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Fossil-Winged Fruits of *Fraxinus* (Oleaceae) and *Liriodendron* (Magnoliaceae) from the Duho Formation, Pohang Basin, Korea

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Abstract: A total of 16 specimens of fossil-winged fruits were found from the Middle Miocene marine deposits, Duho Formation, Pohang Basin, Korea. They were identified into two structurally different groups: 15 specimens into a winged fruit of *Fraxinus*, and one specimen of *Liriodendron*. The most samaras (13 specimens) were identified as *Fraxinus oishii*, which is characterized by narrowly ovate or ovate–elliptic shapes that are 2.7–3.6 cm in length and 0.7–1 cm in width (l/w ratio=3.4–4). The apexes of the *Fraxinus oishii* samara are round or slightly emarginated, and a seed of the samara is always located at the base, of which the general shape is narrow rhombic-ellipsoidal. The seed is 1.2–2 cm long and 0.5–0.7 cm wide. Two specimens are different from the samara of *Fraxinus oishii*. They have a 6.6 length/width ratio (3.3 cm long and 0.5 cm wide), and thus, are temporarily classified into the *Fraxinus* sp. One specimen was recognized as a winged seed of *Liriodendron meisenense*. The wing is broadly lanceolate to elliptic in shape, has a smooth, acute apex, and is approximately 3 cm long and 0.7 cm wide. Samaras of *Fraxinus oishii* and *Liriodendron meisenense* were early reported from the Middle Miocene deposits from North Korea, but these specimens are the first discovery in South Korea. Further study of the Duho Formation may connect flora relationships between North and South Korea.

Key words: winged fruits, *Fraxinus*, *Liriodendron*, Middle Miocene, Pohang Basin, Korea

1 Introduction

Since Linnaeus, many botanists and paleobotanists have long been aware of the floristic similarities between continents separated by ocean (e.g. Boufford and Sponberg, 1983). One case is a floristic similarity between eastern Asia and eastern North America, which is also recently documented by the distribution and occurrence of some extinct and extant genera in both continents. For example, Parks and Wendel (1990), on the basis of molecular data and fossil records of *Liriodendron*, estimated history of speciation and separation of *Liriodendron* between eastern Asia and eastern North America. The genus *Fraxinus* also has been used in understanding evolutionary history in both continents because most of the species occur in the Northern Hemisphere: 20 species in eastern Asia and 20 species in North America among a total of 43 species (Wallander, 2008). Such biogeographic patterns of fossil and modern plants has provided valuable information on flowering plant evolution, divergence time, and the migration of temperate forests in the Northern Hemisphere during the Tertiary (e.g. Hu and Chaney, 1940; Parks and Wendel, 1990; Wen, 1999; Manchester et al., 2009).

The Pohang Basin is one of the best deposits for the Cenozoic plant fossils in South Korea, together with animal fossils (e.g. Yoon and Rhee, 1982; Yun, 1985; Lee and Lee, 2009; Seong et al., 2009) and microfossils (Lee, 1988; Kim, 1990; Yi and Yun, 1995). Since Tateiwa (1924) first reported plant fossils in the Pohang Basin, the number and diversity of plant fossils from the Duho Formation has dramatically increased. The plant fossil record includes leaves (e.g. Huzioka, 1972; Chun, 1982; Jung and Lee, 2007), wood (e.g. Jeong et al., 2004, 2009), and reproductive organs (e.g. Kim, 2005), and recently, more beautifully-preserved and diverse reproductive organs have been reported from the Duho Formation (Jung et al., 2007; Kim, 2008).

In this paper, we report fossil-winged fruits of *Fraxinus* and *Liriodendron* from the Middle Miocene Duho Formation, Pohang Basin, Korea. These fossils of two genera are also the first discovery in South Korea, and we compare winged fossils found in Korea with those from adjacent areas, as well as with their extant relatives.

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2 Geological Setting

The Pohang Basin, widely distributed in the Pohang area, is the most representative and thickest Tertiary basin in South Korea. The basin formed during the period of back-arc opening of the East Sea and is composed of more than 1 km thick, non-marine to marine sediments in sequence, which documents the history of marine basin progress (e.g. Sohn et al., 2001; Choi, 2006). A non-marine sedimentary sequence in the Pohang Basin is known to the Yangbuk Group, while the Yeonil Group is mostly composed of clastic sediments of marine origin.

The Yeonil Group is divided into three formations: the Chunbuk Conglomerate, the Hagjeon Formation, and the Duho Formation in ascending order (Yun, 1986; Yun et al., 1997). The lower two formations (the Chunbuk Conglomerate and Hagjeon Formation), in general, are composed of more or less coarse sediments, including thick conglomerate beds and mixed channel deposits and show a complex geological structure by folding and faulting. In contrast, the Duho Formation, the uppermost formation of the Yeonil Group, is composed mainly of yellowish brown to dark gray mudstone. Mudstone beds are massive, showing no clearly recognizable bedding or lamination. Sandstone beds are often intercalated within the mudstone beds, and concretions (mostly septarian nodules) ranging from 15 to 100 cm in diameter, are also well developed along the bedding plains.

No radiometric ages have been obtained yet from the Duho Formation, but a lot of paleontological research on plant fossils (Huzioka, 1972; Chung and Koh, 2005; Jung and Lee, 2007), invertebrate fossils (Yoon, 1979; Lee, 1992), and microfossils (Kim, 1990; Yi and Yun, 1995; Byun, 1995) strongly indicate that the Duho Formation is most likely to be of Late–Middle Miocene. Yun et al. (1997), based on the dinoflagellate cysts from seven oil exploration cores, suggested that the Duho Formation had been deposited during 14–12 Ma. A paleomagnetic study (Kim et al., 1993) also yielded similar ages (14.5–11.5 Ma) for the Duho Formation. Interpretations of the depositional environment of the Duho Formation vary according to authors. For example, a study on benthic foraminifera (Kim and Choi, 1977; Lee, 1982) documented that the Duho Formation deposited under the shallow water condition within a continental shelf, while Ingle (1975) interpreted the depositional depth of the Duho Formation as being 2000 m.

3 Previous Study and Materials

Since Tateiwa (1924) first reported plant fossils from the Pohang Basin, all the paleobotanical research from the Pohang Basin had been conducted by Japanese authors until 1982. For example, Kanehara (1936) found approximately 50 species of plant fossils in the Pohang area, from which he suggested the depositional age of the Pohang Basin as the Middle to Late Miocene. Huzioka (1972) synthesized paleobotanical studies for Korean Cenozoic plant fossils, reporting a total of 27 genera and 35 species from the Pohang Basin, and correlated Pohang assemblages (Yeonil flora) with Daijima-type flora of Japan. It has only been since 1982 that paleobotanical research from the Duho Formation was first conducted by a Korean specialist, Chun, who interpreted that the Hagjeon and Duho Formations deposited during the Early to Middle Miocene. Recently, publications by Korean paleobotanists for plant fossils from the Pohang Basin have increased.

Fossil-winged fruits from the Pohang Basin were first reported in early 1950s by a Japanese paleobotanist (Tanai, 1952) and a Korean paleobotanist in the 1980s (Chun, 1982). However, they only described the morphology of the winged fruits without any paleoenvironmental considerations. For example, Chun (1982) mentioned winged fruits of *Fraxinus* from the Pohang Basin, but he did not conduct any systematic studies, simply showing a poor illustration of winged fruits of *Fraxinus*. It was the first discovery of winged fruits of *Fraxinus* in the Pohang Basin; no winged fruits of *Liriodendron* were found from South Korea. It was only recently that fossil reproductive organs, including samara from the Duho Formation, were found and interpreted (Kim, 2005, 2008; Jung et al., 2007). However, some diversified, winged fruits, including two genera *Fraxinus* (Huzioka, 1972) and *Liriodendron* (Endo, 1939; Huzioka, 1955) were documented from the Hamjindong Formation equivalent to the Duho Formation in North Korea.

Recently, the paleontology group of Kyungpook National University found more than 200 specimens of fossil-winged fruits from two localities of the Duho Formation, Pohang Basin (Fig. 1). The majority of fossils have been found along Bukbu Beach in Pohang City (locality 1), the most fossiliferous site of the Duho Formation, and locality 2, which is located in a construction area of Jukchendong. Among them, 13 specimens are classified into winged fruits of *Fraxinus oishii*, two specimens into *Fraxinus* sp., and one specimen into *Liriodendron*. Other fossils of winged fruits are under study. All winged fruits identified in this study as *Fraxinus* and *Liriodendron* occur in mudstones as impressions; no preferable direction and/or distribution pattern of the winged fruit fossils are recognized. All fossils collected are permanently deposited in the paleontology laboratory of the Department of Geology, Kyungpook National University (KNU), Daegu, Korea.

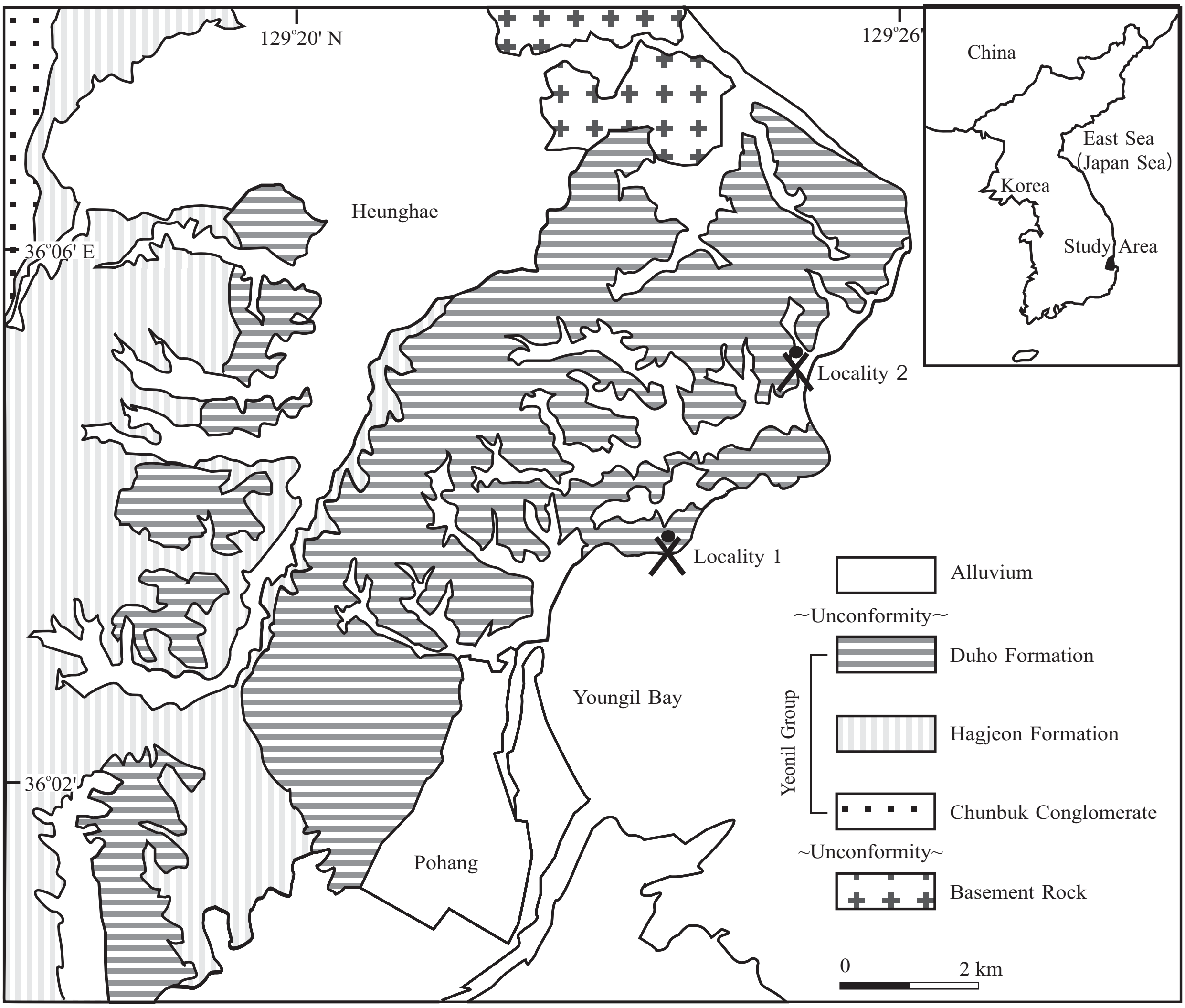

Fig. 1. Locality map of the fossil winged fruits of the Duho Formation, Pohang Basin, Korea.

4 Description of Winged Fruits

4.1 Winged fruits of *Fraxinus*

The winged fruits found from the Duho Formation (13 specimens) display characteristic features of *Fraxinus* samara in shape and position of seed, vein structure, and peduncle (Fig. 2A–H), and are in this study classified into *Fraxinus oishii* Huzioka. Duho samaras are characterized by narrowly ovate or ovate–elliptic shapes that are 2.7–3.6 cm in length and 0.7–1 cm in width at the broadest point (Table 1). The apex of the samara is round or slightly emarginated (Fig. 2C), and the margin of the wing is smooth. A seed of the samara is always located at the base, of which the general shape is narrow rhombic to ellipsoidal, obtuse at both ends, 1.2–2 cm long, 0.5–0.7 cm wide, and mainly broadest in the middle part (Fig. 2G). More than 20 veins are arranged parallel to the long axis of the samara and a thick mid-vein is remarkably developed in the center of the wing, starting from the base and extending to the apex (e.g. Fig. 2C). Most subparallel veins, except for a mid-vein, often bifurcate once or twice. Such dichotomously-branched veins are also visible in broken specimens (Fig. 2F–H). Stout peduncles (maximum length: 0.7–0.8 cm and less than 0.5 mm wide) in most specimens remain attached to the base of the wing, and the direction of the peduncles in general follows one side of the wing margin (Fig. 2A, E, F). In one specimen (Fig. 2B), a peduncle runs parallel to the mid-vein, which is probably a result of fossilization. The specimens, classified as *Fraxinus oishii* in this study, are closely similar to the winged seeds of *Fraxinus dayana* (WGCPC, 1978), a fossil species from the Middle Miocene Shanwang Basin, eastern China in general outline, apex shape, and venation patterns. The samara of the latter, however, is longer than that of the former and is characterized by a relatively small seed.

Two specimens (Fig. 2I) are slightly different from *Fraxinus oishii*, with a 6.6 length/width ratio (3.3 cm long and 0.5 cm wide) and maximum width. The wing is

Table 1 Measurements of fossil samaras of *Fraxinus* and *Liriodendron* from the Duho Formation, Korea and adjacent areas (eastern Asia and eastern North America)

Species	Occurrence	General length (cm)	General width (cm)	General l/w ratio	Seed length (cm)	Seed width (cm)	Peduncle length (cm)	Reference
Fraxinus oishii	Fig. 2A	3.4*	1.0	3.4	1.8	0.6	0.7	This study
Fraxinus oishii	Fig. 2B	2.7*	0.8	3.4	1.2	0.5	0.8	This study
Fraxinus oishii	Fig. 2C	3.1*	0.8	3.9	1.4	0.6	-	This study
Fraxinus oishii	Fig. 2D	3.6	0.9	4.0	1.9	0.6	-	This study
Fraxinus oishii	Fig. 2E	2.8*	0.7	-	1.4	0.5	0.3	This study
Fraxinus oishii	Fig. 2F	2.2*	0.8	-	1.5	0.6	0.3	This study
Fraxinus oishii	Fig. 2G	2.1*	0.8	-	1.7	0.6	-	This study
Fraxinus oishii	Fig. 2H	2.1*	0.7	-	2.0	0.7	0.1	This study
Fraxinus sp.	Fig. 2I	3.3	0.5	6.6	0.9	0.3	0.3	This study
Fraxinus wakamatsuensis	Japan	2.3	0.35	6.6	1.2	0.2	-	Tanai and Suzuki, 1963
Fraxinus k-yamadai	Japan	4.3	0.9	4.8	2.8	0.4	-	Tanai and Suzuki, 1965
Fraxinus honshuensis	Japan	2.1–2.6	0.4–0.55	4.7–5.3	0.8–1.4	0.2–0.25	-	Ishida, 1970
Fraxinus oishii	N. Korea	2.0–2.2	0.5–0.6	-	1.2	0.4–0.5	-	Huzioka, 1972
Fraxinus dayana	China	4.5–6.0	0.9–1.1	4.3–5.1#	1.3–1.6	-	-	WGCPC, 1978
Fraxinus microcarpa	China	3.0–3.5	0.5	6.0–6.4#	-	-	-	WGCPC, 1978
Liriodendron meisenense	Fig. 2J	2.9*	0.7	4.1	0.6 *	0.1	-	This study
Liriodendron meisenense	N. Korea	3.0	0.5	6	0.7	0.1	-	Endo, 1939
Liriodendron fukushimaensis	Japan	2.0	0.5	4	0.5	0.07 #	-	Suzuki, 1959
Liriodendron honsyuensis	Japan	3.0	0.3	10	0.6	0.1	-	Okutsu, 1961
Liriodendron hesperia	USA	1.7–2.8	0.5–0.7	2.9–4.6#	0.5–0.8	-	-	Baghai, 1988

Note: *Estimation from incompleate specimens, # Estimation from monograph.

relatively thicker than that of *Fraxinus oishii* and the margin of the wing is smooth. The gross shape is oblanceolate, the seed is narrowly oblong (obtuse at both ends) with a length of 0.9 cm long and width of 0.3 cm, and the calyx is faintly preserved (Fig. 2I, K). The peduncle is 0.3 cm, relatively shorter than that of *Fraxinus oishii*. These specimens resemble the winged fruits of *Fraxinus microcarpa* from the Miocene Shanwang Basin, Shandong Province, China (WGCPC, 1978) in its general outline, length/width ratio, and size. *Fraxinus wakamatsuensis* (Tanai and Suzuki, 1963) fruits also contain similar characters to these specimens in general morphology and length/width ratio, but the whole size is shorter and narrower than Korean specimens. More characteristic features are necessary to identify Korean specimens as the species level, and thus, we temporarily classify these specimens into the *Fraxinus* sp.

4.2 Winged fruit of *Liriodendron*

The genus *Liriodendron*, which belongs to Magnoliaceae, is a more or less a small group, having only two extant species: *Liriodendron tulipifera* (American tulip tree or yellow poplar) and *Liriodendron chinense* (Chinese tulip tree or goose foot). Both species are large, deciduous trees living in temperate regions of eastern Asia and eastern North America (Baghai, 1988). They first evolved in the Late Mesozoic, have thrived in a temperate region of the Northern Hemisphere during the Miocene (Parks and Wendel, 1990).

Only one specimen (Fig. 2J) from the Duho Formation was recognized as a winged seed of *Liriodendron* and identified as *Liriodendron meisenense* Endo. The samara, which is approximately 3 cm long and 0.7 cm wide, is broadly lanceolate to elliptic in shape (Table 1). The wing has a smooth margin with a more or less acute apex; no emarginating structure is found at the apex. The mid-vein developing in the center of the wing is thick around the base, tapering to the apex. Secondary veins branching from the mid-vein run parallel to the long axis of the wing, and third veins are often visible. Interestingly, numerous dark dots or short lines (Fig. 2J, arrow) are developed along the mid-vein, but we do not understand the origin of this structure at this moment. Both a 3-D pericarp and gross outline of a seed are not observable in this specimen, and only dark places develop at the base, implying the position of the seed.

The samara of *Liriodendron meisenense* was originally described by Endo (1939) from the Hamjindong Formation, North Korea. Subsequently, Huzioka (1955) reported a samara of *Liriodendron meisenense* from the *Engelhardia* bed of North Korea. No samara of *Liriodendron meisenense*, however, has been found from South Korea. The present specimen is closely similar to a winged seed of *Liriodendron fukushimaensis* (Suzuki, 1959) and *Liriodendron honsyuensis* (Okutsu, 1961) from the Middle and Late Miocene deposits of Japan. The former differs from the samara of *Liriodendron meisenense* in a thick mid-vein, while the latter differs in length/width ratio.

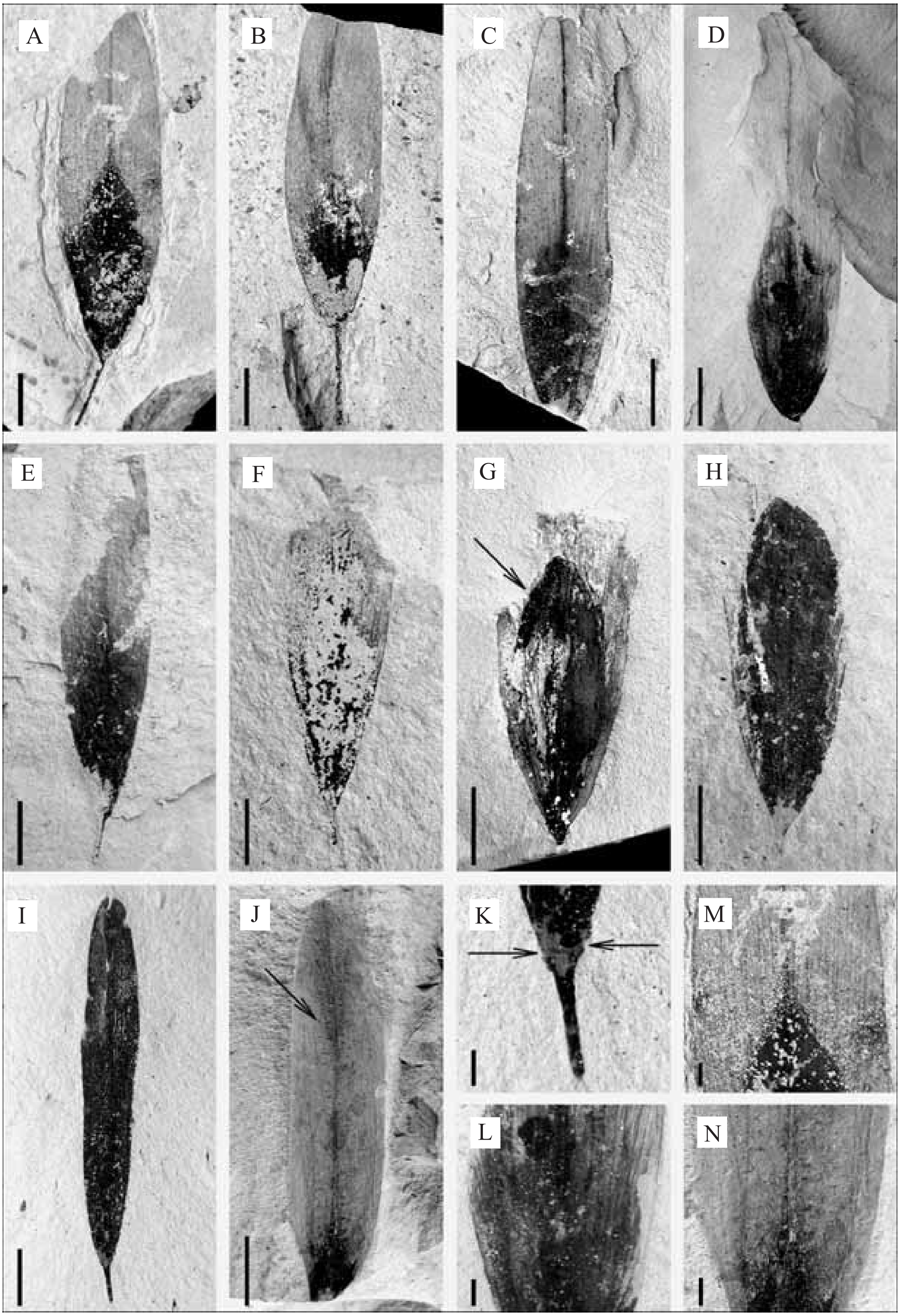

Fig. 2. Fossil winged fruits: A–H, *Fraxinus oishii*; I, *Fraxinus* sp.; J, *Liriodendron meisenense*; K–N, detailed view showing venation (L–N) and calyx (K). Scale bar in A–J represents 0.5 cm and 1 mm in K–N. Fossil collection numbers are PKNU–P1–P10.

Table 2 Geographic distribution of nearest living relatives (NLRs) of *Fraxinus* and *Liriodendron* fossil winged fruits from the Duho Formation, Korea (compiled from Parks and Wendel, 1990; Yang et al., 2007; eFloras web site: www.efloras.org; Flora of Japan web site: www.foj.info)

Species	NLRs	Latitude	Longitude	Altitude
Fraxinus oishii	*F. mandshurica*	33–55°N	106–145°E	400–2100 m
	F. japonica	35–41°N	138–142°E	200–1500 m
Fraxinus sp.	*F. chinensis*	14–45°N	91–131°E	800–2300 m
Liriodendron meisenense	*L. chinense*	21–35°N	101–121°E	900–1000 m

However, because the thickness of the mid-vein varies according to the preservation state and because the small difference in the length/width ratio of the samara may be explained by variations within a species, it is possible that the three species belong to the same species. For example, the difference in the length/width ratio cannot be recognized in some species of *Liriodendron* (Baghai, 1988, *Liriodendron hesperia* 1.7–2.8/0.5–0.7, *Liriodendron chinense* 2.2–3/0.3–0.6, and *Liriodendron. tulipifera* 2.3–3.8/0.5–0.8).

5 Paleoenvironmental Considerations

The genus *Fraxinus* belonging to Oleaceae (the olive family) has approximately 45–65 extant species. They are mainly distributed in temperate to subtropical regions of eastern Asia and North America. Approximately 20 *Fraxinus* species have been reported from the eastern Asian countries, such as China, Korea, Japan, Vietnam, and east Russia (Wallander, 2008). Among the 20 species, the samara of fossil *Fraxinus oishii* is very similar to that of two living species, *Fraxinus japonica* (Huzioka, 1972) and *Fraxinus mandshurica* (WGCPC, 1978; Yang et al., 2007). As Huzioka (1972) mentioned, *Fraxinus japonica* and *Fraxinus mandshurica* are likely to be the nearest living relatives of *Fraxinus oishii*, the most dominant species in the Duho Formation. *Fraxinus mandshurica* lives in open valleys of the mountain regions of China, Korea, Japan, and east Russia, while *Fraxinus japonica* is an endemic species in central–north Honshu, Japan, living in moderately moist places in deciduous forests. The samara of the *Fraxinus* sp. (Fig. 2I), although too immature to identify as a species level, also resembles the fossil fruit of *Fraxinus microcarpa*, whose living relative is *Fraxinus chinensis* (WGCPC, 1978; Yang et al., 2007). *Fraxinus chinensis* inhabits mixed wood forests in mountain regions or slopes along river in China, Korea, Japan, and Vietnam (800–2300 m altitude). The extant two species of *Liriodendron* (*Liriodendron tulipifera* and *Liriodendron chinense*) grow in temperate climates in eastern Asia and eastern North America. *Liriodendron tulipifera* is native to low mountains and hills in eastern North America, while *Liriodendron chinense* inhabits south-eastern China and northern Vietnam at an altitude range of 900–1000 m. As Baghai (1988) suggested, a winged fruit of the Miocene *Liriodendron meisenense* from Korea (this study) and *Liriodendron fukushimaensis* (Suzuki, 1959) and *Liriodendron honsyuensis* (Okutsu, 1961) from Japan could be an ancestral forms of *Liriodendron chinense*.

Recently, Yang et al. (2007) introduced a new method, the overlapping distribution analysis (ODA), to estimate geographic and altitudinal distributions of fossil plants using their modern relatives. The application of the ODA to three fossil species found in this study shows that the estimated overlapping areas for the Duho fossils are 33–35° N of latitude, 106–121°E of longitude, and 900–1000 m of altitude (Table 2). The areas characterized by these geographic conditions are those that are currently overlapped by the southern part of Shannxi, the western part of Henan, and the northern part of Hubei in central China. In the present study, it is immature to estimate precise meteorological data because a few species have been analyzed, and thus the overlapped area is too broad. However, it may be concluded that the climatic conditions of the Duho fossils during the Miocene were similar to those of the overlapped area obtained by ODA.

The Duho Formation has yielded abundant leaf fossils, which are composed of temperate members, such as *Pinus*, *Tsuga*, *Betula, Carpinus, Tilia*, *Castanea*/*Castanopsis*, and *Salix*, together with tropical–subtropical members of *Cinnamomum*, *Carya*, *Liquidambar*, and *Cryptocarya* (e.g. Huzioka, 1972; Chun, 1982). On the basis of such a floral composition of the Duho Formation, authors have suggested that the Pohang area during the Middle Miocene was subjected to a subtropical–temperate climate that would have been a little hotter than today. Recently, Jung and Lee (2007) performed a leaf physiognomy investigation of the Duho Formation using a leaf margin analysis (LMA) and climate-leaf analysis multivariate program (CLAMP). The results yielded that the mean annual temperature was 11.9–14.3°C (CLAMP) and 11.8–16.8° C (LMA), with the warmest month's mean temperature of 24–27.1°C (CLAMP) and the coldest month mean temperature of –0.2–3.6° C. The analysis also suggested that the Pohang Basin during the Middle Miocene was a subtropical–warm, temperate climate. Moreover, although we could not obtain precise meteorological data by ODA in this study, the ODA result for the Duho fossils is close to a general climatic condition in the Pohang area during the Middle Miocene.

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