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Late Quaternary Stratigraphy and its Depositional History in the Inner Shelf off the Southern Coast, Korea

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한국 남해 내 대륙붕 후 제4기 층서 및 퇴적역사

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Abstract : Analysis of high-resolution seismic profiles acquired from the inner shelf off the southern coast of Korea reveals that the inner shelf sequence can be divided into three stratigraphic units formed after the Last Glacial Maximum (LGM). Unit I is characterized by complex seismic facies including semi-transparent, stratified, and hummocky reflections on seismic records. It consists of sandy mud or muddy sand, deposited under estuarine environment during the post-glacial transgression. Unit II acoustically shows semi-transparent or hummocky reflections and consists of sand with gravels and shell debris, produced by shoreface erosion during the transgression. Unit III is characterized by transparent or semi-transparent seismic facies and consists of mud originated from the Nakdong and Seomjin rivers during recent highstand of sea level. Unit III is confined to the inner shelf with an extenal form of stratal wedge.

Keywords : Late Quaternary, Stratigraphy, Sedimentation, South Sea

요 약 : 한국 남해 내대륙붕에서 취득된 고해상 탄성파 탐사 자료의 분석에 의하면 연구해역 내 대륙붕 퇴적층은 지난 마지막 빙하기 이후 형성된 3개의 층서단위로 구분된다. 퇴적단위 I은 탄성파 단면상에서 반투명 음향상, 층리 음향상, 허모키 음향상 특징을 가진다. 이러한 퇴적단위 I은 후빙기 해침동안 하구역 환경에서 퇴적된 사질니 혹은 니질사 퇴적물로 구성된다. 퇴적단위 II는 역과 패각을 포함하는 사질퇴적물로 구성되며 후빙기 해침동안 연안침식에 의해 형성되었다. 퇴적단위 III은 투명 혹은 반투명 음향상 특징을 가지며, 현세 고해수면 조건하에서 퇴적된 낙동강 및 섬진강 기원의 니질 퇴적물로 구성된다. 본 퇴적단위는 내대륙붕에 제한적으로 분포하며 외해를 향하면서 층후가 감소하는 쐐기 형태로 발달한다.

주요어 : 후 제4기, 층서, 퇴적작용, 남해

Introduction

The sea-level rise following the Last Glacial Maximum (LGM) was one of the most important events of the present-day geological history on continental shelves (Demarest and Kraft, 1987; Trincardi *et al.*, 1994; Tortora, 1996). As the shelf was flooded, coastal environments progressively migrated landward, producing various sedimentary bodies over a wide area of the shelf. These sedimentary units are well recorded on the seafloor and testify the complex interplay between depositional and erosional processes during the transgression. Such shelf deposits associated with the sea-level changes are widely interpreted within the framework of sequence-stratigraphic concepts (e.g. Vail, 1987; Posamentier *et al.*, 1988), using high-resolution seismic profiles and sediment data (Boyd *et al.*, 1989; Ercilla *et al.*, 1994; Saito, 1994; Trincardi *et al.*, 1994; Morton and Suter, 1996; Tesson *et al.*, 2000; Yoo and Park, 2000).

The South Sea serves as the major depocenter of terri-

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genous sediments derived from the Nakdong and Seomjin rivers during the late Quaternary (e.g., Park and Choi, 1986; Park and Yoo, 1988; 1992; Park *et al.*, 1999; 2003). Various investigations were carried out on the late Quaternary deposits in the South Sea using high-resolution seismic reflection profiles and sediment data (Suk, 1989; Min, 1994; Park and Yoo, 1992; Yoo *et al.*, 1996; 2003; Yoo and Park, 1997; 2000; Lee and Chung, 2000). The results showed that sedimentation in this area is generally controlled by the sea-level change associated with sediment supply. Especially, during the Holocene transgression, coastal environment progressively migrated landward accompanied by erosional and depositional processes. As a result, various sedimentary units may have been created and left in the modern South Sea shelf (Park and Yoo, 1992; Yoo *et al.*, 1996; Yoo and Park, 2000). Especially, the inner shelf of the South Sea is an area with thick accumulations of late Quaternary sediments since the Holocene transgression (Park *et al.*, 2000). The present study focuses on the inner shelf area off the southern coast of Korea (Fig. 1). In this paper, we describe acoustic characters and geometries of the inner shelf deposits using high-resolution seismic profiles and discuss the depositional history in response to sea-level rise during the late Quaternary.

Description of Study Area

The South Sea is fringed on the north by numerous islands and embayments forming typical ria-type coast (Fig. 1). It is wider toward the southwest, whereas it becomes narrower toward the northeast. The bathymetric contours generally run in the NE-SW direction, showing a gradual deepening to the southeast. The tidal currents play an important role in the transport and dispersal of sediments in the nearshore. They flow west- to southwestward during flood and east- to northeastward during ebb with a maximum velocity of 190 cm/s (Korea Hydrograhic Office, 1982). Superimposed on these tidal currents, an east to northeastward coastal current is also reported in the inner shelf (Kim *et al.*, 1986). In the offshore, however, the hydrodynamic condition is dominated by the northeastward-flowing Tsushima Warm Current, which is a branch of the Kuroshio Warm Current. The speed of the Tsushima Current is about 30 - 90 cm/sec (Korea Hydrographic Office, 1982); it is strongest in summer and weakest in winter. The surface flow speed in this region is about 30 - 90 cm/s, being strongest in summer and weakest in winter (Korea Hydrographic Office, 1982). In contrast, it is reported that a

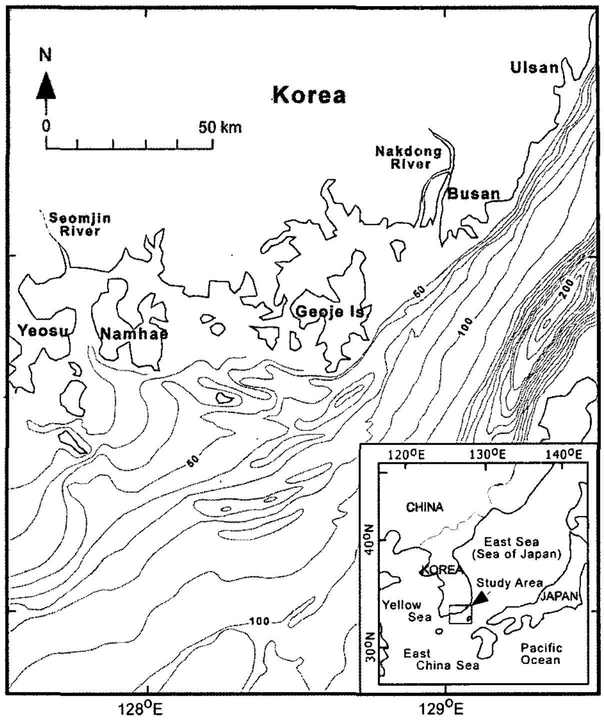

Fig. 1. Location and bathymetric map of the study area. Contour interval is 10 m.

cold water mass flows southward below the Tsushima Current along the southeastern coast of the Korean Peninsula. As this water mass approaches the trough region, the flow speed slows down and becomes very weak.

Two major sediment dispersal systems, the Nakdong and Seomjin rivers, deliver sediments and fresh water to the South Sea shelf. The Nakdong River, which is the second largest fluvial system in Korea, is a major source of terrigenous sediment to the Korea Strait; its drainage basin occupies an area of 23,656 Km^2 (Kim *et al.*, 1986). This river discharges annually about 6.3×10^{10} tons of sediments into the Korea Strait, which are mainly concentrated during the rainy season from July to August. During summer floods, the discharged water extends about 20 km offshore, forming the turbid river plumes, and their dispersal pattern appears to be parallel to the coast influenced by coastal currents (Kim *et al.*, 1986).

Material and Methods

High-resolution (air-gun) seismic reflection profiles used in this study were acquired using a PC-based system of KIGAM during 2002 - 2003 (Fig. 2; Lee *et al.*, 1996). The layout of the survey is shown in Fig. 3. The energy source was a 30^3 in air gun and the receiver was a 40 m long 8 channel

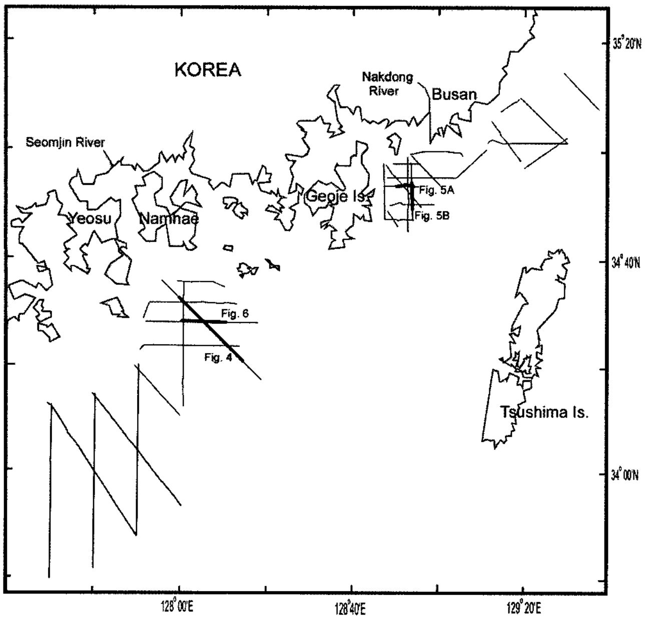

Fig. 2. Map showing the tracklines of 3.5 kHz and air-gun seismic profiles. Heavy lines denote the selected profiles shown in Figs. 4 - 6.

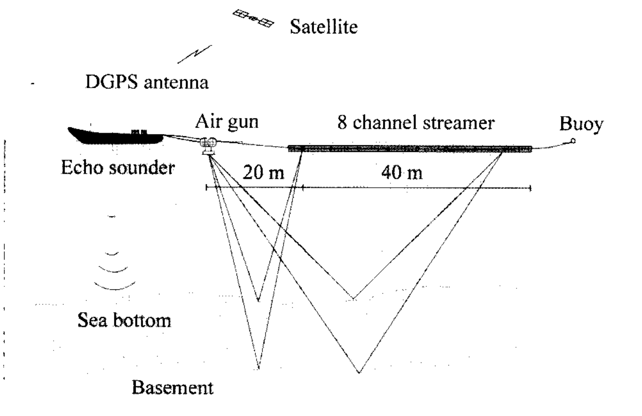

Fig. 3. Layout of 8-channel high-resolution seismic survey. The seismic source was an air gun and the receiver was a 8-channel streamer cable with a group interval of 5 m.

streamer cable with a group interval of 5 m. The offset distance between the source and the first channel was 20 m. The shooting interval was about 5 m, providing 4 folds. The data were digitally recorded with a sample interval of 0.2 ms and a record length of 2 s using KDAPS (KIGAM data acquisition and processing system) PC-based system where an A/D converter and an analog filter board were installed. Shipboard navigation was controlled using a Global Positioning System (GPS). Sheep speed was maintained at about 5 - 6 knots. To improve data quality, the data were processed by KDAPS system. The processing flow involved gain recovery, deconvolution, filtering, normal moveout and CMP (common mid-point) gathering. After data processing, seismic data which have a trace spacing of 2.5 m and 1 fold were plotted with the variable area method.

Results

On the basis of air-gun seismic profiles, the inner shelf deposits in the study area can be divided into three sedimentary units (units I, II, and III, from bottom to top Figs. 4 - 6). The basal boundary (R1) of the inner shelf deposit is characterized by an irregular, erosional unconformity (Figs. 4 and 6). Three units are separated by two bounding surfaces (R2 and R3 from the bottom upwards), which are relatively continuous reflectors with strong reflections. The boundary R2 separating unit I from the overlying unit II is defined by an erosional truncation cutting the internal reflections of the underlying unit, but it is smooth and flat. In contrast, R3 separating unit II from the overlying unit III is well defined by a non-erosional surface with continuous reflectors on seismic profiles.

Unit I directly overlying older sedimentary strata is found on the inner shelf near the eastern part of Geoje Island and off the Seomjin River. It is characterized by a complex seismic facies including semi-transparent, stratified and hummocky reflections (Figs. 4 and 5). Locally, its upper part contains irregular subbottom reflectors and obliquely inclined bedding (Fig. 6). Unit I also shows small-scale progradation or coastal onlap patterns with weakly stratified reflections. In some areas, unit I contains channel-like features, extending from north to south (Yoo and Park, 2000). These channel-like features are deeply entrenched into the underlying Pleistocene sedimentary strata. It is about 10 m deep and 1 - 1.5 km wide. Channel-fill deposits of unit I are characterized by divergent and/or prograding reflection patterns with variable amplitude. Unit I also contains the acoustically turbid layer, which masks the underlying internal structures (Fig. 5). Unit I has variable thickness and depocenter up to 20 m thick is located on the eastern part of Geoje Island where the older sedimentary strata is deeply depressed. It however is about 5 - 10 m thick. Unit I is overlain by unit II.

Unit II above the unit I is acoustically defined by semi-transparent reflections and locally contains hummocky reflection patterns with weakly stratified reflectors (Figs. 4 and 6). It is less than a few meters thick. Externally, it is shaped in a sheet type with a slight increase in thickness landward. Unit II

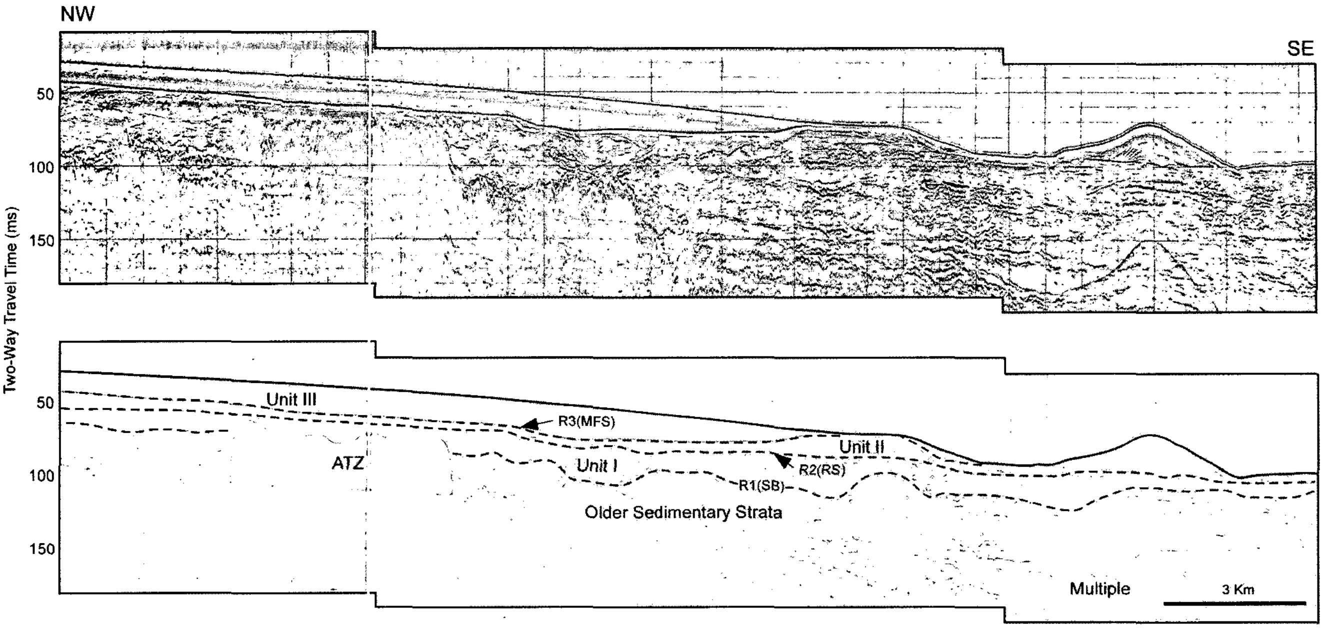

Fig. 4. High-resolution (air-gun) seismic profile collected from the inner shelf off the Seomjin River (for location, see Fig. 2), showing three sedimentary units overlying the older sedimentary strata. MFS, maximum flooding surface; RS, ravinement surface; SB, sequence boundary; ATZ, acoustically turbid zone.

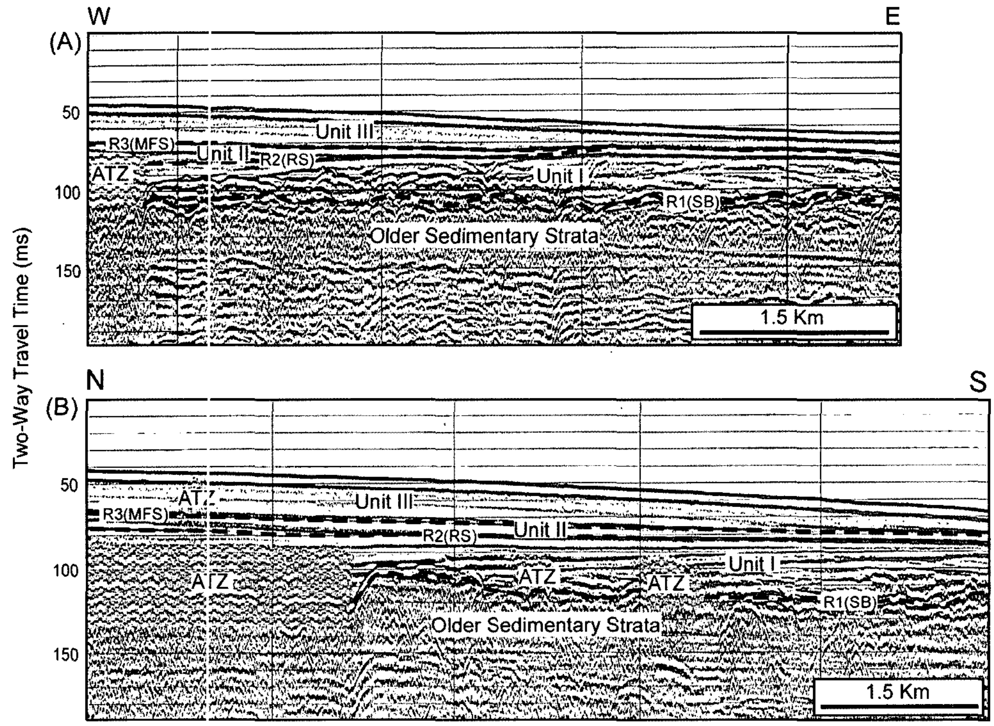

Fig. 5. High-resolution (air-gun) seismic profiles collected from the inner shelf area east of Geoje Island (for location, see Fig. 2), showing three sedimentary units overlying the older sedimentary strata. MFS, maximum flooding surface; RS, ravinement surface; SB, sequence boundary; ATZ, acoustically turbid zone.

is completely covered by unit III. Toward the mid-shelf, it however was exposed on the seafloor (Fig. 4).

Unit III, the uppermost unit in this area, forms a stratal wedge that thins seaward. It is acoustically defined by well-stratified to transparent echo characters (Fig. 5). In the landward portion near the river mouth, it shows continuous,

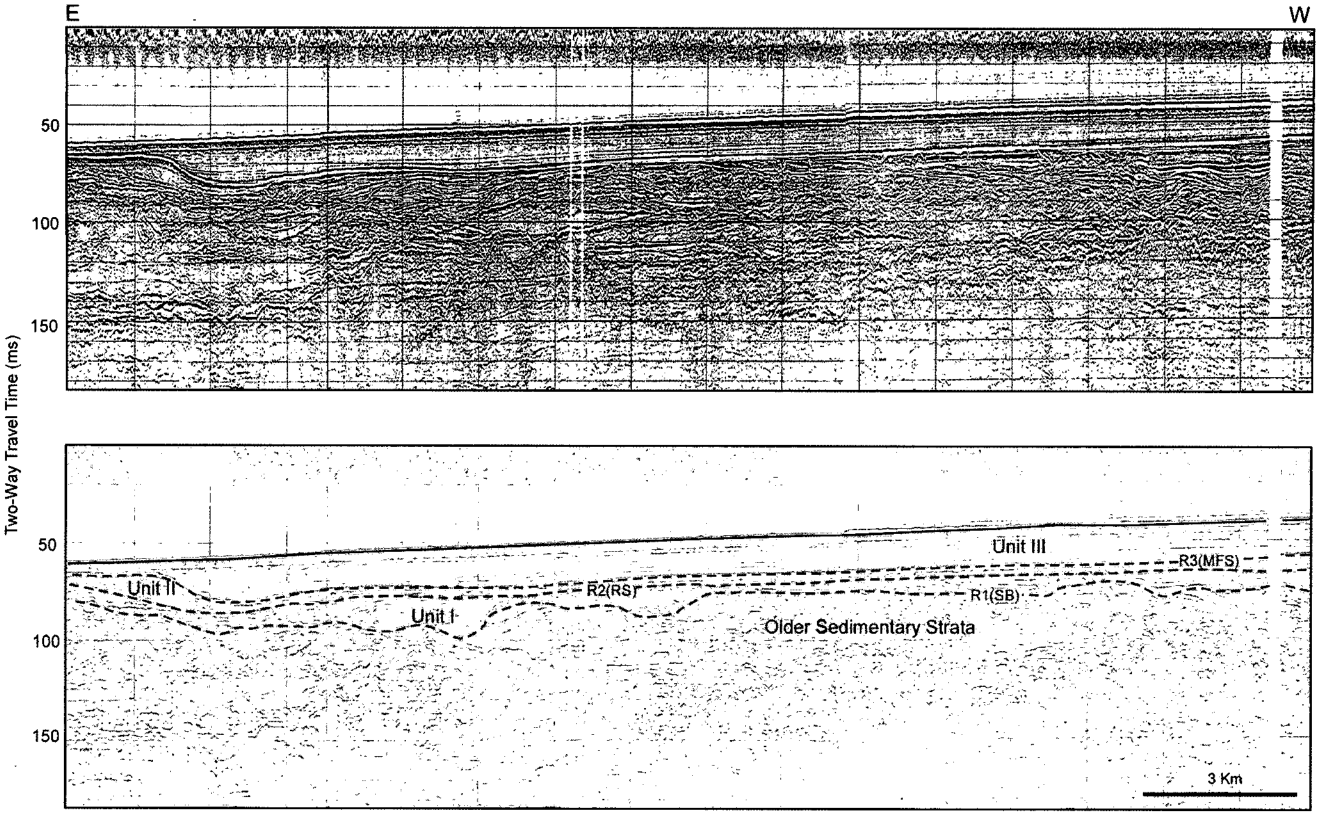

Fig. 6. High-resolution (air-gun) seismic profiles collected from the inner shelf area at the Seomjin River (for location, see Fig. 2), showing three sedimentary units overlying the older sedimentary strata. MFS, maximum flooding surface; RS, ravinement surface; SB, sequence boundary.

well-stratified reflections (Yoo and Park, 2000). Toward offshore, however, internal reflectors become progressively weak with low continuity. For the most part of the inner shelf, unit III shows transparent or semi-transparent acoustic characters (Figs. 4 and 6). In some places, the acoustically turbid layer masks the underlying structures. This feature is isolated or wide-spread over a distance of several kilometers (Min, 1994). Externally, unit III shows a wedge shape, decreasing in thickness seaward. It downlaps the underlying surface at water depths of about 70 - 80 m. It is generally 10 - 20 m thick, but the maximum thickness is more than 25 m near the river mouth. Toward the offshore, its thickness decreases progressively and pinches out at water depths of about 70 - 80 m.

Discussion

Late Quaternary Depositional History

Previous works (Suk, 1989; Min, 1994) of the South Sea suggest that the lowest sea-level at the last glacial maximum was about 120 - 130 m below the present level. Under this condition, the paleo-shoreline was located about 60 km southeast of the present position, corresponding to the shelf margin near the trough region (Yoo and Park, 2000). Much of the study area was subaerially exposed and formed shelf-wide regressive incisions, resulting in formation of the sequence boundary that cut the underlying older sedimentary strata.

In the South Sea, the Holocene transgression began about 15 - 16 ka (Suk, 1989; Min, 1994) and the shoreline migrated landward across the shelf, resulting in a transition of the depocenter from the outer shelf to the inner shelf. Around 11 - 10 ka, the shoreline approached the southern part of the study area approximately 70 - 80 m in water depth below the present sea level (Korea Institute of Geoscience and Mineral Resources, 2000). Under this condition, an estuarine environment probably developed around the inner shelf between Geoje Island and the present river mouth as reported by Yoo and Park (2000). A similar condition is also identified on the inner shelf between Namhae and Geoje Islands. The sediments derived from the paleo-Nakdong and paleo-Seomjin rivers were trapped in this estuary forming unit I. This unit is regarded as the estuarine deposits related to the extent of paleo-rivers, as proposed by Min (1994), and Yoo and Park

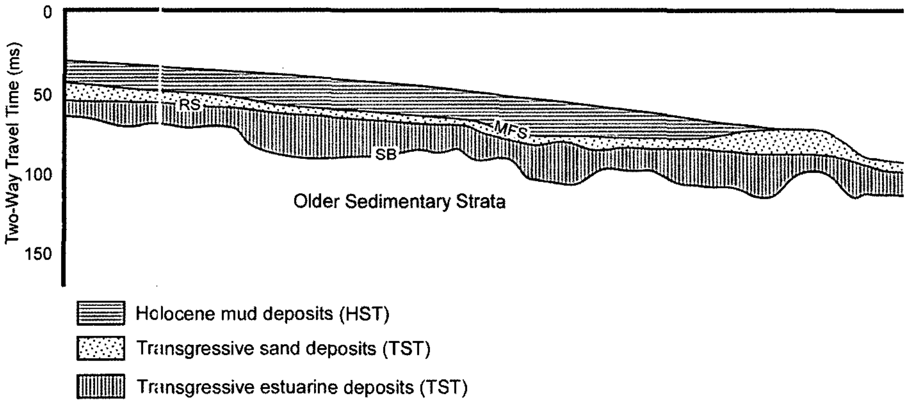

Fig. 7. Proposed stratigraphic architecture for the inner shelf off the southern coast. The inner shelf sequence above the sequence boundary consists of three stratigraphic units forming transgressive and highstand systems tracts separated by ravinement and maximum flooding surfaces. MFS, maximum flooding surface; RS, ravinement surface; SB, sequence boundary.

(2000). Well-studied examples are the Adriatic Sea shelf (Trincardi *et al.*, 1994), the Tyrrhean shelf (Tortora, 1996), Yellow Sea (Lee and Yoon, 1997), and the East China Sea (Yoo *et al.*, 2002). Formation of the estuarine/deltaic system continued until the shoreline approached the present level. Sea level continued to rise and the shoreline migrates further landward. The near-surface sediment was reworked and eroded by shoreface erosion, forming a thin lag of transgressive sands (unit II). Previous works (Park and Choi, 1986; Suk, 1989; Park and Yoo, 1992; Yoo *et al.*, 1996) confirmed that unit II in this area represents a relict facies which experienced subaerial and/or subaqueous weathering for a long time during the Holocene transgression. Unit II also contains weathered carbonate fragments and iron-stained quartz grains (Park and Choi, 1986). Thus unit II, distributed over a wide area of the mid-shelf, is interpreted to be the product of reworking and resuspension of shoreface sediments by wave and current action during the transgression.

Sea level reached the present position approximately 6 ka (Suk, 1989; Min, 1994) and the inner shelf began to receive a large amount of fine-grained sediments from the Nakdong and Seomjin rivers. Formation of unit III initiated at that time and river-derived sediments have been deposited at and just beyond the river mouth, forming a subaqueous prodelta and shelf deposits (Fig. 7; Min, 1994; Yoo *et al.*, 2004).

Sequence Stratigraphy with Bounding Surfaces

In the inner shelf area off the southern coast of Korea, the sequence boundary, ravinement surface and maximum flooding surface are discussed based on seismic record (Figs. 4 - 6). The boundary R1 between the older sedimentary strata and unit I is characterized by an irregular, erosional unconformity with high acoustic impedance contrast on seismic records (Figs. 4 and 6). The unconformable surface is well correlated with the basal boundary of latest Pleistocene-Holocene sequences, reported by Min (1994), and Yoo and Park (2000) (Fig. 7). They regarded it as the type-I sequence boundary in the sense of Posamentier and Allen (1993). The boundary R1 began to develop as the coastline migrated seaward, resulting from subaerial erosion, during the regressive interval of the last sea-level fall. The erosional surface, thus, represents the Pleistocene-Holocene boundary which has been reported in many continental shelves, including the shelf off Mersin Bay (Okyar *et al.*, 1992), the Rhone continental shelf (Tesson *et al.*, 2000), the southeastern Black Sea (Okyar *et al.*, 1994), the shelf along the southern coast of Korea (Min, 1994; Yoo and Park, 2000) and the East China Sea shelf (Yoo *et al.*, 2002).

The boundary R2 between unit I and unit II is an erosional surface, but is relatively flat compared with the sequence boundary (Fig. 4). The erosional surface, showing bedding truncation below, is a ravinement surface closely related to shoreface retreat during the Holocene transgression (Demarest and Kraft, 1987; Nummedal and Swift, 1987; Mitchum and Van Wagoner, 1991; Trincardi *et al.*, 1994). Min (1994), Yoo and Park (2000) suggest that it is a time-transgressive ravinement surface, resulting from the processes of landward migration of shoreface-erosional zone during the sea-level rise.

On the other hand, the boundary R3 can be defined by a non-erosional surface with a reflection of relatively high acoustic impedance contrast (Fig. 4). The occurrence of similar type of boundary R3 on the shelf in several places of the world has been documented by a number of workers (Ericilla *et al.*, 1994; Okyar *et al.*, 1994; Saito, 1994; Trincardi *et al.*, 1994; Tesson *et al.*, 2000; Yoo *et al.*, 2002). The boundary R3 is inferred to represent the maximum flooding surface closely related to the change of sea level during the late Holocene. It represents the shelf-wide sedimentary change from a retrogradational phase forming transgressive deposits (unit I and II) to a progradational phase of highstand deposits (unit III). It is interpreted to have been formed when the shoreline reached its maximum landward excursion.

Therefore, units I and II between the sequence boundary and the maximum flooding surface are defined as the transgressive systems tract formed during the post-glacial transgression, whereas unit III overlying the maximum flooding surface is the highstand systems tract formed during the recent highstand of sea level (Fig. 7).

Conclusions

In the inner shelf off the southern coast of Korea, the inner shelf deposits above the sequence boundary forms a high-frequency sequence comprising three stratigraphic units (unit I, II, and III) separated by ravinement and maximum flooding surfaces. The basal boundary of inner shelf sequence is regarded as the Pleistocene-Holocene boundary, formed in response to falling sea level. The ravinement surface shows an erosional surface related to shoreface retreat during the Holocene transgression. The maximum flooding surface, showing a non-erosional surface, created when the shoreline has reached its maximum landward excursion. Unit I above the sequence boundary is the transgressive systems tract deposited under the estuarine environment during the post-glacial transgression. Unit II between the ravinement surface and the maximum flooding surface belongs to the transgressive systems tract forming a thin lag of transgressive sand with shell debris. Unit III overlying the maximum flooding surface represents the highstand systems tract mainly formed during the recent highstand of sea level. This unit up to 30 m thick is completely confined to the inner shelf forming a subaqueous delta.

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