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Vegetation changes in western central region of Korean Peninsula during the last glacial (ca. 21.1–26.1 cal kyr BP)

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ABSTRACT: Age-controlled pollen record from wetland sediments of Hanam, western central Korean Peninsula (KP), reveals vegetation dynamics response to climate changes during the last glacial, 26.1–20.1 cal kyr BP. The Hanam pollen assemblages are dominated by conifers, *Picea* and *Pinus* and cold tolerant deciduous broadleaved *Betula*, together with common xerophytic herb like *Artemisia* and Gramineae. Principal taxa are similar to those of subalpine forest in modern vegetation of KP. Humidity variation reconstructed by semi aridity index (AI) indicates that, during 26.1–22.7 cal kyr BP, cold and dry conditions were prevailed with an expansion of subalpine coniferous forest and high value of AI. From 22.5 to 20.5 cal kyr BP, cool and wet conditions were reconstructed with low value of AI due to climatic amelioration, enhanced conifers and temperate deciduous broadleaved mixed forests flourished. Between 20.3 and 20.1 cal kyr BP, an abundance of *Picea* and *Betula* associated with high value of AI infers that subalpine conifers forest colonized again in hinterland montane along with open, low grassland under colder and drier conditions owing to climatic deterioration. The principal pollen taxa suggest that prevailing climate conditions were annual mean temperature about 5–6 °C colder and annual mean precipitation 40% drier than today.

Key words: Pollen, vegetation, aridity index, Korea, Hanam, the last glacial

1. INTRODUCTION

Only few records of last glacial deposits of South Korea have known, which are sporadically distributed as glacial paleosol mainly because of erosional conditions on exposed lowland surface (Kim, 2001). Recently the more active Palaeolithic archaeological excavations have provided more late Pleistocene deposits and more opportunities for palynological studies to reconstruct vegetation and environments during the last glacial period.

Pollen is one of the most suitable 'proxies' for terrestrial paleoclimate. It has proven to be a useful tool in investigating climate changes (Birks and Birks, 1980). Palynology is useful to examine the impact of rapid climate changes on terrestrial ecosystems, because vegetation dynamics response to a climate change is pronounced within a decadal time scale (Tinner and Lotter, 2001). Recently a number of postglacial (Holocene) palynological studies from wetlands of the western and central of the Korean Peninsula have been performed (e.g., Yoon, 1997; Yoon and Kim, 2001; Yi et al., 2004, 2005, 2008; Chung et al., 2006; Jang et al., 2006). However, few palynological studies on the last glacial (late Pleistocene) period have been reported so far only in western lowlands of Korea (Chang et al., 1996; Chung and Lee, 2006; Chung et al., 2006; Yi et al., 2007). In this study, we first attempt to implicate vegetation covers in the Korean- 'Western Central Region' based on compiled age-controlled pollen data set.

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2. STUDY AREA

Hanam, a southeastern satellite city of Seoul (the capital city) is located in the western central Korean Peninsula (Fig. 1a). This area is composed of Precambrian Gyeonggi Metamorphic Complex and Quaternary alluvium. The alluvial sediments consisting of gravel, sand and mud are unconformable overlying the basement rocks of Precambrian Gyeonggi Metamorphic Complex. Modern climate of the Hanam area is characterized by mean annual temperature of 12.2 °C and mean annual precipitation of 112 mm. The maximum temperate (monthly mean) is up to 16.9 °C while minimum temperature (monthly mean) is recorded 8.2 °C, respectively, during the last 30 years. The maximum precipitation (monthly mean) is up to 348 mm in August, whereas minimum precipitation (monthly mean) is down to 21.6 mm in January, respectively, during the past 30 years (http://www.kma.go.kr) (Fig. 1b). Modern vegetation of this area is occupied by temperate deciduous broadleaved forest and coniferous forest distributed and controlled by altitude within the landscape. Main components are *Pinus densiflora* Sieb. Et Zucc. and *Quercus acutissima* Carr. (Ministry of Environment, http://www.egis.me.go.kr) (Fig. 1c).

3. MATERIALS AND METHODS

The studied section of core UD–2 was obtained from the Hanam (37°32'43"N, 127°12'34"E) with an elevation of 19 meters. The section consists mainly of organic-rich gray silty mud and massive or finely laminated mud (Figs. 2 and 3). From the 180 cm long core, thirty-four dried subsamples

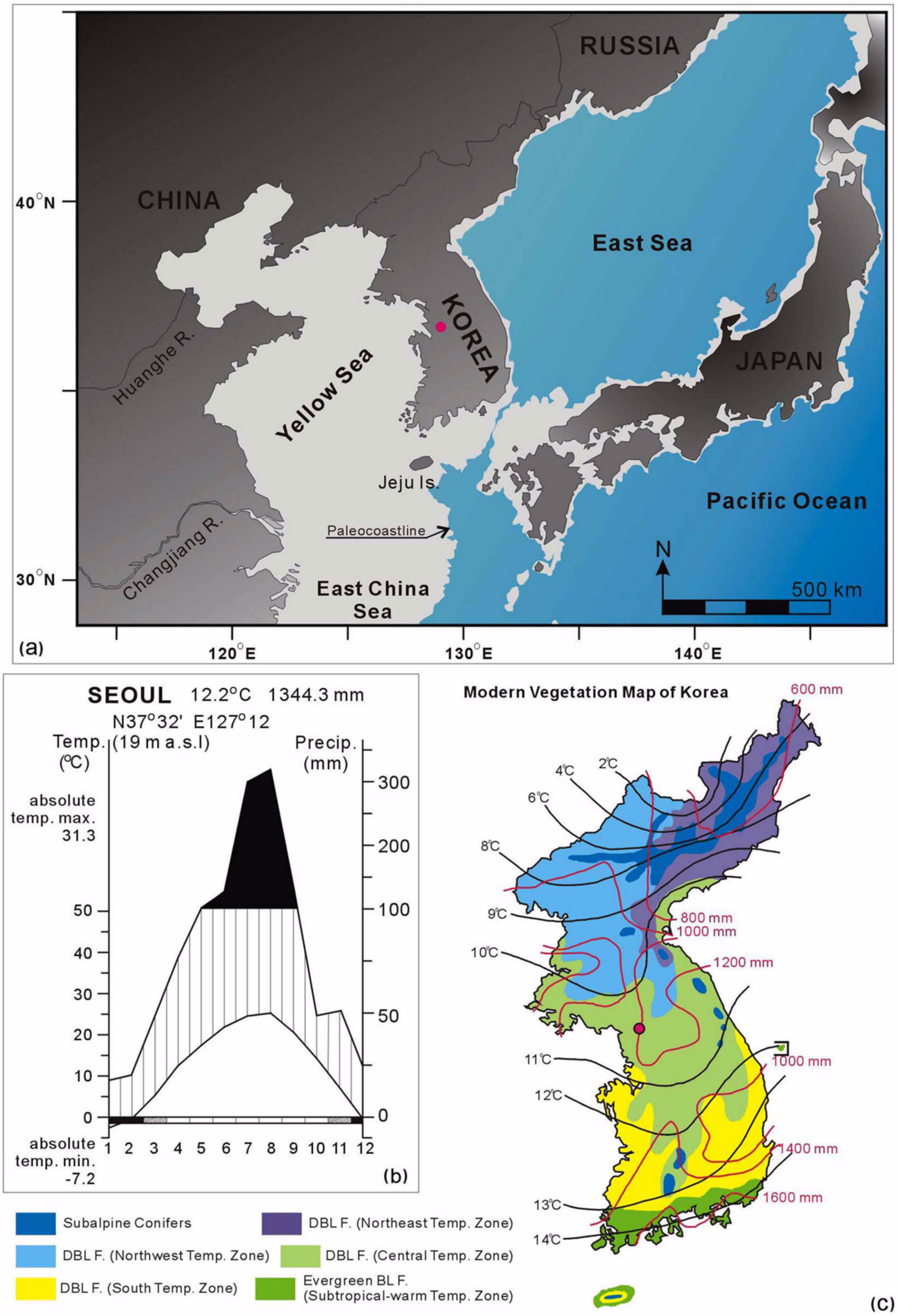

Fig. 1. (a) Paleogeographic map showing the subaerially exposed bottom of the Yellow Sea during the last glacial maximum (LGM). (b) Seasonal changes in temperature and precipitation in Seoul–Hanam area based on Korea Meteorological Administration (http://kma.go.kr). (c) Modern vegetation map with contours of annual mean temperature and annual mean precipitation (modified from Yim and Kira, 1975).

of 5 g each were taken every 5-cm for pollen analysis. Pollen grains were extracted by using standard laboratory methods as suggested by Moore et al. (1991): the sediments were treating with cold HCl and cold HF to remove carbonate

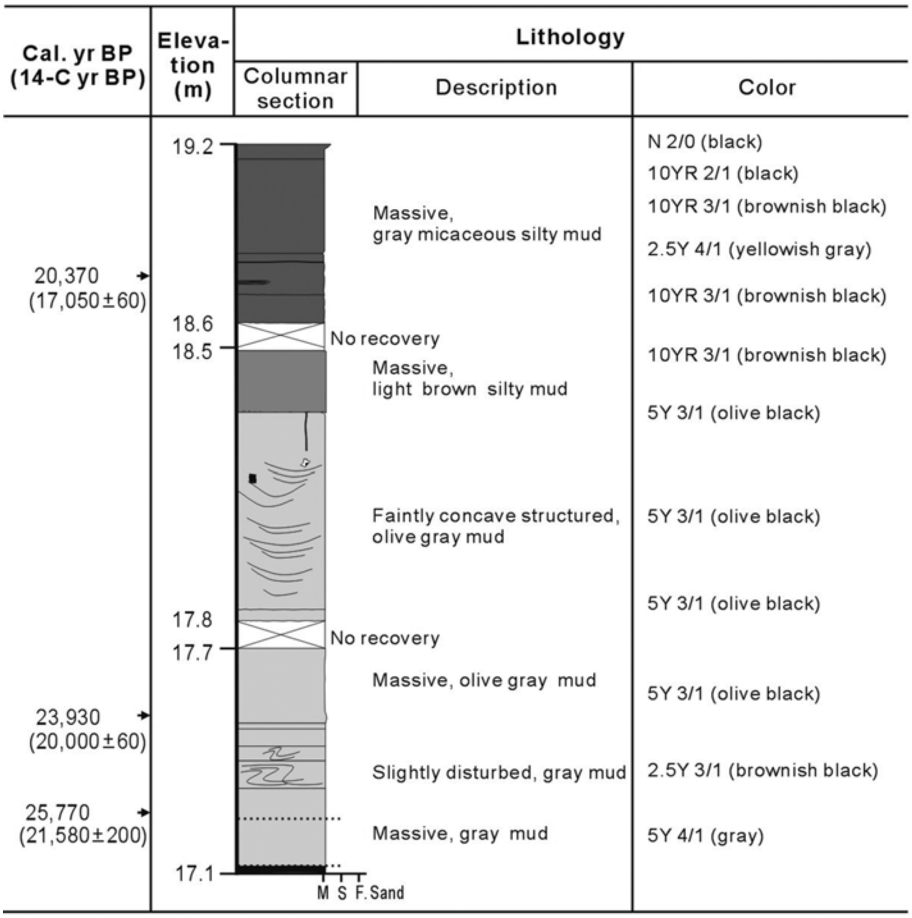

Fig. 2. General lithologic description of Core UD–2, Hanam with calendar ages.

and silicate. An excess organic fraction was removed by boiling in KOH. Sieve of 10 and 120 μm was used to remove fine and coarse fractions, respectively. Two tablets of exotic *Lycopodium* spores were added to each dried subsamples so as to estimate the pollen concentration. Palynofloras were quantified up to 300 for total counts. The percentages of arboreal pollen (AP), nonarboreal pollen (NAP), and spores were calculated from the total palynomorphs sum excluding freshwater algae. Pollen data analysis, pollen diagram and the determination of pollen zones, was carried out with TILIA v2.0, TILIGRAPH v1.25 and CONISS software (Grimm, 1987, 1991, 1993). Pollen taxa used to generate the zonation dendrogram included AP and NAP with values of at 2% in two intervals. Taxonomic identification of pollen was aided by comparative study from the published references material available (Chang and Rim, 1979; Chang, 1986).

4. RESULTS

4.1. Sediment Chronology

The chronological control for the palynological records was supported by radiocarbon dates. Three AMS radiocarbon dates were obtained from the National Center for Inter-University Facilities of the Seoul National University. The dates were calibrated at the 2-sigma confidence level using the CalPal2007$^{\text{online}}$ program by Danzeglocke et al. (2008) with CalPal-2007$_{\text{Hulu}}$ calibration data (Weninger and Jöris, 2008). Calibrated ages before present (cal yr BP) are applied in the present study. We calculated the average only for those age ranges with the highest probabilities (Weninger and Jöris, 2008) (Table 1). The radiocarbon dates of the sediments successions studied here from Core UD–2 span late glacial period from ca. 26.1–20.1 cal kyr BP (21–17 ^{14}C kyr BP).

4.2. Pollen Assemblages

The relative abundance of pollen spectrum studied was sufficient to reveal underlying trends of vegetation history (Fig. 4). The principal pollen taxa observed were specifically of trees – *Picea*, *Pinus*, Taxaceae-Cephalotaxaceae-Cupressaceae (T-C-C), *Betula*, *Quercus* and *Myrica*, and herbs – Cyperaceae, Gramineae, Compositae and *Artemisia*. Pteridophytic spores and freshwater algal zygospores were also present. Three local pollen assemblage zones (HA–I~III) were erected using statistical analysis (CONISS). Ages of

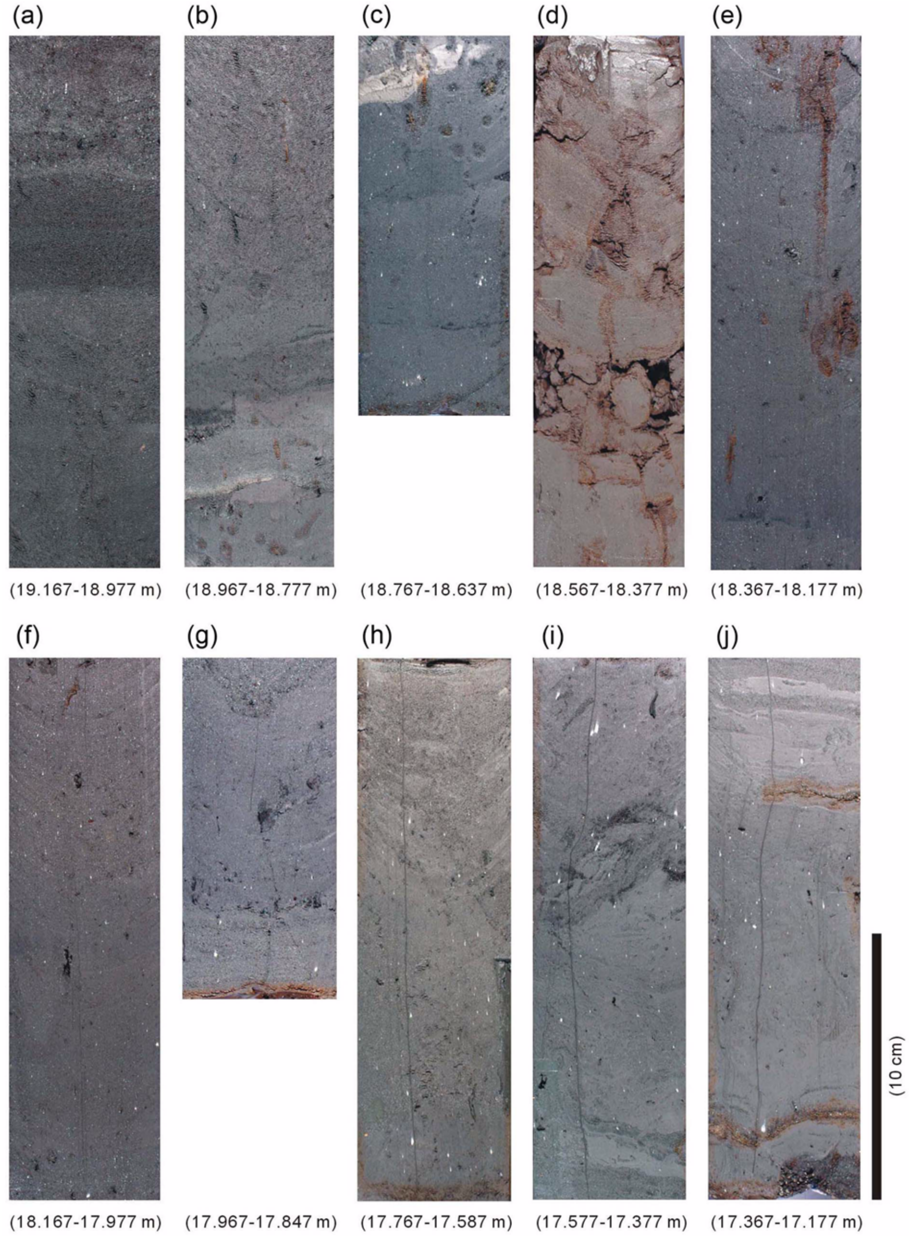

Fig. 3. Photographs from the UD–2 core. (a) (Elevation 19.167–18.977 m): Massive gray micaceous silty mud. (b) (Elevation 18.967–18.777 m): Massive light gray micaceous silty mud in upper part, faintly layered silty mud in lower part. (c) (Elevation 18.767–18.637 m): Massive light gray silty mud. (d) (Elevation 18.567–18.377 m): Massive light brown silty mud, ferromagnetic oxidized margin along the crack. (e) (Elevation 18.367–18.177 m): Massive gray silty mud, ferromagnetic oxidized margin along the vertical crack in upper part. (f) (Elevation 18.167–17.977 m): Faintly laminated gray silty mud. (g) (Elevation 17.967–17.847 m): Faintly laminated gray sandy silt. (h) (Elevation 17.767–17.587 m): Olive gray mud, concave laminated in upper part. (i) (Elevation 17.577–17.377 m): Massive olive gray mud with some sedimentary structures. (j) (Elevation 17.367–17.177 m): Massive olive gray mud, thin ferromagnetic oxidized silt along the crack.

Table 1. Radiocarbon dates of the UD–2 profile dated with the AMS method. Calendar years are recalculated on the basis of CalPal2007^{online} (Danzeglocke et al., 2008)

Core No.	Sample No.	Elevation (m)	Material	δ^{13}C (‰)	Conventional C-14 age (yr BP)	Calendar age (2σ, yr BP)	Calendar year	Laboratory No.
UD2–1	UD2–1–3–65	18.717	Sediment bulk	–23.04	17,050 ± 60	20,375 (20,020–20,730)	BC 18424 ± 354	SNU06–328
	UD2–1–5–27	17.497	Sediment bulk	–22.91	20,000 ± 60	23,925 (23,620–24,240)	BC 21976 ± 314	SNU06–330
	UD2–1–5–54	17.227	Sediment bulk	–26.93	21,580 ± 200	25,770 (25,270–26,270)	BC 23822 ± 500	SNU06–331

pollen zone boundary were also established by the interpolation in age–depth curve (Fig. 5). It should be noted that characteristics of the age-controlled local pollen assemblage zones are described in ascending order.

HA–I (depth 380–305 cm, ca. 26.1–22.7 cal kyr BP) is dominated by conifers, *Picea*, *Pinus* (*Diploxylon*), T-C-C among the AP, along with common broadleaved deciduous trees of *Myrica*, *Betula* and *Ulmus*/*Zelkova*. Herbs, including Cyperaceae and *Artemisia*, with common Gramineae are dominant among the NAP. In addition, accessory herbaceous taxa are present throughout this zone.

HA–II (depth 300–235 cm, ca. 22.5–20.5 cal kyr BP) is

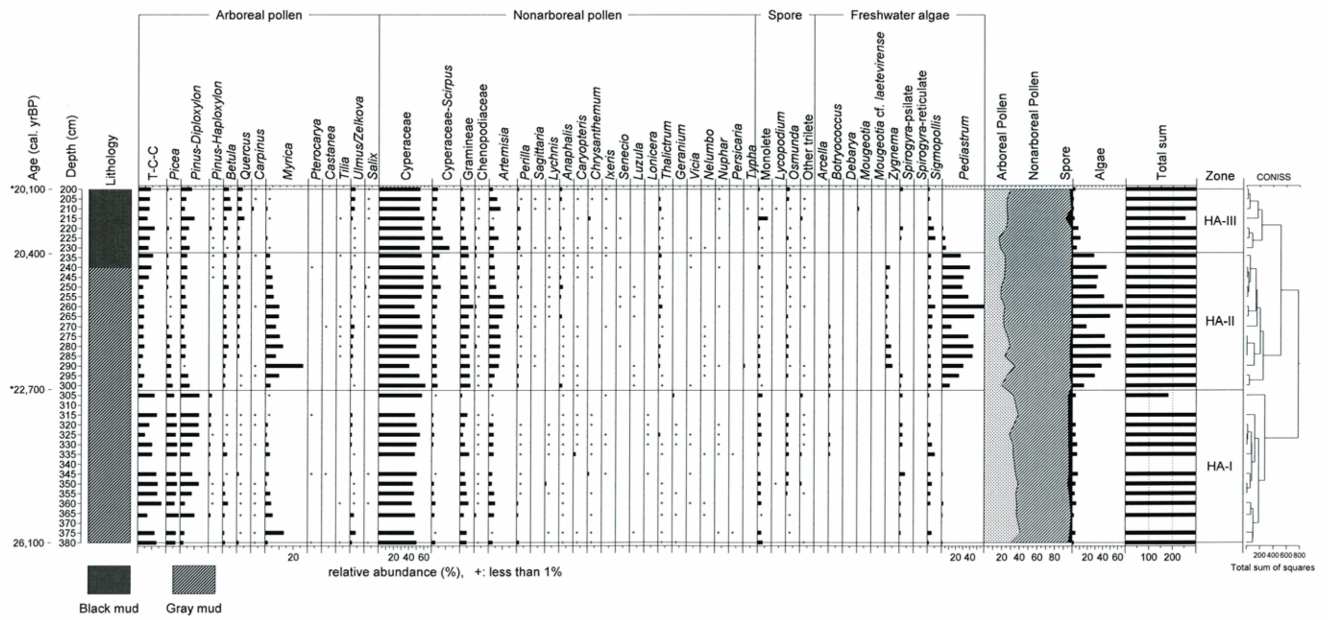

Fig. 4. Pollen diagram of Core UD–2, Hanam. T-C-C: Taxaceae-Cephalotaxaceae-Cupressaceae. Calibrated radiocarbon dates are shown on the left side of the diagram. The dendrogram on the right side was generated by constrained cluster analysis with CONISS software (Grimm, 1987).

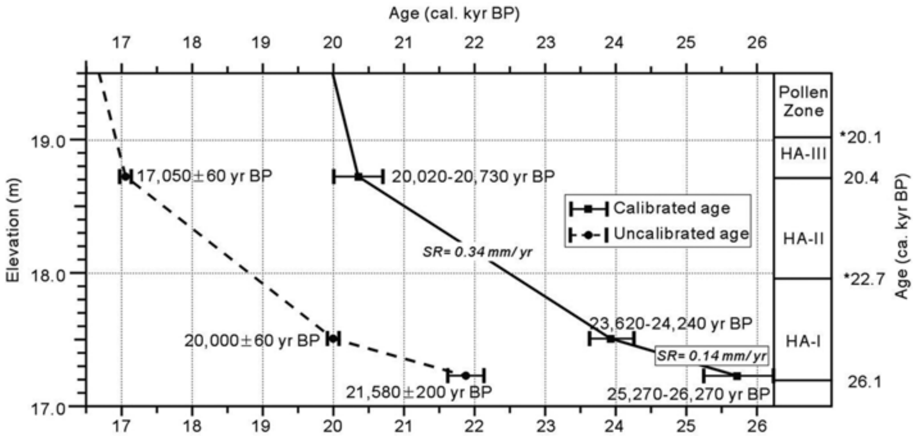

Fig. 5. Age–depth relationship for Core UD–2. Sedimentation rates were calculated by linear interpolation between calibrated ^{14}C ages.

defined by the obviously increase in broadleaved deciduous trees of *Myrica*, *Quercus* and *Betula*, and the apparently decrease in conifers, such as *Picea*, *Pinus* and T-C-C among the AP. In NAP, Cyperaceae is still predominant and slightly increases from the preceding zone. Here Gramineae shows somewhat increasing trend which *Artemisia* decreases throughout the zone. On the other hand, in contrast to the percentage pollen diagram, absolute pollen concentrations of all taxa obviously fall from the preceding zone. Freshwater green colonial alga, *Pediastrum*, is predominant in association with common zygospores namely *Zygnema* and *Spirogyra*.

HA-III (depth 230–200 cm, ca. 20.3–20.1 cal kyr BP) is characterized by relative expansion of conifers, *Picea*, T-C-C and *Pinus*, and broadleaved deciduous trees including *Betula*, *Quercus* and *Ulmus*/*Zelkova*. Cyperaceae predominates among the herbs. Gramineae decreases upward, but *Artemisia* increases toward the top. Colonial green alga, *Pediastrum*, suddenly decreases and finally disappears in the middle of the zone.

5. DISCUSSION

5.1. Vegetation on Western Central Korean Peninsula and Subaerially Exposed Bottom of the Yellow Sea

Palynofloral assemblages from the core UD–2 typically contain 60–76% arboreal pollen (AP) and 20–34% nonarboreal pollen (NAP), and 1–2% pteridophytic spores. The predominant AP includes *Picea*, *Pinus* and T-C-C, together with common *Betula*, *Quercus* and *Myrica*. Cyperaceae, Gramineae and *Artemisia* are the most common NAP taxa

(Fig. 4). In our record, the last glacial (ca. 26.1–20.1 cal kyr BP), is characterized by the expansion of *Picea* (spruce), *Pinus* (pine) and T-C-C in herbaceous-dominant environment along with scattered pockets of deciduous trees. The pollen zones reflect remarkable vegetation changes by the apparent fluctuations in frequencies of principal palynofloras.

The pollen assemblages of HA–I consist mainly of conifers and grasses. The predominance of subalpine taxa, *Picea* (spruce), *Pinus* (pine) and T-C-C, and xerophytic herb *Artemisia* and Gramineae suggests the prevailed open and lower grassland accompanying subalpine forests. Remarkable proportions of subalpine conifers and deciduous broadleaved trees, involving *Picea*, *Pinus* and *Betula* (birch), are assumed to reflect the montane vegetation of the hinterland. At an altitude of about 1,000–2,000 m the subalpine conifers of *Picea* (spruce) are seen in Korea. Moreover, cool-loving deciduous broadleaved *Betula* (birch) is also found today at 800–1,000 m in this region (Lee and Yim, 2002). Considering the low topography of the Hanam area (30–200 m average sea level) and climate deterioration it is observed that considerable colonizing of subalpine taxa has implied the expansion of the subalpine forest belts to the lowland.

Beginning of HA–II, the pollen assemblages reflect a slight moving up of subalpine forest belts. This is evidenced by decline in subalpine conifers of *Picea* (spruce) and *Pinus* (pine) and cool-tolerant *Betula* (birch) together with regress xerophytic herb *Artemisia*. Increase in cool temperate deciduous broadleaved *Quercus* (oak) and *Myrica* (bayberry) is also observed. The HA–II pollen zone indicates that open and low grassland still existed along with the mixed subalpine conifers and deciduous broadleaved forest in the mountainous area under slight climatic amelioration.

The pollen assemblages of HA–III indicate a change similar to HA–I. Subalpine conifers such as *Picea* (spruce) and *Pinus* (pine) and cold preferring deciduous broadleaved *Betula* (birch) are common. Moreover, dry tolerant herb *Artemisia* (sage) and Gramineae (grass) show a high concentration. On the other hand, temperate deciduous broadleaved *Quercus* (oaks) and *Myrica* (bayberry) are found to be decreased. The pollen zone indicates that the subalpine conifers forest belt was further lowering in altitude under climatic deterioration.

For the last glacial period, previous palynological studies from the continental shelf deposits of the Yellow Sea have been conducted. In this study it was noted that terrestrial herb pollen including Chenopodiaceae, Gramineae, Cyperaceae, Compositae, Umbelliferae and *Artemisia* were predominant along with common wind driven coniferous pollen of *Picea* and *Pinus* (Wang et al., 1987; Chang et al., 1996). These herb grains are derived mainly from dry tolerant grasses like steppe in high latitude of northeast Asia today (Fowell et al., 2003). The pollen assemblages also indicate that the prevailing vegetation was steppe on the subaerially exposed bottom with open and low gradient during the last glacial. The reconstruction of late glacial biomes here is broadly consistent with previous palynofloral studies (Xu, 1982; Han and Meng, 1986), which suggest that steppe vegetation occupied the continental shelf of the Yellow Sea. Interestingly the herbaceous vegetation characteristics are very comparable to those of Northern Central Mongolia (Fowell et al., 2003) and Inner Mongolia (Liu et al., 2000) at present.

5.2. Temperature and Precipitation

According to modern vegetation of the Korean Peninsula (Yim and Kira, 1975), the spruce (*Picea jezoensis*) is one of the main taxa of subalpine forest growing at Annual Mean Temperature (AMT) 2–6 °C and Annual Mean Precipitation (AMP) 600–800 mm. Hardwood birch (*Betula platyphlla* var. *japonica* and *B. chinensis*) is main element of northern temperate zone of deciduous broadleaved forest preferring 2–10 °C of AMT with 600–1,100 mm of AMP. At present, Hanam area has an environment with characteristic of AMT 10–11 °C and AMP 1,200 mm and belongs to central temperate zone of deciduous broadleaved forest (Yim and Kira, 1975; Lee and Yim, 2002) (Fig. 1c). Comparing to modern biomes, the principal pollen taxa encountered here suggest that prevailing climate conditions was AMT 5–6 °C colder and AMP 40% drier than today. This estimation is consistent with the high-resolution climate simulation by Kim et al. (2006, 2008) who documented about 5–6 °C colder and much drier in the LGM than present.

The present flora of Mongolia's northern half is covered primarily by steppe and forest-steppe vegetation. This vegetation is controlled by East Asian monsoon system with annual temperatures ranging from a mean summer maximum of 1–5 °C to a mean winter minimum of –20 °C (Fowell et al., 2003). The climate conditions can be assumed to be similar to those of the Korean Peninsula during the last glacial period which is about 5–6 °C colder than those of today (Kim et al., 2008). Moreover, the Yellow Sea during the last glacial period was subaerially exposed and resulted in open, low-gradient surface with steppe vegetation because sea-level was as low as –130 m (Fig. 1a).

In North Central Mongolia today, Chenopodiaceae and *Artemisia* are high pollen producers in cool and arid regions, whereas Cyperaceae and Gramineae exhibit low pollen production. As mentioned earlier, it is presumed that last glacial climate conditions around the Korean Peninsula were comparable to present climate conditions of North Central Mongolia. Here, we adopted the semi-quantitative aridity index (AI) calculated by ratio of (Chenopodiaceae + *Artemisia* / Cyperaceae) (Fowell et al., 2003). High values of the index are indicative of relatively dry conditions,

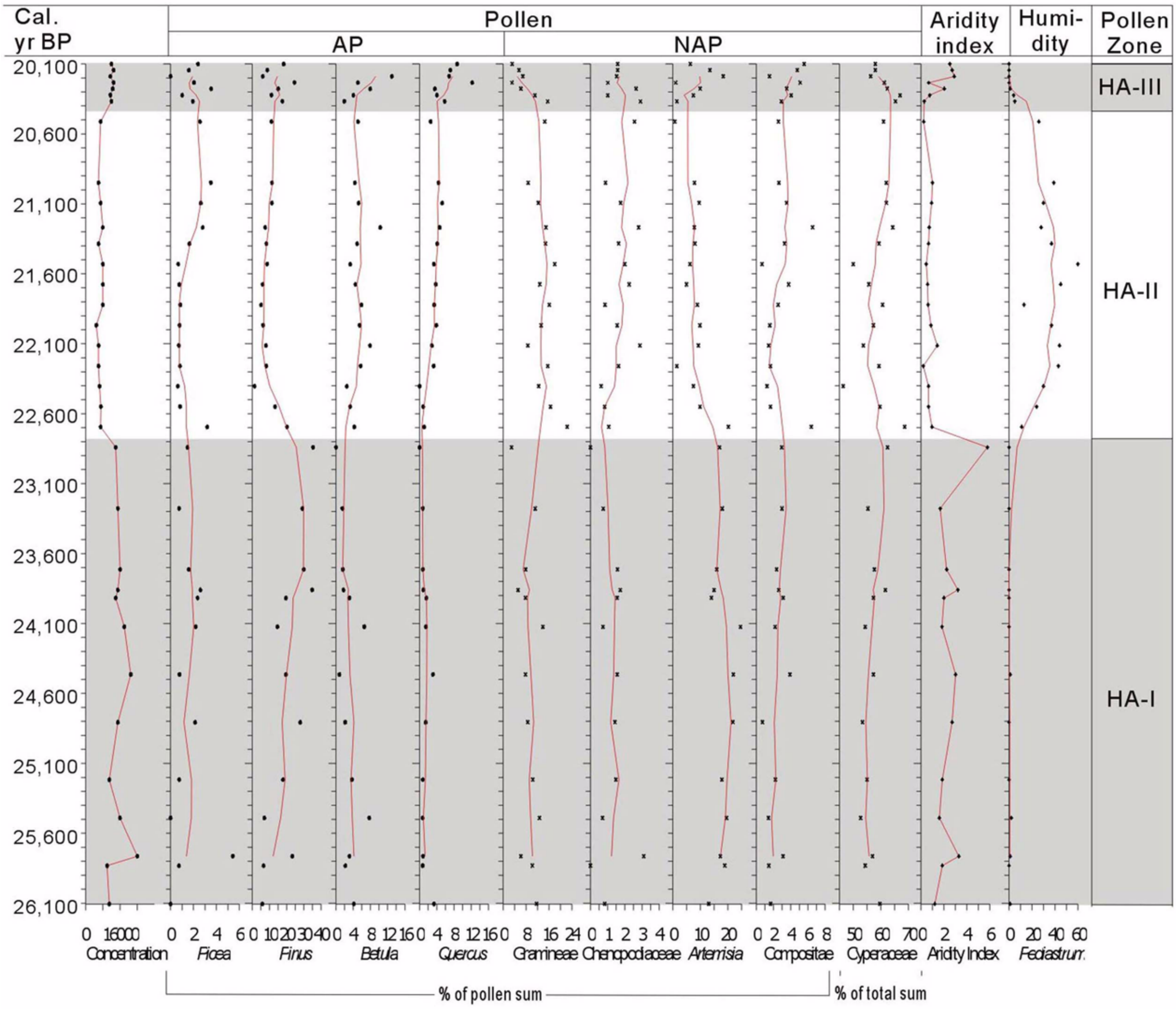

Fig. 6. Selected pollen taxa showing the pollen zones with climate changes during the last glacial. Aridity index = (Chenopodiaceae + *Artemisia*) / Cyperaceae.

whereas low values are associated with relatively humid intervals (Fig. 6).

Pediastrum species are radially-symmetrical colonial green algae that inhabit freshwater environments (Nielsen and Sørensen, 1992; Jankovska and Komárek, 1995; Batten, 1996). An extant *Pediastrum* presents in a wide range of environmental response (Batten, 1996). Factors for the occurrence of *Pediastrum* species in sediments include changes in erosion in the catchment, water chemistry, nutrient status and pH. A good correlation between the increase of *Pediastrum* and that of human indicators has been reported from archaeological sites in Poland (Makohonienko, 1998) and Syria (Yasuda et al., 2000). The studies also pointed out that rapid increase of *Pediastrum* was possibly caused by high precipitation accelerating soil erosion and resulted in an enhanced the nutrient supply to the place where these colonial green algae lived. We, herein, followed this application of the *Pediastrum* flux to infer precipitation (Fig. 6).

The changes in aridity and precipitation from ca. 26.1 cal kyr BP to ca. 20.1 cal kyr BP are discussed on the basis of AI and *Pediastrum* in association with vegetation coverage.

During the basal period (ca. 26.1–22.7 cal kyr BP; HA–I), the dry conditions are indicated by high values (2–6) of AI. *Pediastrum* is extremely rare or absent (0–1.2%) in its spectrum (Fig. 7c), although species of *Spirogyra* and *Sigmopollis* are present sporadically. Cold and dry-tolerant conifers of *Picea* (spruce) and *Pinus* (pine), and hard wood tree of *Betula* (birch) are predominant. Moreover, dry-tolerant herb, *Artemisia* (sage) is very common among the herb pollen assemblage (Fig. 6). The relatively low (SR = 0.14 mm/yr) in sedimentation rate (Fig. 7a) and the high (10,000–22,000 n/g) in pollen concentration (Fig. 7b) suggest low precipitation. This interpretation corroborates with the light oxygen isotope value of GISP2 (Grootes and Stuiver, 1997) and Hulu Cave (Wang et al., 2001) reflecting cold and dry conditions, respectively.

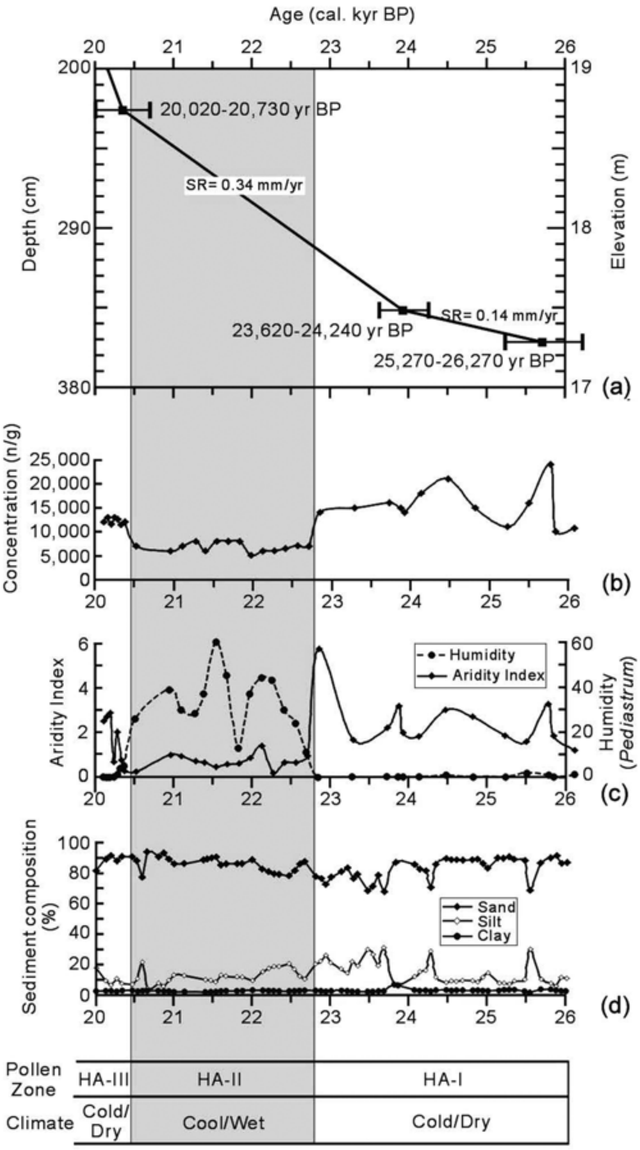

Fig. 7. Schematic diagram of comparing sedimentation rate to various proxies. (a) Age–depth curve. (b) Palynological concentration. (c) Semi-quantitative aridity index (AI) and humidity. (d) Sediment composition. Shadow indicates relatively high precipitation period evidenced by high in sedimentation rate (SR) and humidity, whereas low in palynological concentration, AI and decreased sand content.

From 22.5 cal kyr BP to 20.5 cal kyr BP (HA–II), the climate turned into wet conditions which are reflected by low AI values (0.1–1.8). Freshwater algae of *Pediastrum* (1–5.8%), *Zygnema* and *Botryococcus* begin to increase at the same zone (Fig. 7c), suggesting a change in hydrological conditions with an increase in precipitation and sediment supply. Accordingly, dry-tolerant conifers (*Picea* and *Pinus*) and sage (*Artemisia*) are reduced (Fig. 6). It is observed that pollen concentrations (5,000–7,200 n/g) of all taxa are clearly declined during the same period (Fig. 7b). The lower pollen concentration is presumably ascribed to the diluting effects from the faster sedimentation rate (0.34 mm/yr) (Fig. 7a). Rising of sand and low silt in sediment composition are probably caused by increased precipitation (Fig. 7d). It can therefore be concluded that the precipitation increased during the period of 22.5–20.5 cal kyr BP. This result is consistent with oxygen isotope value of GIPS2 and Hulu Cave (Grootes and Stuiver, 1997; Wang et al., 2001) with indication of cool and wet conditions.

During the upper period (ca. 20.3–20.1 cal kyr BP; HA–III), the dry conditions may be revealed by re-increase in AI value again (0.8–3) combined with decrease in frequency (0–0.25%) of *Pediastrum* (Fig. 7c). On the other hand, dry-tolerant conifers including *Pinus*, *Picea*, and herbs of *Artemisia* (sage) appear to grow in pollen spectrum (Fig. 6). Pollen concentrations (11,000–12,300 n/g) of all taxa are higher than those of preceding period (Fig. 7b). The synthetic data may reflect that the cold and dry conditions have prevailed again from ca. 20.3–20.1 cal kyr BP. This interpretation is supported by oxygen isotope value of GISP2 and Hulu Cave (Grootes and Stuiver, 1997; Wang et al., 2001) which indicates cold and dry climate conditions during this period. During this period the climate was drier. This was understood by calculating the effective precipitation (precipitation–evaporation) using an AGCM coupled with a simplified simple biosphere model (AGCM + SSiB) (Liu et al., 2002). While the paleomoisture conditions were calculated using Chinese lake water level (Herzschuh, 2006) which shows much drier (about 50% of annual precipitation at present) conditions in eastern China than today.

6. CONCLUSIONS

This study provides palynological evidence of vegetation dynamics response to climate changes during the last glacial, ca. 26.1–20.1 cal kyr BP from the wetland sediments of the Hanam located in western central Korean Peninsula. The pollen assemblages are predominated by conifers of *Picea* (spruce) and *Pinus* (pine), and cold tolerant deciduous broadleaved *Betula* (birch), together with common xerophytic herb *Artemisia* (sage) and Gramineae (grass). These principal taxa are closely comparable to those of subalpine forest in modern vegetation of the Korean Peninsula. Humidity conditions are reconstructed by semi-quantitative aridity index (AI). During the basal period (ca. 26.1–22.7 cal kyr BP), an open, low grassland with an expansion of subalpine conifers forest and high value of AI indicates that the cold and dry climate conditions were prevailing. Later conifers and cool temperate deciduous broadleaved mixed forests flourished in mountainous area under cool and wet conditions due to climatic amelioration from 22.5 cal kyr BP to 20.5 cal kyr BP. Finally during the upper period (ca. 20.3–20.1 cal kyr BP), *Picea* and *Pinus* together with *Betula* increased substantially. This indicates that subalpine conifers forest reoccupied in montane of the hinterland along with open, low grassland associated with colder and drier conditions owing to climatic deterioration. With comparison to modern vegetation, the temperature of Korean western central region during period of ca. 26.1–21.1 cal kyr BP was 5–6 °C colder and much drier than today.

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