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Distribution and origin of seismic chimneys associated with gas hydrate using 2D multi-channel seismic reflection and well log data in the Ulleung Basin, East Sea

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Analysis of multi-channel seismic reflection and well-log data from the Ulleung Basin, East Sea reveals that two distinct types of seismic chimneys have been identified in the basin, based on their geometries, seismic reflection patterns, well log response, and lithology. Type-I is a mound-like feature with a transparent or chaotic reflection pattern. Well log interpretation and lithology of this type indicate that Type-I consists of mobilized homogeneous mud including fracture-filling gas hydrate. This type is mainly located on the structural highs, and is mostly restricted to the Pliocene sedimentary succession. In contrast, Type-II is a pipe-like feature with vertically stacked distorted-reflectors. Based on well log data and lithology, Type-II filled with fracture-filling gas hydrate without breaking up primary sedimentary structure. This type appears along the deep-seated fault, and mainly developed within the Quaternary deposit. Our primary conclusion is that Type-I resulted from the subsurface sedimentary remobilization in response to regional uplift in the Pliocene whereas Type-II resulted from the focused vertical fluid flow through fractures triggered by reactivation of deep-seated fault during the Quaternary.

1. Introduction

A seismic chimney is an anomalous imprint of the seismic reflection profile, seen as pipe-like or mound-like columnar zone. In marine sediments, seismic chimneys are widespread and are interpreted as migration pathways of fluids (Heggland, 1997; Berndt, 2005; Løseth et al., 2009; Hustoft et al., 2010). Recent gas hydrate studies focus on seismic chimneys because these structures are strongly associated with gas hydrate generation (Holbrook et al., 2002; Riedel et al., 2006; Haacke et al., 2009). Gas hydrate is an ice-like solid substrate in which guest molecules such as methane or other light hydrocarbons are physically trapped in a cage of water molecules, under high pressure and low temperature (Kvenvolden, 1993). Under these conditions the occurrence and distribution of gas hydrates depend upon the amount of methane present, in excess of the solubility of limit of the pore water (Xu and Ruppel, 1999). Therefore, given that fluid flow can move gas sufficient to form gas hydrate into the gas hydrate stability zone, the fluid migration through seismic chimneys is an important process in the study of gas hydrate.

Seismic chimneys are frequently reported in the data from hydrocarbon explorations or scientific surveys of various depositional systems and tectonic settings (Heggland, 1997; Cartwright et al., 2007; Gay et al., 2007; Løseth et al., 2009). In general, the seismic chimneys appear in impermeable, fine-grain sediments as circular pipe-like features or mound-like features (Hansen et al., 2005; Cartwright et al., 2007; Gay et al., 2007; Løseth et al., 2009; Hustoft et al., 2010). Moreover, these seismic chimney structures have been observed over polygonal fault systems (Gay et al., 2007; Hustoft et al., 2007), diapir (Taylor et al., 2000), and deep-seated faults (Van Rensbergen et al., 2007). These findings suggest that depositional systems or structural events could control the occurrence and spatial distribution of seismic chimneys. Furthermore, based on their forming mechanism and seismic interpretations, previous researchers have classified seismic chimneys into three groups: (1) focused fluid flow through the fractures, (2) subsurface sediment remobilization, and (3) diagenesis of sediment or rock (Cartwright et al., 2007; Løseth et al., 2009).

The Ulleung Basin is well known area for the existence of gas hydrate. It is indicated by several seismic indicators including

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bottom simulating reflectors (BSR), acoustic blanking, and seismic chimneys (Yoo et al., 2013). In recent, seismic chimney has been considered as end-member indicating gas hydrate reservoir, because of the high concentration of gas hydrate (Haacke et al., 2009). Previous studies for the Ulleung Basin reported the presence of many seismic chimneys (Horozal et al., 2009; Yoo et al., 2013). Moreover, two gas hydrate drilling expeditions (UBGH1 and UBGH2) that drilled into a total of six seismic chimney sites revealed that the chimney structure in the Ulleung Basin consists of highly saturated gas hydrate (Chun et al., 2011; Kim et al., 2011; Ryu et al., 2012).

Although gas hydrates have been present within seismic chimney structures in the Ulleung Basin, geologic constraints and origins of seismic chimneys in the entire Ulleung Basin are still unclear. Thus, in the current study, we interpret multi-channel seismic data and well log data, and present the geologic constraints related to the occurrence and origin of seismic chimney structures. Further, we present a possible model for development of seismic chimney in the Ulleung Basin.

2. Geologic setting

The study area is located in the Ulleung Basin, East Sea, off the east coast of the Korean peninsula (Fig. 1). The East Sea is a semi-closed back-arc basin between the Eurasian continent and the Japan Arc. There are three deep basins in the East Sea (i.e., the Ulleung, the Yamato, and the Japan Basins), based on topographic highs including the Korea Plateau, the Yamato Ridge, and the Oki Bank (Fig. 1). The Ulleung Basin is bounded by steep slopes to the west and by relatively gentle shelves to the south and east (Fig. 1). The basin floor gradually deepens to the north and northeast from 1000 m to more than 2000 m. The basin is connected northward to the Japan Basin through the Korea Gap, a long narrow inter-plain gap (Fig. 1).

The Ulleung Basin formed during the Late Oligocene to Early Miocene as a crustal extension associated with drift of the Japanese islands (Chough and Barg, 1987; Tamaki et al., 1992). Since the middle Miocene, the tectonic regime changed from extensional to compressional (Chough and Barg, 1987; Yoon and Chough, 1995; Lee et al., 2001, 2011; Yoon et al., 2014). The change of tectonic regime led to thrust fault and folding structures on the southwestern and western margins of the basin and to compression of sediments (Yoon and Chough, 1995; Lee et al., 2001, 2011; Yoon et al., 2014). The tectonically compressed structural highs on the shelf margin appear to have fed a significant amount of sediment into the deep-sea area until the Holocene (Lee and Suk, 1998; Lee et al., 2001). Neogene sediments in the Ulleung Basin are characterized by mass transport deposits mostly transported by debris flows. These were possibly associated with the slope failures responsible for closing of the basin (Lee and Suk, 1998). These mass transport deposits were stacked vertically and laterally, and gradually changed basinward from slide/slump and debris flow deposits to turbidite deposits (Chough et al., 1997).

3. Data set

For this research, we used 2D multi-channel reflection seismic data (6690 L-km) and Logging while drilling (LWD) data of three seismic chimney sites. The 2D seismic data from the Ulleung Basin were acquired in 2005 as part of the Korea national gas hydrate program conducted by the research vessel Tamhae-II. The seismic source was a 1035-in^3 (2000 psi) six-air-gun array. The streamer had 240 channels (3000-m long). The shot and group intervals were 25 m and 12.5 m. Average line interval design was as approximately 3 km west to east and 5 km south to north. The data were recorded at a sample rate of 1 ms and a maximum recording length of 7 s. The interpretation of the seismic data was performed using the commercial software, Kingdom (HIS) and Petrel (Schlumberger).

The LWD log data were acquired in 2007 and 2010 during the UBGH1 and UBGH2 drilling expeditions. They were gathered using Schlumberger logging tools (i.e., Geovision, SonicVision, PowerPulse, and AdnVision). In this study, we used density, natural gamma, P-wave and resistivity log data from the sites UBGH1-9, UBGH1-10, and UBGH2-2_2.

4. Result

4.1. Seismic stratigraphy and structural features

4.1.1. Seismic stratigraphy

From the seismic interpretation of multi-channel 2D seismic profiles, the present study identified three seismic units bounded by four regional unconformities. Each unit is referred to as Unit-I, Unit-II and Unit-III from oldest to youngest, and the boundaries are referred to as H-1, H-2, H-3 and H-4, respectively (Fig. 2). This stratigraphic interpretation is consistent with the chronostratigraphy suggested by Lee et al. (2001) and Yi et al. (2012).

Unit-I, characterized by hummocky and chaotic seismic facies, occurs at the lowermost part of the sedimentary succession. This unit pinches out to the western slope and thickens toward the south and east. In particular, Unit-I shows relatively thick and uniform chaotic bodies on the central part of the basin floor (Fig. 2). Based on these seismic characteristics and stratigraphic level, Unit-I is correlated with sedimentary successions in the late Miocene defined by Lee et al. (2001). The lower boundary (H-1) is correlated to Middle Late Miocene, and the upper boundary (H-2) to Latest Late Miocene. The upper boundary is highly disturbed by either seismic chimneys or small discontinuities. These anomalous features confuse the boundary between Unit-I and Unit-II.

Unit-II, characterized by well-stratified and parallel reflection patterns with high reflection amplitude, is located at the middle of the sedimentary succession. This unit thins basinward and has a wedge-shaped external form. On the basin floor, lenticular chaotic bodies were intercalated in primarily stratified reflectors (Fig. 2). Unit-II is bounded by H-3 and H-2. The upper boundary of Unit-I (H-3) is correlated with the Plio-Pleistocene boundary defined by Yi et al. (2012).

Unit-III, characterized by well-stratified and parallel reflections with moderate to low reflection amplitude, occupies the upper most part. This unit shows an external form similar to Unit-II. However, the reflections of this unit gently drape the underlying reflections with high continuity (Fig. 2). In the central part of the basin floor, this unit fills the underlying topographic low regions. Unit-III is bounded by the seafloor and the Plio-Pleistocene boundary (H-3) and it is consequently correlated with the Quaternary sedimentary succession.

4.1.2. Structural features

Previous studies revealed that the Ulleung Basin has been under a closing stage due to the changing of tectonic regime, since the middle Miocene (Chough and Barg, 1987; Yoon and Chough, 1995; Lee et al., 2001, 2011; Yoon et al., 2014). Modeling of the basin evolution by Lee et al. (2001) indicated that the regional uplift associated with the compressional tectonic regime was most intensive in from the Middle Miocene to the Early Late Miocene, and rapidly declined in the Quaternary. Fig. 3 shows the time-structure map of H-1 correlated to the Early Late Miocene. The