Marine and Petroleum Geology 47 (2013) 214–221

Contents lists available at ScienceDirect

Marine and Petroleum Geology

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

Seismic characterization and imaging of a gas hydrate deposit in the western part of the Ulleung Basin, the East Sea (Japan Sea)

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ARTICLE INFO

Article history:
Received 28 December 2012
Received in revised form
18 May 2013
Accepted 29 May 2013
Available online 11 June 2013

Keywords:
Ulleung Basin
East Sea
Gas hydrate
Stochastic deconvolution
Full-waveform inversion

ABSTRACT

We investigated character and distribution of the gas hydrate zone in the western part of the Ulleung Basin in the East Sea (Japan Sea) from seismic data using stochastic sparse spike deconvolution, analysis of frequencies, and acoustic-elastic coupled full-waveform inversion. The presence of gas hydrates is primarily indicated by a bottom-simulating reflector (BSR) with negative polarity at approximately 240–250 ms below the seafloor. The instantaneous frequency section defines a high-frequency anomaly above the BSR underlain by a less clear low-frequency anomaly. Sparse spike deconvolution indicates that the BSR occurs horizontally along the boundary between the high- and low-frequency anomalies. Compared to well logs obtained from the seafloor through the BSR, the high-frequency anomaly, maximally 50 ms thick (ca. 45 m), appears to outline the hydrate-bearing zone. The results from full-waveform inversion appear to delineate the hydrate-bearing zone and the underlying gas-bearing zone, although their depth ranges do not coincide accurately with those inferred from well logs. The hydrate-bearing zone is characterized by an increase in both p- and s-wave velocities, while the gas-bearing zone is marked by a decrease in p-wave velocity. The very narrow free gas zone is less than 30 m thick and appears to be concentrated immediately below the gas hydrate stability zone. The hydrate-bearing zone is also defined by decreased Poisson's ratio which suggests appreciable variations of the hydrate-bearing zone in thickness.

1. Introduction

The Ulleung Basin is a sedimentary basin in the southwestern part of the East Sea (Japan Sea), lying between the eastern continental slope of the Korean Peninsula and the southwestern Japan Arc (Fig. 1). The Ulleung Basin is characterized by thick accumulation of sediments; the sediment thickness averages to about 4 km in most of the abyssal plain of the basin and maximally over 11 km in the depocenter, in the southern continental slope and shelf region (Lee et al., 2001). Various seismic indicators of the occurrences of gas hydrates were identified on multichannel seismic (MCS) data in the central and eastern parts of the Ulleung Basin (Horozal et al., 2009); they include bottom-simulating reflectors (BSRs), enhanced reflections below the BSR, and seismic chimneys. The BSR in the plain area occurs from about 200 ms to less than 230 ms below the seafloor on MCS profiles. Locally, the BSR is characterized by high reflection coefficients 1.5–1.7 times that of the seafloor reflection (Kim et al., 2010). The Ulleung Basin is also characterized by high heat flow (Kim et al., 1998), high total organic carbon, and high residual hydrocarbon gas (Ryu et al., 2009). Recent drilling and well logging at many sites in the Ulleung Basin confirmed that gas hydrates occur in massive, fracture/vein-filling, and pore-filling form (Ryu et al., 2012). These features strongly suggest conditions favorable for the formation of natural gas hydrates in the Ulleung Basin.

The Korea Institute of Geoscience and Mineral Resources (KIGAM) acquired MCS data in the western part of the Ulleung Basin plain near the base of the continental slope of the Korean Peninsula (Fig. 1). The MCS profile reveals a flat, strong BSR that is interpreted to mark the base of the gas hydrate stability zone. However, the BSR provides little information about the distribution of gas hydrates and free gas underneath. The objectives of this study are to (1) analyze the seismic character of the reflections associated with the presence of gas hydrates and (2) compute p-

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http://dx.doi.org/10.1016/j.marpetgeo.2013.05.019

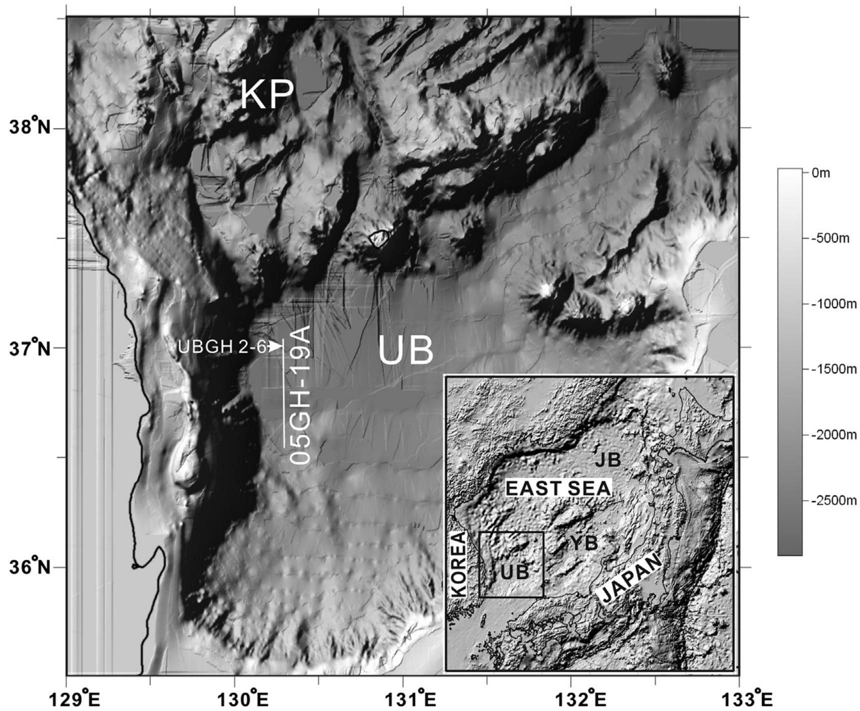

Figure 1. Shaded-relief bathymetry and location of seismic profile 05GH-19A (shown in Fig. 2) in the Ulleung Basin, East Sea (Japan Sea). UB = Ulleung Basin, KP = Korea Plateau. The location of the UBGH 2–6 well is indicated. Inset shows the physiography of the East Sea (JB and YB = Japan and Yamato Basins, respectively).

and s-wave velocities, density, and Poisson's ratio from seismic data using full-waveform inversion to estimate the distribution of the gas hydrate zone and the underlying free gas zone.

2. Geologic setting

The Ulleung Basin, located in the southwestern part of the East Sea (Japan Sea), is a back-arc basin between the Korean Peninsula and the southwestern Japan Arc (Fig. 1). The west side of the basin is bounded by the narrow and steep continental slope of the Korean Peninsula, and the north side by the Korea Plateau with numerous ridges and troughs. The relatively broad and gentle continental slope of the southwestern Japan Arc constitutes the eastern and southern boundaries of the basin. The seafloor in the plain area is deeper than 2000 m and fairly smooth, deepening gently to the northeast. The formation of the Ulleung Basin resulted from continental rifting to back-arc spreading in response to the subduction of the Pacific plate beneath the Japan Arc from late Oligocene to middle Miocene times (Kim et al., 2007). The Ulleung Basin is distinguished from other major sedimentary basins in the entire East Sea such as the Japan and Yamato Basins in that the sediment thickness of over 4 km in most of the Ulleung Basin plain is twice that of the Japan and Yamato Basins (Lee et al., 2001). The thick sediments in the Ulleung Basin are dominantly mass-transport deposits (e.g., slides and debris flows) accumulated from middle to late Miocene times that bypassed the basin margin and directly reached the base of the slope region and the abyssal plain (Lee et al., 2001). Thick mass transport deposits suggest that the sedimentation in the Ulleung Basin is highly dependent on tectonic activity along its peripheral regions. In contrast, turbidite and hemipelagic sedimentation has prevailed in the Japan and Yamato Basins (Tamaki et al., 1992). Since the latest late Miocene, mass-transport deposits in the Ulleung Basin have retreated rapidly in an updip direction and distal turbidite and hemipelagic sedimentation have prevailed in the central and northern plain areas (Lee et al., 2001). The crust underlying the thick sediment cover in the Ulleung Basin averages to 10 km in thickness but it is oceanic in character; it consists of layers 2B, 2C, and 3 with velocities typical of oceanic crust (Kim et al., 1998). The thicker than normal oceanic crust in the Ulleung Basin is interpreted to have been created in a region of hotter than normal mantle temperature (Kim et al., 1998).

The seismic indicators of gas hydrates and associated gas in the Ulleung Basin such as a BSR occur in the latest Neogene-Quaternary sequences consisting dominantly of turbidite/hemipelagic sediments and debris-flow deposits (Yi et al., 2011). Heat flow in the basin plain derived from the depths of the BSR and from direct measurements, ranging from about 90 to over 115 mW/m^2, is high for the age of the basin (Horozal et al., 2009). The high heat flow suggests that the Ulleung Basin has excess heat which may facilitate the emplacement of gas hydrates at relatively shallow depths.

3. Data and methods

The MCS data used in this study were acquired on R/V Tamhae II in 2005. A 1035 in^3 air-gun array generated seismic pulses. Data acquisition was conducted along a 51 km long north-south oriented line on the Ulleung Basin plain that is parallel and close to the base of the continental slope of the Korean Peninsula (Fig. 1). A 240-channel streamer (3000-m long) was used as a receiver. Shot and group spacings were 25 and 12.5 m, respectively, providing 60-fold coverage. The data processing sequence followed standard procedures including velocity analysis, stack, multiple suppression after stack, and conversion the instantaneous frequency section.

BSRs in marine sediments are frequently embedded with densely spaced reflections from layer boundaries. It thus is required to determine amplitude and polarity of individual reflections in seismic data. Sparse spike deconvolution is an effective method to do this. In this study, we applied the iterated window maximization (IWM) method by Kaaresen (1997) to discriminate reflections associated with the presence of gas hydrates by recovering sparse