

Early Miocene terrestrial climate inferred from plant megafossil assemblages of the Joban and Soma areas, Northeast Honshu, Japan.

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Abstract: Five Early Miocene plant megafossil assemblages from two separate sequences in the Joban and Soma areas on the Pacific side of Northeast Japan, which are interpreted to have accumulated from vegetation in near-sea coastal lowland, are analyzed to discuss the temporal change of floral composition and causal change in terrestrial climate. The Mixed Northern Hardwood forest characterized by various species of deciduous woody dicotyledons and deciduous and evergreen conifers in Stage I (ca. 23.4 Ma) shifted gradually to a Mixed Broad-leaved deciduous forest (Stage II: ca. 21 Ma), a Mixed Broad-leaved Evergreen and Deciduous forest (Stage III: ca. 20 Ma) and a Notophyllous Broad-leaved Evergreen forest (Stages IV and V: ca. 16-17 Ma) with an appearance and subsequent increase in evergreen and deciduous species that favors warmer climatic conditions, and a decrease of taxa which inhabited cooler climates. These changes reflect an increase in mean annual temperature in the first half of the period and a decrease in mean annual range of temperature in the latter half, which were caused by mitigation of winter coldness. A quantitative analysis of mean annual temperature based on the leaf margin analysis also revealed a clear trend of increasing temperature. An abrupt change in temperature observed at the transition from Stages I to III, and warm climate during Stages IV to V can be correlated with the periods influenced by subtropical to tropical shallow-marine climate. A comparison between terrestrial and shallow-marine climates in the Joban and Soma areas probably indicates a synchronous response to climate change occurred during the Early Miocene.

Key words: Plant megafossils, Physiognomy, Climate condition, Shallow-marine climate, Early Miocene, Northeast Japan

1. Introduction

Plant megafossil is one of the most important tools for estimating past climate conditions. A number of attempts have been made to reconstruct climates from Tertiary floras in different continents with reference to global change (e.g., White *et al.*, 1997; Pole, 2003; Mosbrugger *et al.*, 2005). One of the problems inherent in this kind of study is a precise age determination for each flora, because many floras are contained in terrestrial deposits. Tertiary deposits in the Japanese Islands, yielding abundant plant megafossils, are often intercalated with biostratigraphically well-defined marine beds. They frequently contain volcanic and volcanoclastic rocks available for radiometric dating. Therefore, Tertiary floras in the Japanese Islands will provide one of the standards in floristic as well as climate change in East Asia (Tanai, 1967).

Tertiary floral change in the Japanese Islands and adjacent countries in East Asia has been summarized by Tanai (1967, 1992). Early Miocene floras in these areas have been divided stratigraphically and floristically into

two types, the Aniai- and Daijima-types (Huzioka, 1949, 1963; Tanai, 1961; Tanai, 1991). The Aniai-type flora of earliest Miocene age is characterized by various species of deciduous broad-leaved trees and conifers. In contrast, the Daijima-type flora, ranging from late Early to early Middle Miocene, consists of a mixture of deciduous and evergreen broad-leaved trees with conifers; most of its modern relatives are distributed in southern, warm areas (Huzioka, 1963; Huzioka and Uemura, 1979).

The origin and the expansion of the Daijima-type flora have been discussed in relation to the opening of Japan Sea and resultant invasion of a warm oceanic current (Huzioka and Uemura, 1979). However, Kano and Yanagisawa (1989) suggested a possible link to the global marine climate and Kano *et al.* (2007) argued for an influence of tectonic movements on the assemblages from the back arc basin. In the present study, the author analyzed five plant megafossil assemblages accumulated from lowland vegetation during the Early Miocene in the Joban and Soma areas on the Pacific side of Northeast Honshu, where tectonic movements did not severely

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affect Tertiary deposition. For climatic reconstruction, the author used a simple linear regression analysis termed the Leaf Margin Analysis (Wolfe, 1979; Wing and Greenwood, 1993) to obtain quantitative data on mean annual temperature (MAT). This method is based on the relationship between MAT of a given area and the percentage of woody dicotyledons with a smooth leaf margin in a given flora under a humid to mesic condition (Wolfe, 1979; Wing and Greenwood, 1993). It is applicable to the Tertiary floras in the Japanese Islands, because they flourished under humid climate conditions as indicated by large leaf size as well as general lack of geologic evidence of arid climate (Tanai, 1993; Uemura, 1993). Relative changes in mean annual range of temperature (MART) were roughly estimated from a comparison of physiognomic characters between the fossil assemblage and present-day forests in East Asia (Wolfe, 1979). Regional floral change that may be affected principally by terrestrial climate change and the influence of warm oceanic current will be discussed.

2. Geologic outline

In the east and northeast foothill plains of the Abukuma Plateau, locating at the Pacific side of Northeast Honshu Island, Late Cretaceous to Tertiary terrestrial to marine deposits are well exposed above the basement consisting of granite, metamorphic rocks and Paleozoic sedimentary rocks (Fig. 1). Tertiary deposits in the Joban area extend northward and contact those of the Soma area through the Futaba Fracture Zone, which runs north to south along the eastern edge of the Abukuma Plateau.

The Lower Miocene sequence in the Joban area is divided into the Shichiku Formation, Yunagaya Group, Nakayama Formation, and the Takaku Group, in ascending order (Sugai *et al.*, 1957; Suto *et al.*, 2005) (Fig. 2). Depositional cycles for these deposits are controlled principally by eustatic sea-level change and secondarily by regional tectonics at that time (Yanagisawa *et al.*, 1989). Plant megafossils, which is the main objective of the present study, are included in most of these deposits, except for the Takaku Group.

The lowermost Miocene Shichiku Formation, which contains abundant plant megafossils (Tanai and Onoe, 1959; Suzuki, 1961; Huzioka, 1964), is a lacustrine deposit and has been included in the Yunagaya Group (Sugai *et al.*, 1957). Suto *et al.* (2005) recently regarded it as a distinct sedimentary unit and separated it from the Yunagaya Group based on a fission track age of 23.4 Ma, approximately 2 Ma older than the overlying formation. The author follows their opinion but treats the Shichiku Formation as a “Neogene” unit, because the depositional sequence of this formation appears to relate to Neogene units rather than to Paleogene offshore sediments (Yanagisawa and Suzuki, 1987). Further, the flo-

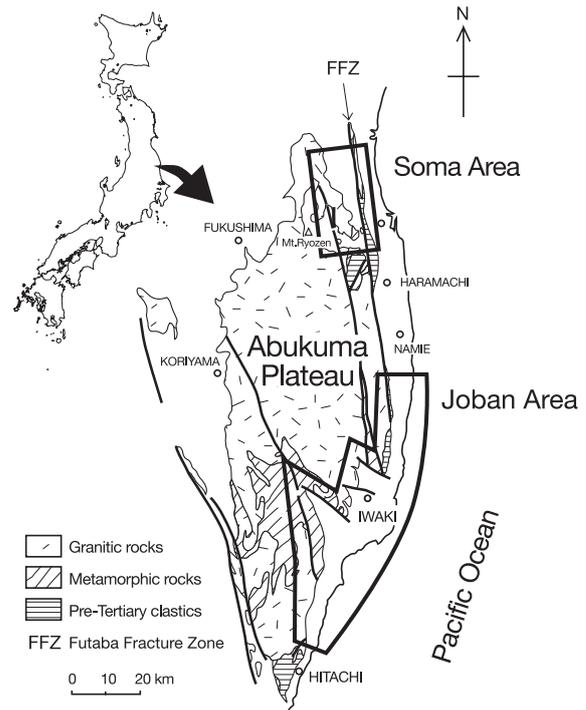


Fig. 1 Index map of the study area (modified from Yanagisawa *et al.*, 1996).

ral composition of the formation is equivalent to those of the earliest Miocene Aniai-type flora as discussed herein.

The overlying Yunagaya Group represents one transgressive-regressive sequence (Yanagisawa *et al.*, 1989) and is subdivided into the Kunugidaira, Goyasu, Mizunoya, Kamenoo and Taira Formations, in ascending order. Plant megafossils have mainly been reported from the basal part, the Kunugidaira and Goyasu Formations (Suzuki, 1963; Yabe *et al.*, 1995a, b), and the top of the sequence, the Taira Formation (Yabe, 1999), but rarely from the other formations of marine origin (Suzuki, 1989). The Kunugidaira Formation also yields shallow-marine molluscs in its upper part, which is represented by such warm-water genera as *Vicarya*, *Vicaryella*, and *Tateiwaia* (Kamada, 1962; Yabe *et al.*, 1995b); the assemblage coincides with the Akeyo-type molluscan fauna (Itoigawa, 1988) that precedes the marine Kadonosawa Fauna of the Miocene thermal maximum. On the other hand, the Goyasu Formation contains the mytilid bivalve *Mytilus tichanovitchi* (O'Hara and Nemoto, 1982), which indicates a mild-temperate to cool-temperate shallow-marine climate (Ogasawara, 2000; Kurihara *et al.*, 2005).

The Nakayama Formation consists of basaltic lava, andesitic volcanic breccia, tuff and tuffaceous sandstone and mudstone with a lesser amount of lignite, deposited in terrestrial to shallow-marine conditions. Plant megafossils come from the middle of the formation, while the molluscan fossils are abundant in the upper

prises conglomerate, sandstone and siltstone with intercalated coal seams and tuff layers. The lower part of the formation is interpreted to be fluvial, whereas the upper part is lacustrine based on the occurrence of diatomaceous mudstone. The formation grades upward into a muddy facies of the Hazama Formation of shallow-marine origin. The Hazama Formation produces diatom assemblages that can be correlated to zone NPD 4A (Takano *et al.*, 2005b). It also contains such characteristic molluscan fossils as *Anadara gentaroensis*, *Crassostrea gravitesta*, and *Babylonia kozaiensis*; the assemblage has been interpreted as representing a cooler marine climate following the Miocene thermal maximum seen in the Kadonosawa Fauna (Takano *et al.*, 2005a, b).

The Shiote Formation is correlated with the Kunugidaira Formation in the Joban area in both its radiometric age and the occurrence of the Akeyo-type molluscan fauna. The Ryozen Formation is comparable with the Nakayama Formation in having a predominance of andesitic volcanoclastic deposits. K-Ar dates from the dyke (16.3 ± 0.8 Ma) in the upper part of the formation (Yanagisawa *et al.*, 1996) and in a basaltic lava (15.0 ± 0.9 and 17.8 ± 1.0 Ma: Baba *et al.* 2007) are concordant with the biostratigraphy of the Nakayama Formation (Fig. 2). The thick tuff bed at the middle of the Ouchi Formation is dated 14.8 ± 1.0 Ma by the fission track method (Yamamoto, 1996). However, based on the biostratigraphy of the marine Hazama Formation (Takano *et al.*, 2005b), the Ouchi Formation is comparable to the Takaku Group of the Joban area.

3. Early Miocene floras in the Joban and Soma areas

Plant megafossil assemblages treated in the present study are those of the Shichiku, Kunugidaira, and Nakayama Formations in the Joban area, and those of the Shiote and Ouchi Formations in the Soma area. These assemblages accumulated in lacustrine, fluvial, or shallow-marine environments, and are interpreted to have derived from vegetations around the near-sea coastal lowland, based on a detailed analysis of occurrence and composition as well as sedimentary environment. The assemblage from the Ryozen Formation (Suzuki, 1961; Yabe unpublished data) was not treated here because it does not represent lowland vegetation. Five plant megafossil assemblages are divided into five stratigraphic levels from the earliest Miocene to the transition between the Early and Middle Miocene and are provisionally named Stages I to V, in ascending order (Fig. 2).

Floral data presented herein are mainly based on the author's unpublished data, which will be described elsewhere (Appendix 1). Some museum collections used by Suzuki (1963) for the Shiote Flora, and by Onoe (in Kono *et al.*, 1969) for the Ouchi Flora were also exam-

ined. Figures 3 to 7 show common species that comprise over 3% of the total specimens in each assemblage and some characteristic species of each assemblage. Inferred vegetation of each assemblage was estimated based on the definition of Wolfe (1979).

Stage I: Shichiku Flora (ca. 23.4 Ma)

The Shichiku Flora is composed mainly of diverse deciduous woody dicotyledons and deciduous and evergreen conifers of temperate climate regime. The most dominant species is *Pseudotsuga tanaii*, followed by *Fagus antipofi*, *Zelkova ungeri*, *Carpinus jobanensis*, *Hemitrapa borealis*, and *Metasequoia occidentalis*. The largest family in the assemblage is Betulaceae represented by 10 species of leaves and Aceraceae with 5 species of leaves. No evergreen woody dicotyledons were found in the assemblage. The percentage of woody dicotyledons with a smooth leaf margin in the assemblage is 21.62%. Inferred vegetation is a Mixed Northern Hardwood forest.

The Shichiku Flora is fundamentally equivalent to the Aniai-type flora in its composition as well as physiognomic characters (Huzioka, 1964), but includes some uncommon genera in this type of flora, such as *Taiwania*, *Cunninghamia*, and *Sassafras*.

Stage II: Plant megafossil assemblage from the lower part of the Kunugidaira Formation (ca. 21 Ma)

The plant megafossil assemblage from the lower part of the Kunugidaira Formation contains diverse temperate genera and species similar to the Shichiku Flora, in conjunction with several elements common to the Daijima-type flora. *Fagus antipofi* is a common species in the assemblage and comprises about 4.9% of the total specimens. Another characteristic species is *Quercus miovariabilis* and comprises about 10%. Both the genera are also represented by their reproductive structures. This assemblage is also characterized by a predominance of swamp or riverside elements, such as *Metasequoia occidentalis*, *Cryptomeria* sp., *Alnus miojaponica* and *Salix* spp. and often yields some water plants, like *Hemitrapa hokkaidoensis* and *Ceratophyllum* sp. Evergreen woody dicotyledons are quite rare in this assemblage and represented by only one species, *Camellia protojaponica*. The percentage of woody dicotyledons with a smooth leaf margin in the assemblage is 26.19%. Inferred vegetation of the assemblage is a Mixed Broad-leaved Deciduous forest.

Stage III: Plant megafossil assemblage from the upper part of the Kunugidaira Formation and the Shiote Formation (ca. 20 Ma)

The plant megafossil assemblage from the upper part of the Kunugidaira Formation co-occurs with the potamidid gastropod *Vicarya yokoyamai* and the other molluscan fossils that are comparable to the Akeyo-type mollus-

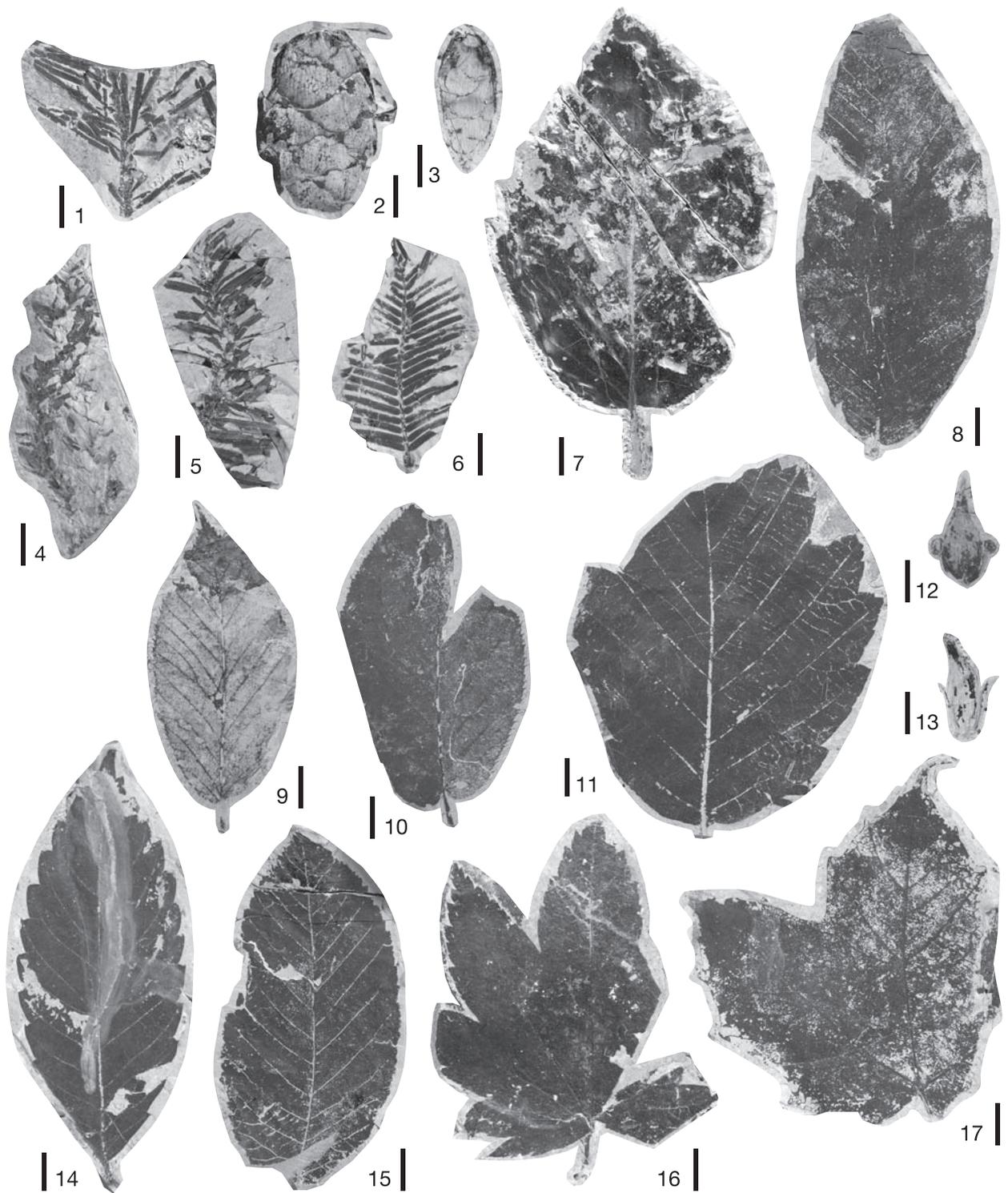


Fig. 3 Selected plant megafossils from the Shichiku Flora (Stage I). Scale bar equals 1 cm long. 1, 2, *Pseudotsuga tanaii* Huzioka (2: cone); 3, *Tsuga* sp. (cone); 4, *Taiwania japonica* Tanai et Onoe; 5, *Cunninghamia protokonishii* Tanai et Onoe; 6, *Metasequoia occidentalis* (Newberry) Chaney; 7, *Betula nathorsti* Suzuki; 8, *Fagus antipofi* Heer; 9, *Carpinus jobanensis* Suzuki; 10, *Carpinus subcordata* Nathorst; 11, *Alnus protohirsuta* Uemura; 12, 13, *Hemitrapa borealis* (Heer) Miki (fruit); 14, *Zelkova ungeri* (Ettingshausen) Kovats; 15, *Ostrya shiragiana* Huzioka; 16, *Acer protojaponicum* Tanai et Onoe; 17, *Acer* sp. cf. *A. yamanae* Tanai et Ozaki.

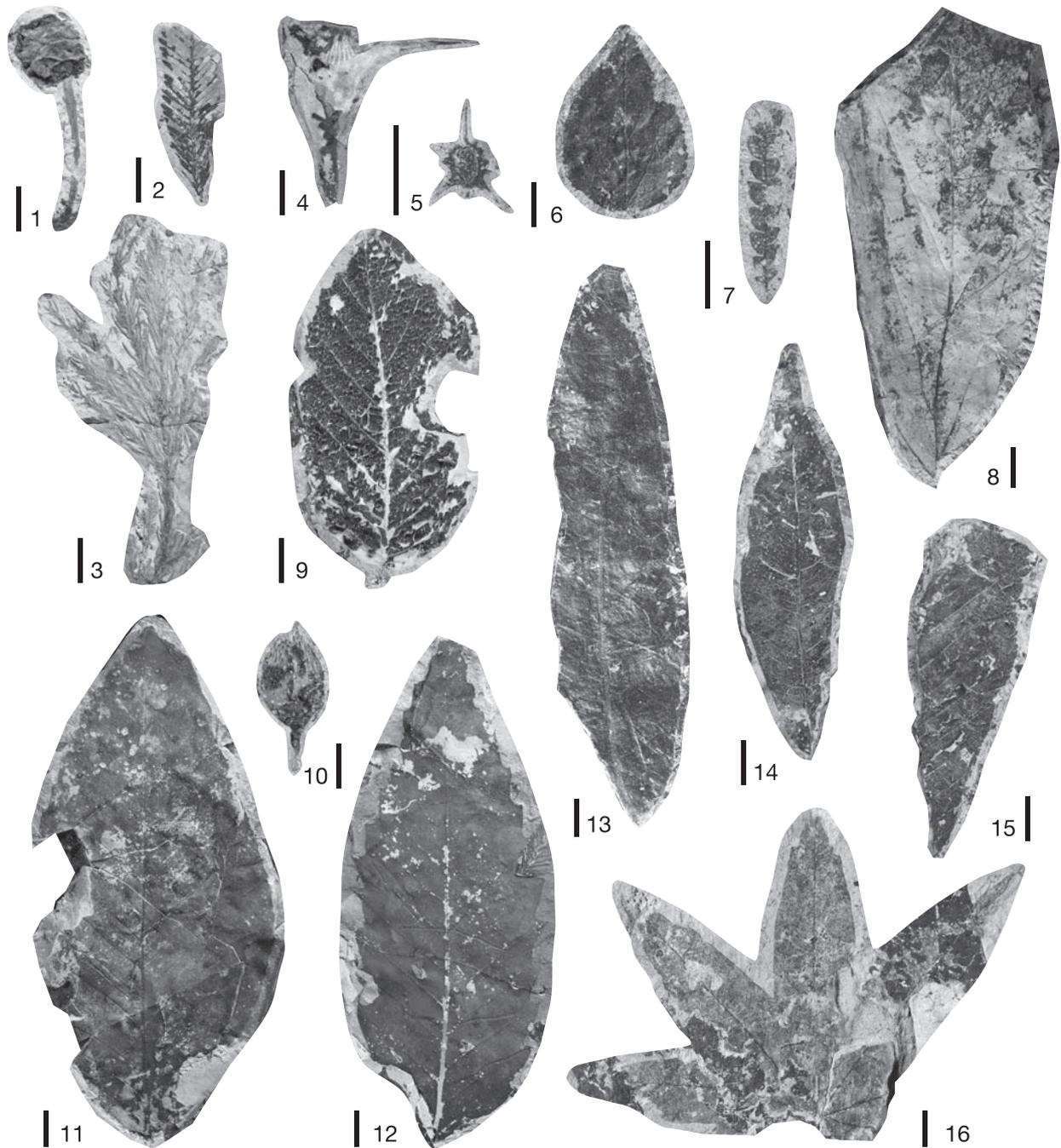


Fig. 4 Selected plant megafossils from the lower part of the Kunugidaira Formation (Stage II). Scale bar equals 1 cm long. 1, 2, *Metasequoia occidentalis* (Newberry) Chaney (1: cone); 3, *Cryptomeria* sp.; 4, *Hemitrapa hokkaidoensis* (Okutsu) Miki (fruit); 5, *Ceratophyllum* sp. (fruit); 6, *Cercidiphyllum crenatum* (Unger) Brown; 7, *Comptonia naumanni* (Nathorst) Huzioka; 8, *Parrotia pristina* (Ettingshausen) Stur; 9, *Alnus miojaponica* Tanai; 10, *Fagus* sp. (cupule); 11, *Fagus antipofi* Heer; 12, *Quercus miovariabilis* Hu et Chaney; 13, *Salix parasachalinensis* Tanai et Suzuki; 14, *Salix* sp. 1; 15, *Aesculus majus* (Nathorst) Tanai; 16, *Acer chiharae* Huzioka.

can fauna. The Shiote Flora was also recovered from a stratum that underlies marine beds containing molluscan fossils similar to those of the Kunugidaira Formation.

The both assemblages are mainly composed of deciduous woody dicotyledons of temperate to warm-temperate conditions, but are admixed with several evergreen

species belonging to the families Lauraceae (*Actinodaphne*, *Cinnamomum* and *Machilus*) and Fagaceae (*Cyclobalanopsis*) (Fig. 5). Just as in previous stages, these assemblages contain abundant *Fagus antipofi* (7 to 9%), which is more common in the Aniai-type flora. The percentages of woody dicotyledons with

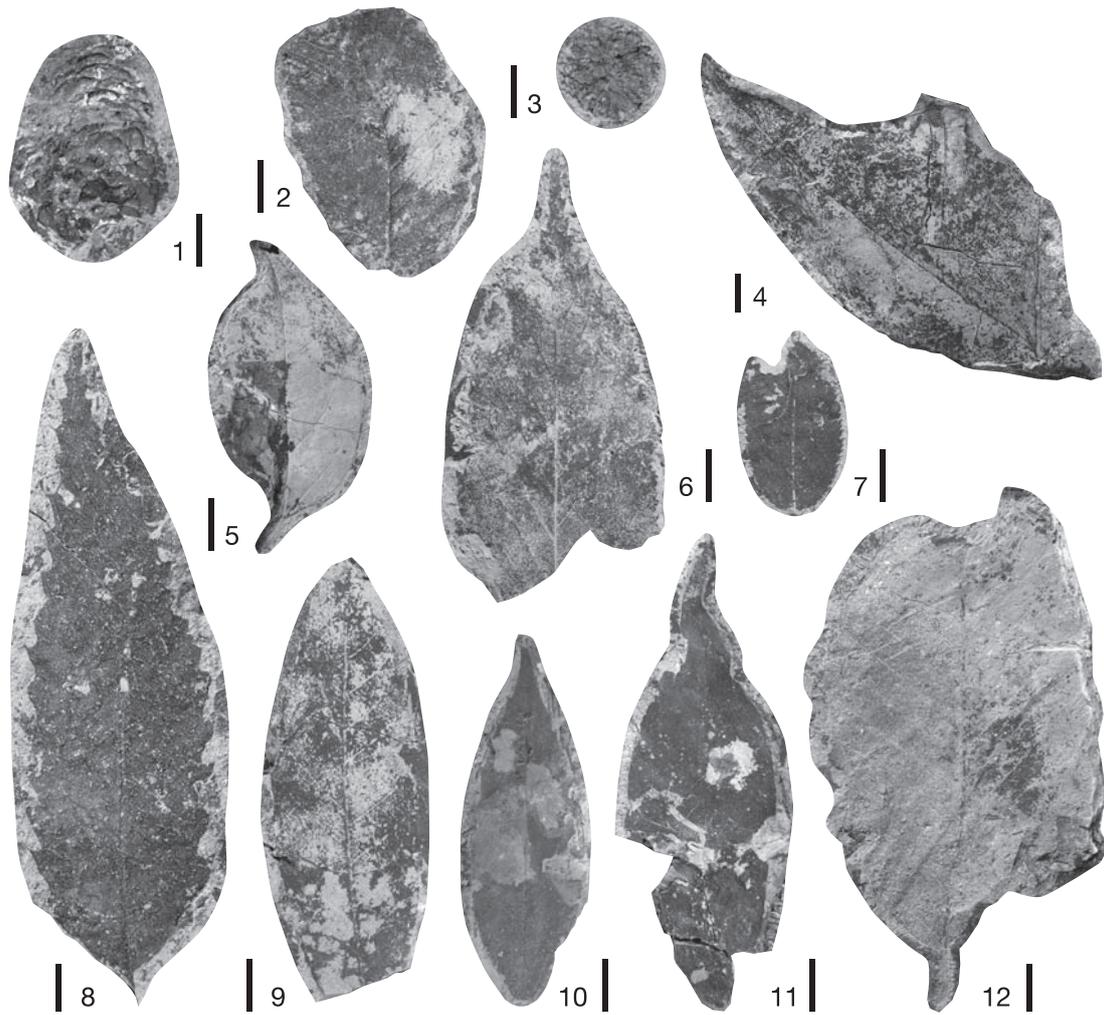


Fig. 5 Selected plant megafossils from the upper part of the Kunugidaira Formation (Stage III). Scale bar equals 1 cm long. 1, *Pinus* sp. (cone); 2, *Ulmus carpinoides* Goepfert; 3, 4, *Liquidambar miosinica* Hu et Chaney (3: fruit); 5, *Ficus* sp.; 6, *Carpinus heigunensis* Huzioka; 7, *Ostrya shiragiana* Huzioka; 8, *Quercus miovariabilis* Hu et Chaney; 9, *Quercus (Cyclobalanopsis) nathorstii* Kryštofovich; 10, *Quercus (Cyclobalanopsis) mandraliscae* Gaudin; 11, *Actinodaphne nipponica* Tanai; 12, *Fagus antipofi* Heer.

a smooth leaf margin are 39.47% (Kunugidaira) and 38.10% (Shiote), respectively (Table 1). Inferred vegetation is a Mixed Mesophytic forest or a Mixed Broad-leaved Evergreen and Deciduous forest. In terms of the common occurrence of evergreen oaks, it is more similar to the latter.

Stage IV: The Nakayama Flora (ca. 17 Ma)

The Nakayama Flora is characterized by an admixture of diverse species of deciduous and evergreen woody dicotyledons. Most of its constituents are common to the Daijima-type flora. Common or abundant species in the assemblage are *Ulmus longifolia*, *Pterocarya proto-stenoptera*, *Cyclocarya ezoana*, *Quercus miovariabilis*, *Parrotia pristina*, *Berchemia miofloribunda*, *Paliurus protonipponicus*, and *Sorbus uzenensis* (Fig. 6); most of which were also found in the Stage III assemblages. The

largest families in this assemblage are Lauraceae and Fabaceae, represented by six species each: most of the former are considered to be evergreens judging from their preservation state as well as the habit of modern equivalents. The percentage of woody dicotyledons with a smooth leaf margin attains 40.98%. Inferred vegetation is a Notophyllous Broad-leaved Evergreen forest.

Stage V: The Ouchi Flora (ca. 16 Ma)

The Ouchi Flora is composed of 28 species represented by 23 genera and 13 families, most of which are common to those from the assemblages of Stages III and IV. Evergreen species belonging to the families Lauraceae and Fagaceae appears dominant in number of species and specimens, although numerical data are not available (Fig. 7). The percentage of possible evergreen species exceeds 36%, while the percentage of woody dicotyle-

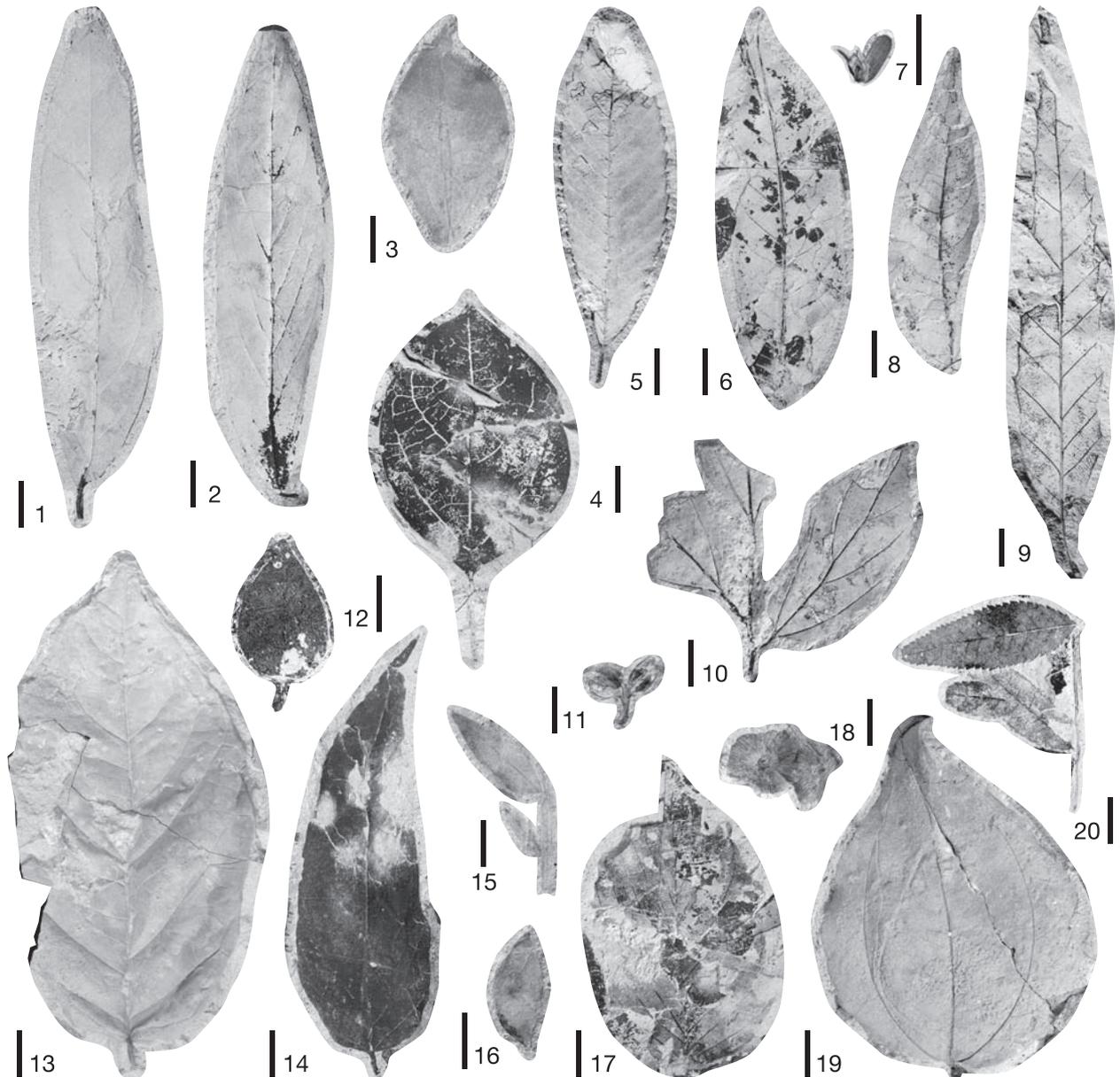


Fig. 6 Selected plant megafossils from the Nakayama Flora (Stage IV). Scale bar equals 1 cm long. 1, *Actinodaphne oishii* Huzioka; 2, *Machilus ugoana* Huzioka; 3, *Cinnamomum miocenum* Morita; 4, *Lindera* sp.; 5, *Ulmus longifolia* Unger; 6, 7, *Pterocarya protostenoptera* Tanai (7: fruit); 8, *Cyclocarya ezoana* (Tanai et Suzuki) Wolfe et Tanai; 9, *Quercus miovariabilis* Hu et Chaney; 10, *Parrotia pristina* (Ettingshausen) Stur; 11, Hamamelidaceae gen. et sp. indet. (fruit); 12, *Maackia onoei* Matsuo; 13, *Cladrastis* sp. cf. *C. chaneyi* Tanai et Suzuki; 14, *Wisteria fallax* (Nathorst) Tanai et Onoe; 15, 16, *Podogonium knorrii* Heer (16, fruit); 17, *Berchemia miofloribunda* Hu et Chaney; 18, 19, *Paliurus protonipponicus* Suzuki (18: fruit); 20, *Sorbus uzenensis* Huzioka.

dons with a smooth leaf margin in the assemblage is 42.31% (Table 1). Inferred vegetation of the assemblage is the same as that of the Stage IV. However, predominance of evergreen species suggests a higher winter temperature than that of the previous stage.

4. Discussion and conclusion

4.1 Floral change and inferred terrestrial climate

Early Miocene vegetation changes were assumed from the relative changes in fossil composition as well as temperatures that were estimated by the Leaf Margin Analysis (Table 1). Most of the MAT estimates, except that estimated with the Stage II assemblage, are concordant with those inferred from the vegetation. The lower

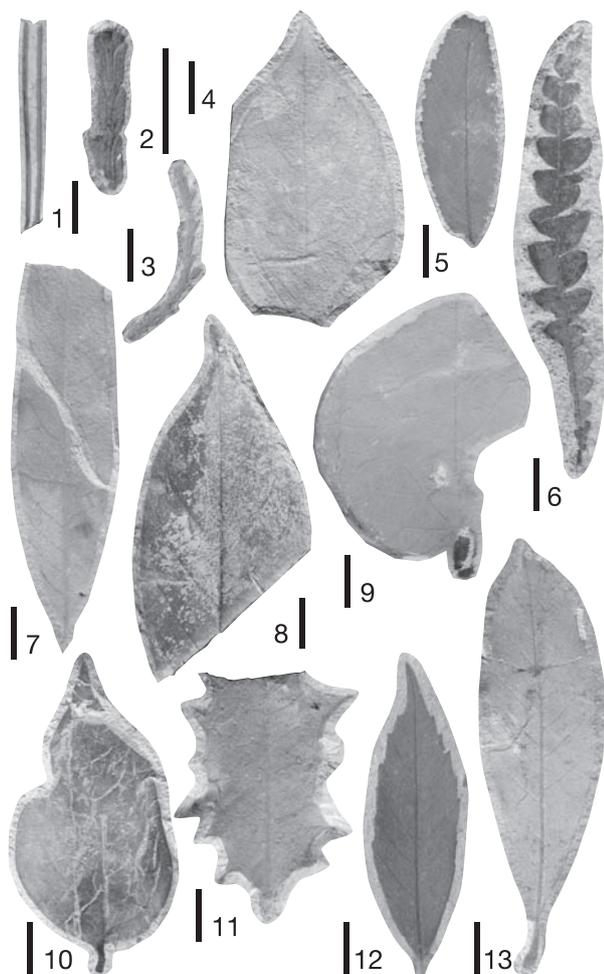


Fig. 7 Selected plant megafossils from the Ouchi Flora (Stage V). Scale bar equals 1 cm long. 1, *Pinus* sp.; 2, 3, *Calocedrus notoensis* (Matsuo) Huzioka; 4, *Cinnamomum miocenum* Morita; 5, *Ulmus longifolia* Unger; 6, *Comptonia naumannii* (Nathorst) Huzioka; 7, *Actinodaphne nipponica* Tanai; 8, *Machilus nathorstii* Huzioka; 9, Cf. *Byttneriophyllum tiliaefolium* (Al. Braun) Knobloch et Kvacek; 10, Fabaceae gen. et sp. indet.; 11, *Osmanthus chaneyi* Matsuo; 12, *Quercus* (*Cyclobalanopsis*) *mandraliscae* Gaudin; 13, *Quercus* (*Cyclobalanopsis*) *nathorstii* Kryshtofovich.

MAT estimate with the Stage II assemblage is probably because of the abundant associations of riparian and wetland vegetation in this assemblage. As pointed out by Burnham *et al.* (2001), such vegetation often yields a higher percentage of species with toothed leaves.

The earliest Miocene Shichiku Flora is fundamentally equivalent to the Aniai-type flora in terms of both composition and foliar physiognomy. However, the presence of some uncommon genera among the Aniai-type flora implies a slightly higher MAT and probably a lower MART than those estimated with the Aniai-type flora from the Japan Sea side. This must be because of the difference between seaside (Shichiku flora) and inland (e.g., Aniai Flora) forests before the rifting of the Japanese

Islands (Huzioka, 1964).

Five Early Miocene floras characterize the gradual change in vegetation (Fig. 8). In terms of fossil composition, this change is characterized by the appearance and subsequent increase in evergreen and deciduous elements that are common among the Daijima-type flora and by the disappearance of elements typically found in the Aniai-type flora. According to Tanai (1967) and Tanai and Uemura (1988), there were marked latitudinal and altitudinal changes in the floral composition at the time of the Daijima-type flora. Thus, the change in the lowland vegetation in the study area can be interpreted as the northward (or northeastward) shift of a warm-temperate forest.

The changes in vegetation and MAT indicate the following 2 trends in climate change: (1) an abrupt increase in MAT during the intervals between Stages I and III; (2) a gradual increase in MAT and a marked decrease in MART during the intervals between Stages III and V. The first trend is characterized by an increase in both summer and winter temperatures. The change in MART during that period is not very significant. In contrast, the second trend is characterized by an increase in the cold month mean temperature (CMMT) rather than a change in the summer temperatures. A distribution of plant species that favors a warmer climate is mainly controlled by winter coldness, while species inhabiting cooler climates are sensitive to summer temperatures. Thus, an increase in the summer temperature during the first half of the period affected the distribution of temperate genera, whereas an increase in the CMMT during the latter half greatly facilitated the colonization of evergreens and warm-temperate elements. The co-occurrence of species common to either the Aniai-type or Daijima-type flora is interpreted as a different ecological tolerance of each species in relation to the change in limiting factors such as cold winter temperatures.

Whether intermittent cooling episodes occurred during the warming trend remain unclear because floral data from the marine deposits between Stages III and IV are still equivocal in terms of the number of species and specimens relevant to the climate. The only exception is the plant megafossil assemblage from the Taira Formation of the Yunagaya Group (Yabe, 1999). This assemblage includes over 40 species of deciduous and evergreen woody dicotyledons. Most species are common to those of the Nakayama Formation and suggest similar climate conditions. Sato (1989) analyzed pollen assemblages from the Tertiary deposits in the Joban area. Although evergreen dicotyledons relevant to the climate were not shown, the relative abundance of *Quercus*, Tricolpate pollen, and *Liquidambar* in the Taira and Nakayama Formations supports the results of megafossil analysis. In contrast, pollen assemblages from the Mizunoya and Kamenoo Formations are characterized by a paucity of these warm elements and an abundance

Table 1 Mean annual temperature estimates based on the Leaf Margin Analysis (Wolfe, 1979).
E: percentage of entire-margined species

Stage	Floras	# leaf species ¹	#enire	E(%)	MAT ²	Error ³
V	Ouchi	26	11	42.31	14.09	2.96
IV	Nakayama	61	25	40.98	13.68	1.93
III	Shiote	42	16	38.10	12.80	2.29
	Kunugidaira Kn-up	38	15	39.47	13.22	2.43
II	Kunugidaira Kn-low	42	11	26.19	9.16	2.08
I	Shichiku	37	8	21.62	7.76	2.07

1: Number of leaf species of woody dicotyledons

2: Regression equation is after Wing and Greenwood(1993) based on data from Wolfe (1979).

$$MAT=1.141+0.306E$$

R²=0.983, p<0.001, standard error of the estimate =0.788 degree celcius

3: Binomial errors were calculated after Wilf (1997).

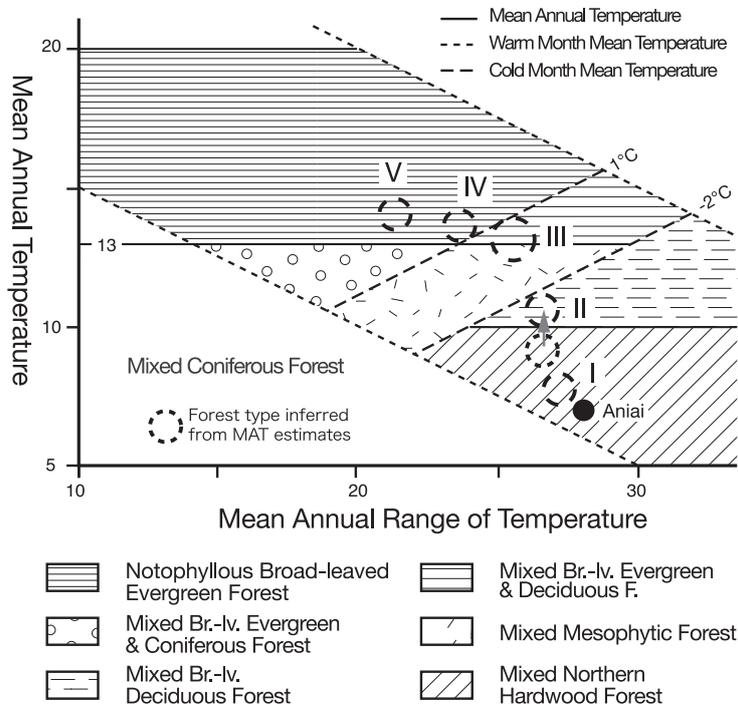


Fig. 8 Inferred vegetation change from the Early Miocene plant megafossil assemblages of the Joban and Soma areas. That of the Stage II assemblage differs from the one inferred from the leaf margin analysis (arrow), probably because of the influence of riparian and wetland vegetations. Nomogram is after Wolfe (1979). Forest type of the Aniai Flora was followed after Uemura (1993).

of temperate elements such as *Tsuga* and *Fagus*. Pollen assemblages from the Kunugidaira and Goyasu Formations did not show any climate signals because they were dominated by local swamp elements such as Taxodiaceae and *Alnus*. Plant megafossils from the Goyasu Formation exclusively comprised deciduous woody dicotyledons such as *Alnus*, *Betula*, *Quercus*, *Ulmus*, *Pterocarya*, *Acer*, and *Cornus* (Yabe unpub-

lished data). This suggests a relatively cooler climate condition than that of the underlying Kunugidaira Formation. Consequently, the terrestrial climate in the Joban and Soma areas represents a warming trend with a cool climate interval between Stages III and IV (Fig. 9).

4.2 Correlation with a shallow-marine climate

Ogasawara *et al.* (2003) discussed the shallow-marine

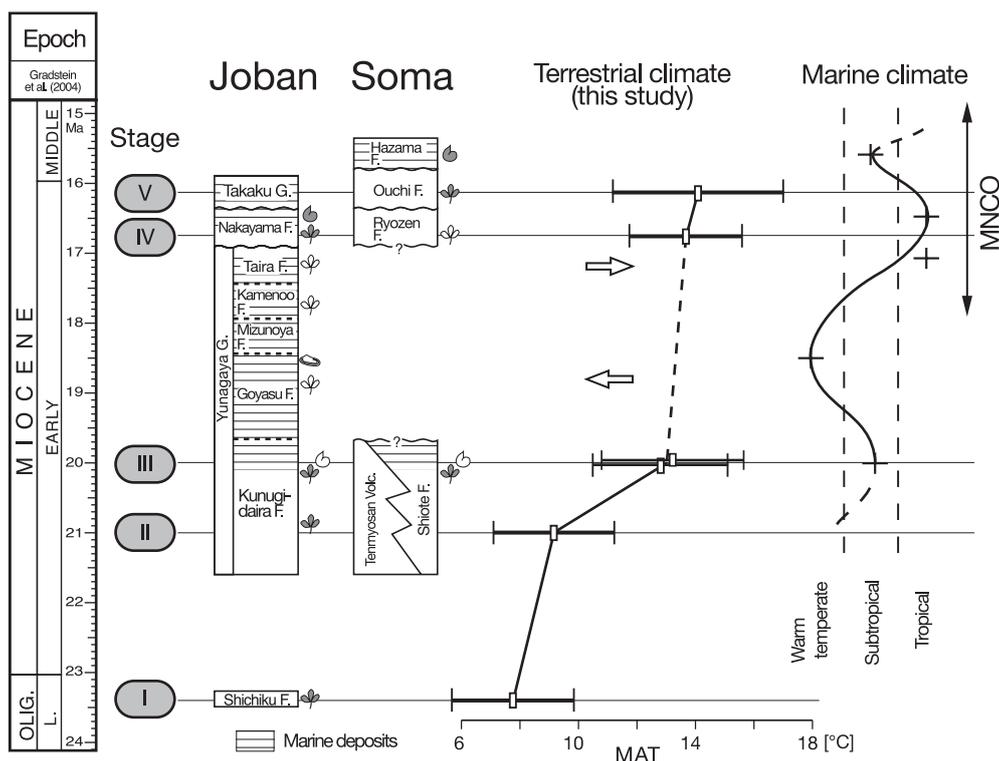


Fig. 9 Early Miocene terrestrial and shallow marine climate change in the Joban and Soma areas. Binomial errors for mean annual temperature estimates are also shown. Marine climate is followed after Ogasawara *et al.* (2003). Open arrows indicate possible cooling and warming climates estimated from the plant megafossil assemblages of marine Goyasu and Taira Formations, respectively. MNCO: Mid Neogene Climatic Optimum. For details of each symbol, see Figure 2.

climate changes in the Japanese Islands during the Early to Middle Miocene, mainly based on molluscan fossils. They recognized at least two warm episodes characterized by the abundant occurrence of shallow-marine organisms inhabiting subtropical to tropical conditions, and an intercalated temperate marine climate denoted by the occurrence of *Mytilus tichanovitchi* and *Felaniella usta*.

Akeyo-type molluscan fauna from both the Kunugidaira and Shiohira Formations represents the first evidence of subtropical shallow-marine condition, while the Kadonosawa Fauna from the Nakayama Formation represents the second, tropical shallow-marine climate during the Miocene thermal maximum, which is termed the Mid-Neogene Climatic Optimum (MNCO). The occurrence of *Mytilus tichanovitchi* from the Goyasu Formation was interpreted to represent a cooler shallow-marine climate (Fig. 9). These changes are also supported by the occurrence of cold-water diatoms from the Mizunoya and Kamenoo Formations (Suto *et al.*, 2005) and warm-water foraminifers from the Taira Formation (Taketani *et al.*, 1990).

A warming trend and possible intercalation of cooler climate was also suggested by floral change in the Joban and Soma areas as discussed in the previous section,

although the duration and degree of cool condition is still unclear. Abrupt changes in temperature observed at the transition from Stages I to III, and a warm climate during Stages IV and V can be correlated with the periods influenced by subtropical to tropical marine climate (Fig. 9). A possible cooler climate between these two episodes is also correlated with shallow-marine records. These evidences may suggest a causal linkage between the change in terrestrial vegetation and that in shallow-marine organisms.

Early Miocene deposits in the Setouchi Geologic Province, located on the Pacific side of Central Honshu, contain various fossils including the plant megafossils. Ina (1992) examined the change in that area in detail and pointed out a clear trend of increasing temperatures with a peak around 16 Ma and one cool-climate interval around 19 Ma. It is concordant with the present author's results obtained in the Joban and Soma areas of Northeast Honshu Island. Thus, it may be concluded that climate change and resultant changes in floral composition took place regionally on the Pacific side during the Early Miocene.

Kano *et al.* (2007) recently argued for tectonic effects on floral change during the Early Miocene: initial rifting of the Japanese Islands produced high mountains

covered by temperate forests, and subsequent tectonic subsidence resulted in an expansion of lowland forest with warm-temperate elements. Detailed correlations between the floras both from Japan Sea and Pacific side of Japanese Islands will be a subject for future study; however, the author's data from the Pacific side do not support a tectonic effect. Floral data and the marine record suggest a synchronous response to regional climate change.

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References

- Baba, A. K., Matsuda, T., Itaya, T., Wada, Y., Hori, N., Yokoyama, M., Eto, N., Kamei, R., Zaman, H., Kidane, T. and Otofujii, Y.-I. (2007) New age constraints on counter-clockwise rotation of NE Japan. *Geophys. J. Int.*, **171**, 1325-1341.
- Blow, W. H. (1969) Late Middle Eocene to recent planktonic foraminiferal biostratigraphy. In Brönnimann, P. and Renz, H. H. eds., *Proceedings of First International Conference on Planktonic Microfossils*. Leiden, Netherlands, 199-422.
- Burnham, R. J., Pitman, N. C. A., Johnson, K. R. and Wilf, P. (2001) Habitat-related error in estimating temperatures from leaf margins in a humid tropical forest. *Am. J. Bot.*, **88**, 1096-1102.
- Gradstein, F. M., Ogg, J. G. and Smith, A. G. eds., (2004) *A Geologic Time Scale 2004*. Cambridge University Press, New York, 589p.
- Huzioka, K. (1949) Two Daijimaian floral types in the Inner zone of northeastern Japan. *Jour. Geol. Soc. Japan.*, **55**, 177. ***
- Huzioka, K. (1963) Aniai flora and Daijima flora. *Fossils, Palaeont. Soc. Japan.*, no. 5, 39-50. ***
- Huzioka, K. (1964) The Aniai flora of Akita Prefecture and the Aniai-type floras in Honshu, Japan. *Jour. Min. Coll. Akita Univ., Ser. A*, **3**, 1-105, pls. 1-18.
- Huzioka, K. and Uemura, K. (1979) The *Comptonia-Liquidambar* forest during the Middle Miocene Daijima age in Japan. *Rep. Res. Inst. Undergr. Resour., Mining Coll., Akita Univ.*, **45**, 37-52, pls. 1-2. ***
- Ina, H. (1992) Miocene vegetational and climatic history of the eastern part of the Setouchi Geologic Province, Japan. *Jour. Earth and Planet. Sci., Nagoya Univ.*, **39**, 47-82.
- Itoigawa, J. (1988) The Miocene Kadonosawa Fauna of Japan. In Grant-Mackie, J. A. et al. eds., *Prof. T. Kotaka Commem. Vol.*, 397-403.
- Kamada, Y. (1962) Tertiary marine mollusca from the Joban coal-field, Japan. *Palaeont. Soc. Japan, Spec. Pap.*, no. 8, 1-187, pls. 1-21.
- Kano, K. and Yanagisawa, Y. (1989) Ages of the Aniai-type and Daijima-type floras in Japan. *Bull. Geol. Surv. Japan.*, **40**, 647-653. *
- Kano, K., Ohguchi, T. and Uemura, K. (2007) Aniai-type and Daijima-type floras: their ages and tectonic implications. In Abstracts Volume of IX International Congress on Pacific Neogene Stratigraphy, 9th RCPNS Tsukuba, Organizing Committee, Tsukuba, 24.
- Kimura, K. (1988) Study on tectonic history of basement rocks in the oil-field region. *Annual Report, JOGMEC, 1987*, 14-17. ***
- Koizumi, I. (1986) Diatom biostratigraphy of the Neogene in the Joban coal-field, Northeast Japan—Yunagaya, Shirado, and Takaku Groups—. In Nakagawa, H. et al. eds., *Essays in Geology, Prof. Nobu Kitamura, Comm. Vol.* Professor Nobu Kitamura Taikan Kinenjigyo-kai, Sendai, 175-191. *
- Kono, M., Sogabe, M., Suzuki, T. and Onoe, T. (1969) Geology and uranium deposits of the Ouchi area, Miyagi Prefecture. *Rep. Geol. Surv. Japan.*, no. 641-658, 641-658. *
- Kubo, K., Yanagisawa, Y., Yoshioka, T. and Takahashi, Y. (1994) *Geology of the Namie and Iwaki-Tomioka district*. With Geological Sheet Map at 1:50,000. Geological Survey of Japan, Tsukuba, 104p. *
- Kubo, K., Yanagisawa, Y., Toshimitsu, S., Banno, Y., Kaneko, N., Yoshioka, T. and Takagi, T. (2002) *Geology of the Kawamae and Ide district*. Geological Survey of Japan, AIST, Tsukuba, 136p. *
- Kurihara, Y., Nakano, T. and Ogasawara, K. (2005) The occurrence of the fossil mytilid bivalve *Mytilus tichanovitchi* Makiyama from the Miocene Shimonita Formation, Gunma Prefecture, central Japan: Re-examination of its biostratigraphic and marine paleoclimatic significance. *Jour. Geol. Soc. Japan.*, **111**, 498-507. *
- Martini, E. (1971) Standard Tertiary and Quaternary calcareous nannoplankton zonation. In Farinacci, A. ed., *Proc. 2nd Conf. Planktonic Microfossils*, **2**, Edizioni Tecnoscienza, Rome, 739-785.
- Mosbrugger, V., Utescher, T. and Dilcher, D. L. (2005)

- Cenozoic continental climatic evolution of Central Europe. *Proc. Natl. Acad. Sci.*, **102**, 14964-14969.
- Motoyama, I. (1999) A review of radiolarian biostratigraphy for the oil-bearing Neogene of Japan—Advances in biostratigraphic resolution—. *Jour. Japan. Assoc. Petrol. Technol.*, **64**, 28-39. *
- O'Hara, S. and Nemoto, N. (1982) Molluscan fossils from the "Goyasu Formation" in the Futaba district of the Joban Coalfield. *Jour. Coll. Arts and Sci., Chiba Univ.*, **B-15**, 57-64, pls. 1-3. *
- Ogasawara, K. (2000) Paleoenvironments of desmostyloid and Cenozoic events of the Northwestern Pacific. *Bull. Ashoro Mus. Paleont.*, no. 1, 25-34. *
- Ogasawara, K., Ugai, H. and Kurihara, Y. (2003) Short-term Early Miocene climatic fluctuations in the Japanese Islands. In *Proceedings of RCPNS 46 - 8th International Congress on Pacific Neogene Stratigraphy*. Chiang Mai University, Chiang Mai., 181-190.
- Okada, H. and Bukry, D. (1980) Supplementary modification and introduction of code numbers to the low-latitude coccolith biostratigraphic zonation (Bukry, 1973, 1975). *Mar. Micropaleont.*, **5**, 321-325.
- Pole, M. (2003) New Zealand climate in the Neogene and implications for global atmospheric circulation. *Palaeoceanogr. Palaeoclimatol. Palaeoecol.*, **193**, 269-284.
- Sato, S. (1989) Palyno-stratigraphic study of the Tertiary in the Joban coal field, Northeast Japan. *Jour. Geol. Soc. Japan.*, **95**, 171-187. *
- Sugai, K., Matsui, H., Sato, S., Kitagawa, Y., Sasaki, M., Miyashita, M. and Kouchi, H. (1957) *Geological map and explanatory text of the Joban coal field*. Geological Survey of Japan, 143p., *
- Suto, I., Yanagisawa, Y. and Ogasawara, K. (2005) Tertiary geology and chronostratigraphy of the Joban area and its environs, northeastern Japan. *Bull. Geol. Surv. Japan.*, **56**, 375-409. *
- Suzuki, K. (1961) The important and characteristic Pliocene and Miocene species of plants from the southern part of the Tohoku district, Japan. *Sci. Rep. Fac. Art and Sci., Fukushima Univ.*, no. 10, 1-97, pls. 1-19.
- Suzuki, K. (1963) Neogene Tertiary of Northeast Japan from the view point of the plant fossils.—Lower Miocene and fossil floral assemblages. *Fossils, Palaeont. Soc. Japan.*, no. 5, 63-77. ***
- Suzuki, K. (1989) On the plant biostratigraphy of the Middle to Lower Miocene strata in the southern part of Northeast Honshu Arc, Japan. *Mem. Geol. Soc. Japan.*, no. 32, 197-205. *
- Takahashi, H. (1984) Molluscan assemblages from the Miocene Nakayama Formation in the Kadono district, Joban Coal-Field, Fukushima Prefecture. *Fossils, Palaeont. Soc. Japan.*, no. 36, 1-17, pl. 1. ***
- Takano, M., Ogasawara, K. and Yanagisawa, Y. (2005a) The Kosai molluscan fauna from the Kakuda basin, Miyagi Prefecture, Northeast Japan.—A peculiar association of the Kadonosawa Fauna in the late of the Mid-Neogene Climatic Optimum—. *Abstracts with Programs, the 2005 Ann. Meet., Palaeont. Soc. Japan.*, 149. ***
- Takano, M., Yanagisawa, Y., Ogasawara, K., Nagane, M. and Kudo, K. (2005b) Geology, age and environmental change of the Tertiary deposits in the Kakuda basin, southern Miyagi Prefecture. *Abstracts with Programs, the 2005 Ann. Meet., Palaeont. Soc. Japan.*, 47. ***
- Taketani, Y. (1995) Radiolaria from the Lower Miocene Yunagaya Group in the Joban Coal Field, Northeast Japan. *Mem. Natl. Sci. Mus.*, no. 28, 48-57. **
- Taketani, Y., Aita, Y., Ono, T., Okada, H., Hasegawa, S., Maruyama, T., Nemoto, N., Kurihara, S. and Takayanagi, Y. (1990) Geologic age and sedimentary environment of the Neogene deposits in the Joban area. *Res. Rep. Fukushima Mus.*, no. 20, 1-99, pls. 1-14. ***
- Tanai, T. (1961) Neogene floral change in Japan. *Jour. Fac. Sci., Hokkaido Univ., Ser. 4*, **11**, 119-398, pls. 1-32.
- Tanai, T. (1967) Miocene floras and climate in East Asia. *Abh. Zentr. Geol. Inst.*, **10**, 195-205.
- Tanai, T. (1991) Tertiary climatic and vegetational changes in the Northern Hemisphere. *Jour. Geogr.*, **100**, 951-966. *
- Tanai, T. (1992) Tertiary vegetational history of East Asia. *Bull. Mizunami Foss. Mus.*, no. 19, 125-163. *
- Tanai, T. (1993) Paleoclimatologic inferences from Tertiary Floras. *Fossils, Palaeont. Soc. Japan.*, no. 54, 35-52. *
- Tanai, T. and Onoe, T. (1959) A Miocene Flora from the Northern Part of the Joban Coal-Field, Japan. *Bull. Geol. Surv. Japan.*, **10**, 261-286, pls. 1-7.
- Tanai, T. and Uemura, K. (1988) Daijima-type floras (Miocene) in southwestern Hokkaido and the northern part of Honshu Japan. *Mem. Natl. Sci. Mus.*, no. 21, 7-16. **
- Tsunakawa, H., Takeuchi, A. and Amano, K. (1983) K-Ar ages of dikes in Northeast Japan. *Geochem. Jour.*, **17**, 269-275.
- Uemura, K. (1993) Cenozoic climate and temperature on the basis of plant megafossils. *Fossils, Palaeont. Soc. Japan.*, no. 54, 24-34. *
- White, J. M., Ager, T. A., Adam, D. P., Leopold, E. B., Li, G., Jette, H. and Schweger, C. E. (1997) An 18 million year record of vegetation and climate change in northwestern Canada and Alaska: tectonic and global climatic correlates. *Palaeoceanogr. Palaeoclimatol. Palaeoecol.*, **130**, 293-306.
- Wilf, P. (1997) When are leaves good thermometers? A new case for Leaf Margin Analysis. *Paleobiol.*, **23**, 373-390.

- Wing, S. L. and Greenwood, D. R. (1993) Fossils and fossil climate: the case for equable continental interiors in the Eocene. *Phil. Trans. Royal Soc. London, B*, **341**, 243-252.
- Wolfe, J. A. (1979) Temperature parameters of humid to mesic forests of Eastern Asia and relation to forests of other regions of the Northern Hemisphere and Australasia. *USGS Prof. Pap.*, no. 1106, 1-36.
- Yabe, A. (1999) Taphonomy of the plant megafossils from marine bed: Deltaic deposits from the Lower Miocene of Joban Area, Northeast Honshu, Japan. *Mem. Geol. Soc. Japan.*, no. 54, 185-195. *
- Yabe, A., Ogasawara, K. and Nakano, T. (1996) Stratigraphy and sedimentary age of the Lower Miocene strata in the Joban coal-field, Northeast Japan, with reference to the stratigraphic relationship between the Kunugidaira and Shichiku formations. *Abstracts of the 103rd Ann. Meet. Geol. Soc. Japan.*, 102. ***
- Yabe, A., Ogasawara, K. and Uemura, K. (1995a) Stratigraphic relationship between the Paleogene and Neogene rocks in the Tono Area of Iwaki, Northeast Honshu, Japan. *Mem. Natl. Sci. Mus.*, no. 28, 31-46. **
- Yabe, A., Ogasawara, K., Uemura, K. and Obuse, A. (1995b) Plant and molluscan fossil assemblages from the Lower Miocene Kunugidaira Formation in the southern part of the Joban coal-field, Japan. *Jour. Geol. Soc. Japan.*, **101**, 532-548. *
- Yamamoto, T. (1996) Stratigraphy and eruption styles of Miocene volcanic rocks in the Ryozen district, NE Japan. *Jour. Geol. Soc. Japan.*, **102**, 730-750. *
- Yanagisawa, Y. and Akiba, F. (1998) Refined Neogene diatom biostratigraphy for the northwest Pacific around Japan, with an introduction of code number for selected diatom biohorizons. *Jour. Geol. Soc. Japan.*, **104**, 395-414.
- Yanagisawa, Y. and Suzuki, Y. (1987) Diatoms and silicoflagellates from the Oligocene Shirasaka Formation of the Joban Coalfield, northeast Japan. *Bull. Geol. Surv. Japan.*, **38**, 81-98, pl. 1. *
- Yanagisawa, Y., Yamamoto, T., Banno, Y., Tazawa, J., Yoshioka, T., Kubo, K. and Takizawa, F. (1996) *Geology of the Somanakamura district*. With geological sheet map at 1:50,000. Geological Survey of Japan, Tsukuba, 144p. *
- Yanagisawa, Y., Nakamura, K., Suzuki, Y., Sawamura, K., Yoshida, S., Tanaka, Y., Honda, Y. and Tanahashi, M. (1989) Tertiary biostratigraphy and subsurface geology of the Futaba district, Joban Coalfield, northeast Japan. *Bull. Geol. Surv. Japan.*, **40**, 405-467. *
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本州北東部、常磐および相馬地域の大型植物化石群集 から推測される前期中新世の陸上気候

矢部 淳

要 旨

東北日本太平洋側に位置する常磐および相馬地域において、主として海岸低地の植生を代表すると考えられる5つの大型植物化石群集を検討し、前期中新世の植生と陸上気候の変化を明らかにした。

最初期中新世には温帯性の落葉広葉樹と針葉樹からなる植生が広がったが、前期中新世を通じて、温暖な気候に生育する常緑・落葉広葉樹の出現と種数の増加傾向が認められる一方、寒冷な気候に生育する種類が減少する傾向が明らかとなった。現在の東アジアの森林植生区分との比較から、この変化は年平均気温の上昇と年較差の減少によるものと解釈され、後者はとくに前期中新世後半に冬季の気温が上昇したことが原因と考えられる。葉相観に基づく年平均気温の定量的な推定から、最初期中新世からおよそ20 Maにかけて気温の著しい上昇が認められたほか、およそ17 Maから16 Maにかけて、さらに温暖な気候が示唆された。これらの温暖期は海棲生物から推測される海洋気候の温暖期に一致する。海成層から報告された花粉などのデータとあわせて考えると、前期中新世の陸上気候と海洋気候は同様な変化傾向を示す。

Appendix 1 Composition of Early Miocene plant megafossil assemblages from the Joban and Soma areas. Some reproductive structures with uncertain affinities were omitted from the list.

Species/Stage			I	II	III		IV	V
	organ	leaf margin*	Shichiku	Kunugidaira Kn-low Kn-up		Shiote	Nakayama	Ouchi
Pteridophyta								
<i>Equisetum</i> sp.	stem	-	+				+	
<i>Osmunda</i> sp. cf. <i>O. japonica</i> Thunberg	fronds	-	+					
Coniferophyta								
<i>Calocedrus notoensis</i> (Matsuo) Huzioka	twig	-						+
<i>Thuja nipponica</i> Tanai et Onoe	twig	-			+			
<i>Keteleeria ezoana</i> Tanai	l	-				+		
<i>Picea kaneharai</i> Tanai et Onoe	s	-	+	+				+
<i>Pinus oishii</i> Ishida	l	-						+
<i>Pinus</i> sp.	l&c	-			+			
<i>Pseudolarix japonica</i> Tanai et Onoe	cone scale	-		+				
<i>Pseudotsuga tanaii</i> Huzioka	l, s, c	-	⊙					
<i>Tsuga</i> spp.	l, s, c	-	+				+	
<i>Torreya yoshiokaensis</i> Tanai et Suzuki	l	-				+		
<i>Cunninghamia protokonishii</i> Tanai et Onoe	twig	-	○					
<i>Cryptomeria</i> sp.	twig	-		○				
<i>Metasequoia occidentalis</i> (Newberry) Chaney	twig, c	-	⊙	⊙	+			+
<i>Sequoia</i> sp.	twig	-		+				
<i>Taiwania japonica</i> Tanai et Onoe	twig	-	+					
Magnoliophyta								
<i>Magnolia</i> sp.	l	E	+					
<i>Actinodaphne nipponica</i> Tanai	l	E			+			+
<i>Actinodaphne oishii</i> Huzioka	l	E					+	
<i>Cinnamomum miocenum</i> Morita	l	E			-	+	-	+
<i>Lindera gaudini</i> (Nathorst) Tanai	l	E		+				+
<i>Lindera</i> sp.	l	E					○	
<i>Litseaephyllum</i> sp. 1	l	E				+		
<i>Litseaephyllum</i> sp. 2	l	E					+	
<i>Machilus nathorsti</i> Huzioka	l	E					+	+
<i>Machilus ugoana</i> Huzioka	l	E			+		⊙	+
<i>Sassafras yabei</i> Endo et Okutsu	l	E	+	+				
<i>Ceratophyllum</i> sp.	f	-		+				
<i>Meliosma shanwangensis</i> Hu et Chaney	l	S				+	+	
<i>Sabia?</i> sp.	l	E			+			
<i>Cercidiphyllum crenatum</i> (Unger) Brown	l	S		+				
<i>Cercidiphyllum</i> sp.	l	S			+			
<i>Liquidambar miosinica</i> Hu et Chaney	l&f	S		+	○		+	+
<i>Liquidambar</i> sp.	l	S			+			
<i>Parrotia pristina</i> (Ettingshausen) Stur	l	S		+	+	+	⊙	+
Hamamelidaceae gen. et sp. indet.	f	-					+	
<i>Celtis miobungeana</i> Hu et Chaney	l	S				+		
<i>Celtis</i> sp.	l	S			+			
<i>Ulmus carpinooides</i> Goeppert	l	S	+		⊙	-		
<i>Ulmus longifolia</i> Unger	l	S				+	⊙	+
<i>Ulmus miopumila</i> Hu et Chaney	l	S						+
<i>Ulmus pseudolongifolia</i> Oishi et Huzioka	l	S	+					
<i>Ulmus takayasui</i> Huzioka	l	S	+	+				
<i>Zelkova ungeri</i> (Ettingshausen) Kovats	l	S	○	+	○	⊙	+	+
<i>Ficus</i> sp. cf. <i>F. erecta</i> Thunberg	l	E					+	
<i>Ficus</i> sp.	l	E			+		-	
<i>Cyclocarya ezoana</i> (Tanai et Suzuki) Wolfe et Tanai	l	S				⊙	○	
<i>Juglans miochinensis</i> (Tanai et Onoe) Suzuki	l	S	+					
<i>Pterocarya protostenoptera</i> Tanai	l&f	S					⊙	
" <i>Pterocarya asymmetrosa</i> Kon'no"	l	S	+	+				+
<i>Comptonia naumanni</i> (Nathorst) Huzioka	l	S		+				+
<i>Castanea miomollissima</i> Hu et Chaney	l	S		-	+	+	+	
<i>Fagus antipofi</i> Heer	l	S	⊙	○	⊙	⊙		
<i>Fagus</i> sp. A	cupule	-		+				
<i>Fagus</i> sp. B	s	-		+				
<i>Quercus (Cyclobalanopsis) mandraliscae</i> Gaudin	l	S			⊙			+
<i>Quercus (Cyclobalanopsis) nathorstii</i> Kryshstofovich	l	S			⊙			+
<i>Quercus (Cyclobalanopsis)</i> sp.	l	S			+		+	
<i>Quercus miovariabilis</i> Hu et Chaney	l	S		⊙	⊙	⊙	⊙	+
<i>Quercus</i> sp. cf. <i>Q. protoserrata</i> Tanai et Onoe	l	S	+					
<i>Quercus</i> sp. 1	l	S					+	
<i>Quercus</i> sp. A	cupule	-		+	+	+		
<i>Alnus arasensis</i> Huzioka	l	S		+				
<i>Alnus miojaponica</i> Tanai	l	S	○	⊙				

Appendix 1 (continued).

Species/Stage			I	II	III		IV	V
	organ	leaf margin*	Shichiku	Kunugidaira Kn-low Kn-up		Shiote	Nakayama	Ouchi
<i>Alnus protohirsuta</i> Uemura	l	S	+					
<i>Alnus usyuensis</i> Huzioka	l	S		+				
<i>Alnus</i> sp. cf. <i>A. sakaii</i> Huzioka	l	S		+				
<i>Betula mioluminifera</i> Hu et Chaney	l	S	+			-		
" <i>Betula mitai</i> Tanai et Onoe"	l	S	○					
<i>Betula nathorstii</i> Suzuki	l	S	+					
<i>Betula oobae</i> Suzuki	l	S	+					
<i>Betula</i> sp. 1	l	S			+			
<i>Betula</i> spp.	f	-	+					
<i>Carpinus chaneyi</i> Tanai et Suzuki	f	-		-	+			
<i>Carpinus heigunensis</i> Huzioka	l&f	S		+	○	+	+	+
<i>Carpinus hokoensis</i> Endo	f	-	+	-		+		
<i>Carpinus jobanensis</i> Suzuki	l	S	◎					
" <i>Carpinus konnoi</i> Suzuki"	l	S	+					
<i>Carpinus miofargesiana</i> Tanai et Onoe	f	-	+					
<i>Carpinus protojaponica</i> Endo	f	-		+				
<i>Carpinus s-satoi</i> Tanai et Onoe	f	-	○					
<i>Carpinus stenophylla</i> Nathorst	l	S		+			+	
<i>Carpinus subcordata</i> Nathorst	l	S	+	+	+	+	+	
<i>Corylus subsieboldiana</i> Suzuki	l	S		-		+		
<i>Ostrya shiragiana</i> Huzioka	l&f	S	○		◎	+	+	
<i>Camellia protojaponica</i> Huzioka	l	S		+				
<i>Actinidia?</i> sp.	l	S				+		
Cf. <i>Plafkera basiobliqua</i> (Oishi et Huzioka) Tanai	l	E		+			+	
<i>Tilia</i> sp.	l	S	+					
Cf. <i>Bytneriophyllum tiliaefolium</i> (Al. Braun) Knobloch et Kvacek	l	E			+			+
<i>Populus balsamoides</i> Goeppert	l	S		+	+		+	
<i>Populus</i> sp. 1	l	S					+	
<i>Populus</i> sp. 2	l	S					+	
<i>Populus?</i> sp. 3	l	S					+	
<i>Salix miosinica</i> Hu et Chaney	l	S					+	
<i>Salix parasachalinensis</i> Tanai et Suzuki	l	E		+	+		+	
<i>Salix</i> sp.1	l	S		+	+			
<i>Salix</i> sp.2	l	S		+				
<i>Salix</i> sp.3	l	S		+				
<i>Salix</i> sp.4	l	E	+					
<i>Styrax protojaponica</i> Tanai	l	S				+	-	
<i>Styrax protoobassia</i> Tanai et Onoe	l	S	+					
<i>Rosa usyuensis</i> Tanai	l	S				-	+	
<i>Rosa</i> sp.	l	S					+	
<i>Sorbus uzenensis</i> Huzioka	l	S				○	○	
<i>Cladrastis</i> sp. cf. <i>C. chaneyi</i> Tanai et Suzuki	l	E	+		+		+	
<i>Cladrastis</i> sp.	l	E		+				+
<i>Gleditsia miosinensis</i> Hu et Chaney	l	S						-
<i>Maackia onoei</i> Matsuo	l	E	-	-	+		+	
<i>Pueraria?</i> sp.	l	E			+			
<i>Podogonium knorrii</i> (Braun) Heer	l&f	E			+		○	
<i>Sophora miojaponica</i> Hu et Chaney	l	E				+		
<i>Wisteria fallax</i> (Nathorst) Tanai et Onoe	l	E		+		+	+	
Fabaceae gen. et sp. indet. 1	l	E					+	+
Fabaceae gen. et sp. indet. 2	l	E					+	+
Fabaceae gen. et sp. indet. A	f	-						+
<i>Hemitrapa borealis</i> (Heer) Miki	f	-	◎					
<i>Hemitrapa hokkaidoensis</i> (Okutsu) Miki	f	-		◎				
<i>Hemitrapa yokoyamae</i> (Nathorst) Miki	f	-						+
<i>Trapa mikii</i> Suzuki	l	-	+					
<i>Cornus megaphylla</i> Hu et Chaney	l	E		+	+	+		
<i>Cornus</i> sp. cf. <i>C. miowalteri</i> Hu et Chaney	l	E				+		
<i>Celastrus</i> sp.	l	S						+
<i>Euonymus</i> sp. cf. <i>E. protobungeana</i> Hu et Chaney	l	S	+					
<i>Ilex daijimaensis</i> Huzioka	l	S					+	
<i>Ilex</i> sp. 1	l	S			+		+	
<i>Ilex</i> sp. 2	l	S				+		
<i>Buxus protojaponica</i> Tanai et Onoe	l	E				+		+
<i>Berchemia miofloribunda</i> Hu et Chaney	l	E			+	+	+	
<i>Paliurus protonipponicus</i> Suzuki	l&f	S					○	
<i>Ziziphus miojuba</i> Hu et Chaney	l	S					+	
Vitaceae gen. et sp. indet.	l	S			+		+	
<i>Sapindus tanaii</i> Onoe	l	E				+	+	
<i>Aesculus majus</i> (Nathorst) Tanai	l	S		+		+		

Appendix 1 (continued).

Species/Stage			I	II	III		IV	V
	organ	leaf margin*	Shichiku	Kunugidaira		Shiote	Nakayama	Ouchi
				Kn-low	Kn-up			
<i>Acer palaeorufinerve</i> Tanai et Onoe	l	S	+	+				
<i>Acer nordenskiöldi</i> Nathorst	l	S		+			+	
<i>Acer protojaponicum</i> Tanai et Onoe	l&f	S	+	+			+	
<i>Acer protomatsumurae</i> Tanai	l	S				○		
<i>Acer chiharae</i> Huzioka	l	S		+				
<i>Acer palaeoplatanoides</i> Endo	f	-	+	+				
<i>Acer rotundatum</i> Huzioka	l	S	+	+		+		
<i>Acer</i> sp. cf. <i>A. protomiyabei</i> Endo	l	S	+					
<i>Acer prototrifidum</i> Tanai	l	S					+	-
<i>Acer pseudoginnala</i> Tanai et Onoe	f	-	+					
<i>Acer</i> sp. cf. <i>A. yamanae</i> Tanai et Ozaki	l&f	S	+			○		
<i>Acer</i> sp. A	f	-	+					
<i>Acer</i> sp. B	f	-					+	
<i>Acer</i> sp. C	f	-						+
<i>Ailanthus yezoense</i> Oishi et Huzioka	f	-	+					
<i>Ailanthus?</i> sp.	l	E	+					
<i>Kalopanax acerifolium</i> (Nathorst) Hu et Chaney	l	S	+	+				
<i>Fraxinus tateiwaie</i> Huzioka	l	S		-	+		+	
<i>Fraxinus</i> sp. 1	l	S	+			+		
<i>Fraxinus</i> sp. 2	l	S	+					
<i>Fraxinus</i> sp. A	f	-	+					
<i>Osmanthus chaneyi</i> Matsuo	l	S						+
<i>Dicotylophyllum</i> sp. 1	l	E	+					
<i>Dicotylophyllum</i> sp. 2	l	E	+					
<i>Dicotylophyllum</i> sp. 3	l	E		+				
<i>Dicotylophyllum</i> sp. 4	l	E		+				
<i>Dicotylophyllum</i> sp. 5	l	E		+				
<i>Dicotylophyllum</i> sp. 6	l	E			+			
<i>Dicotylophyllum</i> sp. 7	l	E			+			
<i>Dicotylophyllum</i> sp. 8	l	S			+			
<i>Dicotylophyllum</i> sp. 9	l	E						+
<i>Dicotylophyllum</i> sp. 10	l	E					+	
<i>Dicotylophyllum</i> sp. 11	l	E					+	
<i>Dicotylophyllum</i> sp. 12	l	E					+	
<i>Dicotylophyllum</i> sp. 13	l	E					+	
<i>Dicotylophyllum</i> sp. 14	l	S					+	
<i>Dicotylophyllum</i> sp. 15	l	S					+	
<i>Dicotylophyllum</i> sp. 16	l	E					+	
<i>Dicotylophyllum</i> sp. 17	l	E					+	
<i>Dicotylophyllum</i> sp. 18	l	S					+	
<i>Dicotylophyllum</i> sp. 19	l	E					+	
<i>Dicotylophyllum</i> sp. 20	l	E				+		
<i>Dicotylophyllum</i> sp. 21	l	E				+		
<i>Dicotylophyllum</i> sp. 22	l	S				+		
<i>Dicotylophyllum</i> sp. 23	l	E				+		
<i>Dicotylophyllum</i> sp. 24	l	E				+		
<i>Dicotylophyllum</i> sp. 25	l	E				+		
<i>Dicotylophyllum</i> sp. 26	l	E				+		
<i>Dicotylophyllum</i> sp. 27	l	E				+		
<i>Smilax trinervis</i> Morita	l	-		○		◎	+	
<i>Monocotylophyllum</i> spp.	l	-		○		◎	+	

*Applied only for woody dicotyledonous species. Organ: c, cone; f, fruit; l, leaf; s, seed. Leaf margin: E, entire; S, serrate. Occurrence: ◎, dominant (over 5% of total specimens); ○, common (3–5%); +, present (less than 3%); -, presence of comparable species (less than 3%).