Title	Fluctuations in the East Asian monsoon over the last 144ka in the northwest Pacific based on a high-resolution pollen analysis of IMAGES core MD01-2421
Author(s)	Igarashi, Yaeko; Oba, Tadamichi
Citation	Quaternary Science Reviews, 25(13-14), 1447-1459 https://doi.org/10.1016/j.quascirev.2005.11.011
Issue Date	2006-07
Doc URL	https://hdl.handle.net/2115/14721
Type	journal article
File Information	QSR25-13-14.pdf

Fluctuations in the East Asian monsoon over the last 144 kyr in the northwest Pacific based on a high-resolution pollen analysis of IMAGES core MD01-2421

Yaeko Igarashi[a] and Tadamichi Oba[b]

[a] Institute for Paleoenvironment of Northern Regions, Koyocho 3-7-5, Kitahiroshima, 061-1134, Japan

Correspondence address: Institute for Paleoenvironment of Northern Regions, Koyocho 3-7-5, Kitahiroshima, 061-1134, Japan. Tel & Fax; 81-11-373-2938 e-mail; VZQ06055@nifty.com

[b] Graduate School of Environmental Earth Science, Hokkaido University Sapporo, 060-0810, Japan

Present address: 2-2-3, Sendagaya, Shibuya-ku, Tokyo, 151-0051, Japan

Abstract

A high-resolution pollen analysis of IMAGES core MD01-2421 (45.83 m) from the northwest Pacific off central Japan was used to clarify the vegetation history of central Japan over the past 144 kyr. An age model was constructed using the oxygen isotope stratigraphy of benthic foraminifera, 12 accelerator mass spectrometry (AMS) ^{14}C datings, and two tephra layers with -known eruption ages. The pollen temperature index T_p [$= 100\times T_w/(T_c + T_w)$, where T_w = sum of temperate taxa and T_c = sum of subalpine taxa] values were high during 129–119, 115–100, 82–76, 53–49, and 15–0 ka. Cool –temperate broad-leaved forests developed during the high-T_p periods and subalpine conifer forests grew during the low-T_p periods. The T_p fluctuated synchronously with summer insolation at 36°N, where the core was collected. During periods with abundant *Cryptomeria* or *Sciadopitys* (120–118, 115–89, 78–70, and 4–0.3 ka), the East Asian summer monsoon was stronger and the annual precipitation was greater in central Japan than at present (>2000 vs. 1500 mm). Fluctuations in the sea-surface temperature (SST) calculated from the oxygen isotopes of foraminifera in core MD01-2421 and changes in the strength of the summer monsoon were synchronous. The SST was determined by the currents passing over the core site, rather than by the strength of summer insolation. Northward movement (high SST) of the Kuroshio Current, which is under the influence of the summer Okhotsk high pressure, was strong near the summer insolation minima when precipitation was high, particularly around 116, 94, and 71 ka. Thus, the strengths of both summer insolation and the East Asian summer monsoon have determined the vegetation history of central Japan for the last 144 kyr.

1. Introduction

The natural environment in Japan is strongly affected by marine currents and the East Asian monsoon due to its location at the eastern edge of the Asian continent, in the middle latitudes of the northwest Pacific. The Kuroshio Warm Current flows northeastward, while the Oyashio Cold Current flows southwestward along the southeastern coast of Hokkaido (Figs. 1 and 2). At present, these two currents meet off the eastern coast of central Japan and produce a mixed water mass between them (Fig. 1). The Tsushima Warm Current flows northeastward along the western coast of Japan in the Sea of Japan and partly flows out to the Pacific Ocean through the Tsugaru Strait between Hokkaido and Honshu, the main island of Japan.

In addition, the East Asian monsoon, which forms as a result of the thermal difference between the Asian continent and the Pacific Ocean, is a principal climatic factor in Japan. The East Asian summer monsoon affects much of Japan, producing heavy rainfall associated with warm, humid southwesterly winds during summer. The winter monsoon is a product of the difference between the Siberian high and Aleutian low in the north Pacific. When an extremely cold, dry air mass forms over Siberia and crosses the Sea of Japan, it receives heat and water vapor from the sea surface where the Tsushima Warm Current flows, creating heavy snowfall on the western coast of Japan during winter.

The present vegetation in Japan is distributed throughout different forest types from south to north: warm –temperate evergreen broad-leaved forest, cool –temperate deciduous broad-leaved forest, pan-mixed forest, and subarctic conifer forest (Fig. 1; Tatewaki, 1955; Yoshioka, 1973; Yamanaka, 1979). The distributions of these forests have shifted in latitude and elevation between glacial and interglacial periods in response to past climatic change (e.g., Tsukada, 1986). Two conifer tree species, *Cryptomeria japonica* (Linn. fil.) D. Don (Japanese cedar) and *Sciadopitys verticillata* Sieb. et Zucc. (Japanese umbrella -pine) characteristically grow in Japan, in high -precipitation areas influenced by the summer and winter monsoons (Hayashi, 1960). *Cryptomeria* is a native tree of the family Taxodiaceae that occurs naturally only in southern China and Japan. The main distribution area in Japan is 30–41°N along the western coast and 30–35.5°N along the eastern coast (Fig. 2). *Cryptomeria* is broadly distributed along the western coast because of the heavy snowfalls resulting from the East Asian winter monsoon. In contrast, the distribution of *Cryptomeria* on the Pacific side depends on the heavy rainfall accompanying the East Asian summer monsoon. It is adapted to temperatures between –8.2°C (mean minimum temperature) and 31.6°C (mean maximum temperature), which occur from the subalpine to the warm –temperate zone. Annual precipitation in the main distribution area of *Cryptomeria* exceeds 2000 mm (Tsukada, 1981, 1986).

Sciadopitys, an endemic Japanese evergreen conifer, is distributed mainly in the mountainous area of western Japan between 32 and 36°N along the Pacific coast (Katoh, 1948). It grows on well -drained soils and is adapted to temperatures between –7.1°C (mean minimum temperature) and 28°C (mean maximum temperature). *Sciadopitys* grows in areas receiving high precipitation during the summer monsoon, where the total annual precipitation is 1500–3000 mm (Fig. 2; Katoh, 1948). Accordingly, fluctuations in the East Asian summer monsoon during the past can be reconstructed by tracing the pollen frequencies of *Cryptomeria* and *Sciadopitys*.

Studies of the East Asian paleomonsoon began with investigations of loess–paleosol sequences in central China (An et al., 1990a, 1991a, b). Since then, studies have examined monsoon records starting from the late Pleistocene in China, Japan, and the northwest Pacific (e.g., Kukla et al., 1988; Inoue and Naruse, 1991; Porter and An, 1995; Sun et al., 1996; Vandenberghe et al., 1997; Zhang et al., 1997; An and Thompson, 1998). High -resolution analysis of pollen and radiolarians in marine core RC14-99 (Fig.2) from the northwest Pacific has provided a correlation between the summer monsoon and summer insolation through three glacial/interglacial cycles (Heusser and Morley, 1997). Most interglacial core samples have contained high percentages (>20 %) of *Cryptomeria* pollen, reflecting increasing precipitation in response to intensification of the summer monsoon and the interglacial SST. Maxima in *Cryptomeria* presence have systematically lagged the maxima in solar insolation at 30°N by several thousand years. This correlation between the summer monsoon and summer insolation corroborates the link between the strength of the Asian monsoon and variation in Northern Hemisphere solar radiation (Heusser, 1989a, 1990; Heusser and Morley, 1990, 1997; Heusser et al., 1992; Morley and Heusser, 1997).

The history of *Cryptomeria* since the last interglacial age has been revealed by several palynological studies of terrestrial sediments in Japan (e.g., Tsuji, 1980; Tsuji and Minaki, 1982; Tsuji et al., 1984; Miyoshi, 1989; Hibino et al., 1991; Miyoshi et al., 1991; Takeuchi and Manabe, 1993; Oshima et al., 1997; Takahara and Kitagawa, 2000). However, those terrestrial sediment records were not continuous, and their chronologies before 44 ka, based on fission track ages of a few widespread tephras and paleomagnetic stratigraphy, were not always accurate.

Marine core MD01-2421 obtained from the northwest Pacific off central Japan, for which a detailed chronology has been determined, consists of a continuous sediment record covering the last 144 kyr (Oba et al., in press). At present, the land near the coring site is not within the main distribution area of *Cryptomeria*, and *Sciadopitys* is absent, due to the low amount of summer precipitation. In this study, we reconstructed a detailed history of East Asian monsoon fluctuations over central Japan during the past 144 kyr using the pollen frequencies of *Cryptomeria* and *Sciadopitys* and the vegetation history of the area.

2. IMAGES core MD01-2421

During the IMAGES (International Marine Global Change Study) VII-WEPAMA (Western Pacific Margin) Leg 2 cruise in 2001, piston core

MD01-2421 (45.82 m long) was recovered by the French R/V *Marion Dufresne* (Fig. 1). The site is characterized by a relatively flat seafloor (36°01.4'N, 141°46.8'E; 2224 m water depth; ca. 100 km offshore of central Japan) on a slightly convex submarine plateau on the continental slope. The core consisted of homogenous olive–gray silty clay containing many calcareous and siliceous microfossils associated with thin intercalated layers of fine sand and volcanic ash.

The age model for the core was constructed by means of oxygen isotope stratigraphy (Martinson et al., 1987) of the benthic foraminifera *Uvigerina* spp. and *Bulimina aculeata*, using calendar ages calculated from the accelerator mass spectrometry (AMS) ^{14}C ages (younger than 44 ka) of 12 samples of the mixed planktonic foraminifera *Neogloboquadrina dutertrei* and *Globorotalia inflata.* We employed the program CALIB 4.3 marine 98 (Stuiver et al., 1998) and the equation of Bard (1998), and used the Aira–Tn ash layer dated at 28.59 ka (Murayama et al., 1993) and the Aso-4 ash layer dated at 88 ± 2 ka (Oba, 1991). The detailed age control points are presented in Table 1 and described in Oba et al. (in press). We constructed a three-point smoothed profile from the combined $\delta^{18}O$ curve of the two benthic foraminifera and compared it to the standard $\delta^{18}O$ curve of Martinson et al. (1987) using AnalySeries software (Paillard et al., 1996) for graphic correlation. Consequently, the marine isotope stage (MIS) boundaries of core MD01-2421 are easily recognized on the smoothed profile, except the boundary of MIS $5_3/5_4$ (Fig. 3). Judging from the smoothed oxygen isotope curve, core MD01-2421 represented a continuous sequence, and its maximum age was 144 ka(during MIS 6). The average sedimentation rate of this core was very high (30 cm/kyr), compared to those of other cores used for pollen analysis in the northwest Pacific (Heusser and Morley, 1997; Kawahata and Ohshima, 2002), facilitating a pollen analysis with higher resolution.

3. Pollen transportation and sedimentation

How do pollen and spores become sediments deposited on the sea bottom? Sea currents can transport pollen 3000–5000 km from land- (Kawahata and Ohshima, 2002). Heusser and Morley (1985) demonstrated that pollen assemblages from marine surface sediments off Japan generally correspond to vegetation patterns in adjacent coastal regions, although marine and air currents do carry minor amounts of pollen from other regions. In addition, an investigation of pollen from surface sediments of the continental margin off northern California showed that the composition of the pollen assemblages reflects the regional vegetation of adjacent rivers and land areas (Heusser, 1988). Wind transports pollen from the coastal vegetation directly to the sea, and rivers carry pollen from regional vegetation offshore (Muller, 1959; Heusser and Balsam, 1977; Heusser, 1988). Accordingly, the majority of pollen and spores from core MD01-2421 was likely transported by river water and wind from the Pacific coast of the northern Kanto region in central Japan (Fig. 2).

Samples for pollen analysis were collected at approximately 20-cm (ca. 630 years) intervals and were treated using the method of Moore et al. (1991). At least 300 fossil pollen and spores were identified per sample under a 400x optical microscope. Forty-four arboreal pollen taxa, 32 non -arboreal pollen taxa, and 7 spore taxa were identified. The percentages of each taxon were calculated based on the total sum of pollen and spores. The concentration of pollen and spores in each sample was 500–5000 per gram of dry sample. Overall, Pinaceae pollen had the highest yield (30–95%), led by *Pinus* (5–63%). *Tsuga*, *Picea*, *Cryptomeria*, *Sciadopitys*, *Larix* (Fig. 3), and *Abies* occurred intermittently at high frequency. The yield of pollen from broad-leaved trees was 4–65%. Of these, *Quercus* subgenus *Lepidobalanus* occurred at the highest rate (ca. 33%), and *Quercus* subgenus *Cyclobalanopsis*, *Fagus*, *Juglans/Pterocarya*, *Carpinus/Ostrya*, *Ulmus/Zelkova*, *Castanea/Castanopsis* (Fig. 4), *Betula*, and *Alnus* were intermittently detected. The percentage of non -arboreal pollen and spores in a marine surface sediment from off northern Japan (38°N) was less than 15% of the total pollen and spores (Uchiyama, 1978). In core MD01-2421, NAP and spores also occurred in low percentages (5–20%). The pollen of *Ephedra*, which grows inland in Eurasia, is transported long distances off central Japan by wind, but its frequency was less than 0.6%.

4. Oscillation of T_p

The distribution of plants depends on an annual accumulated temperature of more than 5ºC/month during the growing season of plants (Warmth Index; Kira, 1949). Warm –temperate evergreen broad-leaved forests and cool –temperate broad-leaved forests are distributed in the regions where the Warmth Indexes are between 85 and 180ºC/month, and 45 and 85ºC/month, respectively. To reconstruct thermal fluctuations, the pollen temperature index (T_p) was calculated using the formula [$T_p = 100 \times T_w / (T_w + T_c)$] following Chinzei et al. (1987). Of the tree pollen taxa, *Larix*, *Picea*, and *Tsuga* were selected as T_c (sum of subalpine taxa; Fig. 3), while for T_w (sum of temperate taxa ; Fig. 4), we used the cool–temperate taxa *Juglans/Pterocarya*, *Carpinus/Ostrya*, *Fagus*, *Quercus* subgenus *Lepidobalanus*, *Ulmus/Zelkova*, *Phellodendron*, *Tilia*, *Eleagnus*, Araliaceae, and *Fraxinus*, the warm –temperate taxa *Q*. subgenus *Cyclobalanopsis*, *Castanea/Castanopsis*, and others such as *Celtis/Aphananthe*, *Aesculus*, *Mallotas*, *Sapium*, *Buxus*, *Largerstroemia*, and

Symplocos. Although the genus *Pinus* includes subgenus *Haploxylon*, which is a cold climate indicator, we did not distinguish this because of its obscure characteristics.

Over the 144 kyr in MD01-2421, we recognized five time periods when T_p was comparatively high (Fig. 3), i.e., 10 kyr during 129–119 ka, 15 kyr during 115–100 ka, 6 kyr during 82–76 ka, 4 kyr during 53–49 ka, and 15 kyr between 15 ka and the present. During 129–119 ka, the maximum T_p occurred at 124 ka. The pollen components were cool –temperate taxa coexisting with warm –temperate and subalpine taxa. This period included a short term of low T_p around 127 ka. The pollen components during this term were subalpine taxa. During 115–100 ka, the maximum T_p occurred at 113 ka. The pollen components were a mixture of subalpine, cool –temperate, and *Sciadopitys*. During 82–76 ka, the maximum T_p appeared at 78 ka. The pollen components were the cool –temperate taxa, *Sciadopitys* and *Cryptomeria*. During 53–49 ka, the maximum T_p occurred at 52 ka. The pollen components were a mixture of subalpine and cool –temperate taxa. Between 15 ka and the present, the maximum T_p occurred at 9.4 ka, which was the highest value across the 144 kyr. The pollen components were a mixture of cool –temperate and warm –temperate taxa between 15 and 4.3 ka, while during 4.3–0.3 ka, *Cryptomeria* became one of the main components.

The periods other than those mentioned above were comparatively cold, during which the T_p was low (Figs. 3 and 5), i.e., 15 kyr during 144–129 ka, 4 kyr during 119–115 ka, 18 kyr during 100–82 ka, 23 kyr during 76–53 ka, and 34 kyr during 49 –15 ka. During 144–129 ka, the minimum T_p occurred at 131 ka. The pollen components were subalpine taxa, and *Larix* was found in the greatest amounts over the 144 kyr. Between 119 and 115 ka, the minimum T_p appeared at 115 ka. The pollen components during the first half of the period were subalpine taxa and *Cryptomeria*, and during the latter half were subalpine taxa. During 100–82 ka, the T_p minimum occurred at 93 ka. The components during the first half of the period were *Cryptomeria*, *Sciadopitys*, and subalpine taxa, and the latter half was composed of subalpine taxa. The minimum T_p during 76–53 ka occurred at 72 ka. The pollen components during the beginning of the period were composed of *Cryptomeria* and subalpine taxa, whereas those during the latter half were subalpine taxa. During 49–15 ka, the minimum T_p appeared at 26 ka. This was the lowest over the 144 kyr. The pollen components were subalpine taxa. From 15 ka to the present, comparatively low values of T_p occurred at 13–12, 8.6, and 6.8 ka.

5. Dynamics of *Cryptomeria* and *Sciadopitys*

The northern Kanto region (Fig. 2) is situated near the northern distribution limit of warm –temperate evergreen broad- leaved forests (Fig. 1; Miyawaki, 1977). In the region north of 36°N along the Pacific coast, *Cryptomeria* is not abundant and *Sciadopitys* does not grow at present (Fig. 2) because of the small amount of summer precipitation (ca. 1500 mm; Wadachi, 1958). The frequency of *Cryptomeria* pollen in recent terrestrial sediments from 36°N along the Pacific coast is around 10% (Tsuji and Suzuki, 1977; Tsukada, 1986). Based on these data, the summer monsoon was stronger than at present during the periods when the *Cryptomeria* pollen exceeded

10%. Four periods when the frequency of *Cryptomeria* pollen exceeded 10% continuously occurred during the past 144 kyr, i.e., 2 kyr between 120 and 118 ka, 20 kyr during 111–91 ka, 8 kyr during 78–70 ka, and 3.7 kyr during 4–0.3 ka (Figs. 3 and 5). The maximum *Cryptomeria* during these periods occurred at 118, 94, 73, and 1.6 ka.

The frequency of *Sciadopitys* pollen in recent terrestrial sediments from the northern Kanto region was less than 1% (Tsuji and Suzuki, 1977), and in regions adjacent to its present distribution area was also less than 1% (Nakamura, 1965; Miyoshi et al., 1999; Kako and Moriyama, 2002). Accordingly, an occurrence above 5% *Sciadopitys* suggests that the summer monsoon was stronger than at present. Dominant periods of *Sciadopitys* (ca. 5%), which were restricted during MIS 5, were 26 kyr during 115–89 ka and 4 kyr during 78–74 ka. Maximum values of *Sciadopitys* during these periods appeared at 98 and 76 ka. Periods when *Sciadopitys* was dominant were synchronous with those when *Cryptomeria* dominated (ca. 10%), except during the first half of MIS 5_4.

An asynchronous trend between *Cryptomeria* and *Sciadopitys*, and T_p, was observed over the 144 kyr. *Cryptomeria* and *Sciadopitys* began to increase after T_p values began to decrease. During MIS 5_5, T_p began to decrease from 120 ka and *Cryptomeria* began to increase. The maximum *Cryptomeria* (118 ka) appeared 6 kyr later than the T_p maximum (124 ka). Then, increases in *Cryptomeria* and *Sciadopitys* began at around 106 ka, which was the same time as the decrease in T_p. Both species were dominant during first half of the low T_p period between 99 and 90 ka. The penultimate increase in *Cryptomeria* and the maximum T_p occurred simultaneously (78 ka). The maximum *Cryptomeria* appeared 5 kyr after the maximum T_p at 73 ka. The last increase in *Cryptomeria* occurred at 4.3 ka, which was 5 kyr after the T_p maximum. The last maximum occurrence of *Cryptomeria* (1.6 ka) was at the same time as a decrease in T_p.

6. Vegetation and climate

The vegetation, inferred from pollen assemblages and climate based on T_p values and the frequencies of *Cryptomeria* and *Sciadopitys* during the past 144 kyr was reconstructed as follows (Table 2 and Fig. 5).

A cool –temperate broad-leaved forest developed during MIS 5_5 and between late-MIS 2 and mid-MIS 1 under warm climate conditions. A mixed forest composed of cool –temperate and warm –temperate trees coexisting with *Cryptomeria* was distributed during late-MIS 1 under warm/humid climatic conditions. During MIS 5_5, warm –temperate trees were distributed less widely than during MIS 1, because the shoreline had retreated about 140 km inland due to marine transgression into the plain of Kanto (Okazaki and Masuda, 1992). The warm –temperate plants were restricted to the narrow coastal lowland (Tsuji, 1983).

Subalpine conifer forests developed under a cold/dry climate during MIS 6, early-MIS 5_4, mid-MIS 5_2 to early-MIS 5_1, mid-MIS 4 to early-MIS 3, and mid-MIS 3 to mid-MIS 2. The climate during MIS 6 was the coldest and driest over the 144 kyr, as suggested by the dominance of *Larix*.

The East Asian summer monsoon strengthened during two interglacial periods. As a result, *Cryptomeria* and *Sciadopitys* increased during MIS 5 and late-MIS 1 in central Japan. *Cryptomeria* increased after 120 ka, and its maximum was reached at 118 ka, 6 kyr after the T_p maximum at 124 ka. This lag is attributed to a gap between the period of maximum insolation around 127 ka and the strengthening of the summer monsoon inferred from increases in *Cryptomeria* and *Sciadopitys* (Fig. 5), similar to what was observed during the Holocene (Kuzbach, 1981). The same gaps between the maximum T_p (insolation) and *Cryptomeria* (maximum summer monsoon) were recognized between early-MIS 5_4 (113 ka) and late-MIS 5_3 (94 ka), between mid-MIS 5_1 (78 ka) and early-MIS 4 (73 ka), and between early-MIS 1 (9.4 ka) and late-MIS 1 (1.6 ka). Inferred from *Sciadopitys*, the longest summer monsoon over the past 144 kyr occurred from MIS 5_4 to MIS 5_2 (113–89 ka).

The climatic changes between glacial and interglacial ages were remarkable. Subalpine forests, which developed during the glacial ages, changed rapidly to cool –temperate forests at 129 and 15 ka. The vegetation change at 15 ka was more dramatic than that at 129 ka. The marked warming at 15 ka was also reported from a pollen analysis in Lake Suigets of western Japan (Nakagawa et al., 2003). These were simultaneous with warmings reported from $\delta^{18}O$ records in Greenland (Dansgaard et al., 1993) and China (Wang et al., 2001). After 15 ka, four short-term cold events occurred, at 13, 12, 8.6, and 6.8 ka. During each event, *Picea* and *Tsuga* increased and the *Quercus* subgenus *Lepidobalanus* decreased. The cold event at 13–12 ka probably corresponds to the Younger Dryas event in the North Atlantic region (Dansgaard et al., 1989; Mayewski et al., 1993; Grafenstein et al., 1998), Lake Suigetsu in Japan (Nakagawa et al., 2003), and Hulu Cave (Wang et al., 2001) and the Yangtze River (Yi et al., 2003) in China. The T_p increased abruptly at 12 ka and reached a high peak around 10 or 9 ka, when the summer insolation at 36°N was nearly maximal (Fig. 5). The cold event around 8.6 ka may be correlated with the cold event at 8.2 ka observed in Greenland ice cores from GRIP (Muscheler et al., 2004) and GIPS2 (Alley et al., 1997), because the age control of this IMAGES core was not as accurate in this part of the core (there were only two AMS ^{14}C ages of 7.57 and 12.01 ka).

When the *Cryptomeria* pollen yields exceeded 5%, *Cryptomeria* was likely distributed around the sampling site (Tsukada, 1980). If we accept this assumption, *Cryptomeria* began to be distributed again in the northern Kanto region at around 8 ka. During 4–0.3 ka, *Cryptomeria* was distributed on a slightly greater scale than at present in the northern Kanto region.

7. Correlation with terrestrial pollen data and data from marine core RC14-99

We compared the *Cryptomeria* pollen data obtained from terrestrial sediments in central Japan for the period since MIS 6 with the pollen data from MD01-2421. The chronostratigraphy of terrestrial sediments (including sediment cores from lake bottoms) older than 44 ka was determined using fission track ages of one to three layers of widespread tephras. Accordingly, there were differences in the accuracy of the chronology among the terrestrial sites.

In Lake Suwa (Loc. 1 in Fig. 2; 36°02'N, 138°06'E), *Cryptomeria* was dominant during 130 (?)–115, 110–90, and 82–67 ka (Oshima et al., 1997). In the central and southern Kanto regions along the Pacific coast (Loc. 2 in Fig. 2; 35°20'N, 139°15'E), *Cryptomeria* was abundant during 130(?)–100, 90–80, 70–60 ka, and in recent times (Tsuji, 1983). The dynamics of *Cryptomeria* from locations 1 and 2 had a similar trend to core MD01-2421, except for the length of each dominant period of *Cryptomeria*. Humid periods during the past 140 kyr, as inferred from an analysis of the diatom valve flux in sediments from Lake Biwa, occurred during 135–68 ka and from 7 ka to the present (Kuwae et al., 2003). The results of this diatom analysis were roughly consistent with the pollen results from locations 1 and 2 and core MD01-2421.

A deep-sea core, RC14-99, (Fig. 2; 36°58'N, 147°56'E), obtained from the northwest Pacific was subjected to high-resolution analyses for pollen and radiolarians (Heusser, 1989a, b; Morley and Heusser, 1989; 1997; Heusser and Morley, 1997). *Cryptomeria* maxima in core RC14-99 were detected during MIS 5_5, 5_3, 5_1, and 1. The results from core MD01-2421 were extremely similar to the data from core RC14-99, except for the length of each period and the specific pollen percentages. In core RC14-99, the *Cryptomeria* maxima systematically lagged behind the summer insolation maxima at 30°N by several thousand years (Heusser and Morley, 1997), and the strength of the Asian monsoon was linked to variation in the Northern Hemisphere solar radiation (Heusser and Morley, 1997). Core MD01-2421 also showed that *Cryptomeria* maxima (indicating a strong East Asian summer monsoon) occurred later than the T_p maxima (an indicator of solar insolation) by several to ten thousand years.

8. Relationships among pollen data, insolation, and SST in the northwest Pacific

Figure 5 shows the down-core T_p values, summer insolation curves at 36 and 65°N, the SST curve calculated from the oxygen isotope difference between benthic and planktonic foraminifera (Oba and Murayama, 2004; Oba et al., in press), and the relative abundances of *Cryptomeria* and *Sciadopitys* in core MD01-2421. Except after

8 ka, the T_p increased during the periods of high summer insolation, which had maxima around 127, 105, 83, and 11 ka and decreased during the low-insolation peaks around 138, 116, 94, 71, and 22 ka (Fig. 5). Moreover, the changes in the SST and abundances of *Cryptomeria* and *Sciadopitys* were roughly in phase. Both values increased during the regression periods from high to low insolation at 65°N in summer, sometimes including the insolation minima, i.e., during 121–117, 104–90, 78–70 ka, and from 8 ka to the present (Fig. 5); however, there were some exceptions, such as during 117–111 and 90–87 ka, when the SST remained high. Both these values decreased during the transgression periods, including the insolation maxima, around the summer insolation maxima at 127, 83, 59, and 11 ka, except at 105 ka, when the occurrences of *Cryptomeria* and *Sciadopitys* did not markedly decrease (Fig. 5). In particular, as well as during the glacial maxima, the SST decreased to minimum values around 127 and 11 ka when the summer insolation at 65°N reached maxima. The SST was strongly influenced by whether the Kuroshio or Oyashio Current passed over the core site, rather than by the strength of the summer insolation at 36°N. At present, the

early summer climate around the Sea of Okhotsk is characterized by the presence of the Okhotsk high-pressure system, which causes thick fog and cool–wet weather conditions in eastern Japan (Kudoh, 1984; Kawano, 1989). The strong northeast wind forcing associated with the Okhotsk high-pressure system causes the penetration of the Oyashio Current to become more southerly and results in a lower SST off the eastern coast of Japan (Sekine, 1988; Minobe, 1999). Therefore, a similar atmospheric pressure system most likely prevailed over the northwest Pacific around 127 and 11 ka. A recent meteorological study has indicated that the Okhotsk high-pressure system is directly enhanced by summer heating in northeastern Siberia (Ogi et al., 2004). The summer insolation at 65°N, where the center of the positive temperature anomaly in northeastern Siberia is located, achieved maxima around 127 and 11 ka (Berger, 1978), as shown in Fig. 5. The enhanced heating of the land surface due to the increased insolation at 65°N might have resulted in a stronger summer Okhotsk high-pressure system and lower SST off the eastern coast of Japan around 127 and 11 ka. Conversely, when the insolation at 65°N was weak, the development of both the Siberian low- and

Okhotsk high-pressure systems was repressed, weakening the southward penetration of the Oyashio Current, while strengthening the northward shift of the Kuroshio Current. Since the insolation cycles at 36 and 65°N were the same, although the heights of their maximum and minimum peaks differed (Fig. 5), the southward penetration of the Oyashio Current was strong around 127 and 11 ka, when the insolation reached maximum values. The northward shifts of the Kuroshio Current were also strong at 117, 94, and 71 ka, when the insolation reached minimum values. Oba et al. (in press) discuss the relationship between these current movements and summer insolation at 65°N, based on changes in the reconstructed SST and the carbon isotope difference of two planktonic foraminifera species in core MD01-2421. If the Kuroshio Current passed northward over the core site off central Japan, a large -scale cold front accompanied by rain between the Siberian low-pressure system and the North Pacific (Ogasawara) high-pressure system would have simultaneously migrated northward, at least over the northern land area of central Japan. The annual mean precipitation in the northern part of central Japan is now about 1500 mm (Wadachi, 1958). The amount of precipitation might have increased in the northern land area during the weak insolation periods around 117, 94, and 71 ka. Consequently, the distribution of *Cryptomeria* and *Sciadopitys* may have increased over the entire land area of central Japan around these periods, including the insolation minima at 65°N, because these taxa grow in areas with more than 2000 mm of annual mean precipitation (Tsukada, 1981; Katoh, 1984).

9. Conclusions

Periods of high T_p occurred during 129–119, 115–100, 82–76, 53–49 ka, and from 15 ka to the present. During these periods, cool –temperate deciduous broad-leaved forests developed, whereas subalpine coniferous forests grew during periods of low T_p. The fluctuations in T_p and the summer insolation strength at 36°N were roughly in phase, except after 8 ka. High-insolation periods around 127, 105, 83, and 11 ka were roughly correlated with high T_p periods, and low-insolation periods around 138, 117, 94, 71, and 22 ka were correlated with low T_p periods. During MIS 1, the T_p was higher and remained so for longer than during MIS 5_5, because the shoreline off central Japan had retreated about 140 km inland as a result of marine transgression during MIS 5_5.

Fluctuations in the values of *Cryptomeria* and *Sciadopitys*, which are adapted to a pluvial climate, displayed synchronous changes. High levels of *Cryptomeria* and *Sciadopitys* during 121–117, 115–89, 80–70, and 4–1 ka indicate that the summer monsoon was stronger during these periods than at present in central Japan. The annual precipitation during these periods may have exceeded 2000 mm. The summer monsoon maxima lagged by several to ten thousand years from the maximum T_p values, which were determined by the summer insolation at 36°N.

The SST calculated from oxygen isotope differences between benthic and planktonic foraminifera in core MD01-2421 and the occurrences of *Cryptomeria* and *Sciadopitys* changed synchronously. The SST was more strongly influenced by the currents passing over the core site, as well as by the strength of the summer insolation at 36°N. When the summer insolation at 65°N was strong, the Okhotsk high-pressure system strengthened indirectly, and a strong northeast wind from the Okhotsk high-pressure zone pushed the Oyashio Current southward, and the SST remained low off central Japan. Conversely, when the summer insolation at 65°N was weak, the Kuroshio Current was strengthened and shifted northward. Therefore, the vegetation in central Japan has been controlled not only by the insolation at 36°N and the East Asian summer/winter monsoons, but also by the currents passing offshore in central Japan.

Figure Legends

Fig. 1. Location of the coring site and a map of the modern vegetation of Japan (after Tatewaki, 1955; Yoshioka, 1973; Yamanaka, 1979) and sea currents. A: subarctic conifer forests; B: pan-mixed forests; C: cool –temperate deciduous broad-leaved forests; D: warm –temperate evergreen broad-leaved forests.

Fig. 2. Periods with abundant *Cryptomeria* (gray areas) during the past 144 kyr based on pollen data (Loc. 1 : Lake Suwa, Loc. 2: southern Kanto region; MD01-2421 and RC-1499 after Heusser and Morley, 1997), and the present main distribution areas of *Cryptomeria* (dotted and black areas; after Tsukada, 1980), *Sciadopitys* (hatched areas; after Katoh, 1948), and areas where the present annual precipitation exceeds 2000 mm (gray).

Fig. 3. Oxygen isotope curve of benthic foraminifera (Oba et al., in press), marine isotope stage (MIS), changes in T_p values, and subalpine conifer pollen diagram from core MD01-2421 over 144 kyr.

Fig. 4. Changes in T_p and the main warm and cool temperate broad-leaved tree pollen diagram from core MD01-2421 over 144 kyr.

Fig. 5. Changes in the percentage of T_p, summer insolation at 36°N and 65°N, SST

(Oba et al., in press) and the percentages of *Cryptomeria* and *Sciadopitys* during the last 144 kyr in the MD01-2421 core. Solid horizontal lines are drawn at the insolation maxima at 65°N and the dashed lines at the insolation minima. The SST is the water temperature shallower than 50 m in May (Oba and Murayama, 2004).

Table 1

Age control points for core MD01-2421 (Oba et al., in press)

Table 2

History of climate and vegetation based on pollen data from core MD01-2421

References

Alley, R.B., Mayewski, P.A., Sowers, T., Stuiver, M., Taylor, K.C., Clark, P.U., 1997. Holocene climatic instability: A prominent, widespread event 8200 yr ago. Geology, 25, 483-486.

An, Z. S., Kukla, G., Porter, S.C., Xiao, J. L., 1991a. Late Quaternary dust flow on the Chinese Loess Plateau. Catena 18, 125-132.

An, Z. S., Kukla, G., Porter, S.C., Xiao, J. L., 1991b. Magnetic susceptibility evidence of monsoon variation on the loess Plateau of central China during the last 130,000 years. Quaternary Research 36, 29-36.

An, Z. S., Liu, T. S., Liu, Y.C., Porter, S.C., Kukla, G., Wu, X. H., Hua, Y. M., 1990a. The long term paleomonsoon variation recorded by the loess-paleosol sequence in central China. Quaternary International 7/8, 91-95.

An, Z. S., Thompson, L. G., 1998. Paleoclimatic change of monsoonal China linked to global change. In: Galloway, J. N. (Ed.), Proceedings of Global Change. Cambridge University Press, London, 18-41.

Bard, E., 1998. Geochemical and geophysical implications of the radiocarbon calibration. Geochimica Cosmochimica Acta 62, 2025–2038.

Berger, A., 1978. Long-term variations of daily insolation and quaternary climate changes. Journal of Atmospheric Science, 35, 2362–2367.

Chinzei, K., Fujioka, K. Kitazato, H., Koizumi, I., Oba, T., Oda, M., Okada, H., Sakai, T., Tanimura, Y., 1987. Postglacial environmental change of the Pacific Ocean off the coasts of central Japan. Marine Micropaleontology 11, 273–291.

Dansgaard, W., Johnsen, S. J., Clausen, H. B., Dahl-Jensen, D., Gundestrup, N.S., Hammer, C.U., Hvidberg, C. S., Steffensen, J. P., Sveinbjomsdottir, A. E., Jouzel, J. & Bond, G., 1993. Evidence for general instability of past climate from a 250-kyr ice-core record. Nature, 364, 218-220.

Dansgaard, W., White, J.W.C., Johnsen, S.J., 1989. The abrupt termination of the Younger Dryas climate event. Nature 339, 532–533.

Grafenstein, U. von, Erlenkeuser, H., Muller, J., 1998. The cold event 8200 years ago documented in oxygen isotope records of precipitation in Europe and Greenland. Climate Dynamics, 14, 73-81.

Hayashi, Y., 1960. Taxonomical and phytogeographical Study of Japanese Conifers. Norin-Shuppan, Tokyo, 233pp (in Japanese).

Heusser, L.E., 1988. Pollen distribution in marine sediments on the continental margin off northern California. Marine Geology 80, 131–147.

Heusser, L.E., 1989a. Late Quaternary atmospheric and oceanographic variations in the western Pacific inferred from pollen and radiolarian analysis. Quaternary Science Reviews 8, 263–276.

Heusser, L.E., 1989b. Northeast Asian climatic change over the last 140,000 years inferred from pollen in marine core taken off the Pacific coast of Japan. In: Leinen, M. and Sarnthein, M. (eds), Paleoclimatology and Paleometeorology: Modern and past patterns of Global Atmospheric Transport. Kluwer Academic Publisher, Utrecht. 665–692

Heusser, L. E., 1990. Northeast Asian pollen records for the last 150,000 years from deep-sea cores V28-304 and RC14-99 taken off the Pacific coast of Japan. Review of Palaeobotany and Palynology, 65, 1-8.

Heusser, L.E., Balsam, W.L., 1977. Pollen distribution in the northeast Pacific Ocean. Quaternary Research 7, 45–62.

Heusser, L. E., Morley, J.J., 1985. Pollen and radiolarian records from deep-sea core

RC14-103: Climatic reconstructions of northeast Japan and northwest Pacific for the last 90,000 years. Quaternary Research 24, 60–72.

Heusser, L. E., Morley, J.J., 1990. Northeast Asian monsoon climates during the last 350,000 years: correlative evidence from terrestrial and marine microfossils. *Eos,* 71, 543.

Heusser, L.E., Morley, J.J., 1997. Monsoon fluctuations over the past 350 kyr: High-resolution evidence from Northeast Asia/ Northwest Pacific climate proxies (marine pollen and radiolarians). Quaternary Science Reviews 16, 565–581.

Heusser, L.E., Morley, J.J., Shackleton, N. J., 1992. Variations in northeast Asian environments over the last 350,000 years reconstructed from pollen records from the northwest Pacific Ocean. *In*: Redmond, K.T.(ed.), Proceedings of the Eighth Annual Pacific Climate (PACLIM) Workshop, pp. 5-12. California Department of Water Resources, Sacramento, CA.

Hibino, K., Morita, Y., Miyagi, T., Yagi, H., 1991. Palynological Study on the Vegetational Change during the Last 120,000 years B.P. in Kawadoi Basin, Yamagata Prefecture, Japan. The Scientific reports of the Miyagi Agricultural College 39, 35–49 (in Japanese with English summary).

Inoue, K., Naruse, T., 1991. Accumulation of Asian long-range eolian dust in Japan and Korea from the late Pleistocene to the Holocene. Catena Suppl., 20, 25-42.

Kako, H., Moriyama, A., 2002. Vegetation and Climate History since the Early Last

Glacial Period in the Takatomi Lowland, Gifu Prefecture, Central Japan. Daiyonki-Kenkyu 41, 443–456 (in Japanese with English summary).

Katoh, T., 1948. Studies on distribution of “Koyamaki” (=*Sciadopitys verticillata* Sieb. et. Zucc.) natural forest and a few factors of its climatic environment. Bulletin of the Kyushu Uniersity Forests 16, 55–115 (in Japanese).

Kawahata, H., Oshima, H., 2002. Small latitudinal shift in the Kuroshio Extension (Central Pacific) during glacial times: evidence from pollen transport. Quaternary Science Reviews 21, 1705–1717.

Kawano, H., 1989. Heat and moisture budgets in the layer containing fog, stratus or stratocumulus over the sea of the southeast of Hokkaido. Tenki 36, 369–375 (in

Japanese).

Kira, T., 1949. Forest zones of Japan. Technological Association of Forestry, Sapporo, 41pp (in Japanese).

Kudoh, T., 1984. Characteristics of Okhotsk air mass during the typical Yamase period (1981.6.18–21). Tenki 31, 411–419 (in Japanese).

Kukla, G., Heller, F., Liu X.M., Xu, T.C., Liu, T. S., An, Z.S., 1988. Pleistocene climates in China dated by magnetic susceptibility. Geology16, 811-814.

Kuwae, M., Yoshikawa, S., Inouchi, Y., 2003. A Record of Precipitation Change for the Past 140 ka Based on Diatom Valve Flux in Lake Biwa, Japan Daiyonki-Kenkyu 42, 305–319 (in Japanese, with English summary).

Kutzbach, J.E., 1981. Monsoon climate of the early Holocene: Climate experiment with the Earth's orbital parameters for 9000 years ago. Science 214, 59–61.

Martinson, D.G., Pisias, N.G., Hays, J.D., Imbrie, J., Moor, JR, T.C., Shackleton, N.J., 1987. Age dating and the orbital theory of the ice ages: development of a high-resolution 0 to 300,000-year chronostratigraphy. Quaternary Research 27, 1–29.

Mayewski, P.A., Meeker, L.D., Whitlow, S., Twickler, M.S., Morrison, M.C., Alley, R.B., Bloomfield, P., Taylor, K., 1993. The atmosphere during the Younger Dryas, Science 261, 195–197.

Minobe, S., 1999. A 50–70 year climatic oscillation over the North Pacific and North

America. Geophysical Research Letters 24 (6), 683–686.

Miyawaki, A. (Eds)., 1977. Vegetation of Japan composed with other region of world. Gakken, Tokyo, 535pp (in Japanese).

Miyoshi, N., 1989. Preliminary pollen analytical study of a Late-Pleistocene deposit from the Tokusa Basin, Yamaguchi Prefecture. Daiyonki-Kenkyu 28, 41–48 (in Japanese with English summary).

Miyoshi, N., Horie, S., Takemura, K., 1991. Pollenanalytische Untersuchungen an einem 85-Meter-Bohrkern aus dem Tokusa-Becken, Prafektur Yamaguchi, West-Japan. Die Geschichte des Biwa-Sees in Japan (Ed. Shoji Horie, 346 pp.) Universitatsverlag Wagner, Innsbruck, 243–256 (in German).

Miyoshi, N., Fujiki, T., Morita, Y., 1999. Palynology of a 250-m core from Lake Biwa: a 430,000-year record of glacial-interglacial vegetation change in Japan. Reviews of Palaeobotany and Palynology 104, 267–283.

Moore, P.D., Webb, J.A., Collinson, M.E., 1991. Pollen Analysis. Blackwell Scientific Publications, 216 pp.

Morley, J.J., Heusser, L.E., 1989. Late Quaternary atmospheric and oceanographic variations in the western Pacific inferred from pollen and radiolarian analysis. Quaternary Science Reviews 8, 236–276.

Morley, J.J., Heusser, L.E., 1997. Role of orbital forcing in east Asian monsoon climates during the last 350 kyr: Evidence from terrestrial and marine climate proxies from core RC14-99. Paleoceanography 12, 483–493.

Muller, J., 1959. Palynology of recent Orinoco delta and shelf sediments. Reports of the Orinoco Shelf Expedition: vol 5, Micropaleontology 1–32.

Murayama, M., Matsumoto, E., Nakamura, T., Okamura, M., Yasuda, H., Taira, A., 1993. Re-examination of the eruption age of Aira-Tn Ash (AT) obtained from a piston core off Shikoku—determined by AMS ^{14}C dating of planktonic foraminifer. Journal Geological Society of Japan. 99, 787–798 (in Japanese with English abstract).

Muscheler, R., Beer, J. Vonmoos, M., 2004. Causes and timing of the 8200 yr BP event inferred from the comparison of the GRIP ^{10}Be and the tree ring Δ^{14}C record.

Quaternary Science Reviews, 23, 2101-2111.

Nakagawa, T., Kitagawa, H., Yasuda, Y., Tarasov, P., Nishida, K., Gotanda, K., Sawai, Y., Yangtze River Civilization Program Members, 2003. Asynchronous climate changes in the North Atlantic and Japan during the last termination. Sciernce, 299, 688-691.

Nakamura, J., 1965. Palynological study of the vegetation history since the late-glacial period of the lowland in Kochi Prefecture (in Japanese, with English summary). Daiyonki-Kenkyu 4, 200–207.

Oba, T., 1991. Aso-4 and Ata tephras estimated from oxygen isotope stratigraphy. Monthly Earth 13(4), 224–227 (in Japanese).

Oba, T., Irino, T., Yamamoto, M., Murayama, M., Takamura, A., Aoki, K., Paleoceanographic change off central Japan since the last 144,000 years based on high-resolution oxygen and carbon isotope records. Accepted to Global and Planetary Change.

Oba, T., Murayama, M., 2004. Sea surface temperature and salinity changes in the northwest Pacific since the last glacial maximum. Journal Quaternary Science 19(4), 335-346.

Ogi, M., Tachibana, Y., Yamazaki, K., 2004. The connectivity of the winter North Atlantic Oscillation (NAO) and the summer Okhotsk High. Journal Meteorological Society of Japan 82 (3), 905–913.

Ohwi, J., 1975. Flora of Japan. Shibundo, Tokyo, 1582pp (in Japanese).

Okazaki, H., Masuda, F., 1992. Depositional system of Late Pleistocene sediments in Paleo-Tokyo Bay area. Journal Geological Society of Japan 98, 3, 235–258 (in Japanese, with English summary).

Oshima, H., Tokunaga, S., Shimokawa, K., Mizuno, K., Yamazaki, H., 1997. Fossil Pollen Assemblages of Core Samples from Lake Suwa, Nagano Prefecture, and Their Correlation to Other Pollen Assemblages in Central Japan. Daiyonki-Kenkyu 36, 183–196 (in Japanese, with English summary).

Paillard, D., Labeyrie, L., Yiou, P., 1996. Mackintosh program performs time-series analysis. Eos Transaction AGU 77: 379.

Porter, S.C., An, Z.S., 1995. Correlation between climate events in the North Atlantic and China during the last glaciation. Nature 375, 305-308.

Sekine, Y., 1988. Anomalous southward intrusion of the Oyashio east of Japan 1. Influence of the seasonal and interannual variations in the wind stress over the North Pacific. Journal Geophyscal Research 93 (C3), 2247–2255.

Stuiver, M., Reamer, P. J., Bard, E., Beck, J.W., Burr, G. S., Hughen, K. A., Kromer, B., McCormac, G., van der Plicht, J., Spurk, M., 1998. INTCAL 98 radiocarbon age calibration, 24,000–0 cal BP. Radiocarbon 40, 1041–1083.

Sun, D. H., Wu, X. H., Liu, T. S., 1996. Evolution of the summer monsoon regime over the Loess Plateau of the last 150 ka. Science in China, Series D39 (5), 503-511.

Takahara, H., Kitagawa, H., 2000. Vegetation and climate history since the last interglacial in Kurota Lowland, western Japan. Palaeogeography Palaeoclimatology Palaeoecology 155, 123–134.

Takeuti, S., Manabe, K., 1993. Quaternary Environmental changes in Northeast Honshu, Japan. Saito-Ho-on Kai Museum Research Bulletin 61, 15–28.

Tatewaki, M., 1955. Pan-mixed Forest Zone. Hoppo-Ringyo, 7, 240-243.

Tsuji, S., 1980. Plant Fossil Assemblages from the Pleistocene Kissawa Formation in Oiso Hills, Central Japan (I). Daiyonki-Kenkyu 19, 107–115 (in Japanese, with English summary).

Tsuji, S., 1983 .Vegetation and climate change since Shimosueyoshi stage in the Kanto

Plain. Urban Kubota 21, 44–47 (in Japanese).

Tsuji, S., Minaki, M., 1982. Plant Fossil Assemblages from the Pleistocene Kissawa Formation in Oiso Hills, Central Japan (II). Daiyonki-Kenkyu 20, 289–304 (in Japanese, with English summary).

Tsuji, S., Minaki, M., Osawa, S., 1984. Paleobotany and Paleoenvironment of the Late Pleistocene in the Sagami Region, Central Japan. Daiyonki-Kenkyu 22, 279–296 (in Japanese, with English summary).

Tsuji, S., Suzuki, S., 1977. Pollen Analysis of the Holocene Higata Formation in the North of the Kujukuri Coastal Plain, Chiba Prefecture, Japan. Daiyonki-Kenkyu 16, 1–12 (in Japanese with English summary).

Tsukada, M., 1980. History of *Cryptomeria*: last 15,000 years. Kagaku 50, 538–546 (in Japanese).

Tsukada, M., 1981. *Cryptomeria japonica* D. Don I. Pollen dispersal and logistic forest expansion. Japanese Journal Ecology 31, 371–383.

Tsukada, M., 1986. Altitudinal and latitudinal migration of Cryptomeria japonica for the past 20,000 years in Japan. Quaternary Research 26, 135–152.

Uchiyama, T., 1978. Palynological studies of marine sediments in Urado Bay, Kochi Prefecture and Sendai Bay, Miyagi Prefecture. Ecological Review 19, 37–44.

Vandenberghe, J., An, Z. S., Nugteren, G., Lu, H.Y., Huissteden, K. V., 1997. New absolute time scale for the Quaternary climate in the Chinese loess region by grain size analysis. Geology 25, 35-38.

Wadachi, K.(Eds), 1958. Climate of Japan. Tokyodo, Tokyo, 452pp (in Japanese)

Yamanaka, T. (1979) Forest vegetation in Japan. Tsukiji Shokan, Tokyo, 223pp.

Yi, S., Saito, Y., Zhao, Q., Wang, P., 2003. Vegetation and climate changes in the Changjiang (Yangtze River) Delta, China, during the past 13,000 years inferred from pollen records. Quaternary Science Reviews 22, 1501–1519.

Wang, Y. J., Cheng, H., Edwards, R.L., An, Z. S., Wu, J.Y., Shen, C. C., Dorale, J. A., 2001. A high-resolution absolute-dated late Pleistocene monsoon record from Hulu Cave, China. Science, 294, 2345-2348.

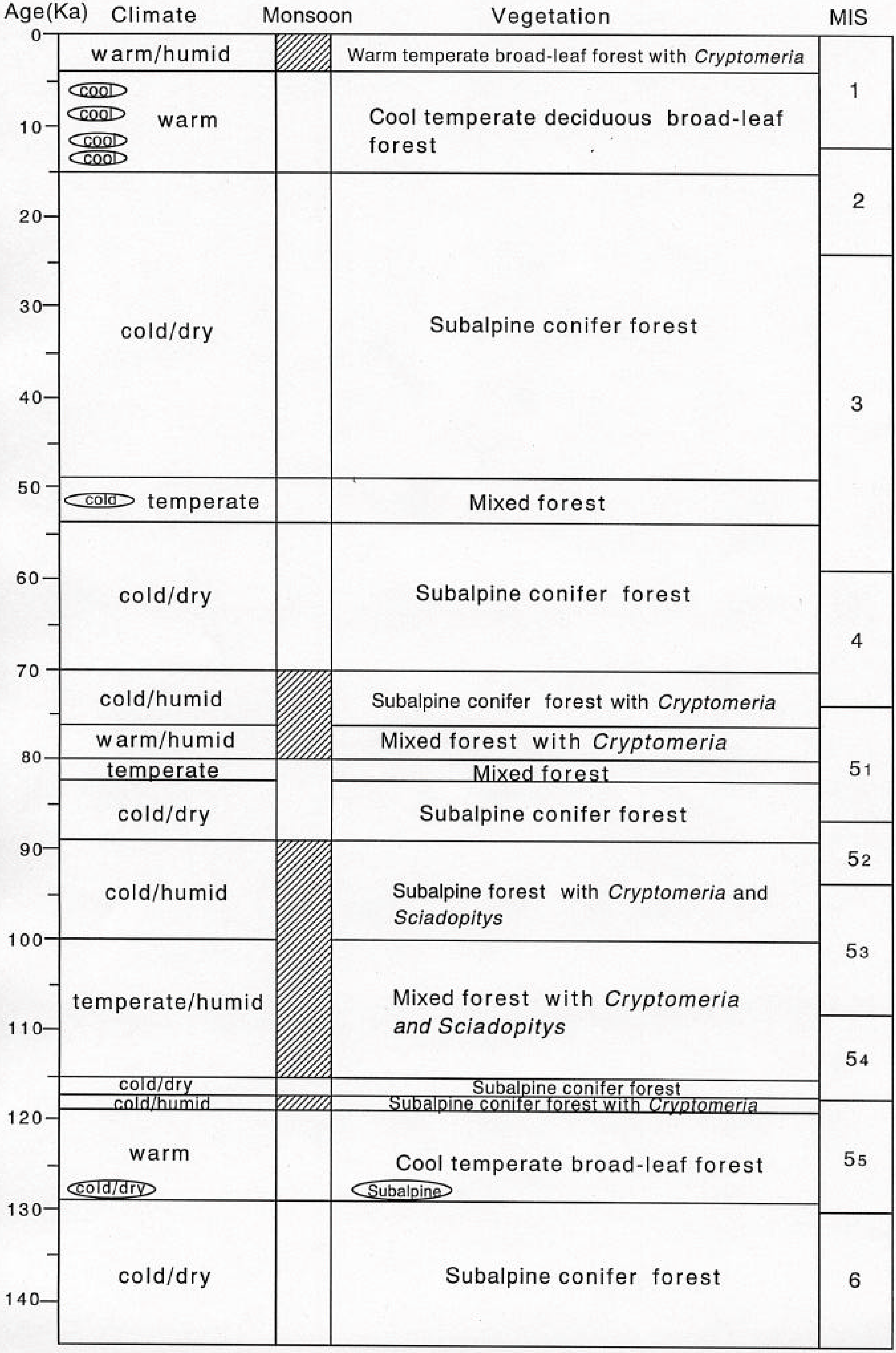
Yoshioka, K., 1973. Plant Geography. Kyoritsu-Shuppan, Tokyo, 84pp (in Japanese).

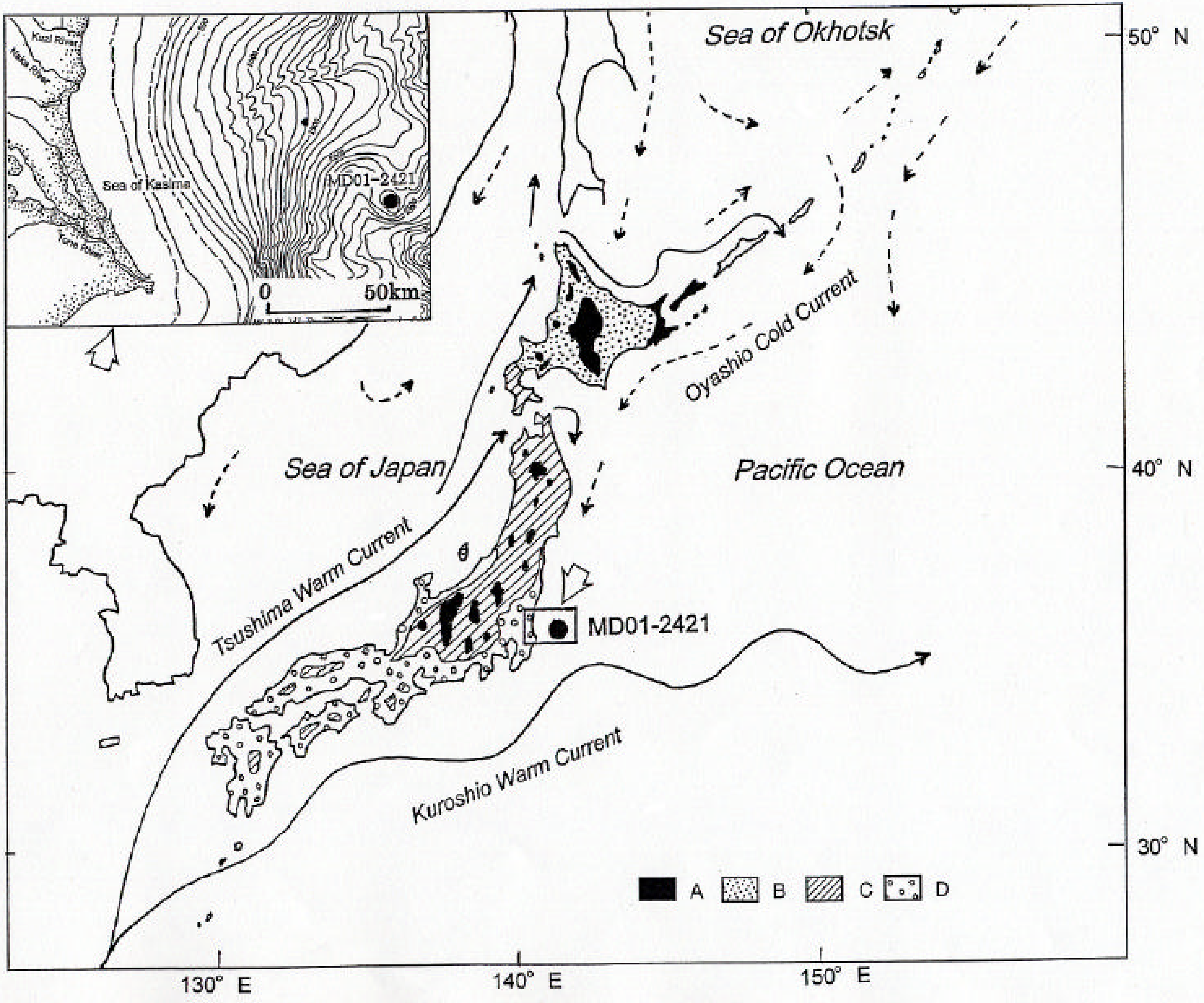
Zhang, X.Y., Arimoto, R., An, Z.S., 1997. Dust emission from Chinese desert sources linked to variations in atmospheric circulation. Journal of Geophysical Research 102 (D23), 28041-28047.

Table 1 Age control points for core MD01-2421 (Oba et al., accepted)

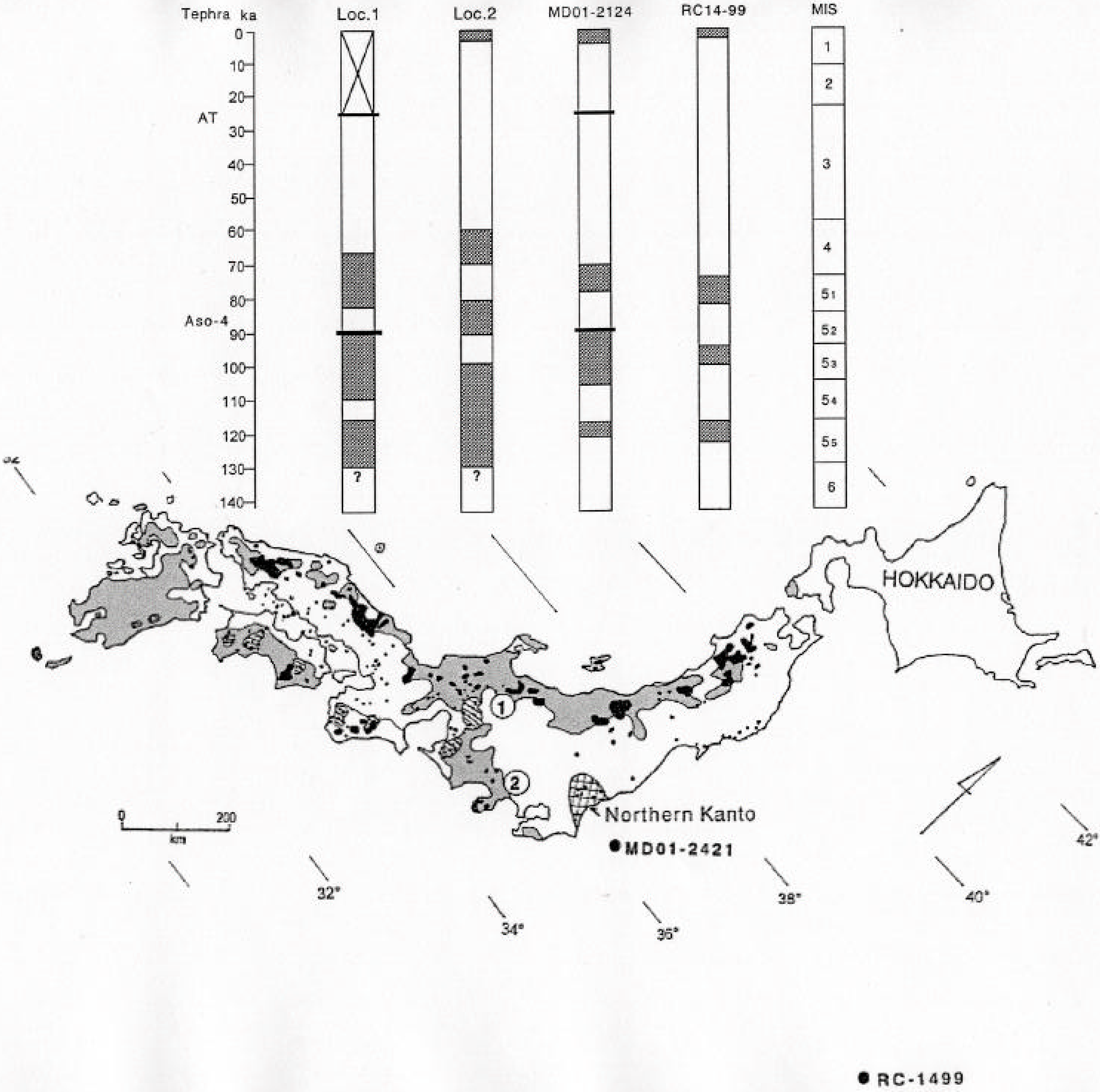
Depth (m)	Cal. kyr BP	Methods
0.08	0.31	AMS^{14}C
1.58	1.79	AMS^{14}C
3.08	3.62	AMS^{14}C
4.56	5.57	AMS^{14}C
6.06	7.57	AMS^{14}C
8.06	12.01	AMS^{14}C
8.27	12.90	AMS^{14}C mean
10.03	21.11	AMS^{14}C
12.10	28.59	AT tephra
13.05	37.51	AMS^{14}C
14.58	43.33	AMS^{14}C mean
17.76	51.57	MIS 3.3/3.31
20.05	58.96	MIS 4.0
20.85	65.22	MIS 4.22
24.27	73.91	MIS 5.0
27.75	79.25	MIS 5.1

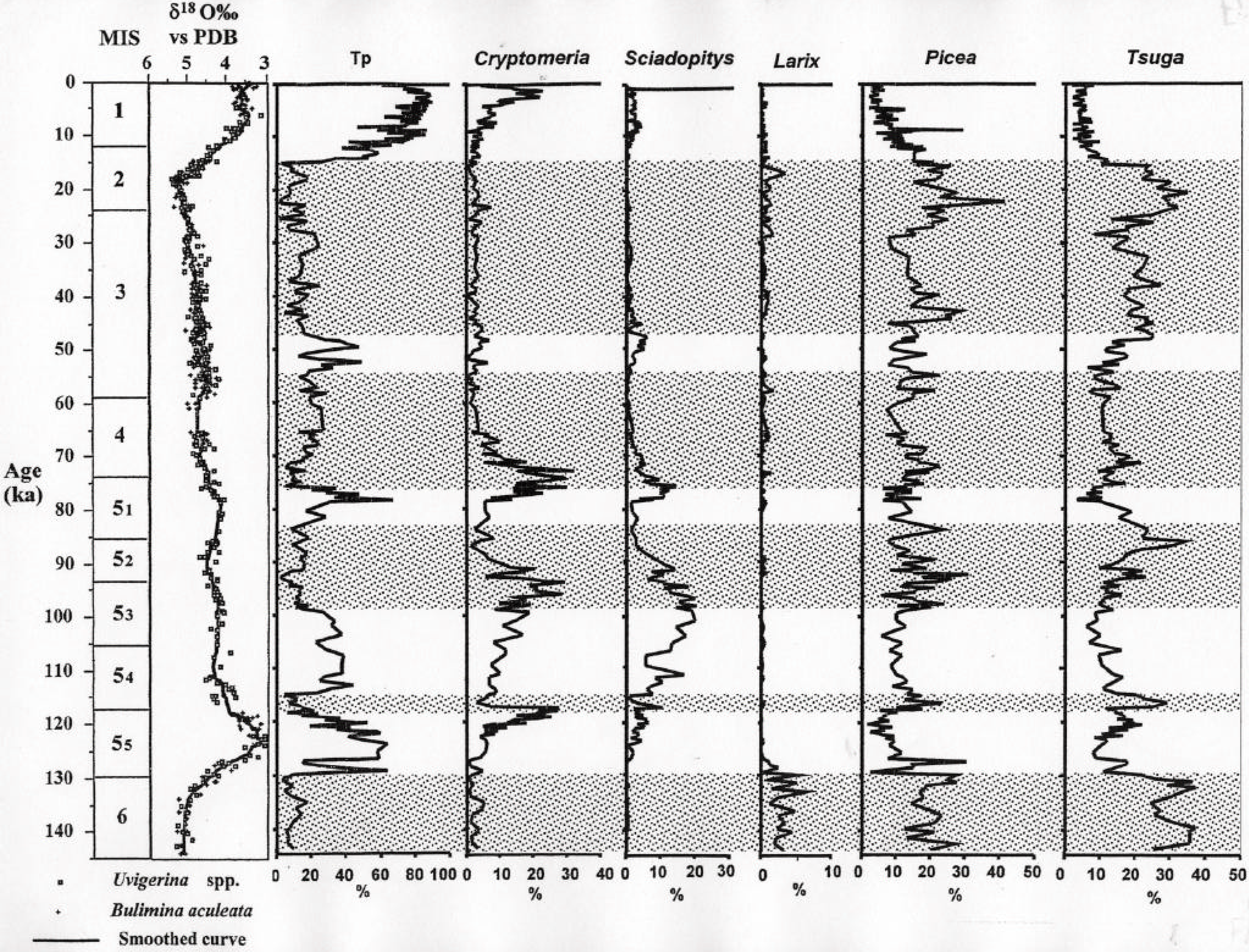
28.27	85.22	MIS 5.1/5.2
28.49	88.00	Aso-4 tephra
29.60	90.95	MIS 5.2
31.17	94.06	MIS 5.2/5.31
33.28	99.38	MIS 5.3
34.13	105.57	MIS 5.33/5.4
34.71	110.79	MIS 5.4
36.48	117.30	MIS 5.4/5.51
40.27	122.56	MIS 5.5
42.41	129.84	MIS 6.0
43.29	132.81	MIS 6.1
44.79	141.33	MIS 6.3

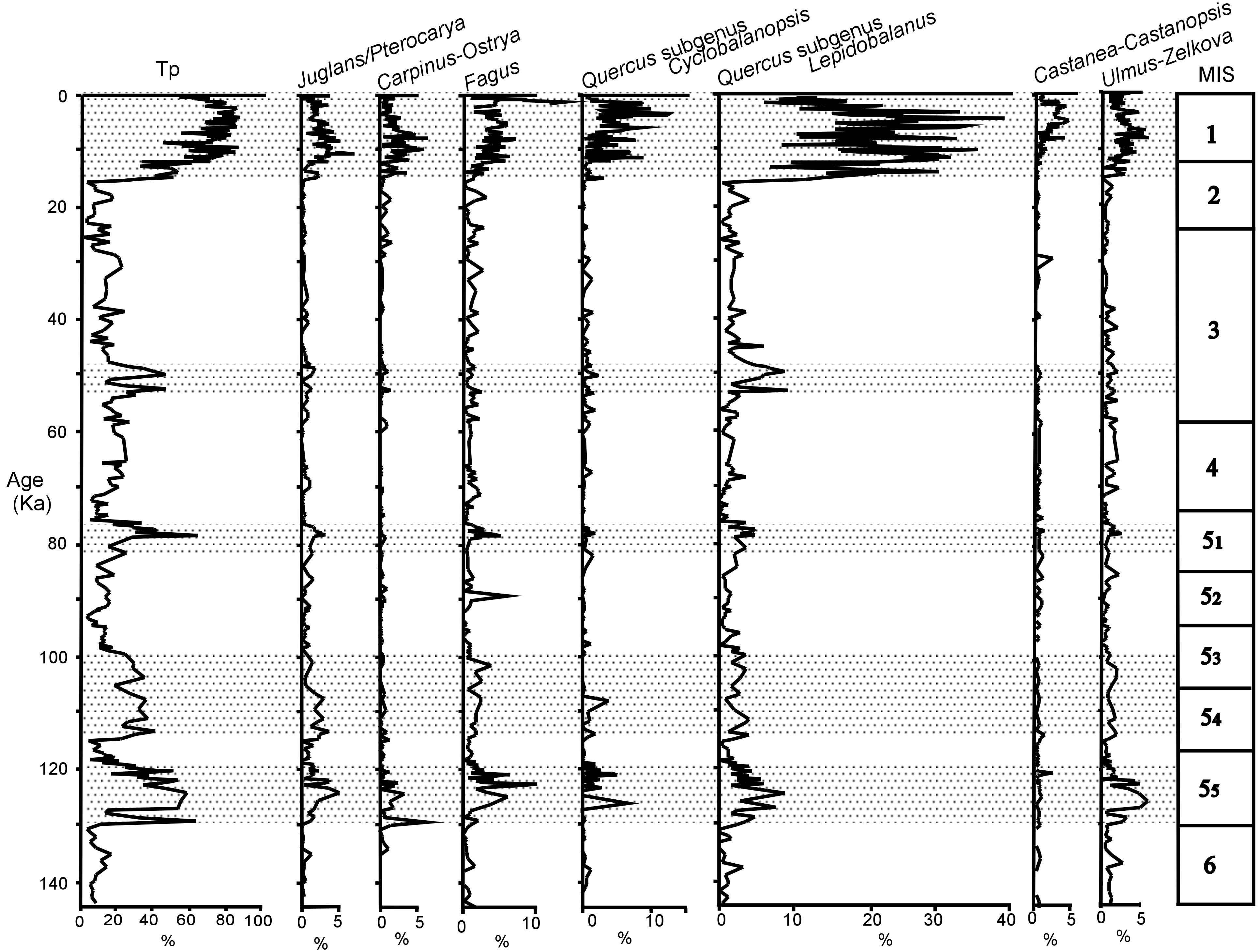

Age(Ka)
Climate
Monsoon
Vegetation
MIS
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
warm/humid
Warm temperate broad-leaf forest with *Cryptomeria*
cool
cool
cool
cool
warm
Cool temperate deciduous broad-leaf forest
1
2
cold/dry
Subalpine conifer forest
3
cold
temperate
Mixed forest
cold/dry
Subalpine conifer forest
4
cold/humid
Subalpine conifer forest with *Cryptomeria*
warm/humid
Mixed forest with *Cryptomeria*
temperate
Mixed forest
5$_1$
cold/dry
Subalpine conifer forest
5$_2$
cold/humid
Subalpine forest with *Cryptomeria* and *Sciadopitys*
5$_3$
temperate/humid
Mixed forest with *Cryptomeria* and *Sciadopitys*
5$_4$
cold/dry
Subalpine conifer forest
cold/humid
Subalpine conifer forest with *Cryptomeria*
warm
Cool temperate broad-leaf forest
5$_5$
cold/dry
Subalpine
cold/dry
Subalpine conifer forest
6

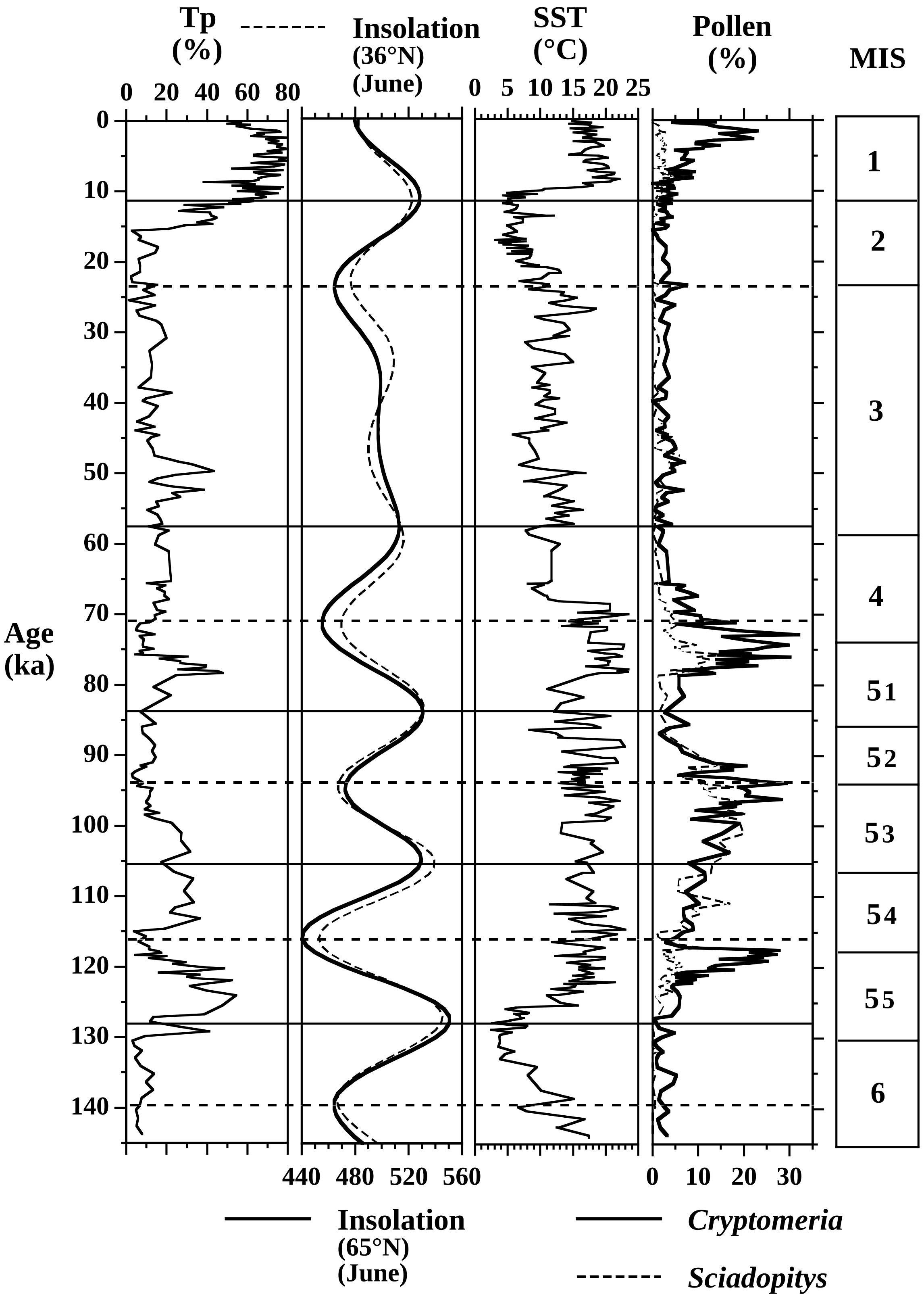


Kuzi River
Naka River
Sea of Kasima
Tone River
MD01-2421
0
50km
Sea of Okhotsk
50° N
Oyashio Cold Current
Sea of Japan
Pacific Ocean
40° N
Tsushima Warm Current
MD01-2421
Kuroshio Warm Current
30° N
A
B
C
D
130° E
140° E
150° E


Tephra ka
0
10
20
AT
30
40
50
60
70
80
Aso-4
90
100
110
120
130
140
Loc.1
?
Loc.2
?
MD01-2124
RC14-99
MIS
1
2
3
4
5_1
5_2
5_3
5_4
5_5
6
HOKKAIDO
①
②
Northern Kanto
MD01-2421
0
200
km
32°
34°
36°
38°
40°
42°
RC-1499


MIS
δ18 O‰
vs PDB
6
5
4
3
Tp
Cryptomeria
Sciadopitys
Larix
Picea
Tsuga
Age
(ka)
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
1
2
3
4
51
52
53
54
55
6
0 20 40 60 80 100
%
0 10 20 30 40
%
0 10 20 30
%
0 10
%
0 10 20 30 40 50
%
0 10 20 30 40 50
%
Uvigerina spp.
Bulimina aculeata
Smoothed curve


Tp
Juglans/Pterocarya
Carpinus-Ostrya
Fagus
Quercus subgenus Cyclobalanopsis
Quercus subgenus Lepidobalanus
Castanea-Castanopsis
Ulmus-Zelkova
MIS
Age (Ka)
0
20
40
60
80
100
120
140
0 20 40 60 80 100
%
0 5
%
0 5
%
0 10
%
0 10
%
0 10 20 30 40
%
0 5
%
0 5
%
1
2
3
4
5₁
5₂
5₃
5₄
5₅
6


Tp (%)
Insolation (36°N) (June)
SST (°C)
Pollen (%)
MIS
0 20 40 60 80
0 5 10 15 20 25
Age (ka)
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140
440 480 520 560
0 10 20 30
1
2
3
4
5 1
5 2
5 3
5 4
5 5
6
Insolation (65°N) (June)
Cryptomeria
Sciadopitys