Riedel et al. (2012) and Scholz et al. (2012). Although the recent recovery of gas hydrate by drilling and piston coring has confirmed the gas hydrate accumulations in the central basin, the regionally distributed characteristics of the seismic indicators of gas and gas hydrates for the entire basin have been only rarely documented. In the present study we interpreted multi-channel seismic reflection and well-log data from the East Sea off Korea to identify and document the seismic characteristics related to gas hydrate and gas. We also present the occurrence types of gas hydrate associated with migration pathways for fluid-gas upwelling into the GHSZ.

2. Geologic setting

The East Sea (Fig. 1A) is a back-arc basin bounded by the eastern Asian continent in the west and the Japan islands both in the east and the south. The semi-enclosed basin consists of three deep-water basins (Japan, Yamato, and Ulleung Basins), separated by submerged continental remnants (i.e., the Korea Plateau, Oki Bank, Yamato Ridge, and Kita-Yamato Ridge). The Ulleung Basin, a bowl-shaped basin, is located in the southwestern East Sea adjacent to the eastern coast of Korea and is bounded by the steep continental slope of the Korean Peninsula to the west and by the rugged Korea Plateau to the north (Fig. 1B). The gentle slopes of the Oki Bank and the Japanese Islands form the eastern and southeastern margins of the basin, respectively. The seafloor is generally smooth and deepens progressively to the northeast; water depths range from less than 1500 m in the south to over 2300 m in the northeast where the basin joins the deeper Japan Basin through a long and narrow interplain gap between the two islands of Ulleungdo and Dokdo (Fig. 1B).

The Ulleung Basin was formed during the Late Oligocene to Early Miocene by crustal extension associated with the southward drift of the Japan Islands (Tamaki et al., 1992; Jolivet et al., 1995; Chough and Barg, 1987). At the end of the Middle Miocene, the tectonic stress regime changed from tensional to compressional (Yoon and Chough, 1995), leading to thrust faultings and foldings in the southern and western margin of the basin and to the sediment compression and consolidation that probably has been responsible for the upward flow of gas-rich fluids and hydrate formation (Ryu et al., 2009). Since this time of tectonic movement, the basin has progressively subsided until the present and has been fed with a significant quantity of siliciclastic sediments (e.g., debris-flow deposits), filling the larger part of the basin. In the Ulleung Basin, the Neogene sediments are characterized by vertically/laterally widespread deposition of mass-transport complexes, caused by margin-wide slope failures in response to back-arc closure (Lee and Suk, 1998). Mass transport deposits in the basin show a zoned distribution pattern that approximately follows the bathymetric contours: slide/slump deposits on the upper slope, debris-flow deposits on the lower slope or base-of-slope, and turbidites on the northern basin (Chough et al., 1997).

3. Data

The total of 6600 L-km of multi-channel seismic reflection data used in this study were collected by the Korea Institute of Geoscience and Mineral Resources (KIGAM) using the research vessel *Tamhae II* in 2005 for the exploration of gas hydrate resources in the Ulleung Basin, East Sea offshore of Korea (Fig. 1B). The seismic data acquisition included a 240-channel and 3-km long streamer with a 1035 in^3 air-gun array that provides a wide range of frequency up to 250 Hz (KIGAM, 2007). The receiver-group interval, and the near and far offsets are 12.5 m, 162 m, and 3149 m, respectively, yielding 60-fold coverage. The distance between shots is 25 m, resulting in a CDP spacing of 6.25 m. The data were digitally recorded with a sample rate of 1 ms and a maximum recording length of 7 s. The seismic data were processed at KIGAM (KIGAM, 2007). True amplitude was preserved during data processing, which is important scheme to clearly interpret amplitude blanking and seismic chimneys. Data processing included resampling, anti-aliasing filtering, bandpass filtering, true amplitude recovery (spherical divergence correlation), velocity analysis, normal move-out correlation, and stacking. The interpretation of the seismic data was performed using Geographix manufactured by Landmark.

The Second Ulleung Basin Gas Hydrate Expedition (UBGH2) in 2010 conducted LWD and coring at 13 sites to identify the overall distribution of gas hydrate in the Ulleung Basin (Fig. 1B; Ryu et al., 2012; Bahk et al., 2013b). The LWD phase was conducted using the Schlumberger's logging tools of the GeoVision, TeleScope, EcoScope and SonicVision. LWD log data include natural gamma, resistivity, velocity, porosity, and density.

4. Seismic characteristics of gas hydrate and associated gas

On the basis of the multi-channel seismic data, we identified six seismic signatures indicative of gas-hydrate existence in the deep-water basin filled with vertically and/or laterally stacked mass-transport complexes (Figs. 3–8). The seismic indicators include BSRs, seismic chimneys, high reflection amplitude within the GHSZ, acoustic blankings, enhanced reflection below the BSR, and seafloor expressions that are illustrated in the following. Figure 2 is a distribution map of these seismic indicators in this area.

4.1. The bottom simulating reflector (BSR)

In the Ulleung Basin, the BSR is commonly observed over much of the basin (Fig. 8) and is well imaged in the multi-channel seismic sections (Figs. 3 and 4). The BSR runs almost parallel to the seafloor and frequently cross-cuts reflectors. It also has high reflection amplitude and reversed polarity with respect to the seafloor reflection (Fig. 3C). Based on the reflection amplitude strength and continuity, we grouped the BSR into two types such as high amplitude with good continuity and low amplitude with poor continuity. The seismic sections from the southern continental slope associated with mass-transport deposits show continuous to discrete BSRs, following the topography of the corresponding seafloor. An example of a continuous and strong BSR is shown in Figure 3. However, as the water depth deepens to the north, the BSR becomes relatively weaker and less continuous than those in the southern slope (e.g., Fig. 4). The strong BSR is also overlain by localized significantly enhanced reflections (Fig. 5A and B); thus the two acoustic