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Vegetation response to climate change on Jeju Island, South Korea, during the last deglaciation based on pollen record

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ABSTRACT: A pollen record (ca. 21,800 to 9,900 cal. yr BP) from a maar reveals a detailed history of vegetation and climate changes during the last deglaciation on Jeju Island, South Korea. During the LGM (ca. 21,800 to 14,400 cal. yr BP) *Artemisia*-dominated grassland with patches of cool temperate deciduous broadleaved forest developed under cold dry conditions. From ca. 14,400 to 11,800 cal. yr BP a vegetation transition from glacial type to interglacial is indicated by the expansion of temperate deciduous broadleaved forest and the retreat of grassland vegetation. The appearance of warm temperate evergreen and deciduous broadleaved forests with a fern understory after ca. 11,800 cal. yr BP suggests warm humid conditions, similar to modern climate of Jeju Island. Prominent fluctuations in *Artemisia* and Polypodiaceae indicate variability in humidity during the Late Pleistocene to Holocene transition. The pollen record reflects a vegetation response not only to the last deglacial warming but also to the influence of geographical change resulted from sea-level rise.

Key words: Late Pleistocene to Holocene, palaeovegetation, palaeoclimate, pollen, Jeju Island of South Korea

1. INTRODUCTION

The transition from the Late Pleistocene to Holocene conditions caused environmental instability, including sea-level and vegetation changes. Various high resolution paleoclimate records show that abrupt and intense climate changes occurred in many parts of the world during the last deglacial period (Bond et al., 1993; Dansgaard et al., 1993; Schulz et al., 1998; Porter, 2001; Wang et al., 2001; Nakagawa et al., 2003). However, the amplitude and timing of the climate changes differed from region to region (Bennett et al., 2000; Nakagawa et al., 2003; Genty et al., 2006). Knowing to what extent the climate changes were felt in a region, may help to identify oceanic and atmospheric teleconnections that linked regional climates during the last deglaciation, and to understand modern climate evolution of the region.

Although a number of palynological studies on the Late Quaternary deposits in Korea have been carried out (Yoon, 1996, 1997; Yoon and Jo, 1996; Choi, 1998; Chung et al., 2004; Yi et al., 2004), most of them were focused on the Holocene deposits, and thus the detailed information on palaeovegetation and/or paleoclimate covering the last deglacial period is rarely known.

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Jeju Island is surrounded by epicontinental seas shallower than 200 m in water depth. During the last glacial maximum (LGM), the continental shelves of the East China Sea and the Yellow Sea in which Jeju Island is situated, were extensively exposed at the low sea-level stand (Fairbanks, 1989; Park et al., 1994; Kim and Kennett, 1998; Ijiri et al., 2005). The change of land and sea distribution must have affected albedo and vegetation of regions in and around the East China Sea and the Yellow Sea.

A volcanic lake of Jeju Island provides an opportunity to study the climate and vegetation histories of Korea during the last deglaciation. In this paper the author describes a pollen record from the Hanon Maar lake of Jeju Island to elucidate the vegetation response to changes in climate and geography.

2. LOCATION AND SETTING

Jeju Island is located in the middle latitudes of the northwest Pacific, the geographical midway between Korea, Japan and China (Fig. 1). The island lies in the path of the northward-flowing Kuroshio Current, which is the Western Boundary Current of the North Pacific Ocean and transports a large amount of heat from the tropics to middle latitudes. The northward-flowing Kuroshio Current diverges in the vicinity of the south coast of Jeju Island, and one branch flows into the Yellow Sea and the other into the East Sea (Fig. 2). Therefore, the warm Kuroshio Current has a strong and direct influence on the climate of Jeju Island as well as Japan and coastal China.

Jeju Island is a shield volcano that is composed of basaltic lava flows and minor pyroclastic rocks (Won, 1976; Lee, 1982; Chough et al., 2000). Over 360 scoria cones and about 10 tuff rings and cones occur on the island. The Hanon Maar is located on the south coast of the island (33°14′30″N - 33°15′00″N, 126°32′45″E - 126°33′15″E) at an elevation of 53 m. The Maar consists of a low-relief tuff ring and a nested scoria cone on the deep crater floor. The tuff ring has a circular morphology with diameter of ca. 1,000 m and height of ca. 50 m. The maar lake is dried and under cultivation at present.

The climate of Jeju Island is characterized by hot humid summers and cool winters as a result of the influence of the

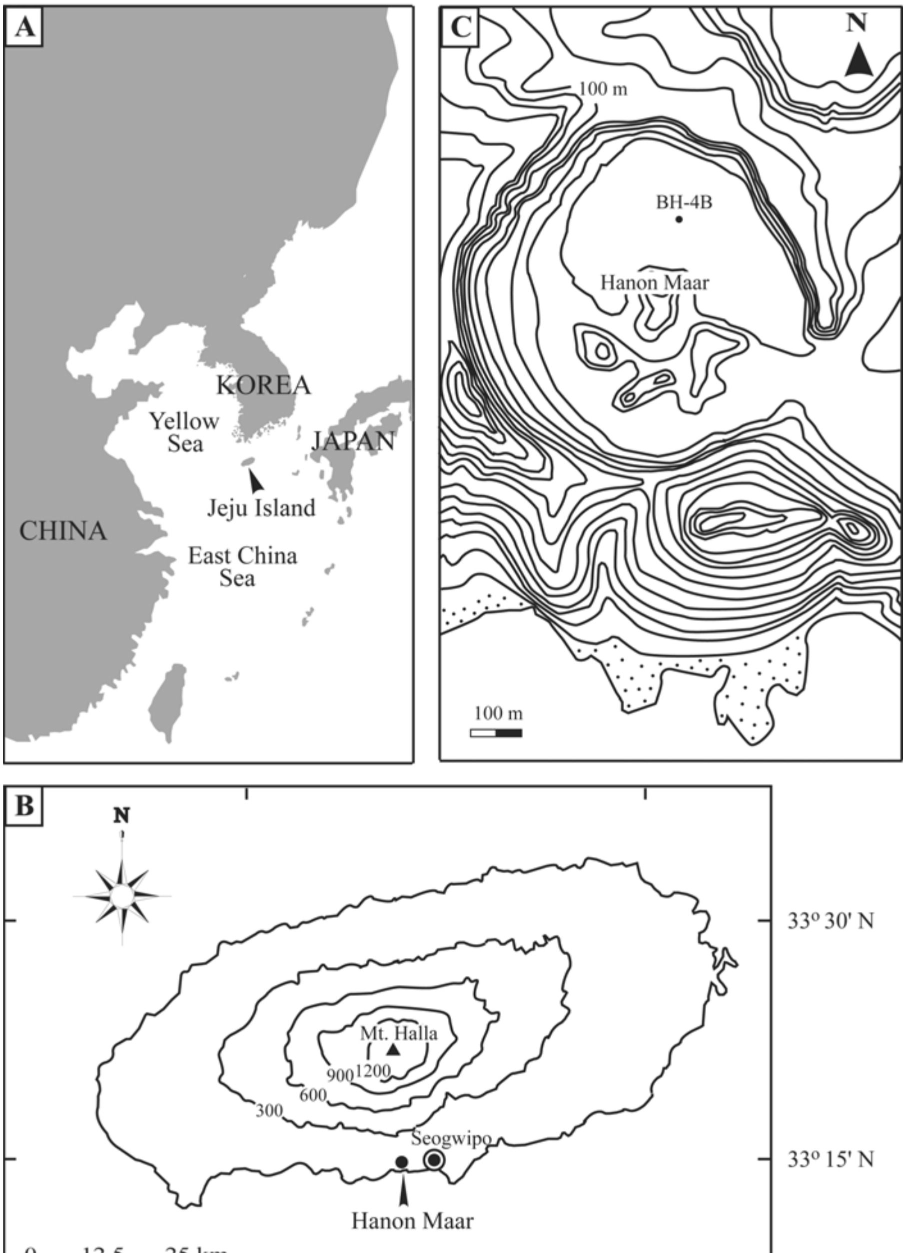

Fig. 1. Map showing location of study area. (A) Location of Jeju Island. (B) Map of Jeju Island showing topography and location of the Hanon maar. (C) Topographical map around the Hanon maar and coring site.

East Asian monsoon. The southeasterly summer monsoon from June to September transports moist air from the West Pacific and the East China Sea, and produces abundant rainfall over the island and the Korean Peninsula (Kim and Lee, 2001). Strong typhoons are frequent during summer. Winter climate is controlled by the dry, cold northwesterly winter monsoon, but conditions are mild and humid, compared with those of other regions at the same latitude, as a result of the maritime influence of the warm Kuroshio Current. Climate conditions of the island vary considerably with topography. Mean annual temperature of the island ranges from 15 to 17°C except at highest elevations on Mt. Halla (1950 m), and mean annual precipitation is 1550-2050 mm (Korea Meteorological Administration, 2003). On the south coast, where the Hanon Maar is located, mean annual temperature is 16.2°C, and mean August and January temperatures are 26.6°C and 6.6°C, respectively. Annual precipitation is high, averaging 1850 mm, and about 40 % falls in summer (June-August).

The modern vegetation of Jeju Island varies with altitude from the warm temperate evergreen broadleaved forest in the coastal lowland to the subalpine coniferous forest near

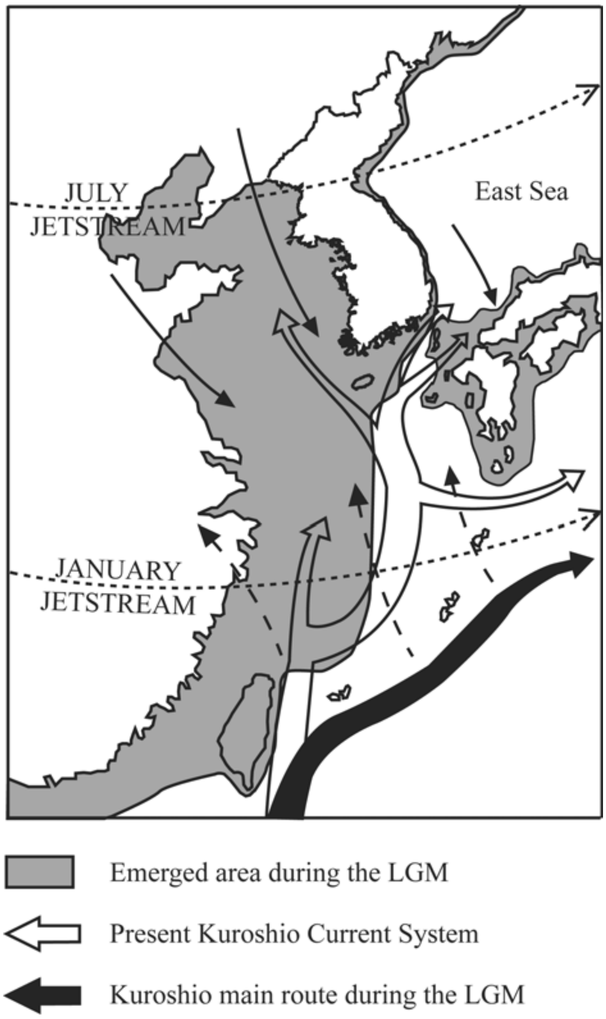

Fig. 2. Map showing the climatic system in East Asia (after Gao (1962) and Zhang and Lin (1992)) and geographical differences between the present and the LGM, in which the path change of the Kuroshio Current is shown. Solid arrows indicate the direction of winter monsoon and dashed arrows, that of summer monsoon.

the summit of Mt. Halla (Uyeki, 1933; Yim and Kira, 1975). There are three main vegetation types: evergreen broadleaved forest, deciduous broadleaved forest, and coniferous forest with scattered scrubs and grasslands (Kim, 1985; Song and Nakanishi, 1985; Yim, 1990; Lee and Yim, 2002).

Evergreen broadleaved forest occupies the coastal plain and slopes up to 600 m elevation, and is composed of evergreen oaks (*Quercus acuta*, *Q. glauca, Q. salicina*), *Castanopsis cuspidate, Camellia japonica, Elaeagnus marophylla, Eurya japonica, Litsea japonica, Mallotus japonicus, Cinnamomum camphora* and *Dendropanax morbifera*.

Deciduous broadleaved forest from 600-1400 m elevation includes *Quercus serrata, Q. grosserrata. Q. acutissima, Carpinus tschonoskii, C. laxiflora, Corylus sieboldiana, Ulmus parvifolia, Castanea crenata, Magnolia kobus* and *Pinus densiflora*. Similar vegetation is widespread in the cool temperate forests of the Korean Peninsula.

Subalpine coniferous forest occurs between 1,400 and 1,950 m elevation. The forest consists mainly of *Abies koreana, Pinus densiflora, Juniperous chinensis* and *Betula ermanii*, and is accompanied by scrubs of *Empetrum nigrum* var. *japonicum, Rhododendron mucronulatum* and *R. yedoense* var. *poukhanense*, and herbs of *Sasa guelpaertensis, Galium verum, Cirsium rhinoceros* and *Ligularia fischeri.*

3. MATERIALS AND METHODS

A 500-cm-long sediment core was recovered from a borehole (BH-4B) drilled at the central part of the Hanon Maar lake in 2000. Core sediments are mainly composed of homogeneous mud and can be divided into black peaty mud from 0 to 200 cm depth and dark brown silty mud from 200 to 500 cm depth (Lee et al., in press). The upper ca. 120 cm of the core is characterized by massive mud with abundant plant debris. Laminated mud occurs at core depths of 175-200 cm. The core below 200 cm is dominated by dark brown mud with numerous thin (1-5 mm in thickness) silty layers.

Seven samples of bulk sediment and plant fragments were prepared for AMS radiocarbon dating at the Rafter Radiocarbon Laboratory of the Institute of Geological and Nuclear Sciences Limited, New Zealand (Table 1).

For pollen analysis, fifty 1-cc samples were taken at 10 cm intervals between 10 and 500 cm in depth from BH-4B core. The samples were processed using standard pollen preparation techniques, which included treatments with 10% KOH and 45% HF, mineral separation with a $ZnCl_2$ Solution (sp. gr., 2.0), acetolysis, and mounting in glycerin jelly. Pollen were identified and counted with a light microscope at 400× magnification, but a magnification of 1,000× was used for some critical determinations. Pollen identifications were based upon Chang and Rim (1979), Nakamura (1980a, b) and Wang et al. (1995). Over 300 pollen grains of trees and herbs were counted for each sample. The percentages of arboreal pollen (AP = trees and shrubs) and nonarboreal pollen (NAP = herbs) were calculated from the total palynomorph sum. Only the principal pollen and spores were included in the percentage pollen diagram and zones established by visual inspection.

4. RESULTS

4.1. Chronology

The Hanon Maar core chronology is based on six AMS radiocarbon dates of Lee et al. (in press), and the results are shown in Table 1. One AMS date was rejected as too young. Radiocarbon dates were calibrated to calendar years using the IntCal04 dataset from Reimer et al., (2004) by means of the CALIB program 5.0 (Stuiver et al., 1998, 2005) (Table 1). Calendar age errors are generally small and

Table 1. AMS ^{14}C ages measured in core BH-4B from the Hanon Maar lake, Jeju Island (Lee et al., in press)

Sample Code	Material	Sample Depth (cm)	AMS ^{14}C Age (yr BP)	Calibrated age (yr BP)
NZA 18091	bulk sediment	127	11,128 ± 60	13,027 ± 60
NZA 18092	bulk sediment	191	12,305 ± 60	14,184 ± 140
NZA 18093	bulk sediment	208	12,460 ± 60	14,481 ± 210
NZA 18005	plant debris	230	2,457 ± 65	
NZA 18094	bulk sediment	386	16,154 ± 75	19,349 ± 90
NZA 18095	bulk sediment	444	17,530 ± 120	20,669 ± 190
NZA 18096	bulk sediment	493	18,029 ± 90	21,319 ± 230

*Calibrated using CALIB 5.0 (Stuiver et al., 2005)

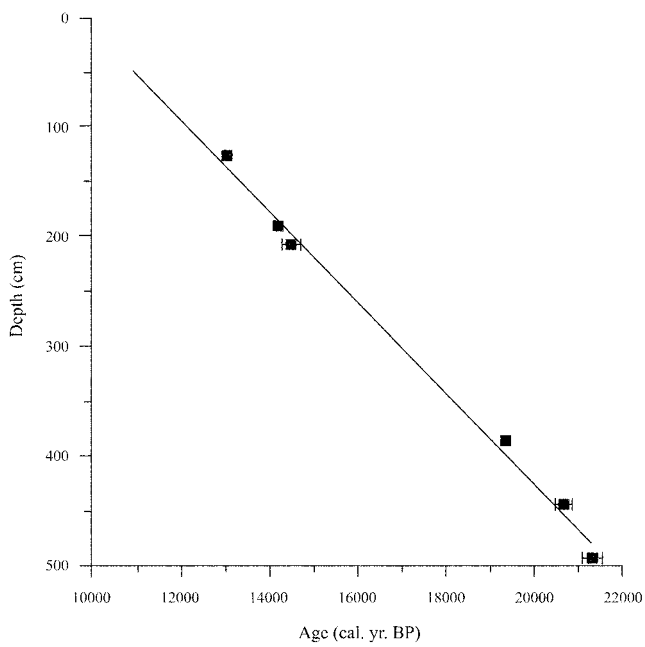

Fig. 3. The age-depth plots of six AMS ages.

this permits the construction of a reliable age-depth model obtained by linear regression (r^2 = 0.99; Fig. 3).

The calibrated age of the core BH-4B sediment ranges from 21.8 to 9.9 cal. kyr BP, which covers the time interval from MIS 2 to the early Holocene. Based on sedimentation rate interpolations between radiocarbon dates the average accumulation rate is roughly calculated to be about 41.2 cm/kyr.

4.2. Pollen Zonation

The pollen record from the Hanon Maar was divided into three local pollen assemblage zones (LPAZ), based on changes in pollen assemblage (Fig. 4). The characteristics of the local pollen assemblage zones are described in ascending order.

4.2.1. Pollen zone I *(500-195 cm depth; ca 21,800-14,400 cal. yr BP)*

This zone is characterized by the predominance of NAP (up to 70%) referable to *Artemisia*, Gramineae, Chenopodiaceae and Compositae. *Artemisia* is the predominant component attaining up to 21-42% of the total palynomorph sum. Arboreal pollen, mainly derived from *Quercus (Lepidobalanus)* (4-12%), *Castanea/Castanopsis* (3-12%), *Betula* (1-5%) and Taxodiaceae-Cupressaceae-Taxaceae (T-C-T) (1-5%), account for 33-42% of the total palynomorph sum. Conifer pollen such as *Pinus, Abies, Picea* and *Tsuga* show low but persistent values of 1-3% throughout the entire record. Fern spores, particularly the monolete type, are rare (1-3%) and occur sporadically. Pollen Zone I suggests the development of grassland on the lowland around the Hanon Maar along with cool temperate deciduous broadleaved trees and subalpine conifers on Mt. Halla.

4.2.2. Pollen zone II *(195 – 85 cm depth; ca 14,400-11,800 cal. yr BP)*

This zone begins with a sharp decrease in NAP (25-37%) and increase in AP (53-61%) and monolete fern spores (5-14%) (Figs. 4 and 5). Predominant AP are *Quercus (Lepidobalanus)* (7-13%), T-C-T (3-9%), *Alnus* (3-9%) and *Castanea/Castanopsis* (3-10%). *Artemisia* pollen falls to 13-25%, Gramineae to 2-5%, Chenopodiaceae to 0-2%, and Compositae to 1-4%. Thermophilic *Quercus (Cyclobalanopsis), Carpinus* and *Ulmus/Zelkova* pollen show an obvious rise in this zone. Pollen of aquatic plants such as *Potamogeton, Myriophyllum* and *Nymphoides* exhibit a trend of increasing upward. Pollen Zone II shows the decline of grassland vegetation and expansion of temperate deciduous broadleaved forest.

4.2.3. Pollen zone III *(85-10 cm depth; ca 11,800-9,900 cal. yr BP)*

This zone is characterized by a continued decrease in NAP and a remarkable increase in fern spores. Pollen zone III is dominated by AP of T-C-T (6-15%), *Quercus (Lepidobalanus)* (5-12%) and *Castanea/Castanopsis* (5-11%), and monolete fern spores of Polypodiaceae (12-22%). The percentages of T-C-T and *Quercus (Cyclobalanopsis)* (4%) pollen attain the highest values throughout the entire record. The increasing trend in pollen of aquatic plants such as *Potamogeton, Myriophyllum* and *Nymphoides* continues. Pollen Zone III

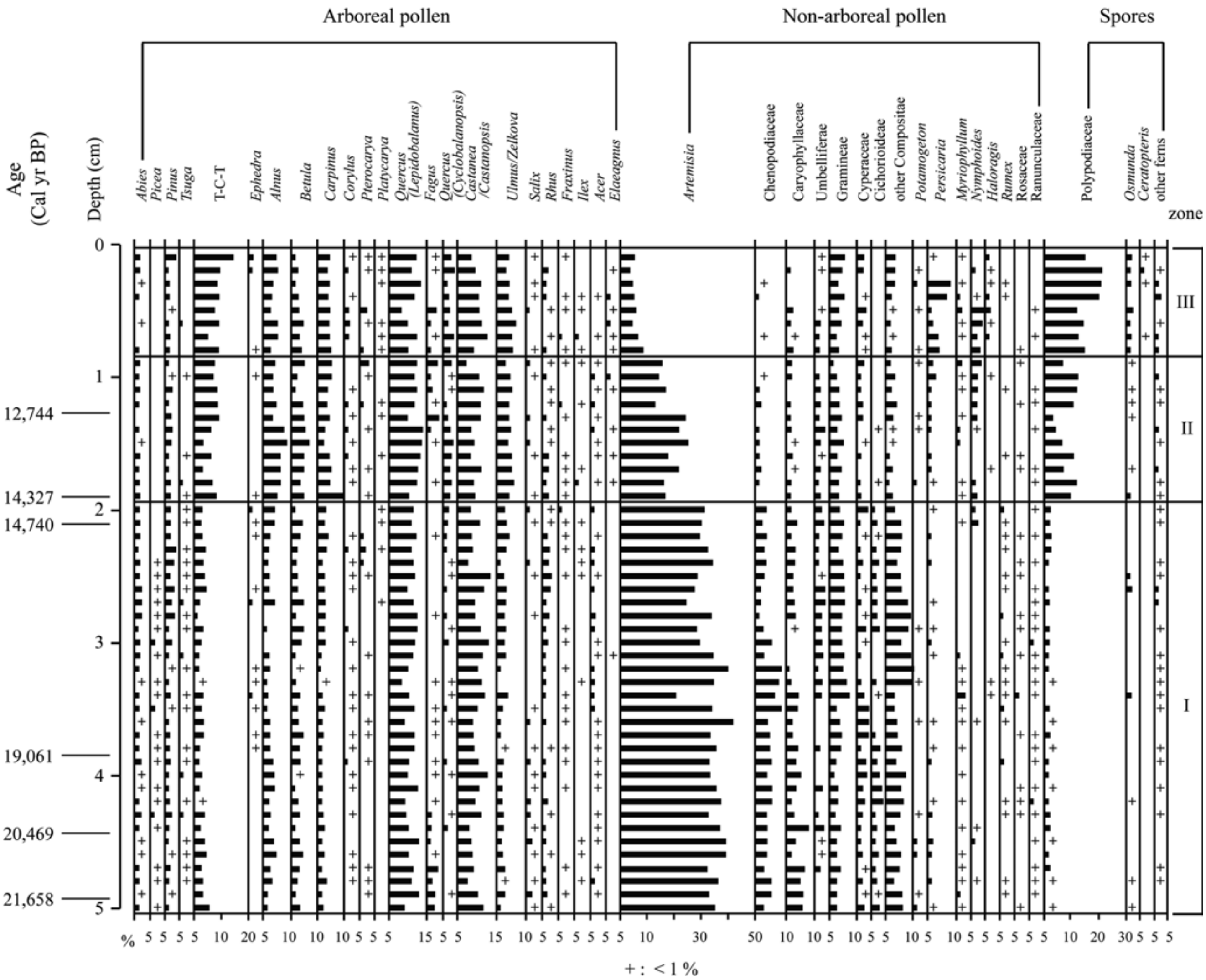

Fig. 4. Percentage diagram of the principal palynomorph taxa. T-C-T in figure is an abbreviation for Taxodiaceae-Cupressaceae-Taxaceae.

indicates the replacement of grassland vegetation by warm temperate evergreen and deciduous broadleaved forests with a fern understory.

5. DISCUSSION

5.1. Vegetation History

The pollen record from the Hanon Maar provides a detailed vegetation history of Jeju Island during the last deglaciation. Remarkable fluctuations in the percentages of principal pollen taxa between pollen zones indicate that the vegetation changes were distinct and extensive.

The period from ca. 21,800 to 14,400 cal. yr BP suggests the development of *Artemisia*-dominated grassland on the lowland around the Hanon Maar lake with patches of cool temperate deciduous broadleaved forests composed of *Quercus (Lepidobalanus), Castanea* and *Ulmus/Zelkova*. Herbs such as *Artemisia* and Gramineae are good indicators of grassland or steppe. The glacial-interglacial cycles are systematically characterized by the alternation of AP/NAP (Tzedakis et al., 1997). According to pollen data from northeast coastal China and the continental shelves of the Yellow, East China and South China seas (Liu et al., 1987; Meng et al., 1989; Sun and Chen, 1991; Sun et al., 2000; Yi et al., 2002), the open, grassland vegetation dominated by *Artemisia* was extensively distributed over northeast China and the exposed continental shelves during the glacial period, and the predominance of xerophytic herbaceous pollen such as *Artemisia*, Gramineae and Chenopodiaceae indicates cold, dry conditions. A pollen-climate relationship in northern China shows that 30-50% of *Artemisia* pollen is indicative of an annual precipitation range of 300-500 mm, with an average July temperature range of 15-24°C (Sun et al., 2000), which is much colder and drier than that of Jeju Island at present. Thus the development of grassland vegetation (e.g., *Artemi-*

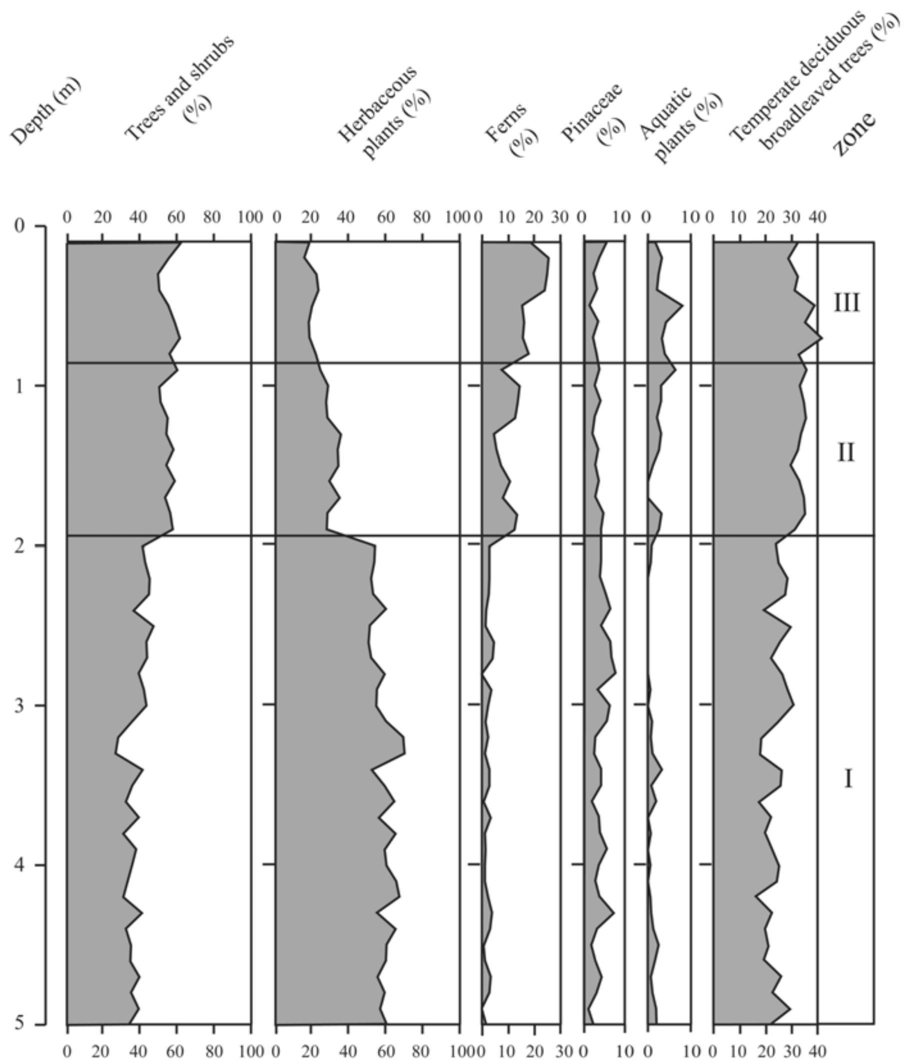

Fig. 5. Fluctuation in abundances of arboreal pollen, non-arboreal pollen, fern spores, Pinaceae pollen, pollen of aquatic plants and of temperate deciduous broadleaved trees.

sia, Gramineae, Chenopodiaceae and Compositae) from the Hanon Maar suggests cold, dry condition during the LGM and late-glacial periods. Subalpine coniferous and deciduous broadleaved trees such as *Pinus, Abies* and *Betula* were present in low but persistent pollen percentages and are probably attributable to long-distance transport of pollen grains from Mt. Halla.

The end of the late-glacial (ca. 14,400-11,800 cal. yr BP) is marked by a sudden rise in Polypodiaceae ferns and an abrupt decline in herbaceous taxa. The expansion of temperate deciduous broadleaved forests is indicated by an increase in the proportion of deciduous broadleaved trees (*Alnus, Carpinus, Quercus (Lepidobalanus)* and *Ulmus/Zelkova*) and conifers (T-C-T) (Figs. 4 and 5). An abrupt increase in Polypodiaceae spores is known as a sign of vegetation transition during the last deglacial period in Korea (Yasuda et al., 1980; Lee and Yim, 2002). Ferns are widely distributed today from subtropical lowland to cool temperate highland in Korea (Lee and Yim, 2002), with a great number of taxa occurring either in forested formations or in open scrublands. High spore representation has been found associated with high-energy stream current and rapid sedimentation near river mouths and lake inlets (DeBusk, 1997; Zheng and Lei, 1999), and with organic swamps with moderate humidity (Jo et al., 1994). The retreat of grassland vegetation and expansion of temperate deciduous broadleaved forests suggest a warmer climate than before. The pollen assemblage of pollen zone II might be the transitional vegetation from glacial type to interglacial type.

A further expansion of temperate deciduous broadleaved forests in combination with continued retreat of grassland vegetation is recognized from ca. 11,800-9,900 cal. yr BP, and indicates the vegetation change from glacial type to interglacial type. Warm temperate evergreen broadleaved taxa, such as evergreen *Quercus (Cyclobalanopsis)* and *Castanopsis* which are important constituents of the modern warm temperate evergreen broadleaved forests in the coastal lowland of Jeju Island reach the highest values throughout the entire record. The grassland vegetation during the last glacial period was gradually replaced by temperate deciduous broadleaved forests with a fern understory and patches of evergreen broadleaved trees. Subalpine conifers on Mt. Halla, such as *Picea* and *Tsuga* almost disappeared, but *Abies* and *Pinus* survived.

5.2. Climatic and Geographical Implications

The vegetation history from the Hanon Maar suggests environmental changes related to climate and sea-level rise. The predominance of grassland vegetation prior to 14,400 cal. yr BP indicates cold, dry conditions during the LGM and late-glacial period. During the LGM, the weakening of the summer monsoon and the strengthening of the winter monsoon would have lowered temperature and increased aridity. In addition, exposed continental shelves of the East China Sea and the Yellow Sea meant that Jeju Island region was connected to the Korean Peninsula and the Chinese mainland (Emery et al., 1971; Zhao et al., 1982; Saito, 1998; Ijiri et al., 2005; Kong et al., 2006). The present-day climate of Jeju Island is characterized by mild and humid winter under the influences of a maritime climate and the Kuroshio Current, and relatively high precipitation in winter is attributed to moisture supplied from the East China and Yellow seas. The exposed continental shelf around Jeju Island might have created locally arid conditions, compared with the present, and weakening of thermal transport by the Kuroshio Current. The high representation of xerophytic herbs in Jeju Island during the LGM differs from Japanese pollen records at a similar latitudinal position (Tsukada, 1985; Miyoshi et al., 1999; Yasuda et al., 2004). Most of the East Sea remained to submerged and supplied moisture to the Japanese Islands during the LGM, whereas the East China and Yellow seas supplying moisture to Jeju Island dried out (Fig. 2).

The decline in xerophytic herbaceous plants such as *Artemisia* and Chenopodiaceae, and rise in temperate deciduous broadleaved trees and Polypodiaceae ferns mark the transition from glacial to interglacial conditions from ca. 14,400 to 11,800 cal. yr BP. This vegetation change reflects not only the last deglacial warming but also the geographical variation resulted from the submergence of continental shelves of the East China and Yellow seas (Qin et al., 1996; Kim and Kennett, 1998; Wang, 1999; Liu et al., 2004; Kong et al., 2006). According to sedimentological and foraminiferal data (Jin and Chough, 1998; Liu et al., 2004; Kong et al., 2006), the marine transgression started earlier than 16,000 yr BP and reached the present sea-level at about 7,000 yr BP in and around Jeju Island region. Along with the deglacial warming, the submergence of continental shelves around Jeju Island resulted in strengthening of the East Asian summer monsoon and more maritime conditions that locally increased humidity and reduced seasonality at the Hanon Maar. Enhancement of summer monsoon and increased precipitation are indicated by an increase in representation of aquatic plants such as *Ceratopteris*, *Potamogeton, Myriophyllum* and *Nymphoides*, and by an abundance of fern spores resulted from strengthened influence of stream run-off (DeBusk, 1997; Zheng and Lei, 1999).

Stronger influence of the East Asian summer monsoon and maritime conditions is recognized in pollen record after ca. 11,800 cal. yr BP, which indicates a warm and humid condition, similar to modern climate of Jeju Island. The stepwise vegetation change from glacial type to interglacial is considered to be related to the climatic and geographical variation resulted from a stepwise marine transgression during the last deglaciation (Liu et al., 2004; Kong et al., 2006).

6. CONCLUSIONS

The pollen assemblages from the Hanon Maar in Jeju Island, South Korea, reveal the histories of vegetation and climate in Jeju Island during the Late Pleistocene to Early Holocene. Xerophytic *Artemisia*-dominated grassland vegetation from ca. 21,800 to 14,400 cal. yr BP indicates a cold and dry condition during the LGM and late-glacial period. Expansion of temperate deciduous broadleaved forests and retreat of grassland vegetation imply a vegetation transition from glacial type to interglacial from ca. 14,400 to 11,800 cal. yr BP. The establishment of temperate deciduous broadleaved forests with warm temperate evergreen broadleaved trees after ca. 11,800 cal. yr BP suggests warm and humid conditions in the Early Holocene. The extensive exposure of the continental shelves of the East China and Yellow seas during the LGM and the subsequent submergence during the postglacial period amplified the deglacial climate change by the strengthened influence of the East Asian summer monsoon and maritime conditions.

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