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Plio–Quaternary seismic stratigraphy and depositional history of the Ulleung Basin, East Sea: Association with debris-flow activity

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ABSTRACT

We analyzed multi-channel seismic reflection profiles to decipher the Plio–Quaternary stratigraphic architecture and resolve the depositional history of the Ulleung Basin. A detailed seismic stratigraphic interpretation revealed nine seismic units (Units 1–9) separated by unit boundaries in the Plio–Quaternary deposits of the Ulleung Basin. Unit 1 (Pliocene) is dominated by debris-flow deposits (DFDs) throughout the basin. Units 2–9 (Quaternary) are characterized by stacked DFDs interbedded with thin hemipelagic sediments along the southern slope, whereas the northern basin floor is filled with hemipelagic and pelagic sediments. The areal distribution and dimensional characteristics of the DFDs indicate that sedimentation in the Ulleung Basin has been controlled by a combination of tectonic movement, eustatic changes in sea level, and gas hydrates dissolution and dissociation. During the Pliocene (Unit 1), sedimentation was mainly controlled by tectonic movements, causing margin-wide slope failures under the compressional regime. Large sediment deposits were supplied to the basin through mass-transport processes, resulting in an abundance of DFDs throughout the basin. During the Quaternary (Units 2–9), compressive stress decreased sharply, causing the DFDs to retreat landward. At that time, sedimentation was mainly influenced by eustatic changes in sea level and gas hydrates dissolution and dissociation. As the sea fell to the lowstand, slope failures were activated by the generation of high pore-water overpressure and the generation of weak layers in the sediments, resulting in stacked DFDs. However, as the sea level rose to the highstand, sediment was primarily deposited via hemipelagic and pelagic processes due to increased hydrostatic pressure and slope stability.

1. Introduction

Seismic stratigraphy, as defined by the Exxon Production Research Group in the 1970s, is a general methodology for reconstructing stratigraphic frameworks using seismic data (Vail, 1987; Posamentier et al., 1988; Van Wagoner et al., 1988). In the late 1980s, seismic stratigraphy evolved into sequence stratigraphy with the incorporation of outcrop, well, and seismic data (Posamentier et al., 1988; Posamentier and Vail, 1988). Because sequence stratigraphy provides a framework for accurately predicting depositional environments and depositional history, it has been applied to stratigraphic and structural analyses, such as those conducted during early deep-ocean oil exploration. Moreover, it is a useful method for describing large-scale sedimentary sequences in terms of long-term changes in sea level (Haq, 1991; Posamentier et al., 1992). In the 1990s, sequence stratigraphy was useful for interpreting higher-frequency cyclothemic sequences influenced by glacioeustatic sea level cycles (Mitchum and Van Wagoner, 1991). Therefore, sequence stratigraphy is commonly used to study Quaternary depositional sequences using high-resolution seismic reflection profiles (Tesson et al., 1990; Aksu et al., 1992;

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Ercilla et al., 1994; Hiscott and Aksu, 1996; Tesson et al., 2000; Garziglia et al., 2008).

The Ulleung Basin is a back-arc basin located in the southwestern region of the East Sea (Fig. 1A). Since the 1970s, studies have applied sequence stratigraphy to understand the stratigraphic framework, depositional history, and depositional environment of the Ulleung Basin from seismic data (Choi, 1995; Park, 1998; Shin, 2000; Yoon et al., 2003; KIGAM, 2006). Park (1998) and Yoon et al. (2003) constructed sequence stratigraphic frameworks associated with eustatic changes in sea level and tectonic movement in the southwestern Ulleung Basin. In addition, Shin (2000) and KIGAM (2006) described four mega-sequences in the southwestern margin of the basin based on its tectonic evolution history: syn-rift megasequence, post-rift megasequence, syn-compressional megasequence, and post-compressional megasequence. However, most stratigraphic studies in the past 30 years have focused on the southern shelf of the Ulleung Basin. There has been poor understanding for development of sedimentary sequences in the slope and basin floor of the Ulleung Basin. In the late 1990s, the application of seismic stratigraphy began in earnest in the deep Ulleung Basin (Chough and Lee, 1992; Lee and Suk, 1998; Lee et al., 2001). For example, Lee and Suk (1998) documented the seismic stratigraphic expression of the most recent Neogene–Quaternary sedimentary section by interpreting seismic reflection data acquired from the deep Ulleung Basin. In addition, Lee et al. (2001) described five deep basin seismic units and presented a stratigraphic evolution model of the deep Ulleung Basin. However, there has been great difficulty in understanding the geology and stratigraphy of the deep Ulleung Basin in any detail due to the paucity of seismic data.

The shallow sedimentary sequence of the Ulleung Basin is predominantly composed of basin-wide, mass-transport deposits (MTDs) that follow a contour-parallel trend (Chough et al., 1997; Lee et al., 1999, 2002; Horozal et al., 2016). Chough et al. (1997) classified 11 discrete echo types using high-resolution (chirp, 2–7 kHz) reflection profiles in the uppermost sedimentary sequence of the Ulleung Basin. They revealed a zonal distribution of MTDs, slide and slump deposits on the upper to middle slope, debris-flow deposits (DFDs) at the bases of slopes, and turbidites on the basin floor (Fig. 1B). Meanwhile, Lee et al. (1999) investigated the downslope evolution of the rheological behavior of a single debris-flow from detailed spatial distribution and geometry of the large-scale debris lobes using high-resolution seismic data (chirp, 2–7 kHz). However, most of these studies examined the shallow (~50–70 m below the seafloor) sedimentary sequence using high-resolution reflection profiles, resulting in a poor understanding of the detailed geometric characteristics of the MTDs that dominate the Plio–Quaternary sequence of the Ulleung Basin. Recently, Horozal et al. (2016) analyzed multiple MTDs within the Plio–Quaternary interval in the Ulleung Basin. Although they provided meaningful results for a geometric characteristics and spatial distribution pattern of MTDs, the study was only focused on MTD source and triggering factors for MTDs.

In this study, we deciphered the Plio–Quaternary seismic stratigraphy framework from the slope and basin floor of the Ulleung Basin by analyzing multi-channel, two-dimensional seismic data. Moreover, we illustrated the large-scale nature of the Plio–Quaternary DFDs, including their seismic characteristics, distribution, and dimensions. Finally, we determined the Plio–Quaternary depositional history of the Ulleung Basin, emphasizing the role of tectonic movement, eustatic changes in sea level, and gas hydrates dissolution and dissociation controlling sedimentation.

2. Tectonic and geological setting

The East Sea is a semi-closed back-arc basin off the east coast of the Korean peninsula (Fig. 1A). It is bordered by the Eurasian continent to the west and the islands of Japan to the south. It consists of three deep basins (Japan, Yamato, and Ulleung Basins) separated by submarine topographic highs, which include the Korea Plateau, Oki Bank, and Yamato Ridge (Fig. 1A). The East Sea is a marginal sea that opened in the Early Oligocene due to the continental rifting of the proto-Japan island arc in the northeastern Japan Basin (Tamaki et al., 1992; Tamaki, 1995). In the Late Oligocene, crustal stretching evolved into seafloor spreading in the Japan Basin (Jolivet and Tamaki, 1992). While seafloor spreading occurred in the Japan Basin, the southern East Sea experienced crustal extension, accompanied by drifting and rotation of the Japanese archipelago, resulting in the formation of the Ulleung and Yamato Basins (Tamaki et al., 1992). In the Middle Miocene, tectonic inversion took place due to the northward collision of the Izu-Bonin Arc against Honshu Island, resulting in the formation of compressional structures (e.g., thrusts, anticlines, and folding) in the southern margin of the Ulleung Basin (Yoon and Chough, 1995; Lee et al., 2011).

The Ulleung Basin is a bowl-shaped basin located in the southwestern East Sea (Fig. 1B). The basin is bordered by the steep slopes of the Korean Peninsula and Korea Plateau to the west and north and by the relatively gentle shelves of the Japan Arc and Oki Bank to the south and east (Fig. 1B). The basin gradually deepens northeastward and the basin floor reaches as low as 2000–2300 m below sea level where the basin connects to the Japan Basin via the Ulleung Interplain Gap between Ulleung and Dok Islands. The Ulleung Basin formed from the Late Oligocene to the Early Miocene via crustal extension associated with a southward drift of the Japanese Arc (Tamaki et al., 1992; Yoon and Chough, 1995). In the Middle to Late Miocene, the tectonic stress regime changed from tensional to compressional, leading to back-arc closure and crustal shortening (Yoon and Chough, 1995; Lee et al., 2011; Yoon et al., 2014). This tectonic inversion resulted in various compressional deformations, including thrusts, folding, faults, and anticlines in the southern Ulleung Basin (Ingle, 1992; Lee et al., 2011; Yoon et al., 2014). Under the influence of tectonic movement, a substantial volume of sediment was supplied to the Ulleung Basin from the Miocene to the Holocene (Lee and Suk, 1998; Lee et al., 2001). The sedimentary succession of the Basin is predominantly composed of basin-wide MTDs originating from slope failures along its southern and western margins (Lee and Suk, 1998; Lee et al., 2001; Horozal et al., 2016). These MTDs are stacked vertically and laterally, and gradually change basinward from slide/slump deposits to DFDs to turbidites (Fig. 1B; Chough et al., 1997).

3. Datasets and methods

The datasets used in this study include 8775 km of multichannel seismic data acquired by the Korea Institute of Geoscience and Mineral Resources (KIGAM) using the research vessel *TAMHAE 2* in 2001 and 2005, referred to as the KIGAM 2001 and KIGAM 2005 data, respectively (Fig. 2).

The KIGAM 2001 data comprise 2085 km of stacked seismic profiles (Fig. 2). An 80-channel (1000 m long) streamer recorded shots from a six-airgun, one-source array at hydrophone group intervals and shot spacing of 12.5 m and 25 m, respectively. Data processing at the KIGAM included geometry definition and CMP sorting, first minimum phase bandpass filtering, signature deconvolution, second minimum phase bandpass filtering, normal moveout, true amplitude recovery, semblance velocity analysis, and full-offset range stacking.

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