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Characteristics and Stratigraphy of Late Quaternary Sediments on a Macrotidal Mudflat Deposit of Namyang Bay, Western Coast of Korea

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Abstract: In Namyang Bay of western Korea, macrotidal-flat deposits are divisible into three late Quaternary units: Unit M1 of upper marine mud, Unit T1 of middle siderite-bearing terrestrial clay, and Unit M2 of lower marine mud. Unit M1 represents typical Holocene intertidal mudflat deposits, showing a coarsening-upward textural trend. It probably resulted from the continual retrogradation of tidal flat during the mid-to-late Holocene sea-level rise. Reddish brown-color Unit T1 consists of homogeneous clay with abundant freshwater siderite grains and plant remains. Unit T1 is clearly separated from the overlying Unit M1 by a sharp lithologic boundary. Radiocarbon age, siderite grains and lithologic features indicate that Unit T1 is originated from freshwater bog or swamp deposition infilling the localized topographic lows during the early Holocene age. Overlain unconformably by early Holocene swamp clay, Unit M2 is orange to yellow in color and mottled, suggesting significant degree of weathering during the sea-level lowstand. Such subaerial oxidation is confirmed in the vertical profiles of geotechnical properties, clay mineral assemblages and magnetic susceptibility. Unit M2 appears to be correlated with the upper part of the late Pleistocene tidal deposits developed along the western Korean coast. The sedimentary succession of the Namyang-Bay tidal-flat deposit provides stratigraphic information for the Holocene-late Pleistocene unconformity and also permits an assessment of the preservation potential of the late Pleistocene marginal marine deposit along the western coast of Korea.

Keywords: Late Quaternary sediments, macrotidal-flat deposit, unconformity, late Pleistocene, western coast of Korea

Introduction

The western coast of Korea is characterized by a broad, low-sloping geometry and large tidal range, allowing for the development of extensive tidal flats. Such a typical Korean tidal flat is developed in Namyang Bay (Fig. 1). Fine-grained sediments derived from the Korean rivers are accumulated (up to 30 m thickness) mostly in the coastal zone and flats (Jin and Chough, 1998; Lee and Chu, 2001). The Korean tidal flats, often deeply indented and penetrating far into the land, are typically under non-barred macrotidal environments subjected periodically to intense monsoonal wind surges during winter.

The flats in the west coast of Korea can be divided into three zones, generally, on the basis of the sedimentological criteria: high-tidal, mid-tidal and low-tidal flats (Lee *et al.*, 1998). On the high-tidal flats, shelly sand ridges of chenier systems are common, showing gently landward-dipping interbeds of coarse- to medium-grained shelly sands (Lee *et al.*, 1994; Park *et al.*, 1996; Yang, 2000). In contrast to most of large tidal flats worldwide, the Korean tidal flats lack seaward barriers and spits, landward salt marshes and intricate tidal drainage systems (Wells *et al.*, 1990; Alexander *et al.*, 1991). Also, large river systems seldom enter the tidal flats. The non-barred, muddy tidal flats of Korea flanking open coasts are unique and seem to be distinctly different from other protected tidal-flat environments associated with large rivers.

According to the recent lithostratigraphic investigations, the Holocene tidal-flat sequence unconformably overlies the pre-Holocene tidal or fluvial muds and/or directly Precambrian or Jurassic basement rocks (Kim and Park, 1992; Park *et al.*, 1998; Kim *et al.*, 1999; Choi and Park, 2000). Further-

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more, some previous studies demonstrated that such pre-Holocene sequence can be divided into two subunits on the basis of the degree of weathering: an upper weathered sediment and a lower unweathered sediment (Park *et al.*, 1998; Choi and Park, 2000). Recently, Khim *et al.* (1999) also reported on early Holocene terrestrial sediments intercalated between the Holocene and pre-Holocene deposits from the tidal flat of Youngjong Island, western coast of Korea. This description reveals that the stratigraphy of the Korean tidal-flat deposits is more complex than previously suggested. Compared with extensive and well-constrained studies for mid-to-late Holocene tidal deposits, furthermore, those for early Holocene or pre-Holocene sediments have been relatively rare. The purpose of this study is to understand the sedimentologic characteristics and distribution pattern of late Quaternary sediments in a macrotidal mudflat of Namyang Bay.

Study Area

Namyang Bay, located in the northern part of west coast, Korea, is a large, east-west-oriented, funnel-shaped embayment with 12 km long and 3 ~9 km wide (Fig. 1). Tidal range varies between 8.3 m at spring tide and 4.9 m at neap tide (mean tidal range, 5.7 m) (Chung and Park, 1978). The bay is bounded on the south and north by a main channel (up to 25 m deep and about 1~2 km wide at baymouth) with its axis trending approximately east-west (Fig. 1). Bifurcated tidal channels (less than 4 m deep) are common on the tidal flats but stable on the temporal scale of decadal years, probably because of the cohesive, fine-grained nature of the sediments (Reineck and Singh, 1975; Wells *et al.*, 1990). Well-defined seaward barrier, river and typical salt marsh system are rare in the bay. Only two small inland streams, entering from the northeast, deliver meager amount of terrigenous materials into the bay. The bedrock lithology around the bay is characterized mostly by Precambrian metamorphic rocks such as granite gneiss and schist.

Distribution patterns of surficial sedimentary facies were evaluated along several transects across the tidal flats of Namyang Bay (Kim, 1989; Alexander *et al.*, 1991). Namyang tidal flat consists of approximately 0~20% sand, 50~70% silt, and 20~30% clay, although lower tidal-flat sediments near the tidal channel contain more than 50% sand. As shown in Figure 2, three sedimentary facies were identified on the intertidal flat surface (in a seaward direction): silt and mud facies occupying the zone nearest to the mean high water line; sandy silt facies on the central flats; relatively narrow and restricted silty sand facies along the outer edge of the intertidal flats. Silt and mud facies consist of 50 ~70% silt and less than 10% sand, and mean grain size ranges from 6 to 8 phi. Sandy silt facies contain 10~30% sand and 60~70% silt sediments with mean grain size of 4 to 6 phi. Silty sand facies reach up to 60% in sand content, and their mean grain size ranges from 3 to 4 phi. This seaward-coarsening distribution of surficial sediments, which similar to those of North Sea tidal flats, is attributed to a general increase in wave and tidal current energy in a seaward direction, causing progressive winnowing of finer-grained sediments (Thompson, 1968; Alexander *et al.*, 1991).

Materials and Methods

The continuous stratigraphic sediment sections were taken from seven sites that traverse the Namyang tidal flat using vibra-coring equipment (Fig. 1). Vibra-cores were taken at 1994 year and their diameter and length are 6.5 cm and 2~7 m respectively. All the cores were longitudinally split into halves and logged in detail on the basis of visual examination and X-radiography. Grain size analysis was performed by standard sieving and pipetting method, and the textural parameters were calculated following the graphic method (Folk, 1954). Shear strength was gauged by using a Torvane Rheometer at about 10 cm intervals, and water

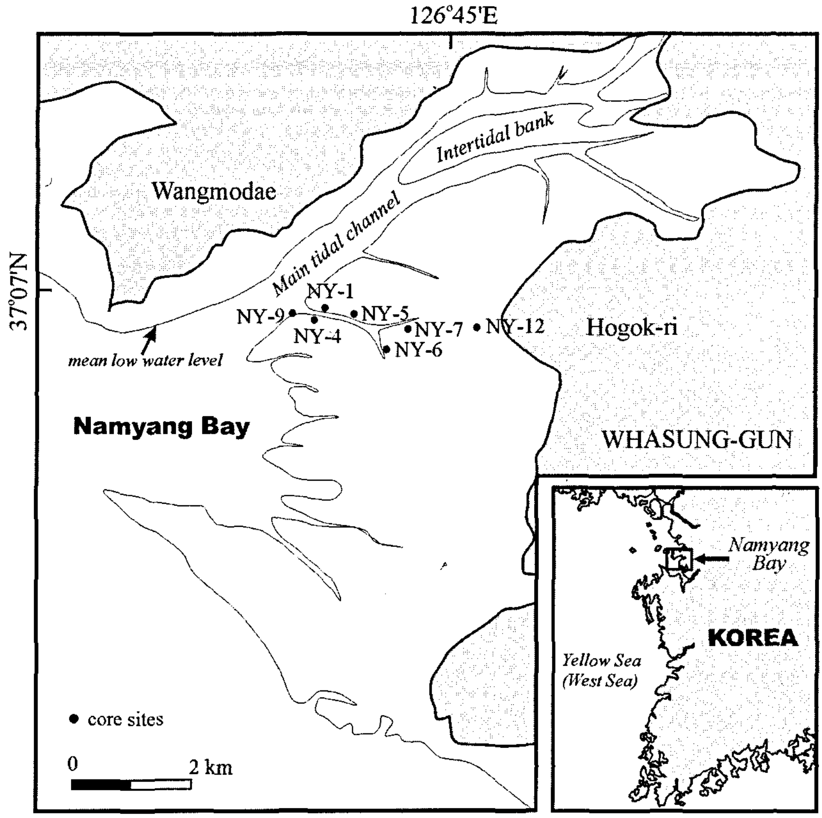

Fig. 1. Index map showing Namyang Bay, western coast of Korea (eastern Yellow Sea) and enlarged map of study area and core locations on the intertidal flat of the bay.

contents of sediments were also measured at same intervals. The water content (%) of sediment is defined as the ratio of the weight of water to the weight of sediment dried at 80 overnight. Low-field magnetic susceptibility and frequency dependence were measured on a Bartington magnetic susceptibility meter (MS2). A specimen of paramagnetic Mn_2O_3 was used as a standard for calibration of the instrument. Particulate organic carbon (POC) contents of sediments were measured by back-titeration method.

For the analysis of clay minerals, preferably orientated aggregates of clay fractions (<2 μm) were made by the smear method on glass slide. X-ray diffractograms were obtained from untreated and ethylene glycol-treated samples using a Mac Science MXP-3 XRD system with Ni-filtered Cu$K\alpha$ radiation. Relative abundance of major clay minerals (illite, kaolinite, chlorite and smectite) was estimated semiquantitatively on ethylene-glycolated diffractograms by integrating peak areas (Biscaye, 1965). The diffractogram peak areas used in this study are as follows: 17 Å ethylene-glycolated peak for smectite; 10 Å peak for illite; 3.54 and 3.58 Å peaks for kaolinite and chlorite, respectively. Radiocarbon age was dated for well-preserved shell and *in situ* plant remnant using the AMS technique (DSIR Physical Science, New Zealand and ICNSRF, Seoul National University).

Lithostratigraphic Units

Vertical deposits of the Namyang tidal flats can be divided into three lithostratigraphic units on the basis of sharp lithological and erosional boundary. They are soft greenish gray mud/sandy silt (Unit

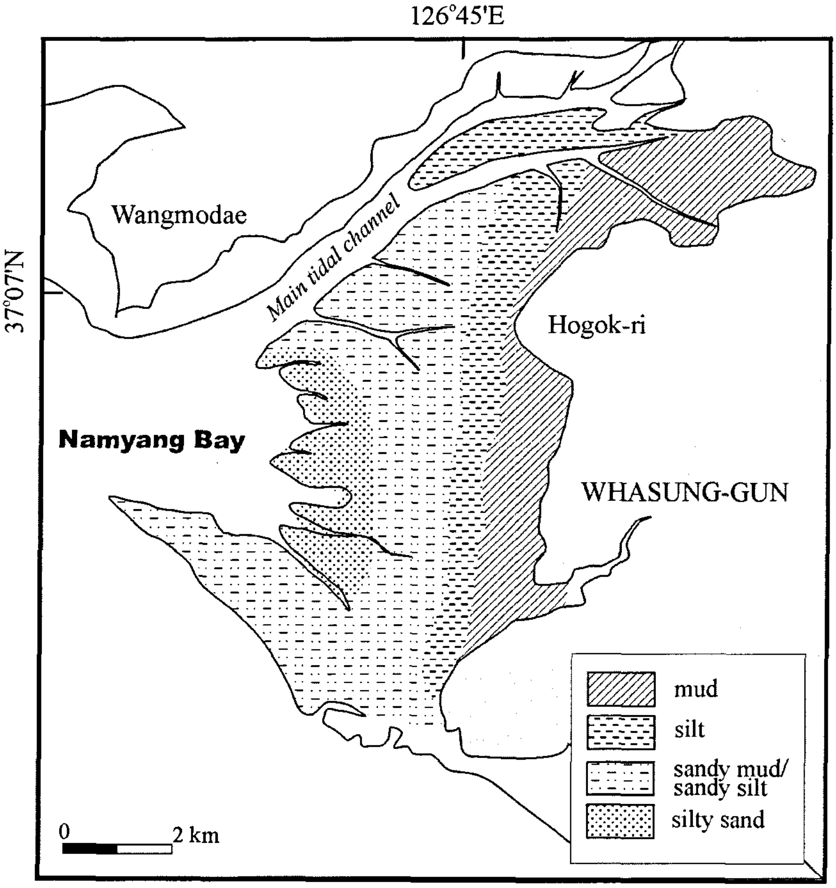

Fig. 2. Map of surface sediment distribution in the Namyang tidal flat. Note that sedimentary textures coarsen toward main tidal channel. (After Kim, 1989 and Alexander *et al.*, 1991).

M1), reddish brown clay with siderite grains (Unit T1) and semi-consolidated, yellowish orange mud (Unit M2) in descending order (Fig. 3).

Unit M1: soft, gray mud/sandy silt

Unit M1, up to 6 m in thickness, is composed mainly of soft, gray mud and sandy silt sediments. The unit can be subdivided into sand-dominated upper part and mud-dominated lower part. The upper part consists of dark gray (N3) to greenish black (5GY 2/1), sand and sandy silt, ranging from 4 to 6 phi in mean grain size (Figs. 3 and 4). The sediments contain 23% sand, 56% silt and 21% clay on average, respectively, and are partly disturbed by biogenic activities, forming abundant burrows and biogenic escape structures (Fig. 5a). Occasionally infilled burrows are different in texture from the surrounding host sediments (Fig. 5b). Continuous and/or discontinuous parallel lamination and disrupted small-scale ripple bedding are dominant sedimentary structures (Fig. 5c to 5e). The preservation of lamination increases toward the top of core; the uppermost 50 cm in most of cores are characterized by very well-preserved laminations without bioturbation (Fig. 5f). These laminations consist of couplets of silt-rich and clay-rich laminae. Each couplet ranges from 0.2 to 1.5 mm in thickness and frequently reveals an apparent rhythmic pattern from the bottom to the top. Water content in the upper part ranges from 32 to 60% (average, 41%), and value of shear strength ranges from 0 to 0.28 kg/cm^2, (average, 0.13 kg/cm^2) (Fig.

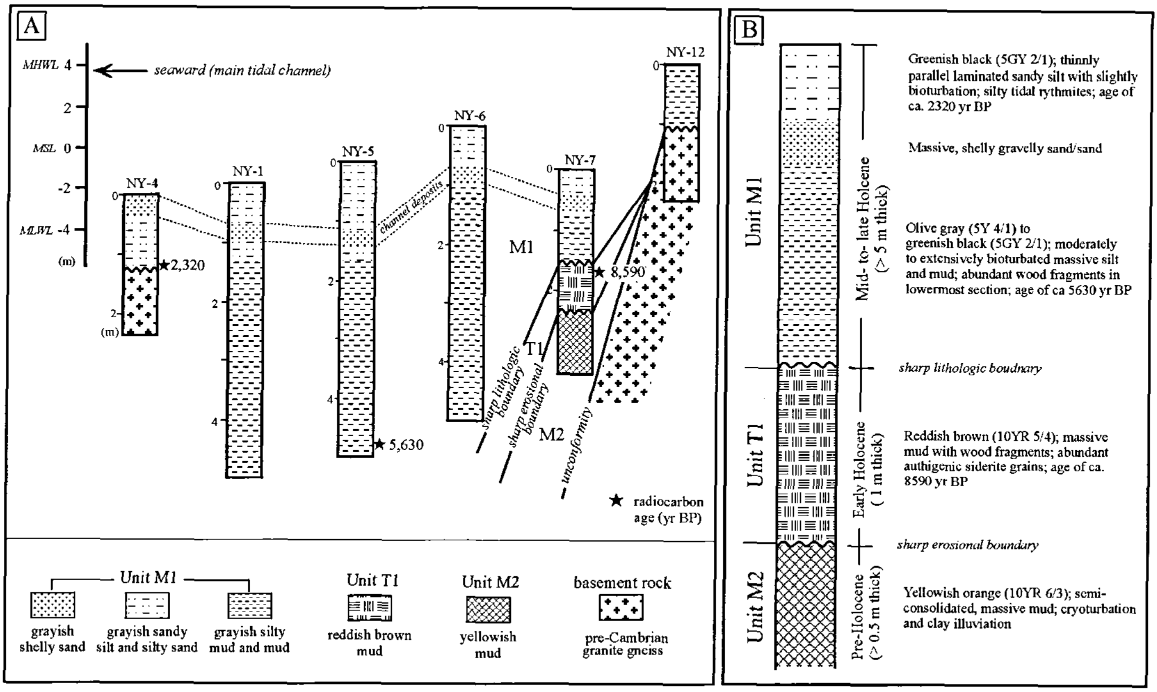

Fig. 3. (a) Lithostratigraphic cross-section of the Namyang tidal-flat deposits. (b) Representative columnar section and detailed description of Namyang-Bay cores. There are three stratigraphic units (Units M1, T1 and M2) overlying basement rock.

4). Coarse-grained (gravelly sand) sediments with abundant shell fragments occur at the upper 12 m core depth of all cores (Fig. 5g). The gravelly sand layers with 2030 cm thickness are bounded by a sharp erosional base.

The lower part of Unit M1 comprises a massive, greenish black (5GY 2/1) silt or mud having mean grain size of 7 to 9 phi with less than 10% sand content (Figs. 3 and 4). Mud contents are usually more than 85%, and increase gradually with core depth (Fig. 4). Overall, the sediments are homogeneous by intensive biogenic activities of benthic organisms but faint, thin parallel and undulatory laminae rarely occur as the alternations of silt- and clay-rich layers (Fig. 5h and 5i). Characteristically, lowermost section of this subunit contains the abundant plant debris and *in situ* wood stems (Fig. 5j). Water content and shear strength are average 37% (range, 32 to 45%) and 0.3 kg/cm^2 (range, 0.1 to 0.52 kg/cm^2), respectively (Fig. 4). In most of cores, water content decreases and shear strength increases with depth of burial, as a result of sediment compaction and consolidation.

Unit T1: reddish brown clay including siderite grains

Unit T1 is characterized by reddish or dark yellowish brown (10YR 4/2) clay sediments (average 8 phi in mean grain size) containing abundant authigenic siderite grains. This unit, which is overlain by Unit M1 with a distinctive sediment color and textural boundary, overlies Unit M2 with a sharp erosional boundary. This unit (0.7 m thick) consists predominantly of 53% silt and 45% clay, respectively. No primary sedimentary structures are found; but, burrows made by dwelling and feeding activities of benthic organisms are abundant. Wood fragments are abundantly scattered throughout this unit. Water content and shear strength are average 30% (range, 27 to 33%) and 0.32 kg/cm^2 (range, 0.22 to 0.56 kg/cm^2), respectively (Fig. 4). Organic carbon (POC) content ranges from 0.5 to 0.7%

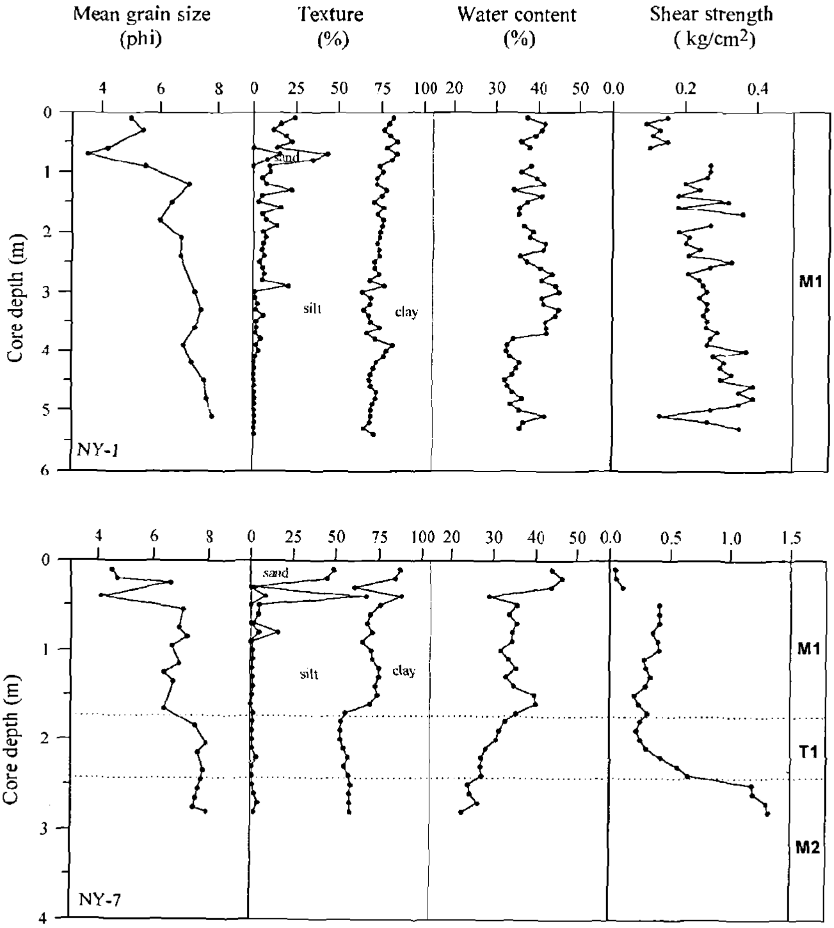

Fig. 4. Vertical variations of mean grain size, texture, water content and value of shear strength in core sediments. Unit Ml deposit shows a distinct coarsening-upward textural trend.

(average, 0.6%), that is considerably higher than Units Ml (range, 0.2-0.4%) and M2 (range, 0.3-0.4%), associated with abundant wood fragments. Characteristically, Unit T1 contains considerable amounts of diagenetic siderite grains and mud pellets. The more detailed description and interpretation on the siderite grains will be discussed later.

Unit M2: semi-consolidated, yellowish mud

Unit M2 consists of a fine silt and clay, yellowish orange (10YR 6/3) in color. The contact with the overlying unit is sharp and irregular, indicating an erosional nature of the boundary. Sand content is less than 4%, whereas silt and clay fractions are average 56% and 42%, respectively (Fig. 4). Sedimentary structure is rarely observed but the contorted laminations and irregularly spaced silt patches are observed occasionally. Cryoturbated structure and clay illuviation are the most characteristic features in this unit. Water content is very low (less than 25%), and shear strength abruptly increases to more than 1.3 kg/cm^2 across the boundary between Units T1 and M2 (Fig. 4). Organic carbon (POC) content ranges 0.3 to 0.4%, similar to that of Unit M1. Compared to the overlying Units M1 and T1, the yellowish sediment of Unit M2 is very stiff to hard, and is readily recognizable in the profile of geotechnical properties.

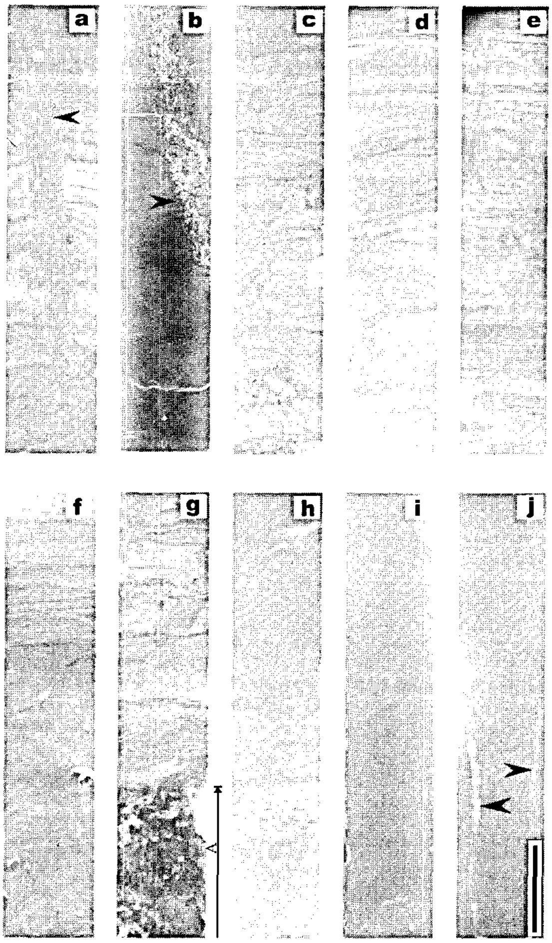

Fig. 5. Photographic prints of X-radiographs showing sedimentary structure of selected samples from Unit M1 deposit. (a) Biogenic escape sturcture (arrow); NY-5 at a depth of 0.6 m. (b) Burrow structure infilled by sands; NY-5 at a depth of 1.8 m. (c) to (e) Slightly bioturbated silt sediments with parallel laminae, corss-bedding and alternation of sand and silt layer; NY-1, 6 and 9 at depths of 0.1 m, 0.3 m and 2.7 m, respectively. (f) Well-laminated silt and fairly homogeneous silt sediment; NY-4 at a depth 0.1 m. (g) Intercalated shelly sand layer (Interval A); NY-1 at a depth of 0.6 m. (h) and (i) Extensively bioturbated, massive mud sediment; NY-6 at depths of 3.9 m and 4.2 m, respectively. (j) Mud sediments showing wood stems (arrow); NY-6 at a depth of 4.5 m. Scale bar is 5 cm.

Clay Mineral Assemblage and Magnetic Susceptibility

Clay mineral assemblage

Vertical variations of relative abundances of clay minerals are shown in Figure 6. Illite is the most dominant clay mineral, ranging from 50 to 67% (average 59%). Smectite varies from 1 to 11% (average 6%), and kaolinite and chlorite from 13 to 26% (average 19%) and from 11 to 27% (average 16%), respectively. According to Figure 6, clay mineral composition exhibits significant changes at the Unit M1-T1 zone boundary of the lithologic change. The abundance of illite and smectite minerals largely decreases below this boundary. Mean values of these two minerals in Unit T1 of core NY-7 are 50% and 3%, whereas 63% and 5% in Unit M1, respectively. Peak intensities are also greatly reduced in X-ray diffractograms compared with those of the overlying Unit M1. The clay mineral assemblages of Unit M2 are similar to those of Unit M1, although smectite mineral is in trace amount. They consist of 58% illite, 1% smectite, 22% kaolinite and 19% chlorite.

Magnetic susceptibility

Magnetic susceptibility (MS) and frequency dependence (FD) values in core NY-7 show a characteristic vertical variation, corresponding to lithostratigraphical unit (Fig. 6). In Unit M1, MS values range from 1.1 to 4.1 μSI (average, 1.9 μSI). Average MS values in the uppermost 0.4 m of Unit M1 are higher than 3.0 μSI, but are relatively constant between 1.1 and 2.0 μSI below 0.4 m. In Unit T1, on the other hand, MS values increase greatly from 2.0 to 12.0 μSI (mostly between 10.0 to 12.0 μSI), which are nearly 6 times as high as those of the overlying Unit M1. In Unit M2, MS values decrease again, ranging from 5.0 to 6.0 μSI (average, 55 μSI). The values, however, are higher than those of the soft gray muddy sediments in Unit M1. This result indicates that Units T1 and M2 sediments are largely enriched with ferromagnetic minerals.

Magnetic granulometry can be achieved with analysis of the frequency dependence (FD) of MS, giving only the magnetic domain state or effective magnetic grain size of the bulk sediment samples.

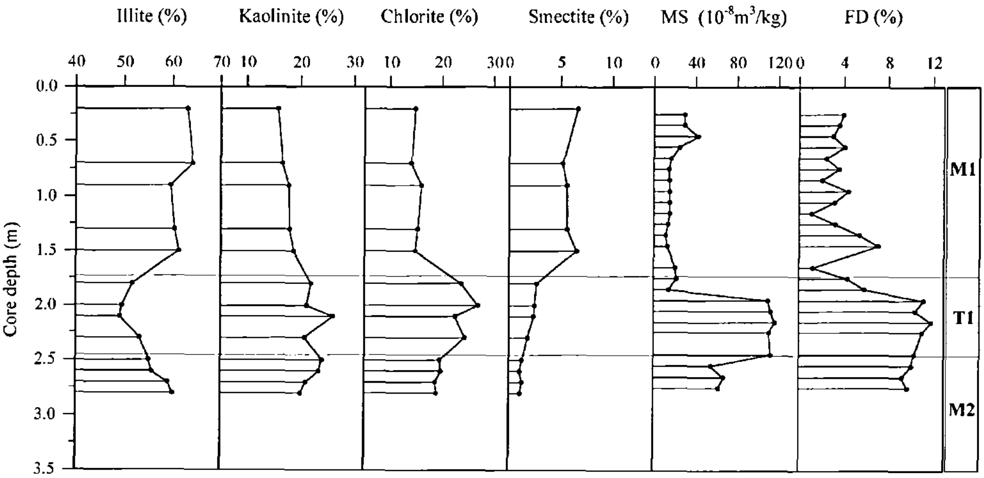

Fig. 6. Vertical variations of clay minerals, magnetic susceptibility (MS) and frequency dependence (FD) in core NY-7. Values of MS and FD largely increase in Unit T1 and M2.

That is, the increase in FD values indicates the enrichment of relatively finer magnetic minerals. In Unit M1, the FD values range from 1 to 6%, which appears to be fairly low compared with the underlying Units T1 and M2 (Fig. 6). In Units T1 and M2, the FD values are generally greater than 11%. MS values of Unit T1 are twice as high as those of Unit M2, but the FD values are constant in these two units. It suggests that the grain sizes of ferromagnetic minerals are similar in these two units (T1 and M2).

Authigenic Siderite Grains from Unit T1

Since siderites are generally formed in some special settings where sulfate activity is inhibited or restricted, the most favorable environments for its formation are the organic-rich, reduced freshwater sedimentary environments such as lake, swamp and marsh (Postma, *1981* and *1982*; Bahrig, *1989*; Zodrow *et al.*, 1996). Thus, the presence of siderite and its elemental composition are still of importance for understanding of the depositional environment (Browne and Kingston, 1993; Baker *et al.*, 1996; Khim *et al.*, 1999).

The early diagenetic siderite grains were abundantly identified from Unit T1 sediments (Fig. 7a). In Unit T1 sediments, siderite coalesces to form a band or chain shaped cluster up to several centimeters in length (Fig. 7b and 7c) and these bunches may be easily separated into individual spherosiderite grains. Each siderite grain typically occurs as a small spherulitic concretion, generally about 250 ìm in diameter, and is readily identified because of their dark yellowish brown color and rounded morphology. SEM image shows that each siderite grain is well-rounded and nearly spherical with texturally well-developed rhombs on the surface. Internal texture is massive and homogeneous without oolitic or concentric structure. Numerous ultra-fine grains (impurities) are randomly scattered within the grain (Fig. 7d and 7e). These impurities are commonly quartz, feldspar, and other foreign minerals. Similar spherulitic siderite grains of comparable size and morphology have also been reported in the lacustrine and swamp sediments (Zhang *et al.*, *1996*; Khim *et al.*, *1999*).

Geochemical compositions of siderite are relatively pure, containing 63 mol% $FeCO_3$ (range, 54~69%), 23 mol% $MnCO_3$ (range, 18~30%), and 11 mol% $CaCO_3$ (range, 7~15%) (Cho and Lim, 2002). $MgCO_3$ content ranges from 1 to 11 mol% (average, 3%) but mainly less than 4 mol%

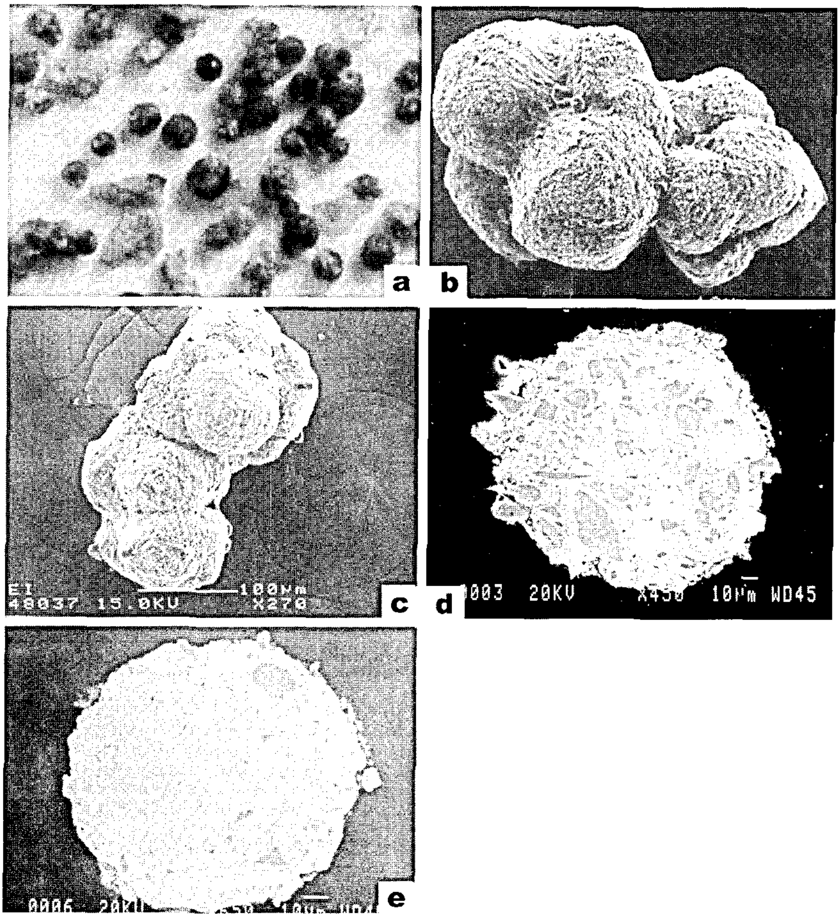

Fig. 7. (a) Siderite grains obtained from 2 phi fraction of the reddish brown sediments (Unit T1). (b) and (c) Scanning electron microphotographs showing a typical spherulitic form of authigenic siderite. (d) and (e) Back-scattering electron images of thin-sectioned siderites. Internal texture is massive, and many fine-grained quartz particles are randomly scattered within grains (After Cho and Lim, 2002).

$MgCO_3$. In the Mn-Ca-Mg ternary diagram, most of data (62 : 29 : 9) well fall into a group, suggesting that the siderite from Unit T1 sediments has a relatively uniform composition (Fig. 8). The compositional characteristics are very similar to those of freshwater siderites reported from the swamp sediments of Kyunggi Bay, Korea (Khim *et al.*, 1999), as well as the other non-marine environments elsewhere (Mozley, 1989; Baker *et al.*, 1996). Accordingly, the Mn-enriched and Mg-depleted siderites with consistent elemental ratios are the typical early diagenetic siderites formed in porewater with low Mg^{2+}/Ca^{2+} ratio of freshwater (Mozley, 1989).

Environment of Deposition

Mid-to-late Holocene tidal-flat deposit (Unit M1)

Unit M1 overlies Units T1 and M2 with a sharp boundary and different color. It consists primarily of thick deposits of sand, sandy silt, and mud extending across the entire intertidal flat of Namyang Bay. The lower part of Unit M1 is characterized by intensively bioturbated mud (> 85% mud), low water content and high value of shear strength. Faint, thin, parallel and undulatory laminae rarely occur as the alternation of silt-rich and clay-rich layers, and abundant wood stems and fragments are

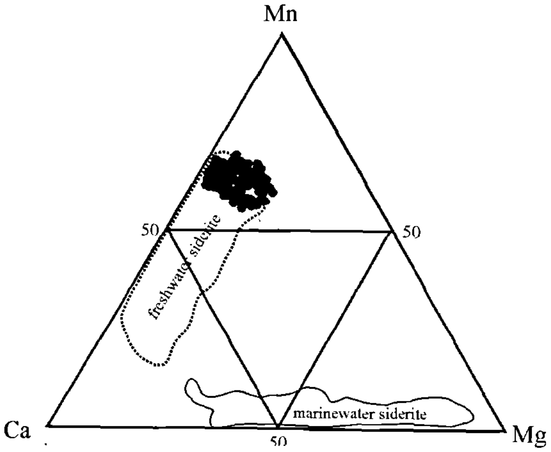

Fig. 8. Elemental composition of early diagenetic siderite from Unit T1 sediments (After Cho and Lim, 2002).

scattered in the lowermost section. Considering the modern surficial sediment distribution of tidal flat, the relatively high mud contents, massive structure by homogenizing effect of intense bioturbation and plant debris represent deposition in high tidal-flat environment dominated by suspension depositional processes (Reineck and Singh, 1980; Kim, 1989). Accordingly, the lower part of Unit M1 is interpreted as the mud-flat facies accumulated near high tide zone. Radiocarbon age of wood stems from the lowermost of this part is 5,630 ± 85 yr BP (core NY-5), suggesting that high tidal-flat deposits were beginning to develop in Namyang Bay.

The upper part of Unit M1, on the other hand, is characterized by moderately bioturbated sand and sandy silt with relatively well-preserved laminae showing rhythmic pattern in their thickness. These laminae are related to typical tidal deposition processes consisting of alternations of bedload and suspension sedimentation processes under fair-weather condition and their rhythmic pattern also indicate a vertical record of neap-spring tidal cycles. Considering the sedimentological characteristics and the modern surficial sediment distribution, the upper part of the unit is considered to represent mixed-flat sedimentation between high water level and low water level. A fresh oyster shell from the base of this subunit is dated at 2,321 ± 65 yr BP (core NY-4), which is regarded as the initiation of mixd-flat deposition above the muddy hightidal flats. Relatively coarse texture, abundant shell fragments and sharp erosional base of the gravelly sand layers in this unit are interpreted as the basal lags of channel bottom (Reineck and Singh, 1980; Kim *et al*, 1999), as most of core sites are near the tidal channel (sea Fig. 1).

Overall, Unit M1 exhibits a coarsening-upward textural trend from mud (high tidal-flat deposition) to sandy silt (mixed tidal-flat deposition), suggesting that the Korean tidal flats have been of a retrogradational system during the rapid Holocene sea-level rise over the last 5,000 yr BP. This retrograding, coarsening-upward succession of Namyang mudflat deposit is opposite to that of the generalized models for worldwide prograding intertidal flats such as the North Sea and Bay of Fundy (Klein, 1977, 1985; Reineck and Singh, 1980; Dalrymple, 1992). Generally, prograding coastal sequence models are often associated with high sedimentation rate in the downdrift deltaic setting of major rivers providing the numerous sediment input or the protective embayment setting that sedimentation are restricted. By contrast, the retrograding, coarsening-upward sequence in the non-barred, macrotidal tidal flats of Korea seems to result largely from relatively low sedimentation rate during the mid-to-late Holocene transgression (Kim *et al.*, 1999).

Early Holocene swamp or bog deposit (Unit T1)

The clay sediments of Unit T1, which are overlain by Unit M1 with a distinctive lithologic boundary and underlain by Unit M2 with a sharp boundary, are characterized by reddish sediment color, homogeneous sediment structure, and abundant siderite grains and wood fragments. Fine-grained sediment texture and abundant wood fragments strongly suggest a fine suspension depositional process. In addition, siderite grains from this

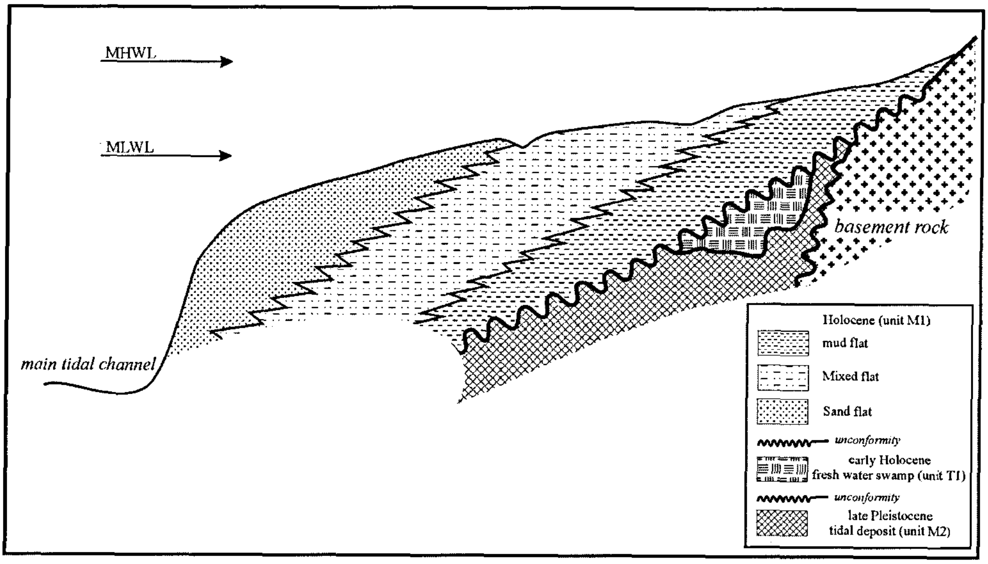

Fig. 9. A Schematic diagram showing stratigraphy of Namyang macrotidal flat deposit, west coast of Korea, based on the sedimentary facies of surficial and vertical core sediment samples. MHWL: Mean High Water Level, MLWL: Mean Low Water Level.

unit might have precipitated in non-marine environments, like the swamps or bogs. Wood fragments obtained from this unit were dated at 8,597 ± 77 yr BP. At this time, the sea-level in the western coast of Korea (e.g., Park, 1969; Chang *et al.*, 1996) was below at least 10-20 m from present-MSL (mean sea-level). This fact indicates that Unit T1 may then have not been directly related to the sea-level. Considering a series of results such as radiocarbon age, authigenic siderite grains and lithological features, Unit T1 is interpreted as freshwater deposition (e.g., swamp or bog), infilling the topographic depressions that locally existed before the formation of mid-to-late Holocene tidal flats (Unit M1). In this unit, magnetic susceptibility enhancement with a high FD value is strongly suggestive of the relatively high concentration of ultrafine ferrimagnetic minerals. It is attributed presumably to either an increase of the detritus supply of ferromagnetic minerals or ferrimagnetic authigethesis due to *in situ* redox variations. The formation of authigenic siderite implies that authigenic formation of ultrafine ferromagnetic minerals is possible in this swamp deposit. Furthermore, the systematic difference in clay mineral composition showing the low abundance of illite is probably associated with non-marine depositional environments (Chough, 1983).

The siderite-hosting clay sediments (Unit T1) are coeval with those from tidal flats of Youngjong Island (Khim *et al.*, 1999). By 7-8 ka BP, the Holocene transgression had not yet reached the present-day tidal flat, whereas the warm and humid climate favored the formation of freshwater swamp in the topographic lows where fine-grained sediment and organic debris accumulated.

Late Pleistocene deposits (Unit M2)

Although the retrieved core samples by vibracoring technique is limited, recognition of Unit M2 seems to be important finding on the stratigraphic study of the Korean tidal-flat deposit. Compare with the overlying units, Unit M2 is characterized by semi-consolidation condition of sediment, yellowish sediment color, and mud facies with clay-illuviation and cryoturbation. The yellowish sediment color and the dewatered nature (high shear strength and low water content) preliminarily attest to a subaerial exposure of the sediments during the sea-level lowstand. Further supporting evidence for the subaerial exposure is provided by the depletion of smectite and the high value of magnetic susceptibility. Unit M2 sediments are characterized by the lack of smectite, in contrast to the clay mineral assemblages of Unit M1. Generally, smectite is well known to be a unstable clay mineral in the subaerial condition, and thus may be vulnerable to acidic groundwater dissolution and/or mechanical weathering (Adams *et al.*, 1971; Boles and Franks, 1979; Segal *et al.*, 1987; Park *et al.*, 1998). Similar change due to post-depositional weathering of marine clays have been documented from the subaerially exposed upper part of the late Pleistocene deposits of Korea (Park *et al.*, 1997; Park *et al.*, 1998). This interpertation is further corroborated by the high degree of magnetic susceptibility. Authigenic pyrites that is commonly rich in marine clays (especially tidal flat with abundant organic materials) were likely to be subjected to oxidation when the deposits were under terrestrial conditions. As a consequence of the oxidation of non-magnetic pyrite, the iron oxide content within the sediments may have been higher and would have led to the formation of other authigenic magnetic minerals (mainly ultrafine maghemite and magnetite) increasing the magnetic susceptibility (Yim, 1997). So, the relatively high abundance of these magnetic minerals in the exposed sediments is attributed to *in situ* pedogenic production during the sea-level lowstands. Similar formation of diagenetic magnetic minerals by *in situ* pedogenic processes have been reported from the upper late Pleistocene deposits of the Haenam and Youngjong Island tidal flats (Park *et al.*, 1998; Moon *et al.*, 2000).

As a result, Unit M2 was subjected to subaerial exposure after deposition, with the consequent development of a soil exhibiting a cryogenic structure (cryoturbation), a kind of periglacial signature, which reflects the dry and cold climatic condition with almost freezing temperature (Butrym *et al.*, 1964; Oh *et al.*, 1995). Although direct inference of age of the weathered deposit is difficult, pre-Holocene age to Unit M2 deposit can be indirectly inferred from the circumstantial evidence including an age of the overlying Unit T1, a protracted period of subaerial exposure and diagenetic properties. Geologically, in many locations, such altered pre-Holocene sediments with an interpolated age of 125 ka (oxygen isotope substage 5e) are recognizable in the stratigraphic sections of the western Korean coasts (Kim and Park, 1988; Park *et al.*, 1991; Park *et al.*, 1997; Park *et al.*, 1998). Therefore, the subaerial unconformity between Holocene and pre-Holocene deposits might be coeval with among the Korean tidal flats, and can be used as a regional stratigraphic marker.

The lithologic features of Unit M2 are very similar to those of the upper part of the late Pleistocene interglacial tidal deposit, subjected to post-depositional weathering during at least one episode of sea-level lowstand (Park *et al.*, 1997; Park *et al.*, 1998; Park and Choi, 1998). The late Pleistocene deposits in other Korean tidal flats are up to 20 m in thickness and contain a variety of tide-influenced sedimentary structures including a silty rhythmic tidal bedding, fossil crab burrows and abundant marine dinoflagellate cysts (Park *et al.*, 1998; Park and Choi, 1998; Lim, 2001). Because of the subaerial exposure providing a potential condition to degrade the original properties of sediments, sedimentary structures and microfossils are poorly preserved in their upper part (Lim, 2001). Nevertheless, fine-grained muddy sediments of Unit M2 indicate a low-energy regime in the depositional condition, which is most likely to be analogous to the modern tidal flat. In addition, the clay mineral assembalges of Unit M2 are similar to those of the Holocene coastal muds (Unit M1), but are different largely from those of terrestrial sediments or soils with a low content of illite and high content of kaolinite (Chough, 1983; Park *et al.*, 1998; Moon *et al.*, 2000). Consequently, Unit M2 sediments in this study are interpreted as a remnant of a much thicker late Pleistocene tidal deposit, although the studied cores cannot provide a proof of a complete succession. This unit permits an assessment of the preservation potential of late Pleistocene tidal deposit and also provides stratigraphic information that may be used to account for the Holocene-late Pleistocene unconformity along the western coast of Korea.

Conclusions

Seven vibra-cores (down to 6.0 m long) have been analyzed to understand sedimentology and stratigraphy (Holocene to pre-Holocene) of the macrotidal deposits of Namyang Bay, western coast of Korea. The stratigraphy of the Namyang tidal-flat deposit consists of three late Quaternary units: a soft, gray mud and sandy silt deposit (Unit M1), a reddish brown mud deposit (Unit T1), and a semi-consolidated, yellow mud deposit (Unit M2) in descending order (Fig. 9). The uppermost stratigraphic Unit M1, which overlies two different stratigraphic Units unconformably, is a typical mid-to-late Holocene tidal-flat deposit showing a coarsening-upward, retrogradational sequence. Such coarsening-upward sequence in the Korean tidal flats may be attributable chiefly to a considerably low sediment accumulation during Holocene transgression. The underlying Unit T1 consists of reddish brown sediments containing abundant plant remains and freshwater siderite grains. This unit is interpreted to have accumulated in the terrestrial environments (swamp or bog) during early Holocene (8,597 ± 77 yr BP) before Holocene transgression. Overlain by Unit T1 with a sharp erosional unconformity, Unit M2 is characterized by the semi-consolidated, yellowish muddy sediments and is probably correlated with late Pleistocene interglacial tidal deposit. Sedimentological and clay mineralogical data, geotechnical properties and magnetic susceptibility indicate that Unit M2 has undergone intensive weathering during the sea-level lowstand(s), possibly last glacial maximum (LGM).

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