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Late Pleistocene Unconformity in Tidal-Flat Deposit of Gyeonggi Bay, Western Coast of Korea

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한국 서해 경기만 조간대 퇴적층의 후기 플라이스토세 부정합

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요 약: 현세-후기 플라이스토세의 부정합적 경계면을 조사하기 위하여 한국 서해 경기만 조간대에서 심부시추와 탄성파 탐사를 실시하였다. 분석된 모든 시추 퇴적물에서 현세 퇴적층(Unit I) 하부에 놓이는 최대 4m 두께의 산화되고, 반고화된 특징을 보이는 황갈색의 산화대층(oxidized-sedimentary layer)이 발견되었다. 이 세립질의 산화대층에서 나타나는 황갈색의 퇴적물 색, 높은 N 값과 낮은 함수율의 준고화된 상태, 동토구조, 스멕타이트 광물의 부재 그리고 높은 퇴적물 화학적 풍화지수(Ba/Sr 비) 등의 다양한 특성은 퇴적물의 대기중 노출과 풍화의 중요한 증거로 제시된다. 탄소동위원소 연대와 함께 이러한 여러 증거들을 고려할 때, Unit II의 상부 산화대층은 초기 현세까지 계속되는 저해수면 동안 대기중에 노출되어 풍화 및 산화작용으로 인하여 퇴적물의 특성이 변질되어 형성된 것으로 해석된다. 따라서 산화대층의 상부 경계면은 현세와 선현세(후기 플라이스토세) 퇴적층을 구분하는 부정합면으로 제시되며, 탄성파 자료에서 나타나는 강한 반사면(prominent near-surface reflector)과 잘 일치한다.

주요어: 후기 플라이스토세 부정합, 산화대층, 탄성파 반사면, 경기만

Abstract: Deep-drilled core sampling and high-resolution seismic survey were carried out to identify a Holocene-late Pleistocene boundary in Gyeonggi Bay, western coast of Korea. Analysis of core sections revealed the existence of an oxidized and semi-consolidated sediment layer, lying immediately below a Holocene horizon (Unit I) and being developed at the top of a late Pleistocene deposit (Unit II). The oxidized sedimentary layer (uppermost part of Unit II) is characterized by semi-consolidated, yellowish sediments showing signs of desiccation and alteration such as high N value, low water content, periglacial cryogenic structure, depletion of smectite, and high geochemical weathering index (Ba/Sr ratio). This feature, together with radiocarbon ages, suggests that the layer has formed as a result of prolonged subaerial exposure of Unit II sediments during the late Wisconsin sea-level lowstand, producing a regional unconformity. Such unconformitic-bounding surface corresponds to a prominent near-surface reflector (R), which is observed in seismic profiles obtained across the drilled-core sections in the study area. Consequently, the buried oxidized-sedimentary layer associated with the seismic reflector possibly plays a key horizon for the understanding of late Quaternary environmental changes as well as evidence of the emergence of the Yellow Sea shelf during the late Wisconsin sea-level lowstand.

Keywords: late Pleistocene unconformity, oxidized-sedimentary layer, seismic reflector, Gyeonggi Bay

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Introduction

The Yellow Sea rests on a flat, broad, and tectonically stable seafloor in which the water averages 55 m in depth with a maximum of less than 100 m. The shallowness of the Yellow Sea shelf may have caused it to become completely exposed to subaerial conditions during the late Wisconsin maximum lowstand when the sea level was approximately 135 m lower than at present (Bloom and Park, 1985). It is expected that any such prolonged subaerial exposure would have led the pre-Holocene interglacial marine strata to be altered by desiccation and pedogenesis with the consequential formation of oxidized-sedimentary layer (or paleosol). Thus, the subaerially exposed pre-Holocene sediments would be expected in marginal marine strata of the Yellow Sea if the sea level had fallen sufficiently to expose the sediments. Generally, paleosols occurring in marine strata provide invaluable marker in the stratigraphic record allowing identification of boundaries between interglacial deposits and/or glacial deposits as well as the related paleoenvironmental changes (Retallack, 1988; Stanley et al., 1996: Yim and Tovey, 1995). In many instances, however, the paleosols were partially or totally eroded due to the subsequent Holocene transgression. Elsewhere, they failed to form as a result of burial of the pre-Holocene marine deposit by alluvial deposits formed either during or after the regression (Demarest and Leatherman, 1985; Nichol and Murray-Wallace, 1992). So, the preservation potential of paleosols is not high in marginal marine strata, although the sedimentological character of the buried paleo-surface is still of interest. In this respect, direct geological sample supporting the shelf emergence of the Yellow Sea during glacial lowstands is rare.

Since the 1980's, numerous high-resolution seismic profiling studies have been carried out in and around the Yellow Sea shelf and nearby coastal zones to characterize the pre-Holocene deposits and identify the associated boundaries (Kang and Chough, 1982; Park et al., 1990, 1991; Lee and Yoon, 1997; Jin and Chough, 1998; Lee and Chung, 2000). In these researches, a prominent near-surface reflector with a large difference in acoustic impedance has been interpreted as the former subaerially exposed late Pleistocene surface, presumably the late Wisconsin unconformity (Park et al., 1991; Lee and Yoon, 1997). However, no evidence confirming that this reflector is in fact the former subaerial surface has been found, although two studies have reported oxidized sediments in the stratigraphic sequences of both the Yellow Sea shelf and its eastern coastal zone (Park et al., 1998; Chun et al., 2000). Indeed, correlations of the seismic reflector with a pre-Holocene subaerial surface (regional unconformity) in previous studies seem to be even conjectural.

In this study, we characterize a Holocene-late Pleistocene boundary in coastal deposits off the western coast of Korea and establish the relationship between the seismic reflection boundary and the lithologic paleo-surface on the basis of seismic profiles and deep-drilled core samples.

Study Area

The Yellow Sea is a shallow body of water with an average depth of 55 m and has a tidally dominated epicontinental shelf with a vast terrigenous sedimentary input of about 109 ton/yr (Qin et al., 1989; Hay, 1998) derived from the nearby landmass of China and Korea. The western parts of the Yellow Sea are surrounded by a rock-embayed coast in the north and an huge deltaic or mudflat coast in the south, derived mainly from Yangtze and Hunaghe rivers, whereas the eastern coast (Korea side) are bordered by numerous ria-type embayments, estuaries, and indented islands formed by inundation during the Holocene sea-level rise. Radiocarbon dates indicate that the eastern coastal area became submerged at an average rate of 1.6 mm/yr during the early postglacial transgression and 0.3 mm/yr during the last 5,000

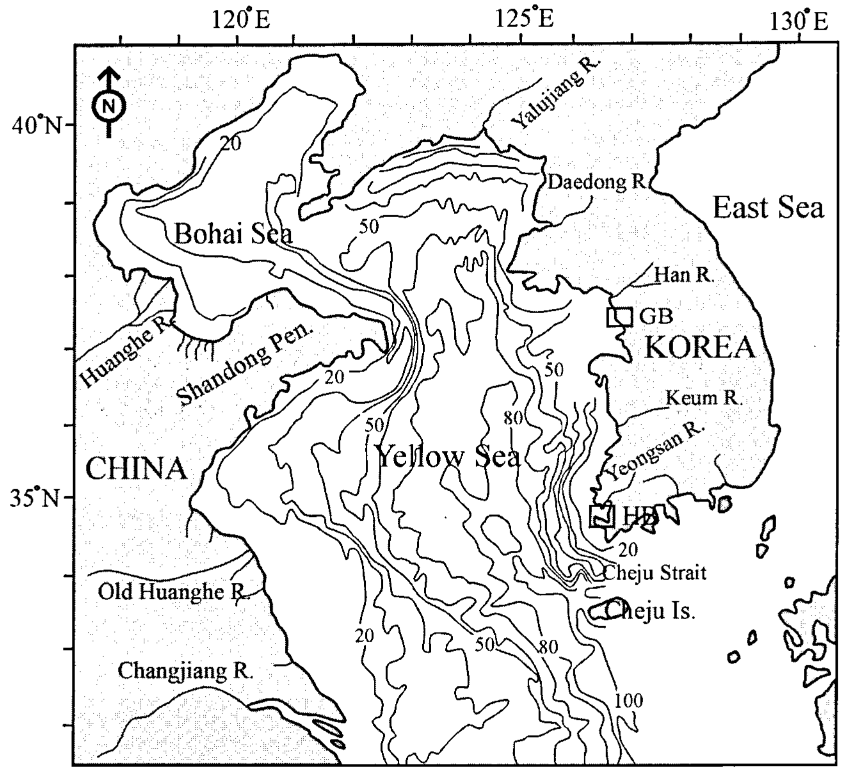

Fig. 1. The Yellow Sea shelf with bathymetry. Isobaths are in meters. GB: Gyeonggi Bay, HB: Haenam Bay.

years (Bloom and Park, 1985). In particular, the eastern coast of the Yellow Sea is characterized by one of the highest tidal ranges in the world (4 to 8m), producing extensive shallow tidal flats that extend over several kilometers and are major depocenters for fine-grained sediments. The Korean Holocene tidal-flat sequence provides an excellent example of a coarsening-upward, retrogressive tidal-flat succession, associated with a non-barred, sediment-barren coastal setting (Kim et al., 1999; Lim et al., 2003a).

The present study was carried out in the typical macrotidal flats of Gyeonggi Bay, one of the major tidal embayments along the west coast of Korea (Fig. 1). At Inchon harbor, tides are predominantly semidiurnal with mean annual tidal range of about 6.5 m; mean minimum neap tides range between 3 and 3.5 m, and mean maximum spring tides range between 8 and 9 m. During spring tides, flood currents range between 0.9 and 1.8 m/sec and ebb currents range between 1.2 and 2.3 m/sec (Yi, 1972). Mean spring tidal current velocities are approximately 1.8 times greater than mean neap tidal current velocities. The bay is bounded on the east and west by major subtidal channels. Widespread intertidal flats occur along both sides of the bays with widths of 1-3 km. Well-developed intertidal drainage networks, landward salt marshes, and barrier islands are absent. Major river drainage systems discharging into the bays are also lacking, but two or three tributary streams enter each bay and deliver only meager amounts of fine-grained material. Surfacial sediments consist mainly of sand, sandy mud and mud, and change progressively across the tidal flat, from landward sandy mud to seaward silty sand (Frey et al., 1989). Mean grain size of surficial sediment on the inner flat is about 6 phi and on the middle flat is about 5 phi. These trends presumably reflect subtle gradations in elevation, energy levels and sediment-transport mechanisms.

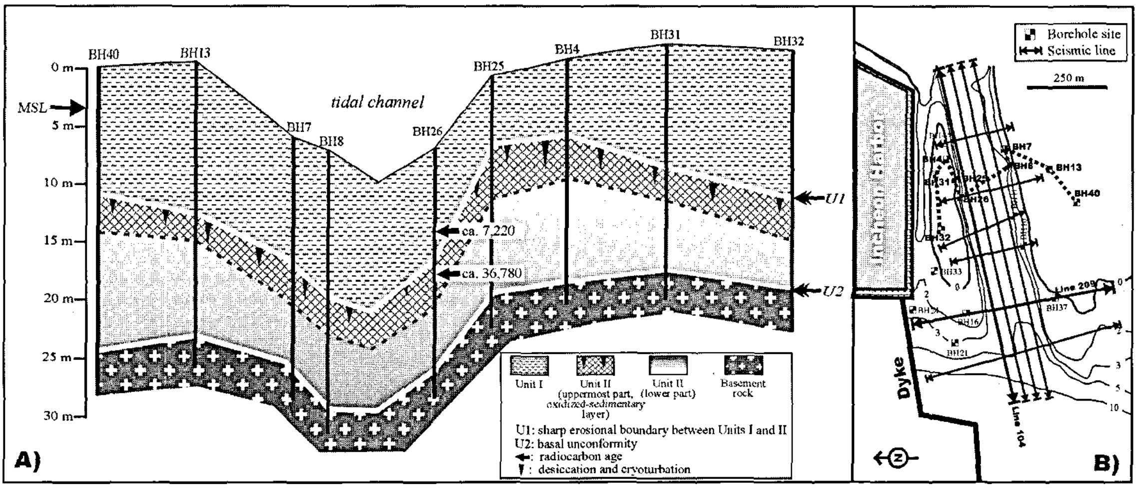

Fig. 2. Lithostratigraphic cross-sections (A) of the Late Quaternary coastal deposits based on the boreholes obtained from the Gyeonggi Bay tidal-flat, with index maps (B) showing the sampling sites and seismic lines. Note the Unit II deposit consisting of two lithofacies: an uppermost oxidized, muddy sedimentary layer and a lower grayish mud layer.

Materials and Methods

Several scores of undisturbed, deep-drilled (5.5 cm in diameter and >25 m in length) cores were retrieved from the tidal flats of Gyeonggi Bay (Fig. 2). All cores were split lengthwise, photographed and logged in detail. Sediments for grain size analyses were subsampled at each lithologic boundary or at intervals of less than 50 cm within thick homogeneous layers. Standard sieving and pipetting methods were used for the grain size analyses and the textural parameters were calculated using graphic methods (Ingram, 1971). Relative water content (%) were measured at 10- to 50-cm intervals using oven-drying method and engineering N-values, defined as the sum of the number of blows required to drive the sampler through the 6-in. (152.4-mm) interval of each horizon, was also measured. This value indicates the stiffness of muddy sediments and may be correlated approximately with their unconfined compressive strength.

Clay mineral analysis was performed on oriented <2 μm sediment fractions by X-ray diffraction using a Rigaku D/Max-3C diffractometer (Rigaku Corporation, Osaka, Japan) with nickel-filtered CuKα radiation (λ=1.514 Å). Semi-quantitative calculations were made according to the standard peak area method of Biscaye (1965). For elemental composition analysis, powdered sediment samples were digested with a mixed solution of HF-HNO_3-$HClO_4$ in an airtight Teflon bomb and then leached with dilute HCl solution (Kitano and Fujiyoshi 1980). Elemental contents of Ba and Sr were measured by ICP-MS at the University of London, UK, and the analytical accuracy was checked using BCSS-1 as a standard reference material. Radiocarbon age-dating was performed on representative plant stems and organic debris using AMS techniques at the National Center for Inter-University Facilities in Korea.

High-resolution sub-bottom profiles (X-STAR Digital Sub-Bottom Profiler; Edgetech, Milford, MA) were collected by the Samsung Institute of Construction Technology, Korea, and used to interpret the shallow subsurface stratigraphy of the study area. After testing six possible bandwidths of the towfish SB-0512 in the study area, the 1-6 kHz bandwidth was found to provide the best resolution and acceptable penetration. Velocities of 1,600m/sec were used for time-distance conversions in both water and sediment and a GPS was utilized to position the vessel.

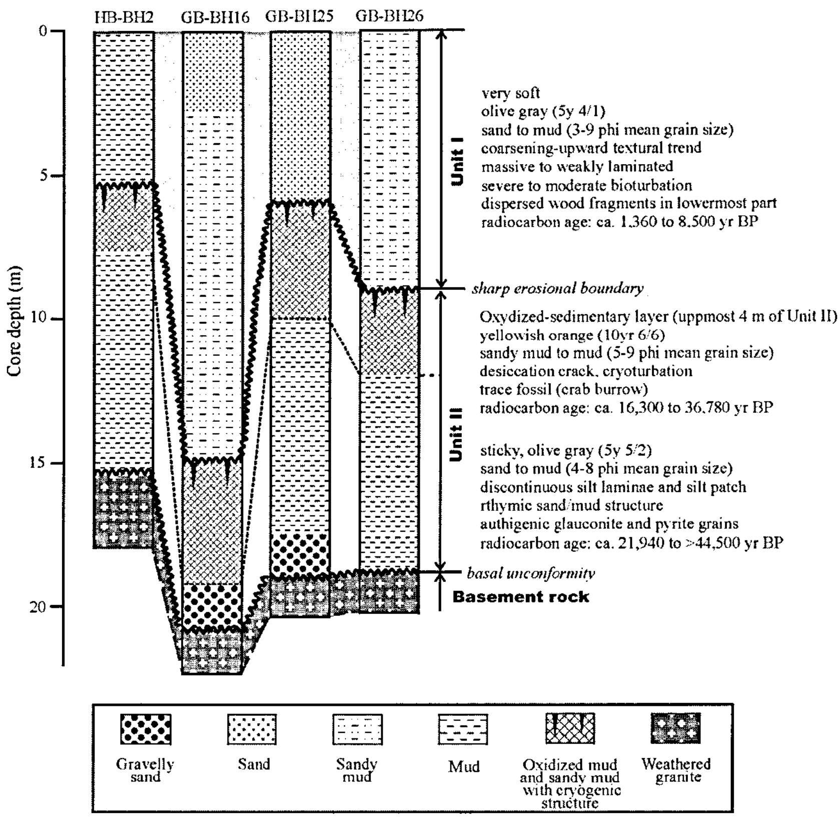

Fig. 3. Lithological description of representative boreholes (BH16, 25, 26) from the study area and stratigraphic correlation with borehole (HB-BH2, Lim and Park, 2003) from Haenam Bay (see Figure 1 for the location) based on lithologic and radiometric information. Note the oxidized-sedimentary layer providing a basis for correlating the boreholes.

Results and Discussion

Lithostratigraphic framework of boreholes

As shown in stratigraphic cross-sections derived from the boreholes (Fig. 2), the sedimentary sequence can be divided into two major stratigraphic units: an upper Holocene gray sand to mud (Unit I), and a lower pre-Holocene yellowish mud to gray muddy sand (Unit II). The two units are separated by an oxidized and desiccated sedimentary layer (Figs. 3 and 4). Unit I consists mostly of soft, grayish mud and sandy silt, ranging from 3 to 8ϕ in mean grain size. It can be interpreted as a sequence typical of mid-to-late Holocene tidal flat deposits, such as those that occur in Korean tidal flats along the eastern coast of the Yellow Sea (Frey et al., 1989; Chang et al., 1996; Kim et al., 1999; Lim., 2001, Lim and Park, 2003a).

Even though Unit II occurs at 5-15 m below the present-MSL and varies in thickness up to 5-10 m, it is laterally persistent throughout the two study areas. The unit resembles the late Holocene tidal-flat sediments of Unit I in texture, sedimentary structure, and sediment color, except that the uppermost 4m of the unit have been oxidized and desiccated to yield a yellowish, oxidized layer. Overall, this pre-Holocene unit is characterized by olive-gray (5Y 5/2), cohesive, poorly sorted mud and sand sediments ranging from 4 to 8ϕ in mean grain size (Fig. 5). Sedimentary structures are dominated by discontinuous, moderately bioturbated silt laminae, except for some sediment sections including lenticular bedding and interlaminated sand and mud. The lithostratigraphic and sedimentologic

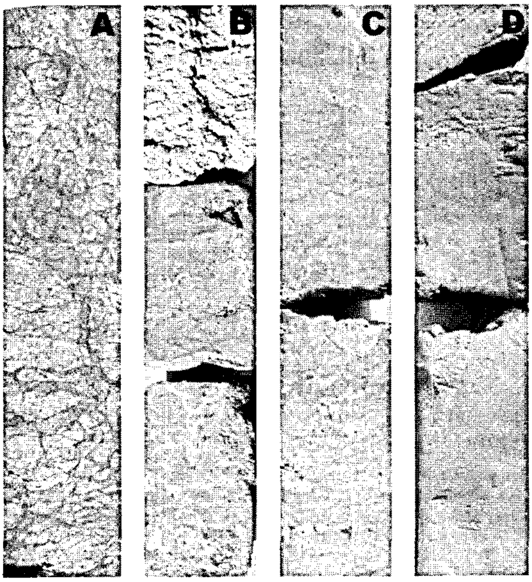

Fig. 4. Photographs of representative sediment samples selected from each unit. (A) and (B) Oxidized, yellowish muddy sediments of Unit II (uppermost part of Unit II). (C) and (D) Grayish muddy sediments of Unit II (lower part of Unit II). Scale bar is 10cm.

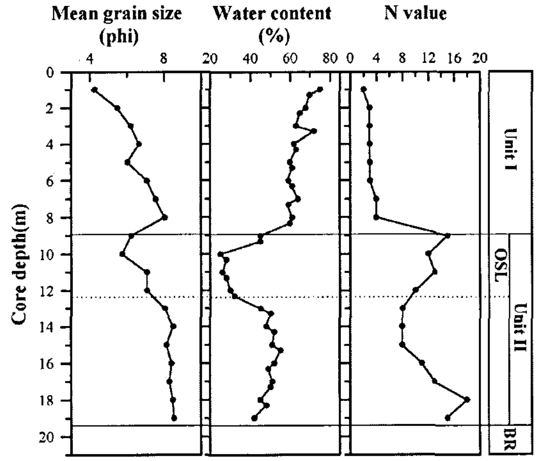

Fig. 5. Vertical changes of mean grain size, water content and N value in the sediments of borehole (BH26). Note the abrupt increase of water contents and N values in the oxidized-sedimentary layer (OSL) of Unit II.

observations allow Unit II to be correlated with the late Pleistocene interglacial tidal sediments with an interpolated age of 125ka described by Lim et al (2001) and Lim and Park (2003) and from Cheonsu Bay and Haenam Bay on the western coast of Korea (Fig. 3). However, additional and independent evidences (e.g. microfossils and tidal rhythmites) need to be obtained to constrain the depositional environment of Unit II deposition in this study area.

An oxidized-sedimentary layer (upper part of Unit II)

One of the most important stratigraphic findings in this study is the identification of the pre-Holocene oxidized-sedimentary layer, which occurs as the uppermost part of Unit II and is separated from the overlying Holocene unit (Unit I) by a sharp erosional boundary. This oxidized-sedimentary layer, up to 4 m in a maximum thickness, is moderate yellow (5Y 7/6) to dark yellowish orange (10YR 6/6) in color and mottled in appearance, showing a significant degree of weathering (Fig. 4). Rust-colored traces of plant roots occur in some sections along with oxidized sand lenses and speckled with Fe/Mn oxide muds. The water contents and N values range from 30% to 50% and from 2 to 4, respectively, in Unit I, and from 10% to 30% and from 8 to 10 in the lower part of Unit II. In the oxidized uppermost sediments of Unit II, however, the water contents decrease abruptly to 10% and the N value increases to 12 (Fig. 5). This abrupt change indicates that the sediments are very stiff and hard as a result of dewatering and desiccation.

Cryogenic structures are common feature of the oxidized layer, supporting the interpretation of subaerial exposure and weathering of Unit II during the late Wisconsin sea-level lowstand. Cryogenic structures are generally known to be conspicuous post-depositional, periglacial structures (Butrym et al., 1964; Oh et al., 1995). In the study area, they consist of irregular wavy lamellae at intervals of 2-8 mm (Fig. 6). Each appears as a black stripe, 0.2-0.5 mm thick, with a very compact fabric composed of discrete rounded or spheroidal aggregates covered by a silt coating. Each black lamella is comprised of very fine-grained materials of which pores are cemented by organic-colloids. Such structures

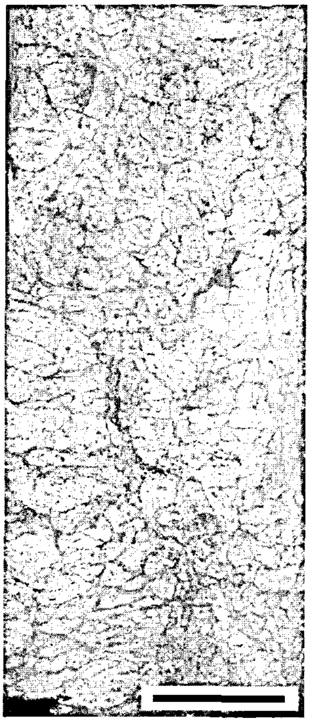

Fig. 6. Photograph showing a detailed texture of cryogenic structure. A black stripe (lamella) consists of extremely fine-grained clay particles bonding by organic compounds. It may by due to clay illuviation during the subaerial exposure of the sediments.

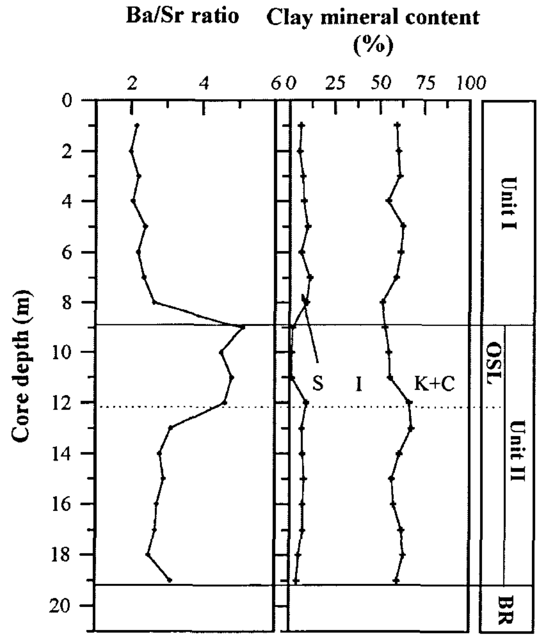

Fig. 7. Vertical variations of Ba/Sr ratio and clay mineral contents analyzed in the sediments of borehole (BH26). S: smectite, I: illite, K: kaolinite, C: chlorite.

develop where soil freezes under cold and dry conditions, and segregated ice lenses develop via cryophoresis pressure from the growing ice and disturbance by frost-creep (Butrym et al., 1964; Oh et al., 1995).

Additional evidences of former subaerial exposure are provided by the depletion of smectite and the geochemical weathering index. The oxidized-sedimentary layer is characterized by the lack of smectite, in contrast to the clay mineral assemblages of Unit I and lower part of Unit II (Fig. 7a). In general, smectite and/or chlorite are unstable under subaerial weathering condition: these minerals are vulnerable to mechanical or chemical destruction and transformation into other minerals (Altschuler et al., 1963; Boles and Franks, 1979; Pederstad and Jørgensen, 1985; Segal et al., 1987). Hence, such abrupt decrease in smectite content in this layer seems to reflect post-depositional and diagenetic alteration rather than depositional processes. This interpretation is further corroborated by the increase in Ba/Sr ratio that express the degree of chemical weathering in terms of the ratio of mobile Sr to the less mobile Ba (Feakes and Retallack, 1988). High values of Ba/Sr in the oxidized upper layer of Unit II indicates the selective leaching of Sr from this horizon, which might may have occurred under the same subaerial weathering processes that contributed to the destruction of smectite. Similar changes have been marine clays that have been subjected to post-depositional weathering (Fig. 7b, Park et al., 1998; Lim et al., 2003b).

Radiocarbon age of plant stems from the upper oxidized layer of Unit II was 36,780±450, indicating that subaerial exposure of the late Pleistocene sediments (Unit II) has lasted at least the late Wisconsin maximum lowstand. It is during this period that the uppermost Unit II sediment could have become altered by subaerial weathering and developed its cryogenic structure, forming the

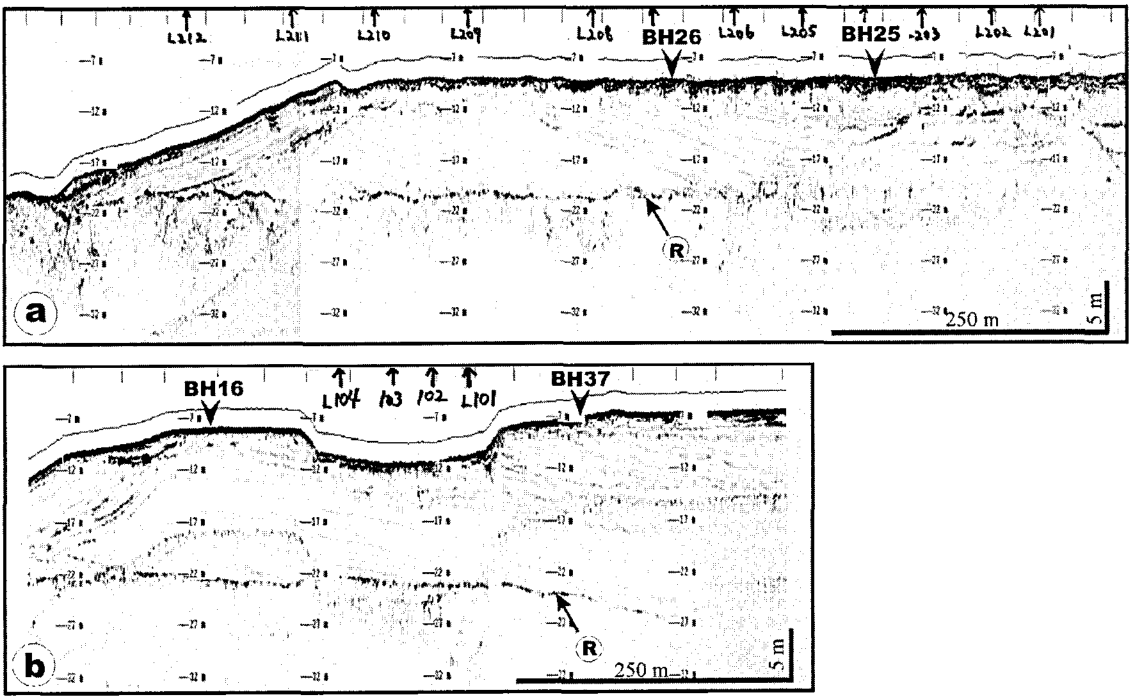

Fig. 8. High-resolution seismic profiles (see Figure 2B for locations of cores and seismic profiles) showing two major sedimentary sequences separated by a strong reflector (R), which can be correspond with the surface of the oxidized-sedimentary layer.

oxidized-sedimentary layer which can be described as a paleosol of marine origin. Such buried paleosol was also found in coastal deposits of Hong Kong coastal deposits as well as other Korean tidal flats (Yim et al., 1990; Yim and Tovey, 1995; Park et al., 1998; Lim et al., 2001). Considering that the majority of paleosols are described from continental deposits, most commonly from alluvial strata, the widespread development of the buried paleosol within the marine strata is remarkable, and also points to shelf emergence of the Yellow Sea. If this is indeed the case, then the surface of the oxidized layer mark the late Wisconsin unconformity (LWU), which is of subaerial origin, and which corresponds to a period of non-deposition during a long hiatus. It thus serves as a readily recognizable stratigraphic marker for regional correlation of strata throughout East Asian marginal sea.

Seismic evidence for unconformity

High-resolution seismic-reflection profiles obtained in Gyeonggi Bay typically showed the two distinct, major depositional sequences, A and B, separated by a strong reflector (R), which occurs at a depth of 5-15 m below the seafloor (Fig. 8). Although the bottom boundary of the sequence B in the seismic profiles is indistinct, possibly due to limited seismic-wave penetration, the strong reflection boundary (R) between sequences A and B is well defined. This reflector (R) can be traced throughout the entire bay and may represent an erosional discontinuity that cuts across the underlying sedimentary sequence B. Sequence A, overlying the reflector (R), is characterized by clearly defined and often inclined internal reflectors of an acoustically simple and stratified nature. The lower sequence B is indistinctly layered and almost reflection-free, being acoustically transparent or partly diffuse. Similar seismic pattern with strong near-surface reflectors have been found in many embayments along the eastern coast of the Yellow Sea (Kang and Chough, 1982; Park et al., 1991; Min et al., 1996) and even extends across the Yellow Sea shelf (Lee and Yoon, 1997). In particular, these strong reflectors in most previous seismic studies have been inferred to be a subaerially exposed surface of pre-Holocene sediments.

The marked correlation of the present core lithological data with the seismic profiles shows that the strong reflector (R) corresponds with the surface of the buried-oxidized sedimentary layer (late Wisconsin unconformity). A sharp erosional contact between Units I and II at approximately 6-16 m in cores BH16, BH25, BH26 and BH37 concurs with the strong reflector (R) in seismic profiles of Line 104 and 209 (Fig. 8). In light of the radiocarbon ages of core samples and depositional environments interpreted above, sequences A and B are interpreted, respectively, as being Holocene (Unit I) and late Pleistocene (Unit II) deposits. The strong seismic reflector is due to the difference in geotechnical properties resulting from subaerial compaction and desiccation of Unit II sediment, i.e., the upper part of Sequence B (oxidized-sedimentary layer) is denser than sequence A. Consequently, we feel justified in interpreting the contact and underlying Unit II (or sequence B) deposits as the land surface exposed during the late Wisconsin lowstand of the Yellow Sea. This result points to the major reflector found below the youngest coastal and/or shelf deposits in the study area, as well as under the Yellow Sea shelf, as being the regional Holocene-late Pleistocene unconformity (LWU) formed by subaerial exposure of the late Pleistocene marine deposit (Unit II). Furthermore, mapping of this buried oxidized-sedimentary layer along the LWU in the Yellow Sea may be allows for an improved correlation of sedimentary facies that show differences in acoustic responses in high-resolution seismic profiles.

Conclusions

During the late Wisconsin lowstand, the environment of the Yellow Sea shelf was characterized by a dry and cold climate with locally desertized landscapes (Park and Yi, 1995). This environmental and sea-level change in the Yellow Sea shelf is represented by a yellowish, oxidized-sediment layer, or paleosol, that constitutes the upper part of Unit II, and which developed a distinct desiccation crust with a peculiar cryogenic structure, indicating a dry and severely cold paleo-climate. The upper surface of this layer, formed upon the subaerial exposure and weathering of the Yellow Sea continental shelf at the time of the lowered sea level, corresponds with the regional late Wisconsin unconformity (LWU). It also corresponds precisely with a strong acoustic reflector (R), as has been conjectured in previous seismic profile studies. This result supports a basic assumption that the major seismic reflection line in the seismic stratigraphy of the Yellow Sea shelf is isochronous. Consequently, the buried oxidized-sedimentary layer provides clear evidence of the emergence of the Yellow Sea shelf during the late Wisconsin sea-level lowstand and is a basis both for understanding late Quaternary environmental changes and for stratigraphical correlation (and/or unconformity) within the Yellow Sea region of East Asia.

Acknowledgments

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