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Palaeogeography, Palaeoclimatology, Palaeoecology 235 (2006) 406–430

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Palynological record of climate change during the last deglaciation from the Song Hong (Red River) delta, Vietnam

Zhen Li [a,b,c,*], Yoshiki Saito [d,*], Eiji Matsumoto [a], Yongji Wang [c], Shigeko Haruyama [e], Kazuaki Hori [f], Le Quoc Doanh [g]

[a] *Graduate School of Environmental Studies, Nagoya University, Furo-cho, Chikusa-ku, Nagoya 464-8601, Japan*
[b] *College of Marine Geoscience, Ocean University of China, 5 Yushan Road, Qingdao 266003, China*
[c] *First Institute of Oceanography, 6 Xianxialing Road, Qingdao 266061, China*
[d] *AIST, Geological Survey of Japan, IGG, Central 7, Higashi 1-1-1, Tsukuba 305-8567, Japan*
[e] *Graduate School of Frontier Sciences, University of Tokyo, Hongo 7-3-1, Bunkyo-ku, Tokyo 113-0033, Japan*
[f] *Faculty of Science and Technology, Meijo University, Shiogamaguchi 1-501, Tempaku, Nagoya 468-8502, Japan*
[g] *Vietnam Agricultural Science Institute, Thanh Tri, Hanoi, Vietnam*

Received 28 March 2005; received in revised form 31 October 2005; accepted 3 November 2005

Abstract

The palynological sequence from core ND-1 on the Song Hong delta in the northern Vietnam reveals the climate change during the last deglaciation. The identified pollen in the core is dominated by *Castanopsis* (*Lithocarpus*), *Elaeocarpus*, *Ficus*, Piperaceae and *Quercus*. High percentages of temperate taxa including the conifers *Dacrydium*, *Podocarpus*, *Pinus*, Cupressaceae, Txodiaceae and *Cryptomeria*, and broad-leaved taxa of *Carpinus*, *Alnus*, *Juglans*, *Carya*, *Ulmus*, *Fagus*, *Ilex*, *Castanea*, *Quercus*, which have a mainly upland distribution, is possibly associated with a lowering of the montane vegetation boundary. On the other hand, intensified river influence can also result in an increase in the temperate allochthonous taxa. After analyzing the magnitude of river influence on pollen assemblages during the sedimentary environment evolution, we extracted the climate information and used this to reconstruct climate change during the last deglaciation. A cooler climate during 14.5–10.9 cal. kyr BP than at present is indicated by higher percentage of temperate types than at present under a similar river influence on the floodplain. The Younger Dryas cooling event is recognized by widely developed grasslands between 12.9 and 11.6 cal. kyr BP, adding to the evidences for this period from both terrestrial and marine records in regions influenced by the East Asian monsoon. Two other cooling periods, 9.4–9.0 cal. kyr BP and 6.5–5.2 cal. kyr BP, are indicated by increases of temperate pollen taxa such as *Cryptomeria*, *Alnus*, *Quercus*, and *Castanea*.

Keywords: Climate change; Palynology; Sedimentary environment; Last deglaciation; Song Hong (Red River) delta

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1. Introduction

The climate of the Asian region is strongly influenced by the monsoon system, which controls the atmospheric heat budget in the Northern Hemisphere and influences or is influenced by global climatic changes (Tchernia, 1980; An, 2000). An intensified winter monsoon is linked mainly to dry glacial and

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* Corresponding author. Z. Li can be contacted at: Institute of Estuarine & Coastal Research, East Normal University, North Zhongshan Road 3663, Shanghai, 200062, China. Y. Saito can be contacted at: AIST, Geological Survey of Japan, IGG. Central 7, Higashi 1-1-1, Tsukuba 305-8567, Japan.

E-mail addresses: imlizhen@hotmail.com (Z. Li), yoshiki.saito@aist.go.jp (Y. Saito).

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doi:10.1016/j.palaeo.2005.11.023

cold stages, whereas an intensified summer monsoon with high moisture content is associated with a warming climate and increased precipitation (Kudrass et al., 1991; Banerjee, 1995; Porter and An, 1995; Sirocko et al., 1996; Wang et al., 1999).

The Song Hong (Red River) delta of Southeast Asia faces the South China Sea and is strongly influenced by the migration of summer and winter monsoons between tropical and temperate regions. It is one of the important regions of East and Southeast Asia for obtaining a better understanding of the East Asian monsoon, since marine records from the northern part of the South China Sea have shown that drastic changes have occurred in both the summer and winter monsoon since the last glacial maximum (Wang et al., 1999).

Recently, the evolution of the Song Hong delta has been described in detail on the basis of sediment and radiocarbon analyses of drill cores (Tran et al., 1991; Mathers and Zalasiewicz, 1999; Tanabe et al., 2003a,b; Hori et al., 2004; Saito et al., 2004). High sedimentation rates of incised-valley fills and deltaic sediments allow high-resolution investigations of centennial to millennial scale climate changes to be performed. It is very complex to reconstruct climate change based on the palynological record in delta areas because the pollen assemblages are usually also influenced by sedimentary environment changes. Fortunately, detailed information about sedimentary environment change has been obtained from previous studies (Tanabe et al., 2003a; Hori et al., 2004), and it is possible to reconstruct the climate change by extracting the information from the palynological record after eliminating the influence of environment changes. In this paper, we undertake such research to report on climate changes that occurred between 15 and 5 cal kyr BP, including several clear climate events.

2. Environmental setting

2.1. Geological and geographical setting

The course of the Song Hong, which has its mouth on the western coast of the Gulf of Bac Bo (Tonkin) in the South China Sea, is controlled by the Neogene Red River fault system, which extends NW–SE. The sedimentary basin is filled with Neogene and Quaternary sediments (thickness > 3 km) (Fig. 1). The Quaternary sediments, which unconformably overlie the Neogene deposits, are composed mainly of sands and gravels with subordinate lenses of silt and clay. The uppermost

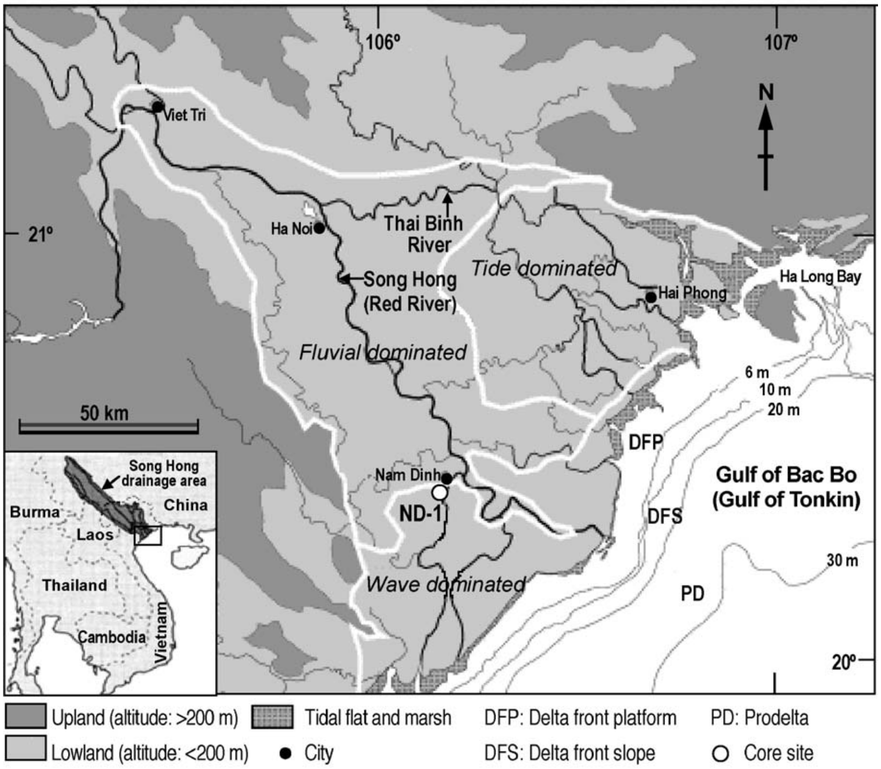


Fig. 1. Geographical location of core ND-1 on the Song Hong delta (modified from Tanabe et al., 2003a).

Quaternary sediments deposited since the LGM comprise three formations, the Vinphuc, Haihung and Thai Binh formations, in ascending order (Fig. 2) (Mathers et al., 1996; Mathers and Zalasiewicz, 1999; Tanabe et al., 2003a). The Song Hong delta plain can be divided into wave-, tide- and fluvial-dominated systems, located in the southeastern, northeastern and western parts of the delta plain, respectively. The subaqueous delta is divided into delta front and prodelta on the basis of its subaqueous topography and the delta front is further subdivided into delta front platform and delta front slope (Fig. 1) (Tanabe et al., 2003a).

2.2. Climate

The Song Hong delta is characterized by a tropical monsoonal climate with a pronounced maritime influence, and Pfeiffer (1984) classed its climate as seasonal, moist subtropical. The average annual rainfall is 1300–1800 mm, 85% of which falls during the rainy season (April to October). The heaviest rainfall occurs in August and September. The summers are warm and very humid; average temperatures range from 27 to 29 °C, with mean maxima of 31 to 33 °C. The winters are cool and dry, with mean monthly temperatures varying from 16.3 to 20.9 °C and mean minimum temperatures from 14.4 to 19 °C. The prevailing winds are northerly and easterly in winter and easterly and southeasterly in summer (World Conservation Monitoring Center, 1992).

2.3. Vegetation

The Song Hong delta is one of the most densely populated regions in the world and much of the natural forest has been cleared to make room for human settlements and agricultural cultivation. The regional vegetation, as preserved in several natural forest protection areas, is typical of a tropical seasonal rain forest and consists mainly of tropical moist semi-evergreen and tropical evergreen forests (World Conservation Monitoring Center, 1992). A dense canopy is formed by sclerophyllous evergreen members of the families Fagaceae (*Castanopsis* spp., *Lithocarpus* spp), Lauraceae (*Cinnamomum* spp., *Lindera* spp. and *Caryodaphnophis* spp.), Anacardiaceae (*Dracontomelum* spp.), Meliaceae (*Aphanamixis* spp., *Aglaia* spp. and *Chisocheton* spp.), Moraceae (*Artocarpus* spp. and *Ficus* spp.), and Tiliaceae (*Kydia calicina*). Deciduous trees include *Terminalia myriocarpa* and *Pometia pinnata*. The forest on the hills surrounding the delta is characterized by tropical evergreen species, including *Spondias lakonensis*, *Milius flipes*, *Endospermum* spp., *P. pinnata*, *Euphorbia* spp., *Carralli lancaefolia* and *Dimerocarpus brenieri.* Species of the Urticaceae and Orchidaceae are dominant in the lowest stratum of the forest. On the summits, *Sasa japonica* is dominant. Common species of the swamps and foothill forests include the upper stratum species *Dracontomelum duperreanum*, *Aglaia gigantea*, *Duabanga sonnera-*

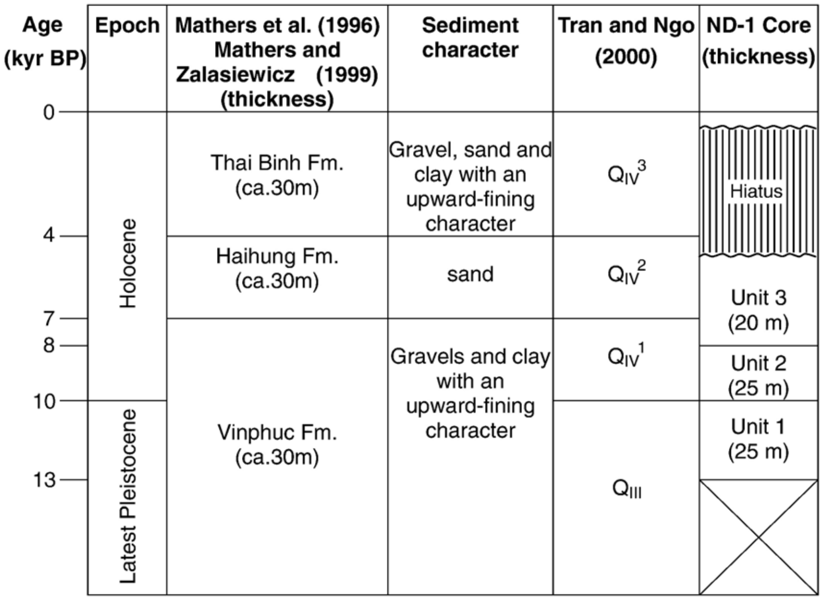
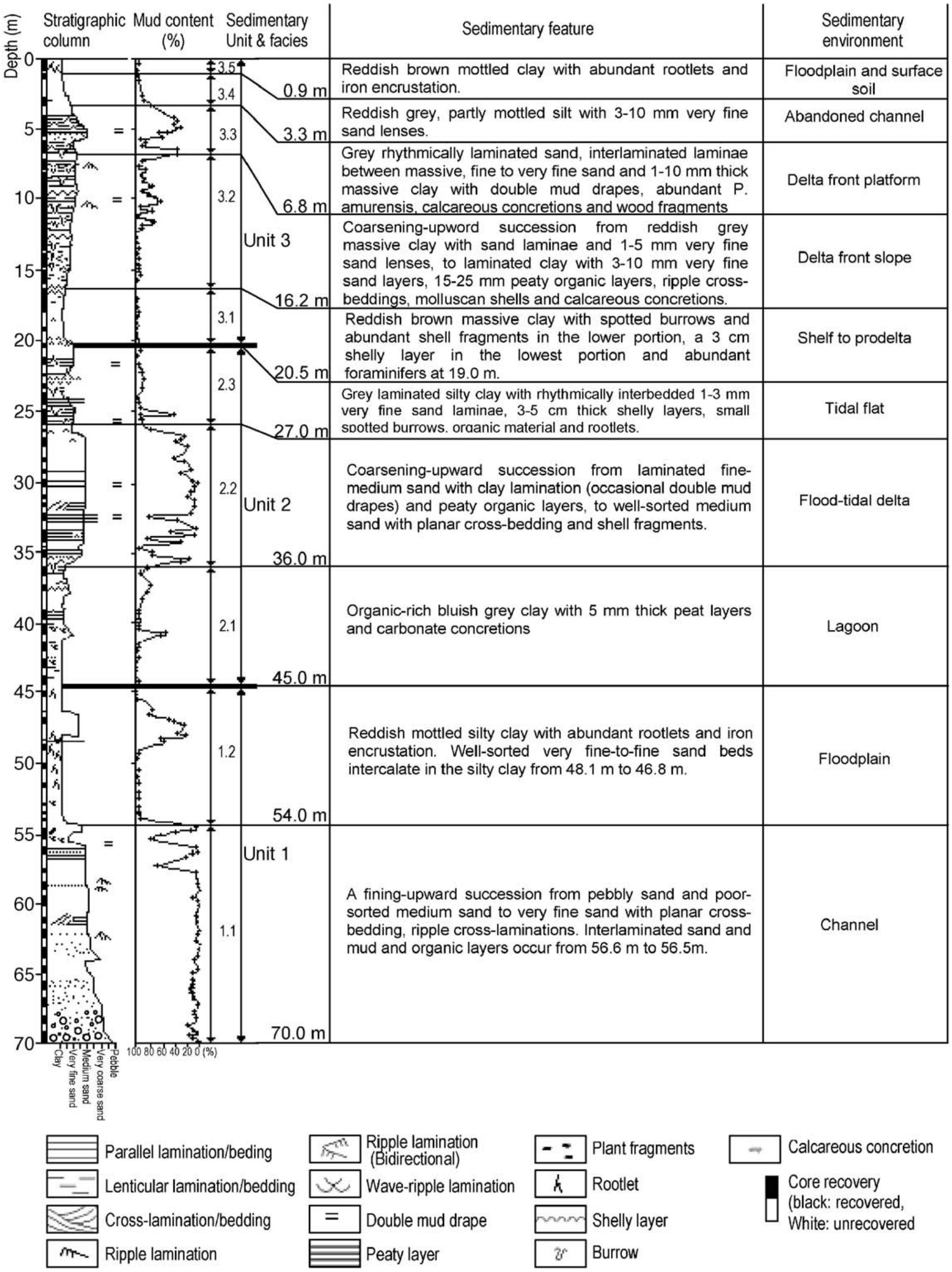


Fig. 2. Schematic diagram showing the correlation of the core stratigraphy with the latest Pleistocene–Holocene stratigraphy for the Song Hong delta region. The boundary dates of the units of core ND-1 were interpolated from the age–depth relationship curve (Fig. 4) (modified from Tanabe et al., 2003a).

tioides, *Lagerstroemia balansae*, *Pterospermum* spp., *Cinnamomum* spp., *Caryodaphnopsis tonkinensis* and *Peltaphorum tonkinensis* as well as the lower stratum species *Engelhardtia spicata*, *Gironniera subaequalis*, *Garcinia* spp., *Alphonsea* spp. and *Ardisia tonkinensis*. The undergrowth is composed of herbaceous plants,



Sedimentary Unit & facies	Sedimentary feature	Sedimentary environment
0.9 m	Reddish brown mottled clay with abundant rootlets and iron encrustation.	Floodplain and surface soil
3.3 m	Reddish grey, partly mottled silt with 3-10 mm very fine sand lenses.	Abandoned channel
6.8 m	Grey rhythmically laminated sand, interlaminated laminae between massive, fine to very fine sand and 1-10 mm thick massive clay with double mud drapes, abundant P. amurensis, calcareous concretions and wood fragments	Delta front platform
16.2 m	Coarsening-upword succession from reddish grey massive clay with sand laminae and 1-5 mm very fine sand lenses, to laminated clay with 3-10 mm very fine sand layers, 15-25 mm peaty organic layers, ripple cross-beddings, molluscan shells and calcareous concretions.	Delta front slope
20.5 m	Reddish brown massive clay with spotted burrows and abundant shell fragments in the lower portion, a 3 cm shelly layer in the lowest portion and abundant foraminifers at 19.0 m.	Shelf to prodelta
27.0 m	Grey laminated silty clay with rhythmically interbedded 1-3 mm very fine sand laminae, 3-5 cm thick shelly layers, small spotted burrows, organic material and rootlets.	Tidal flat
36.0 m	Coarsening-upward succession from laminated fine-medium sand with clay lamination (occasional double mud drapes) and peaty organic layers, to well-sorted medium sand with planar cross-bedding and shell fragments.	Flood-tidal delta
45.0 m	Organic-rich bluish grey clay with 5 mm thick peat layers and carbonate concretions	Lagoon
54.0 m	Reddish mottled silty clay with abundant rootlets and iron encrustation. Well-sorted very fine-to-fine sand beds intercalate in the silty clay from 48.1 m to 46.8 m.	Floodplain
70.0 m	A fining-upward succession from pebbly sand and poor-sorted medium sand to very fine sand with planar cross-bedding, ripple cross-laminations. Interlaminated sand and mud and organic layers occur from 56.6 m to 56.5m.	Channel

☰ Parallel lamination/beding	Ripple lamination (Bidirectional)	Plant fragments	Calcareous concretion
Lenticular lamination/bedding	Wave-ripple lamination	Rootlet	Core recovery (black: recovered, White: unrecovered
Cross-lamination/bedding	= Double mud drape	Shelly layer	
Ripple lamination	Peaty layer	Burrow	

Fig. 3. Lithological section indicating the sedimentary environments of core ND-1 (Tanabe et al., 2003a).

including members of Rubiaceae, Araceae, Commeliaceae and Urticaceae, and numerous ferns. In marshes and ponds, aquatic plants include *Nymphaea* spp., *Lotus* spp., *Vallisneria spiralis* and *Myriophyllum spicatum* (World Conservation Monitoring Center, 1992; Vo and Le, 1994).

The principal taxa in the estuary marshes include *Phragmites* spp., *Cyperus* spp. and algae such as *Rhizosolenia* spp., *Chaetomorpha* spp., *Clenophora* spp., *Enteromorpha* spp., *Oedogonium* spp., *Pterothamnion crispum* and *Gracilaria* spp. The natural mangrove vegetation of the delta includes a variety of species, such as *Sonneratia caseolaris*, *Kandelia candel*, *Aegiceras corniculatum*, *Avicennia* spp., *Rhizophora stylosa*, *Bruguiera gymnorhiza*, *Acanthus ebracteatus* and *Derris trifoliata*. However, the natural mangrove forests have long been replaced by a much simpler, planted community dominated by *S. caseolaris*, *B. gymnorhiza* and *A. corniculatum*. The secondary forests consist mainly of bamboo, shrubs and grasses, especially *Imperata cylindrica*, *Melastoma candidum*, *Rhodomyrtus tomentosa*, *Cratocxlon* spp., *Macaranga* spp., *Lygodium microphyllum*, *Pinus* spp., *Trema orientalis*, *Miscanthus sinensis* and some members of the Euphorbiaceae (World Conservation Monitoring Center, 1992; Hong and San, 1993).

The principal land use throughout the delta is the cultivation of paddy rice and jute. Saline aquaculture is practiced along the coast. Some upland cultivated plants such as *Ipomoea* sp. (sweet potato), *Colocasia esculenta* (taro) and *Dioscorea* spp. (yam) are cultivated mainly in scattered fields in upland or mountainous areas (World Conservation Monitoring Center, 1992).

3. Materials and methods

Core ND-1 is located 8 km southeast of Nam Dinh in the Song Hong delta plain (lat 20°22′22″N, long 106°08′48″E, altitude +1 to +2 m) (Fig. 1) (Tanabe et al., 2003a). The sediments of core ND-1 have been divided into three lithologic units in ascending order units 1, 2, and 3, consisting of two, three and five sedimentary facies, respectively, based on grain size, color, sedimentary structures, textures, type of contact and molluscan fossils (Fig. 3) (Tanabe et al., 2003a). Unit 1 (70.0–45.0 m) reflects a fluvial sedimentary environment with a fining-upward succession and abundant organic materials; facies 1.1 is composed of channel infill sediments (Miall, 1992; Tanabe et al., 2003a) and facies 1.2 is composed of floodplain sediments, with reddish mottled silty clay, abundant rootlets and iron encrustation (Tanabe et al., 2003a). Unit 2 (45.0–20.5 m) is interpreted as an estuarine sequence, consisting of salt marsh (facies 2.1), flood–tidal delta (facies 2.2) and tidal flat (facies 2.3) sediments in ascending order, respectively indicated by bluish, organic-rich clay, a coarsening-upward succession from laminated fine- to medium-grained sand to well-sorted sand and laminated silty clay with shell fragments and burrows (Tanabe et al., 2003a). Unit 3 (20.5–0 m) reflects a deltaic sedimentary environment, as indicated by a coarsening-upward succession from facies 3.1 (massive clay) to facies 3.2 (laminated clay) and facies 3.3 (laminated sand), overlain by a fining-upward succession from facies 3.4 (brown silt) to facies 3.5 (red clay); the coarsening upward sediments correspond to a prodelta to delta front succession and the fining-upward sediments to a delta front to delta plain succession (Fig. 3) (Tanabe et al., 2003a).

In accordance with the lithology and sedimentary structures (Tanabe et al., 2003a), we selected 66 samples to process for palynological analysis. Each sample was 50 mm thick and weighed between 8 and 24 g (dry weight). All samples were treated chemically according to the standard procedure outlined by Wang and Xu (1988). Before treatment, tablets with exotic *Lycopodium* spores were added to each sample for use in calculating pollen concentration and pollen influx values. Pollen samples were mounted in a glycerin medium. Pollen and spore types in each sample were counted under an optical microscope, mostly at 400×, except where difficulty in identification required higher magnification. Modern reference pollen was obtained from Tongji University, Shanghai, China and identification was based on Kremp (1957), Krutzsch (1962), Huang (1972), Academia Sinica (1976, 1982), Stuijts (1993), Wang et al. (1997) and Yamanoi (2003).

The number of added *Lycopodium* spores averaged about 200 grains per sample. The natural content of pollen and spore grains was variable. Twenty-three samples yielded more than 300 grains, whereas 26 samples contained 100–300 grains and 17 samples yielded fewer than 100. We excluded these 17 samples from the statistical analysis. The pollen data analysis, including the creation of pollen diagrams and the determination of pollen zones, was carried out with Tilia, Tilia-Graph and CONISS software (Grimm, 1991, 1992).

4. Chronological control and sedimentation rates

Radiocarbon dates provide the chronological control for the pollen records in the Song Hong delta. Twenty-one accelerator mass spectrometry (AMS) radiocarbon

Table 1
List of ^{14}C ages used to establish the chronology of core ND-1

Depth (M)	Altitude (M)	Material	Species	δ^{13}C (‰)	Conventional ^{14}C age (yr BP)	Calibrated ^{14}C age[a]			Sample code
						(cal. yr BP)	Probability[a] (%)	Mean[b] (cal. yr BP)	(BETA-)
ND-1									
3.2	−1.7	Wood	–	−30.2	440 ± 50	344–345	0.7		142 396
						461–533	99.3	500	
4.8	−3.3	Molluscan shell	*Potamocorbula amurensis*(Schrenck)	−5.1	6040 ± 30	6432–6524	100.0	6480	142 397
5.1	−3.6	Molluscan shell	*Potamocorbula amurensis* (Schrenck)	−8.4	4930 ± 40	5241–5339	91.6	5290	142 398
						5356–5364	2.9		
						5373–5385	5.5		
6.7	−5.2	Molluscan shell	*Potamocorbula amurensis* (Schrenck)	−5.4	4970 ± 40	5294–5403	100.0	5350	142 399
10.9	−9.4	Molluscan shell	*Solidicorbula erythrodon* (Lamarck)	−2.7	5780 ± 40	6188–6266	100.0	6230	142 400
14.0	−12.5	Molluscan shell	*Mactra (Mactra) veneriformis Reeve*	−2.9	6060 ± 40	6443–6558	100.0	6500	142 401
15.3	−13.8	Molluscan shell	*Varicorbula sp. cf. V. rotalis* (Hinds)	−1.3	6170 ± 40	6569–6682	100.0	6630	142 402
16.7	−15.2	Shell fragments	–	−2.4	6420 ± 40	6866–6980	100.0	6920	142 403
19.3	−17.8	Shell fragments	–	−1	6860 ± 80	7314–7461	100.0	7390	142 404
20.5	−19.0	Molluscan shell	*Placamen tiara* (Dillwyn)	−0.9	7230 ± 80	7631–7786	100.0	7710	142 405
22.4	−20.9	Molluscan shell	*Estellarca olivacea* (Reeve)	−5.8	8340 ± 120	8712–8971	100.0	8800	142 406
23.4	−21.9	Molluscan shell	*Potamocorbula amurensis* (Schrenck)	−4.8	8530 ± 80	8899–9082	86.4	8990	142 407
						9248–9303	13.6		
25.6	−24.1	Molluscan shell	*Corbicula sp. cf. C. fluminea* (Muller)	−8.6	9020 ± 100	9457–9564	28.5		142 408
						9575–9825	71.5	9700	
27.8	−26.3	Molluscan shell	*Potamocorbula amurensis* (Schrenck)	−6.1	8560 ± 70	8927–987	76.5	9010	142 409
						9244–9310	17.5		
						9335–9360	6.0		
30.6	−29.1	Wood	–	−28.8	8360 ± 70	9285–9292	3.1		142 410
						9295–9363	38.3		
						9368–9389	11.3		
						9397–9473	47.3	9440	
33.8	−32.3	Molluscan shell	*Corbicula sp. cf. C. fluminea* (Muller)	−10.9	9330 ± 100	9848–9903	16.4		142 411
						9924–10198	83.6	10 100	
37.2	−35.7	Molluscan shell	*Anisocorbula venusta* (Gould)	−11.8	9040 ± 80	9474–9550	20.6		142 412
						9588–9828	79.4	9710	
40.2	−38.7	Wood	–	−26.7	9330 ± 80	10 670–10 242	21.3		142 413
						10 404–10 463	61.0	10 430	
						10 467–10 600	12.9		
						10 609–10 641	4.8		
43.4	−41.9	Wood	–	−30.2	9970 ± 90	11 231–11 444	66.6	11 340	142 414
						11 465–11 563	30.1		
						11 621–11 628	1.4		
56.4	−54.9	Wood	–	−27	12 470 ± 110	14 165–14 891	91.4	14 500	142 417
						15 190–15 288	8.6		
67.1	−65.6	Wood	–	−28.3	12 650 ± 110	14 344–14 790	65.1	14 600	142 418
						15 569–15 531	34.9		

Dates were recalculated to calendar years on the basis of Stuiver et al. (1998) (from Tanabe et al., in press).

[a] Relative area under the distribution curve.

[b] The intermediate age with the maximum probability, rounded to the nearest multiple of 10 yr (error < 100) or 100 yr (error ≥ 100).

dates (yr BP) were obtained from core ND-1 (Tanabe et al., 2003a) and recalculated as calendar years (cal. yr BP) according to the method of Stuiver et al. (1998). Age uncertainties of the calibrated ages using CALIB 4.3 correspond to 1σ estimates, and we calculated means only for those age ranges with the highest probabilities (Stuiver et al., 1998) (Table 1).

The relationship between age and depth was expressed by the change-point model, with linear interpolation between the change points (Fig. 4) (Bishop et al., 2003). Sedimentation rates were calculated without taking into account sediment compaction effects or basin subsidence (Fig. 4). Two core intervals, 22.4–20.5 and 4.8–3.2 m, displayed obvious, abrupt decreased sedimentation rates of 0.04 and 0.17 cm/yr, respectively. Tanabe et al. (2003a) inferred that the sediment-starved condition in the stratum at 22.4–20.5 m was caused by rapid submergence when sea level rose and suggested that a hiatus at about 5.0 m was caused by erosion in a fluvial channel.

5. Pollen stratigraphy

5.1. Identified pollen and spore types

All together, 101 species and genera belonging to 78 families were identified and categorized according to the climatic and environmental conditions to which they are adapted (Academia Sinica, 1982; Stuijts, 1993; Maxwell, 2001) (Table 2).

Only the principal pollen and spore taxa are included in the pollen diagrams. The percentages of the main groups, including arboreal pollen (AP), nonarboreal pollen (NAP), mangrove group, ferns and unknown types (visible and in fair condition but unmatched to any reference type) and the percentages of spore com-

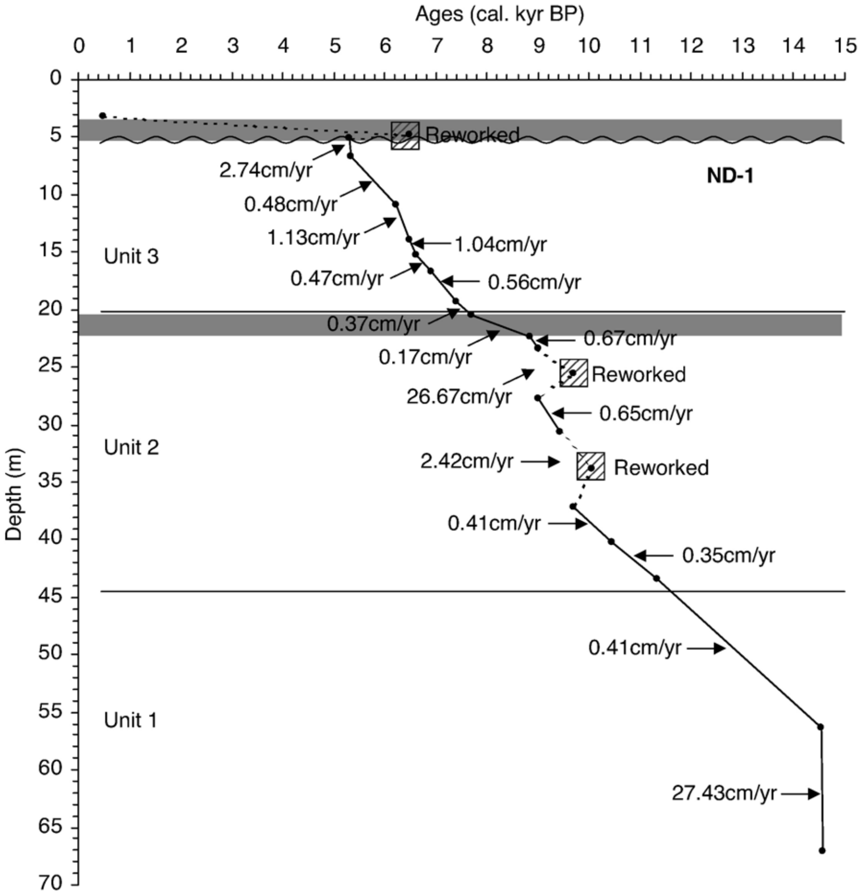


Fig. 4. Age–depth relationship in core ND-1. Sedimentation rates were calculated by linear interpolation between ^{14}C ages. “Reworked” means that the dated molluscan shells from those intervals are considered to have been derived from underlying strata. Three sedimentary units, 1, 2, and 3 correspond to a fluvial, an estuarine, and a deltaic sedimentary system, respectively (Tanabe et al., 2003a). The shaded bands mark two strata with low sedimentation rates.

Table 2
List of all taxa identified in core ND-1 from the Song Hong delta, Vietnam

Tropical arboreal pollens	Subtropical arboreal pollens	Temperate arboreal pollens	Herbs	Ferns and algae	Mangrove and back-mangrove
Altingia [Altingiaceae]	*Aglaia* [Meliaceae]	*Actinidia* [Atinidiaceae]	*Acalypha* [Euphorbiaceae]	*Acystopteris* [Athyriaceae]	*Acanthus* [Acanthaceae]
Antidesma [Euphorbiaceae]	*Allomorphia* [Melastomaceae]	*Alnus* [Beltulaceae]	*Acorus**[Araceae]	*Angiopteris* [Angiopteridaceae]	*Acrostichum* [Acrostichaceae]
Canarium [Burseraceae]	*Camptotheca* [*Nyssaceae*]	*Broussonetia**[Moraceae]	*Alisma* [Alismataceae]	*Araiostegia* [Davalliaceae]	*Excoecaria* [Euphorbiaceae]
Carya [Juglandaceae]	*Castanopsis* [Fagaceae]	*Castanea* [Fagaceae]	*Alocasia**[Araceae]	*Cheilanthes*[Sinopteridaceae]	*Heritieras* [Sterculiaceae]
Claoxylon [Euphorbiaceae]	*Congea* [Verbenaceae]	*Celtis* [Ulmaceae]	*Artemisia* [Compositae]	*Cibotium* [Dicksoniaceae]	*Kandelia* [Rhizophoraceae]
Clausena [Rutaceae]	*Dianthus* [Caryophyllaceae]	*Cryptomeria* [Taxodiaceae]	Asclepiadaceae	*Concentricytes*	Lumnitzera.litterea [Combretaceae]
Cratoxylum [Guttiferae]	Elaeocarpaceae	Cupressaceae	*Calophanoides* [Acanthaceae]	*Cyathea* [Cyatheaceae]	*Rhizophora* [Rhizophoraceae]
Dacrydium [Podacarpaceae]	Hamanelidiaceae	*Delavaya* [Sapindaceae]	*Chenopodium* [Chenopodiaceae]	*Dicranopeteris* [Pteridaceae]	*Sonneratia* [Sonneratiaceae]
Datiscaceae	*Helicia* [Proteaceae]	*Fagus* [Fagaceae]	*Cuscuta* [Convolvulaceae]	Gymnogrammaceae	*Xylocarpus* [Meliaceae]
Dipterocarpaceae	*Liriodendron* [Magnoliaceae]	*Heteropanax* [Araliaceae]	Cyperaceae	*Hicriopteris* [Gleicheniaceae]	
Engelhardtia [Juglandaceae]	*Lithocarpus* [Fagaceae]	*Ilex* [Aquifoliaceae]	*Denolranthema* [Compositae]	*Hymenophyllum* [Hymenophyllaceae]	
Ficus [Moraceae]	*Mastichodendron* [Sapotaceae]	*Juglans* [Juglandaceae]	Gesneriaceae*	*Hypolepis* [Hypocepidaceae]	
Gossampinus [Bombacaceae]	*Phyllanthus**[Euphorbiaceae]	*Myrica* [Myricaceae]	Gramineae*	Lycopodiaceae	
Gouania [Rhamnaceae]	*Rapanea* [Myrsinaceae]	*Pericampylus* [Menispermaceae]	*Hedyotis*[Rubiaceae]	*Lygodium* [Lygodiaceae]	
Horsfieldia [Myrsticaceae]	Sapindaceae	*Pinus**[Pinaceae]	*Jussiaea* [Onagraceae]	*Microlepia*[Dennstaedtiaceae]	
Lasianthus [Rubiaceae]	Theaceae	*Quercus* [Fagaceae]	Nymphaceae	*Myriophyllum*	
Loranthus [Loranthaceae]	*Trachycarpus**[Palmae]	*Rhododendron* [Ericaceae]	Orchidaceae	*Osmunda* [Osmundaceae]	
Maesa [Myrsinaceae]	*Uncaria* [*Rubiaceae*]	*Rhus* [Anacardiaceae]	Papilonaceae	*Polypodium* [Polypodiaceae]	
Mischocarpus [Sapindaceae]	*Vernicia* [Euphorbiaceae]	*Smilax* [Smilaceae]	*Passiflora* [Passifloraceae]	*Pteridium* [Pteridaceae]	
Piperaceae	Wyrtaceae	Taxodiaceae	*Polygonum* [Polygonaceae]	*Pteris* [Pteridaceae]]	
Podocarpaceae		*Toona**[Meliaceae]	Potamogetonaceae	*Pyrrosis* [Polypodiaceae	
*Taxotrophis**[Moraceae]		*Trachelaspermum* [Apocynaceae]	*Rubia* [Rubiaceae]	*Salvinia* [Salvinaceae]	
Terminalia [Combretaceae]		*Ulmus* [Ulmaceae]	Saururaceae	*Selaginella* [Selaginellales]	
Urticaeae		*Wikstroemia* [Thymelaeaceae]	Trilliaceae	Stenochlaena [Blechnaceae]	
Vitex [Verbenaceae]			Typhaceae	Vittariaceae	
			Umbelliferas		

Some genera or species have been lumped into their respective family or genera in the table. The types are not strictly classified according to geobotanical method; the grouping merely indicates that they can grow well in tropical, subtropical, or temperate areas.(Academia Sinica, 1982; Stuijts, 1993; Maxwell, 2001). Secondary taxa firmly associated with human activity are marked by *.

ponents were calculated on the basis of total grains counted (including spores, algae and unknown types), whereas the principal pollen percentages in the detailed pollen diagram were calculated on the basis of the total pollen sum (Figs. 5 and 6).

To understand the ecological significance of the taxa found in core sediments, we carried out a comparison of the modern pollen rain in the Indonesian mountains, northeastern Cambodia and southern China. For further analysis of the pollen data and their climatic implications, many taxa are grouped and discussed in relation to their relative abundance. From the results of our palynological analysis, we classified the taxa into 10 groups (Fig. 5), but we list only the main components of each group on the palynological diagrams (Fig. 6) as follows: tropical semi-evergreen forest taxa (mainly Datiscaceae, Urticaceae and *Ficus*); tropical moist forest (mainly Piperaceae, Podocarpaceae, *Dacrydium*, *Taxotrophis*, *Clausena*, *Vitex* and *Mischocarpus*); subtropical taxa (mainly *Castanopsis* [*Lithocarpus*], *Elaeocarpus*, *Trachycarpus*, *Helicia*, *Allomorphia* and Hamamelidaceae); temperate taxa (*Pinus*, *Cryptomeria,* Taxodiaceae, *Quercus*, *Castanea*, *Alnus*, *Rhus*, *Rhododendron* and *Juglans*); mangrove (dominated by *Rhizophora*, *Xylocarpus*, *Kandelia* and *Excoecaria*); back-mangrove (*Acanthus*, *Sonneratia* and *Excoecaria*); wetland/riparian (Cyperaceae, *Myriophyllum*, *Concentricytes*, *Acoru*, *Alocasia*, and Typhaceae); drought-tolerant herbs (*Chenopodium*, *Artemisia* and *Dendranthema*); wild upland herbs (Gramineae, *Cuscuta*, Gesneriaceae, Orchidaceae, and Trilliaceae) and ferns (*Microlepia*, *Polypodium*, *Pyrrosia*, *Hicriopteris*, *Dicranopteris*, *Pteris*, *Hymenophyllum*, Vittariaceae, *Cyathea*, *Lygodium*, Gymnogrammaceae, *Stenochlaena* and *Lycopodium*) (Stuijts, 1993). Less-abundant types not included in the pollen diagrams can be found in the complete listing in Table 2. The 17 samples, excluded from the statistical analysis because they contained little pollen, are listed in Table 3.

5.2. Pollen stratigraphy

At the bottom (70.0–65.3 m) of core DN-1, we only found a few pollen of *Cryptomeria*, *Pinus* and Cupressaceae, which are the typical coniferous types (Table 3). This part of the core is marked by “no pollen” in the pollen diagrams (Figs. 5, 6). Based on the results of our analysis and considering both the conspicuous changes in the dominant AP and NAP taxa and the age data, we divided the record into seven pollen zones and six subzones.

Pollen zone ND-1-I (>12.9 cal. kyr BP, >50 m deep) is characterized mainly by a high content of spores, with an average value of 40–45%, whereas percentages of AP and NAP are 20–40% and 20–30%, respectively. Mangrove pollen is less than 5% and is dominated by *Rhizophora*. Temperate taxa (20–40%) dominate the AP, consisting mainly of coniferous trees and some broad-leaved trees, such as *Cryptomeria* (0–15.3%), Taxodiaceae (0–8.2%), *Pinus* (0–9%), *Quercus* (8.6–20.1%), *Castanea* (0–15%), *Alnus* (0–5%) and *Juglans* (0–3%). Tropical and subtropical taxa are represented only by *Taxotrophis*, *Clausena*, *Castanopsis* (*Lithocarpus*), a low percentage of *Phyllanthus,* and a sparse scattering of *Elaeocarpus*, Piperaceae, *Helicia*, *Allomorphia* and *Altingia*. Among NAP, the wetland/riparian group (10–40%) prevails, with its main components being Cyperaceae (0–35%), *Acorus* (3–10%) and some freshwater algae such as *Concentricytes*, whereas the natural Gramineae content is 5.6–18.3%, the highest level in the whole core. In the interval 53.85–54.95 m, the percentages of *Cryptomeria* (0–3%) and Cyperaceae (1–2.1%) rapidly decrease, with a corresponding rapid increase in the percentages of broad-leaved trees such as *Castanopsis* (*Lithocarpus*) (5–8%), *Castanea* (10–15%), *Alnus* (2–5%) and *Juglans* (2–5%). Fern spores consist mainly of *Polypodium* (5–20%), *Hicriopteris* (6–10%), Gymnogrammaceae (0–15%) and *Lygodium* (0–18%), with small amounts of *Pyrrosia*, *Pteris* and *Stenochlaena*.

Pollen zone ND-1-II (12.9-10.9 cal. kyr BP, 50.0–42.0 m depth) is characterized by a low concentration (10 000–20 000 n/g) of pollen and generally high content of temperate group taxa, dominantly *Pinus*, *Cryptomeria*, Taxodiaceae, *Quercus* and *Castanea*. The NAP and AP contents show sharp shifts. An obvious character of this zone is a sharp increase in herb pollen at 47.0 m, caused by an abrupt rise (to as much as 80%) in *Artemisia*. The main components of both ferns and AP show a sharp decrease, corresponding to the change in herbs, except for *Pinus,* which gradually increases, as does the fern, *Microlepia*. Mangrove taxa gradually decrease and finally disappear. Above 45.0 m depth (11.6 cal. kyr BP), the percentage of NAP decreases with the fall in the percentage of *Artemisia* to about 1%, whereas the percentage of AP increases to 30–55%, dominated by temperate broad-leaved taxa such as *Quercus* (5–20%) and *Castanea* (0–18%) and mixed with some coniferous taxa, including *Pinus* (8–10%), *Cryptomeria* (2–10%) and Taxodiaceae (0–8%). Tropical and subtropical components begin to increase gradually and diversity is higher.

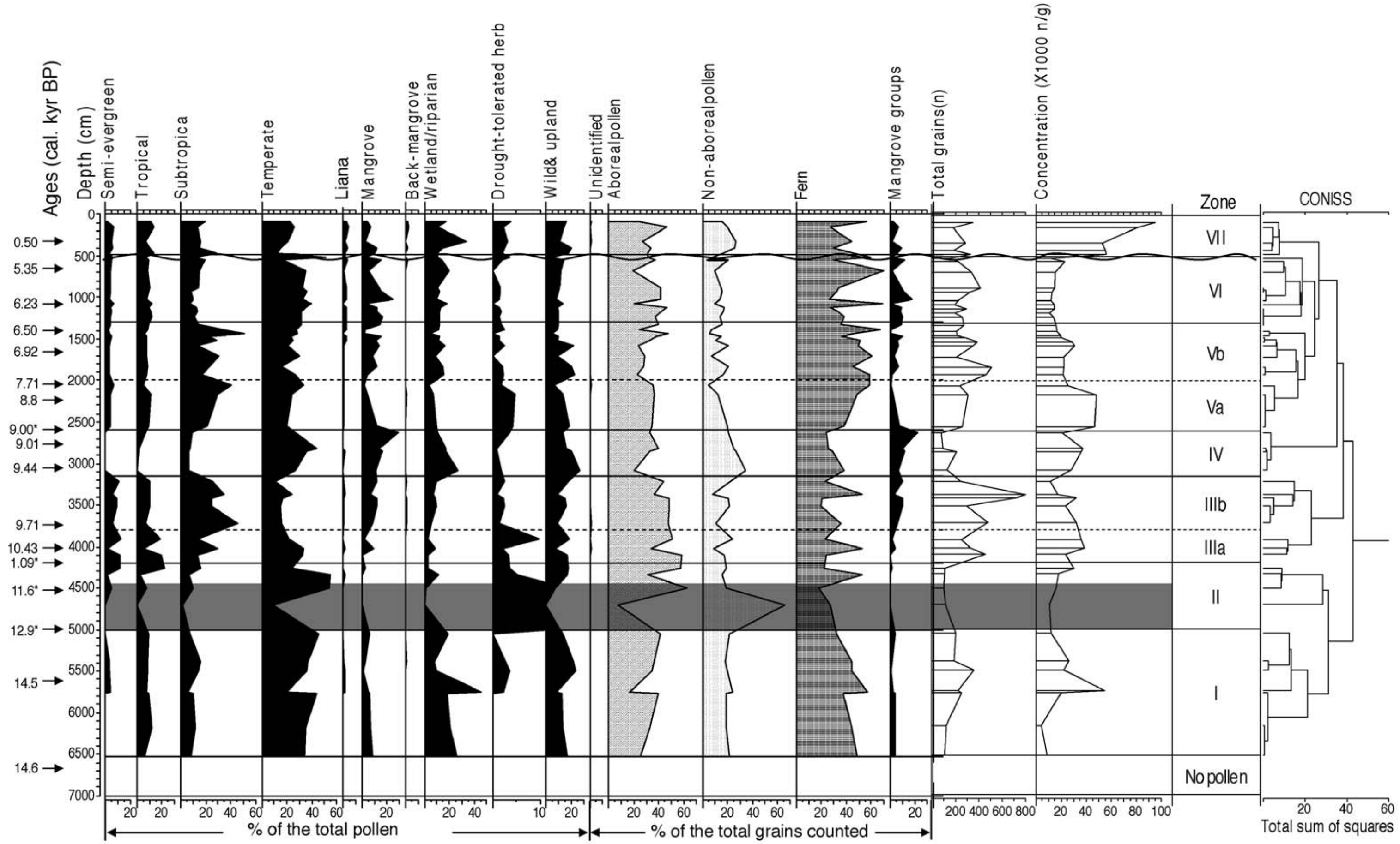


Fig. 5. Pollen diagram of grouped taxa percentages of core ND-1. (The shadow marks the highest percentage of NAP dominated by *Artemisia*. The ages marked by * were calculated on the age–depth relationship.)

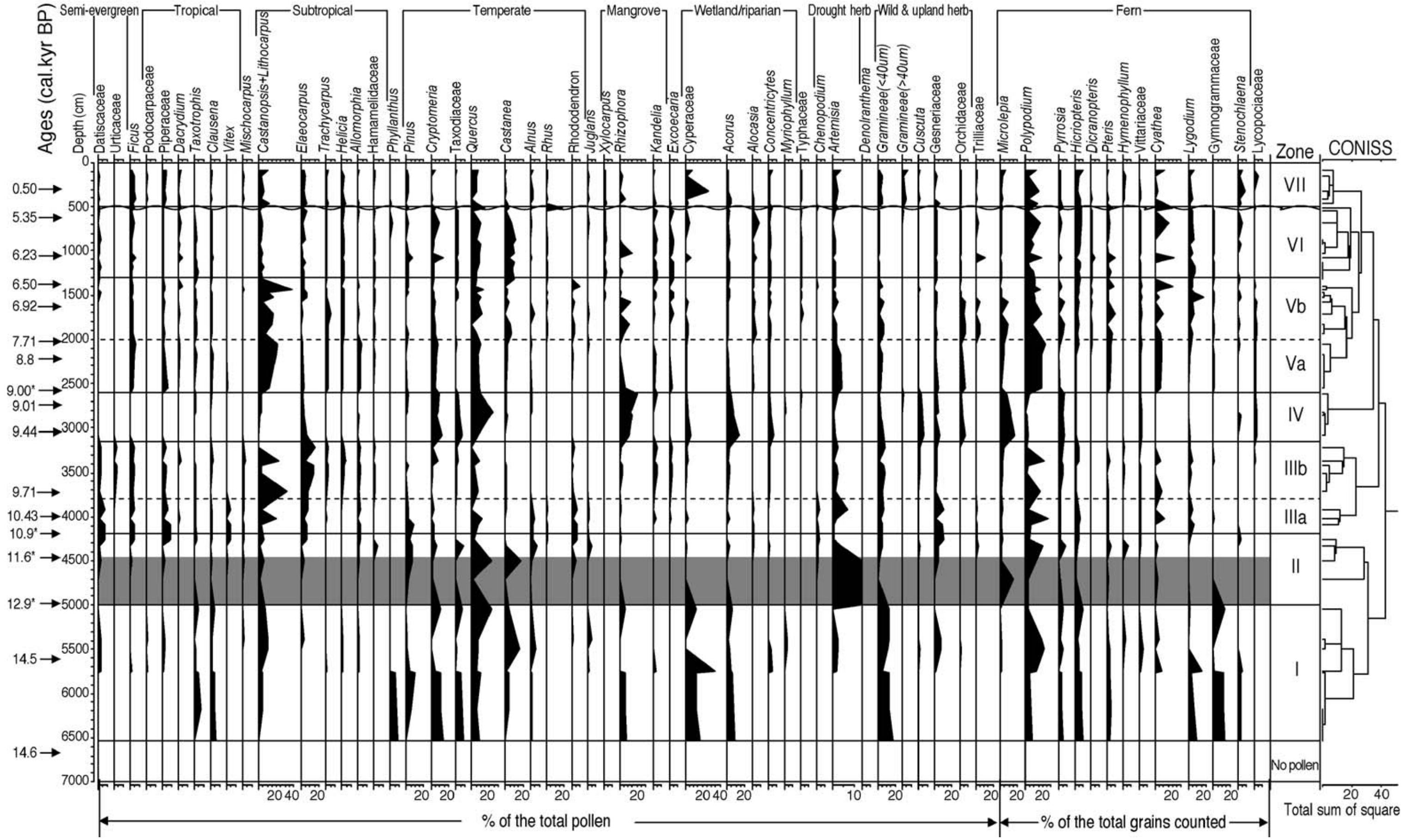


Fig. 6. Pollen diagram of selected main components and groups in core ND-1 (the ages marked by * were calculated on the age–depth relationship).

Table 3
The samples, with pollen less than 100 grains, not included in the pollen diagrams in core ND-1 from the Song Hong delta, Vietnam

Depth (cm)	Semi-(*n*)	Tropical (*n*)	Subtropical (*n*)	Temperate (*n*)		Herb (*n*)	Fern (*n*)	Total (*n*)
				Broad-leaved	Coniferous			
2285	2	11	14	11		3	44	85
2335	6	2	3	1			5	17
2405	12	13	18	24	2	7	18	94
2505	7	15	19	17	5	11	25	99
2735		3	2	1	16	8	51	81
3050			4		13		16	33
4990			5	5	13	5	30	58
5285	1			1	4			6
5595								8
5635							2	2
6255					2	1		2
6355					4	1	5	10
6435				1	7	8		9
6665	1			4	20		9	42
6715					3		1	4
6889				1	15			16
6995					9	1	1	11

Pollen zone ND-1-III (10.9–9.4 cal. kyr BP, 42.0–31.5 m depth) is characterized by relatively high percentages (13–41%) of subtropical taxa such as *Castanopsis* (*Lithocarpus*) (5–35%) and *Elaeocarpus* (8–15%). Semi-tropical (3–12%) and tropical (7–15%) taxa, in particular Datiscaceae (5–8.6%), *Ficus* (0–3%) and Piperaceae (3–8.5%), also increase, whereas, in contrast, the temperate group decreases to 10–25%. Mangrove pollen increases to 10% or so. In this zone, the pollen concentration increases to 15 000–35 000 n/g. Two subzones were identified as follows:

Subzone ND-1-IIIa (10.9–9.7 cal. kyr BP, 42.0–38.0 m depth) is characterized clearly by its high percentages of drought-tolerant herbs (3–8.5%), mainly *Artemisia* (0–7.2%) and *Chenopodium* (0–3.4%), whereas the wetland/riparian group is present at a relatively low percentage. Among AP, the conifers of temperate taxa begin to decrease whereas broad-leaved components become more abundant.

Subzone ND-1-IIIb (9.7–9.4 cal. kyr BP, 38.0–31.5 m depth) is characterized by high percentages of subtropical AP (25–42%) and wetland/riparian NAP (8–10%). The percentages of semi-evergreen and tropical taxa increase and become relatively stable at 6–8% and 8–12%, respectively. Temperate taxa, dominated by broad-leaved trees such as *Quercus,* decrease to 15–21%.

Pollen zone ND-1-IV (9.4–9.0 cal. kyr BP, 31.5–26.0 m depth) is characterized by a decreasing percentage of AP and increasing NAP. Temperate taxa compose up to 21–40%, dominated by *Quercus* (5–18%), *Cryptomeria* (10–15%), Taxodiaceae (3–8%) and others such as *Pinus*, *Castanea* and *Alnus* in low percentages. Subtropical taxa decrease to 5–7%, with the main components being *Castanopsis* (*Lithocarpus*) and *Elaeocarpus*. The semi-evergreen and tropical taxa decrease very sharply and appear only sparsely. Mangrove increases to its first peak, at 21.2%; the group is dominated by *Rhizophora* (8–18%), with some scattered *Kandelia* and *Xylocarpus*. The wetland/riparian group increases to 15–25%, with its main components being Cyperaceae (4–10%), *Acorus* (5–15%), *Concentricytes* (3–7%) and scattered *Myriophyllum* and Typhaceae. Wild upland herb taxa (15–23%) also increase to their maximum value in the core; they consist mainly of Gramineae (4–8%), *Cuscuta* (3–7%), Gesneriaceae (2–8%) and Orchidaceae (2–5%). Among ferns, *Microlepia* is most abundant at 15–20%. Spores of *Pyrrosia* (2–5%), Vittariaceae (1–3%) and Lycopodiaceae (1–2.3%) increase, whereas those of *Polypodium* (0.8–1.6%), *Cyathea* and *Hicriopteris* decrease. In this zone, the pollen concentration is 25 000–36 000 n/g.

Pollen zone ND-1-V (9.0–6.5 cal. kyr BP, 26.0–13.0 m depth): Ferns increase to their highest percentage (40–65%) in the core; *Polypodium* in particular shows an obvious increase from 0.8–1.6% to 10–20%. The semi-evergreen, tropical and subtropical taxa increase to 5–8%, 6–10% and 15–35%, respectively, with a corresponding decrease in temperate taxa (15–25%). In AP, the dominant taxa include *Castanopsis* (*Lithocarpus*) (10–32%), *Quercus* (3–8%), *Ficus* (2–5%) and Piperaceae (2–4%), along with low percentages of pollen from taxa such as Datiscaceae, *Dacrydium*, *Taxotrophis*, *Clausena*, *Trachycarpus*, *Elaeocarpus*, *Helicia* and *Allomorphia*. Two subzones were identified by characteristic changes in the contents of various components.

Subzone ND-1-Va (9.0–7.7 cal. kyr BP, 26.0–20.0 m depth): The pollen concentration increases to a maximum at 23 000–50 000 n/g. Mangrove taxa decrease to low values. *Artemisia* increases from 1.5–2.2% to 2–5%, as do other drought-tolerant herb taxa such as *Chenopodium*, whereas wetland/riparian taxa decrease, with a scattering of Cyperaceae, *Acorus*, *Concentricytes* and *Alocasia*. In ferns, *Polypodium* (about 20%) replaces *Microlepia* (0–5%) as the dominant component, and there is a rapid increase in *Cyathea* (6–8%) and *Pteris* (3–7%).

Subzone ND-1-Vb (7.7–6.5 cal. kyr BP, 20.0–13.0 m depth): The pollen concentration decreases to 15 000–28 000 n/g. The most obvious characteristic is that fern rises to its highest percentage in the core, with high diversity; *Microlepia* (0–8%), *Polypodium* (10–15%), *Pyrrosia* (1–5%), *Hicriopteris* (2–4%), *Pteris* (0–8%), Vittariaceae (1–3%), *Cyathea* (0–15%), *Lygodium* (3–15%) and Lycopodiaceae (0–3%) are dominant. Mangrove pollen (0–10%), composed mainly of *Xylocarpus, Rhizophora, Kandelia* and *Excoececaria*, also begins to gradually increase. With regard to NAP, aquatic algae and taxa such as *Concentricytes*, *Myriophyllum*, Cyperaceae, and *Alocasia* begin to increase, becoming more common as *Artemisia* content is reduced.

Pollen zone ND-1-VI (6.5–5.2 cal. kyr BP, 13.0–4.9 m depth) is characterized by a low pollen concentration (12 000–18 000 n/g) and a high percentage (15–40%) of temperate taxa, mainly consisting of the broad-leaved tree taxa *Quercus* (5–10%), *Castanea* (4–12%), *Rhus* (0–15%), *Alnus* (0.6–2%), and *Juglans* (0.8–2.1%), and by the coniferous tree taxa *Cryptomeria* (2–12%), Taxodiaceae (0.6–2%) and *Pinus* (0–6%). Subtropical taxa decrease to 9–15% and are composed mainly of *Castanopsis* (*Lithocarpus*) (3–7%), *Elaeocarpus* (2–5%), *Helicia* (1.2–3%) and a low percentage of Hamamelidaceae, along with low percentages of some semi-evergreen and tropical taxa. Mangrove pollen continues increasing to a peak value (about 15%), comprising *Xylocarpus* (1.2–3%), *Rhizophora* (0–12%), *Kandelia* (0–4%) and *Excoecaria* (0–7.2%), with a low amount of back-mangrove pollen such as of *Acanthus*. Wetland/riparian and drought-tolerant herbs maintain relatively stable percentages as before. Ferns begin to decrease generally, except for two abnormally peaks at about 11.0 and 6.75 m.

Pollen zone ND-1-VII (0.76–present, 4.9–0 m depth): This zone is characterized by the highest concentration of pollen in the core at 55 000–95 000 n/g. Ferns and AP percentages decrease to 27–42% and 25–45%, respectively, whereas NAP increases to 15–28% as a result of a rapid increase in Cyperaceae (5–24%) together with aquatic algae and other taxa such as *Concentricytes*, *Myriophyllum*, and *Alocasia.* Drought-tolerant herbs still maintain a low percentage. Wild upland herbs increase a little, with contributions from Gramineae, *Cuscuta*, Orchidaceae and Trilliaceae, and pollen of Gramineae more than 40 µm in diameter begins to be common. AP is dominantly composed of *Ficus* (2–5%), Piperaceae (3–5%), *Castanopsis* (*Lithocarpus*) (5–11%), *Elaeocarpus* (4–6%) and *Quercus* (2–8%). *Polypodium* (3–12%), *Hicriopteris* (5–10%), *Hymenophyllum* (0–4%), *Cyathea* (0–8%), *Stenochlaena* (0–6%) and *Microlepia* (2–5%) are the main fern components, with diversity decreasing.

6. Interpretation and discussion

6.1. Ecological information

The identified pollen in the core was dominated mainly by taxa of the tropical upland rain forest or subtropical lowland monsoon forest, for example, *Castanopsis* (*Lithocarpus)*, *Elaeocarpus* and *Quercus*. However, many samples contained not only pollen types associated with today's tropical seasonal rain forest but also conifer pollen, for example, *Dacrydium*, *Podocarpus*, *Pinus*, Cupressaceae, Taxodiaceae and *Cryptomeria*, and some temperate forest components such as *Carpinus*, *Alnus*, *Juglans*, *Carya*, *Ulmus*, *Fagus*, *Ilex*, and *Castanea*. Montane conifer taxa such as *Dacrydium*, *Pinus*, *Podocarpus*, *Cryptomeria* and Taxodiaceae grow today mostly at high elevations (more than 800 m) (Zheng and Lei, 1999). In the Song Hong delta, which lies at an elevation of less than 200 m, the present local vegetation does not include montane conifers as well as some temperate broad-leaved trees such as *Alnus*, *Ulmus*, which only grow in upstream area of Song Hong. However, in the surface and uppermost samples in core ND-1 (after 0.76 cal. kyr BP), pollen assemblages include high percentages of those pollen, e.g., *Quercus* (2.4–11.2%), *Alnus* (1.8–2.7%), *Cryptomeria* (0.5–3.7%). Thus the pollen of temperate groups may mainly transported by the river from upstream area since the location is near the river course as floodplain environment as Tanabe et al. (2003a) described. In general, pollen preserved in the delta area, especially near the river discharge area, mainly records vegetation in or around the river drainage area. For example, Chmura et al. (1999) proposed that pollen preserved in coastal sediments provided a record of vegetation in the Mississippi drainage area rather than local coastal area, based on the study of the pollen distribution patterns in coastal waters in Mississippi area. In this study, because the site of core ND-1 stayed within or near the course of Song Hong or in the river discharge area during the last deglaciation, pollen sources would be mainly from the vegetation in or near Song Hong drainage area. Being in much abundance generally, the allochthonous pollen content also varies with different sedimentary environments resulting from more or less continuous change of river influence. Hofmann (2002) found the percentages of allochthonous taxa are very high (even up to 80%) in sediment of the Orinoco delta, and autochtonous taxa are various with 41%, 71% and 52% at the minor distributary of Cano Guaneira, the mangrove forest at the mouth of the main Macareo distributary and at the palm-swamp covering the floodplain, respectively. Thus, when we interpret the temperate group increasing in fossil pollen assemblages in delta areas, two aspects should be considered: 1) the substantial increase in pollen from these conifers as well as temperate broad-leaved trees may reflect a lowering of lowland–montane forest boundary, responding to climate cooling; 2) an increase in temperate group is also possibly caused by intensified fluvial influence in the process of the evolution of sedimentary environment.

6.2. Palaeoclimate implications, pollen assemblages and palaeoenvironment

With the sea-level rising in the last deglaciation (Fig. 7), sedimentary environment evolution of the Song Hong delta area incorporated fluvial, estuary and delta environments (Hori et al., 2004; Tanabe et al., in press). In core ND-1, the evolution process was shown by sediment facies (Fig. 3) : fluvial sediment system (Unit 1) during the period of 14.5–11.6 cal. kyr BP, estuary system (Unit 2) during the period of 11.6–7.7 cal. kyr BP and delta system (Unit 3) after 7.7 cal. kyr BP (Fig. 7) (Tanabe et al., 2003a). During the whole evolution process, near or in the course of Song Hong, the site of core ND-1 accumulated a thick sediment sequence with high sedimentation rates due to a strong river influence, and the prevalence of deposition over erosion regardless of the sedimentary environment, except for the transition from estuary to delta about 8.5–7.7 cal. kyr BP. The magnitude of river influence varies from the different sedimentary environments. On the basis of the patterns of sediment, the environments of floodplain, lagoon and abandoned channel are relatively less influenced by the river than other environments. When the river influence decreases, the river-transported pollen, largely of conifers and temperate broad-leaved arboreal trees, will be reduced. Thus, to extract climate information, it is important to distinguish the climate factor on the pollen assemblages from the environment factor.

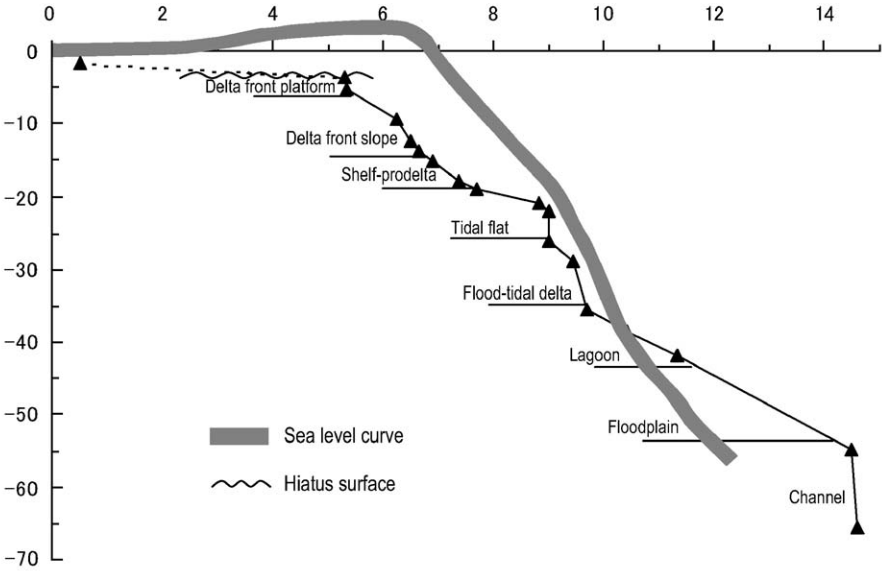


Fig. 7. Correlation between the sea-level change and the sedimentary environment recorded in the cores ND-1 from the Song Hong delta, Vietnam (modified from Hori et al., 2004).

6.2.1. Before 11.6 cal. kyr BP (fluvial plain sedimentary environment)

Being the channel environment, the lowest part of this core, consisting mainly of pebbly sand and poorly sorted medium to very fine sand (the "no pollen" zone in Figs. 5, 6 and 8), did not yield enough pollen to determine the characteristics of the climate. Only a few pollen grains were found below 65.30 m (about 14.58 cal. kyr BP), and some coniferous pollen types were found at depths of 67.15, 68.89 and 69.95 m (Table 3). Below the 54.0 m depth, pollen assemblages are characterized by high percentage of temperate taxa, especially *Cryptomeria*, Taxodiaceae, *Quercus* and *Pinus*, as well as the wetland herb, Cyperaceae, which may be firmly connected with a great amount of pollen transported by river from upstream, since the sediment facies is channel fill. Above 54.0 m (about 14.48 cal. kyr BP), subtropical and tropical species belonging to *Castanopsis* (*Lithocarpus*), *Taxotrophis* and *Clausena* begin to occur in low percentages which together with the declines of fern spores content (Fig. 5) and sedimentation rate (Fig. 4), are possibly associated with lessened fluvial influence when the sedimentary environment changed from channel to floodplain with sea level rise. Decreasing river influence will result in decreased abundances of river-transported relative to wind transported pollen. That is to say, sedimentary environment change is possibly one of the factors inducing a reduction in long-distance river transported mountain taxa and increasing the representation of short-distance wind transported local vegetation.

On the other hand, the pollen assemblages within the interval 54.0–45.0 m (14.5–11.6 cal. kyr BP) obviously show higher percentages of *Cryptomeria*, Taxodiaceae, *Quercus*, *Castania* and *Alnus* than those in the surface and uppermost samples, which have similar floodplain sedimentary environments (Fig. 3). Thus, the higher content of temperate taxa should also reflect a cooler climate than at present. At 54.0–50.0 m internal (14.5–12.9 cal. kyr BP), abundance of wetland/riparian group similar to those in surface and uppermost samples indicates similar wet condition to present. Above 50.0 m depth, the decrease of Cyperaceae and sharp increase in *Artemisia* might indicate drier conditions in the period of 12.9–11.6 cal. kyr BP (50.0–45.0 m). Pollen in the sample at the depth of 49.9 m is not abundant enough to be calculated statistically, but in 58 total grains, there are 5 herb (all are *Artemisia*) grains and 18 temperate taxa grains (Table 3). Thus, the pollen assemblages in the interval of 50.0–45.0 m indicated a cooler and drier climate. Moreover, based on the relationship between depth and age, we calculated the age range is about 12.9–11.6 cal. kyr BP, which corresponds exactly with the Younger Dryas cool period widely recorded globally (Dansgaard et al., 1989; Liu et al., 1992; Severinghaus et al., 1998; Sbaffi et al., 2001, 2004). Therefore, we consider this is a reflection of the Younger Dryas period. Another possible reason for the high percentage of herb pollen is local vegetation on floodplain dominated by grassland due to rapid sedimentary environment changes. However, the sediments during the interval of 48.1–46.8 m (12.48–12.16 cal. kyrBP) are characterized by the silty clay intercalated with well-sorted very fine to fine sand beds (Fig. 3), which is interpreted as crevasse splay sediments associated with breaks in the channel bank by Tanabe et al. (2003a). That means the sediment at this interval should have been influenced more strongly by the river than layers below in a typical floodplain environment (Miall, 1992). Thus, the record with a high percentage of herbs is possibly associated with widely developed grassland vegetation under a drier and cooler climate than at present, corresponding to the Younger Dryas cooling period, rather than to sedimentary environment changes.

6.2.2. 11.6–7.7 cal. kyr BP (estuary sedimentary environment)

During the period 11.6–9.7 cal. kyr BP (45.0–36.0 m), the sedimentary environment has changed into a lagoon/estuary in the Song Hong incised valley, and the sediment in core ND-1 is characterized by clay with peat layers and carbonate concretions. The lagoon/estuary was confined to the valley; it received riverine sediments and was connected to the open sea through narrow estuarine inlets (Reinson, 1992; Tanabe et al., 2003b). Sediment mainly comes from terrigenous material together with seasonal freshwater input by the river. Because the sedimentation rate (about 0.35–0.41 cm/yr) is similar to that of the floodplain before (0.41 cm/yr), we can assume that the magnitude of river influence is similar. That means the pollen preserved in the sediments come from the same sources with the similar content of allochthonous pollen transported by river. Within the interval of 45.0–42.0 m (11.6–10.9 cal. kyr BP), NAP abruptly decreases, and AP, dominated by temperate taxa such as *Quercus*, *Pinus*, *Castanea*, *Alnus*, *Cryptomeria* and Taxodiaceae, began to increases. The character of the pollen assemblages may indicate that the climate was still cooler that at present. Above 42.0 m (10.9 cal. kyr BP), pollen of tropical trees increases, and the content of temperate taxa is reduced to about 20%, dominated by *Quercus* (ND-1-IIIa, IIIb), and is similar to present. This change of

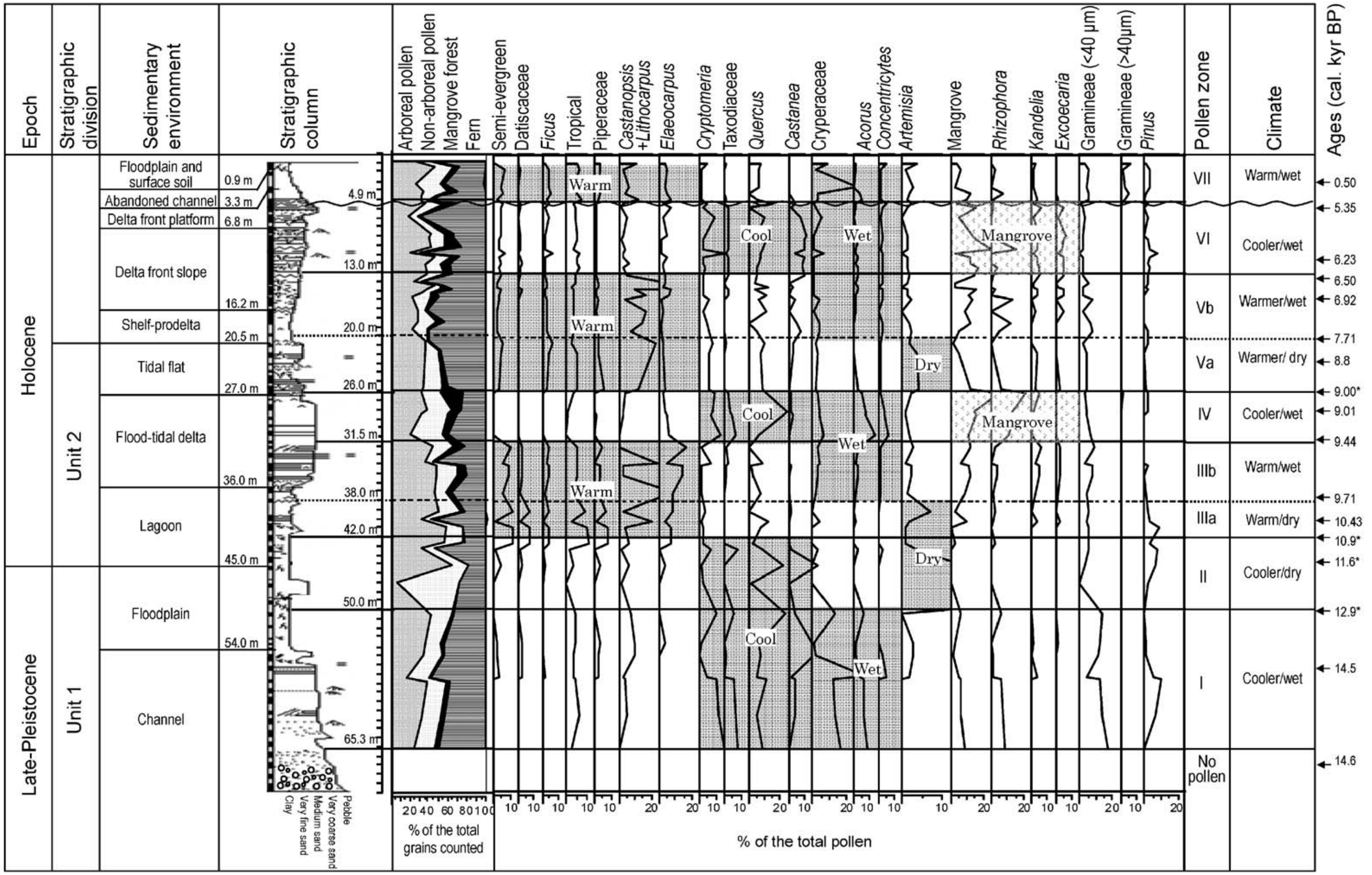


Fig. 8. Schematic diagram showing the climatic conditions indicated by the pollen zones compared with the depositional environments of core ND-1. *Indicates ages estimated from the age–depth relationship. The slash shadow marks the period with high content of *Artemisia* preserved in sediments of crevasse splay.

pollen assemblage is likely to have been associated with a warming climate since the sedimentary environment was not changing. This pollen assemblage lasted until 9.4 cal. kyr BP (31.5 m), when conifers of *Cryptomeria* and Taxodiaceae increased as well as the broad-leaved trees of *Quercus* (ND-1-IV). The sedimentary environment had already changed from a lagoon into a flood–tidal delta.

In an estuary environment, a flood–tidal delta forms landward of the barriers, and is only slightly influenced by wave- and wind-generated processes (Reinson, 1992). After about 10.0 cal. kyr BP, the rate of sea level rise increased and kept in pace with the sedimentation rates (Fig. 7). At 36.0 m depth (9.7 cal. kyr BP), lagoon sediment in core ND-1 became into flood–tidal delta sediment which is usually used to indicate the estuary mouth (Reinson, 1992). Occasional double mud drapes, peaty organic layers and high sedimentation rate without an erosion surface reflect relatively week wave action. Because the sedimentary environment of the interval 27–36 m is a flood tidal delta, the main sediment source would have been the coastal zone and not the Song Hong drainage area. The higher content of tropical taxa might reflect only the vegetation in the coastal zone. This pollen assemblage persists until 9.4 cal. kyr BP (31.5 m), when conifers of *Cryptomeria* and Taxodiaceae increased, as did broad-leaved *Quercus* trees in the same flood–tidal delta environment, (ND-1-IV). high percentages of temperate taxa, predominantly *Quercus*, *Cryptomeria* and Taxodiaceae, during 9.4–9.0 cal. kyr BP (ND-1-IV) were possibly induced by a cooling climate. In addition, the increase in wetland/riparian pollen dominated by *Acorus*, suggests wetter condition than before. Pollen of mangroves increases gradually and reaches a first peak at about 9.0 cal. kyr BP, coherent with the shoreline migration landward due to the sea level rise.

During the period 9.0–7.7 cal. kyr BP (27.0–20.5 m), the sedimentary environment is characterized by tidal flats (Tanabe et al., 2003a). The sediment consists of rhythmically laminated clay or silty clay with shelly layers, burrows and rootlets. In the estuary environment, the tidal flats are situated adjacent to the barrier or on the landward side of the lagoon abutting the hinterland marsh and swamp flatland (Reinson, 1992). The concentration of in situ *P. amurensis* (Shrenck) and *Corbicula sp.* shells were interpreted by Tanabe et al. (2003a) as a primary biogenetic concentration in a brackishwater environment. Rootlets are commonly found in salt marsh and upper tidal flat sediments (Fray and Basan, 1985). This sedimentary environment can be regarded as the landward boundary zone of subaqueous lagoon that are different from open-coast tidal flats. The hydrodynamic conditions of the tidal flats in estuary system are mainly from wave and tidal currents of subaqueous lagoons due to the shelter the barrier from the open sea. That is to say, the wave and tidal erosion or scouring is not so strong as it is in open-coast tidal flats. The relatively constant re-working from wave and tidal currents generally inhibits the accumulation of pollen (Woo et al., 1998), which may be the main reason for less pollen in samples at 27.35, 25.05, 24.05, 23.35 and 22.85 m (Table 3). With an exception of a very low sedimentation rate at 0.17 cm/yr during 8.8–7.7 cal. kyr BP, due to the transition from an estuary environment to a delta environment (Tanabe et al., 2003a), a generally high sedimentation rate indicates that the site of core ND-1 was possibly located on a tidal flat near the river mouth, and the sediment came mainly from river discharge, similar to a flood–tidal delta. During the period of 9.0–7.7 cal. kyr BP, pollen content of conifers and temperate broad-leaved trees decline, whereas tropical taxa increase with higher diversity. *Castanopsis* (*Lithocarpus*) obviously became the main pollen component. Datiscaceae, *Dacrydium*, *Taxotrophis*, *Clausena*, *Trachycarpus*, *Elaeocarpus*, *Helicia* and *Allomorphia*, which grow well in warm tropical and subtropical environments, maintained stable contents. This pollen assemblage lasted until about 6.5 cal. kyr BP, when the delta environment had already started developing. The levels of the various components are stable and the diversity is enhanced, indicating that the vegetation had adjusted to the warming climate and that the warm-adapted taxa were flourishing in the warmer climate. At the beginning of the period (before 7.7 cal. kyr BP), *Artemisia* as well as other drought-tolerant herbs such as *Chenopodium* increased, which possibly indicates a dryer condition.

6.2.3. 7.7–5.2 cal. kyr BP (delta sedimentary environment)

After the transition period from an estuary environment to a delta environment with very low sedimentation rate, a seaward progradational delta had developed since 6.5 cal. kyr BP when the sea level fell gradually due to the geological and hydrologic equilibrium state (Fig. 7) (Hori et al., 2004). With the centre of sediment deposition migrating seaward, the environment changed from a shelf–prodelta 7.7–6.8 cal. kyr BP into a delta front slope during the period 6.8–5.4 cal. kyr BP and a delta front platform after 5.4 cal. kyr BP (Tanabe et al., 2003a). Pollen assemblages in marine sediments are generally regarded as a product of complex interactions between river discharge, marine currents and coastal wind patterns and it is frequently assumed that, in absence of marine currents, pollen concentrations will decrease with distance offshore from terrestrial pollen sources, or mouths of rivers. However, we found the highest pollen concentration (20 000–28 000 n/g) was shown in shelf–prodelta sediment, not in the sediments of delta front slope and delta front platform (15 000 n/g). Because the sedimentation rates were similar, we attribute this difference to greater similarity of transportation/deposition mechanisms between pollen and prodelta to shelf clay to silty clay sediments, compared with the sandier delta front sediments. Prodelta to shelf sediments, as well as pollen, are typically transported in suspension. However, delta front sediments display tide- and wave-influenced sedimentary structures, for example, wave ripples and mud drapes, indicating that they are transported both in suspension and as bed load. The high pollen concentration in the prodelta to shelf sediments should be ascribed to these differences in transportation and deposition. Thus, the impact of the sedimentary environment on pollen deposition and transportation is reflected in the pollen concentration.

In the process of transport and deposition of suspension, there are flocculation, agglomeration and pelletization (Nemec, 1995), which may not be expected to discriminate among pollen taxa. That is to say, deposition of individual pollen types will be in the same proportion as they are supplied in the river plume at any one point in time (Chmura et al., 1999). Thus, we presume that the proportion of changes in pollen components are mainly contributed by climate change rather than sedimentary environment change. During the period of 7.7–6.5 cal. kyr BP, contents of tropical, subtropical and temperate groups keep stable with the same levels of the various components as previously. The pollen diversity is enhanced, indicating that the warm-adapted taxa were flourishing in the warmer climate. Wetland herbs, for example, Cyperaceae, *Alocasia* and *Concentricytes*, prevail over drought-tolerant herbs, also indicating that conditions have become wet again. At the same time, the percentage of fern reaches its highest value due to the increase of moist taxa such as *Pteris*, Vttariaceae, *Cyathea*, Lycopodiaceae, *Microlepia*, *Pyrrosia*, *Hicriopteris*, while *Polypodium* decreased. Mangrove taxa, mainly *Xylocarpus*, *Rhizophora*, *Kandelia* and *Excoececaria*, also begin to gradually increase, corresponding to the shoreline seaward migration.

During the period 6.5–5.2 cal. kyr BP, the increase in coniferous trees belonging to *Cryptomeria*, Taxodiaceae, and *Pinus*, along with scattered temperate broad-leaved trees such as *Alnus* and *Juglans*, distinctly indicate a cooling climate. Wetland and drought-tolerant herbs reflect a wet character similar to that before without obvious changes in content. Ferns generally decrease, and mangrove forest, consisting of *Xylocarpus*, *Rhizophora*, *Kandelia* and *Excoecaria* and back-mangroves such as *Acanthus*, develops to a second peak at 10.25 m depth, dating 6.09 cal. kyr BP. The sedimentary environment is a delta front slope farther than a delta front platform from the tidal flat, where mangrove are adapted to grow. Thus, the mangrove peak may be associated with enlarged mangrove contribution.

6.2.4. 0.76 cal. kyr BP-present (abandoned channel and flood plain)

Tanabe et al. (2003a) reported that there is a time gap of about 4.8 kyr at 3.3 m depth (boundary between delta front platform sediments and abandoned channel-fill sediments), based on the sedimentation rate and sediment characteristics. From the palynological results, in which the pollen concentration sharply increases to its highest level in the whole core of 55 000–95 000 n/g, Cyperaceae and wild Gramineae are present in large quantities, and large-size a Gramineae pollen (possibly from cultivated varieties) becomes common, a climate change is suggested at 4.9 m depth (about 0.76 cal. kyr BP), between the hiatus surface and 3.3 m, a little lower than that inferred from the sediment characteristics (Tanabe et al., 2003a). In general, in this sedimentary environment, less river influence results in decreased abundance of river-transported pollen. However, in the pollen assemblages from the surface sample, the temperate broad-leaved and conifer pollen, which are regarded as allochthonous mainly transported by the river, account for 20%. This high percentage of allochthonous pollen may be associated the relatively frequent river influence since core ND-1 is near the course of Song Hong and even within its distributary area. Similar to the surface, high percentages of Cyperaceae together with those of aquatic algae and plants such as *Concentricytes*, *Myriophyllum*, and *Alocasia*, associated with humidity-loving ferns such as *Hicriopteris*, *Hymenophyllum*, *Cyathea*, *Stenochlaena*, and *Microlepia*, indicates very wet conditions. Tropical and subtropical moist forest composed of *Ficus,* Piperaceae, *Castanopsis* (*Lithocarpus*), *Elaeocarpus*, and *Quercus* indicates a present warm climate. An increase in herbs, especially of upland taxa (e.g., Orchidaceae and Trilliaceae) and in cultivated Gramineae, reflects human impact on the vegetation.

6.3. Climate change during the last deglaciation

Excluding the potential change of allochthonous pollen content influenced by sedimentary environment evolution, we can get the information of climate change during the last deglaciation, which is shown in Fig. 9. The coarse sediment of channel fill at the bottom of core ND-1 does not easily catch pollen until the sedimentary environment changed into floodplain after 14.5 cal. kyr BP. Because sediments of floodplain and lagoon mainly come from intermittently river-transported material, we supposed that the allochthonous pollen are similarly transported by river to a large degree. Thus, a cooler climate than at present is shown by the fact that there are higher contents of temperate taxa during 14.5–11.6 cal. kyr BP than at present under similar floodplain environment.

One sample from crevasse splay sediments at 47.0 m with highest content of *Artemisia* strongly reflects the vegetations on natural levees. However, two other sam-

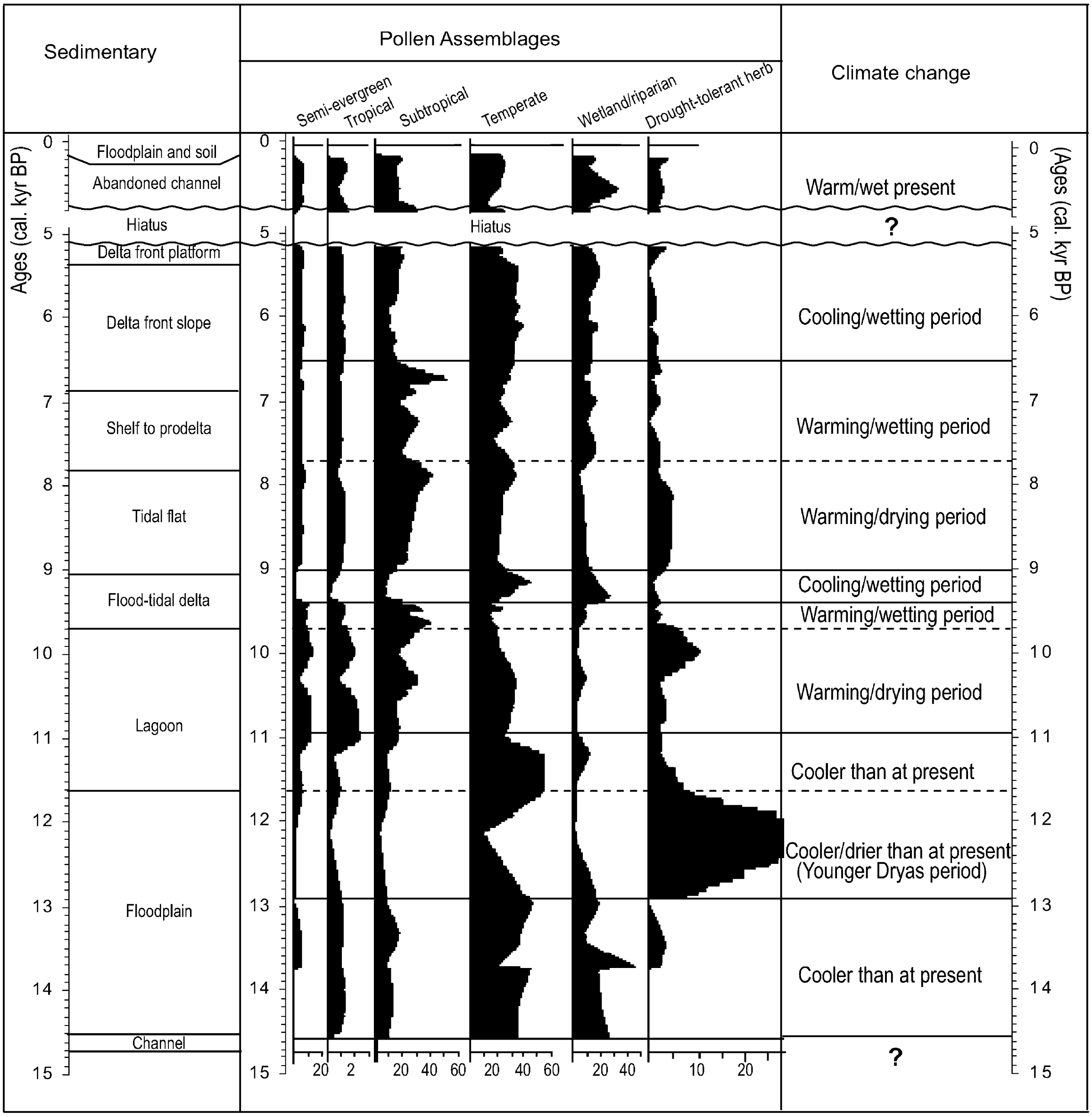


Fig. 9. Age-controlled climate change inferred from pollen assemblages comparing with the sedimentary environment evolution. The vertical dotted line in the column of sedimentary environment evolution indicate the present condition of allochthonous pollen transported by river, − and + mean less and more abundance than at present, respectively. The relative magnitude of the difference is shown by the offset of the heavy black lines.

ples at 45.0 and 49.9 m where abundant *Artemisia* possibly indicates a widely developed grassland under a drier and cooler condition than at present since the age correlates with the Younger Dryas period, 12.9–11.6 cal. kyr BP. The brief Younger Dryas event exerted a severe impact on the natural environment in the circum-North Atlantic region and has also been reported in other parts of the world as well (Broecker, 1994). In this period, the climate in the region of the Asian monsoon deteriorated owing to the strengthening of the winter monsoon and the weakening of the summer monsoon, as indicated by records in both marine and continental sediments (Figs. 10 and 11). We compared our result (Fig. 10, site H) with other records from the Southeast Asia region, including those from sea level change, oxygen isotope proxy data, pollen, and sea-surface temperatures recorded in cores from the South China Sea and the Sulu Sea. The cooling stage clearly occurred between about 12.9 and 11.7 cal. kyr BP in these regions (Sun and Li, 1999; Wang et al., 1999; Steinke and Kienast, 2001; Kiefer and Kienast, 2005). During this period, the water content of lakes was low (Fig. 11, site I) (Mingram et al., 2004), a cool climate reflected both by pollen assemblages with abundant *Alnus* and low values of total organic carbon values in sediment (Fig. 11, site J) is recorded (Zhou et al., 2004), and drought-tolerant grasslands were possibly widely developed in delta plains as indicated from our research (Fig. 11, site H).

In the East Asian area, Nakagawa et al. (2003) reported that the Younger Dryas dated to 12.3–11.25 cal. kyr BP in Japan, postdating the North Atlantic event by a few centuries, and suggested that there must be a mechanism to slow the transmission of the effects of oceanic forcing from the North Atlantic to the Northwest Pacific. They attributed the reduced amplitude of the climatic shift in Japan to a rather peripheral water body connected to the Pacific Ocean. However,

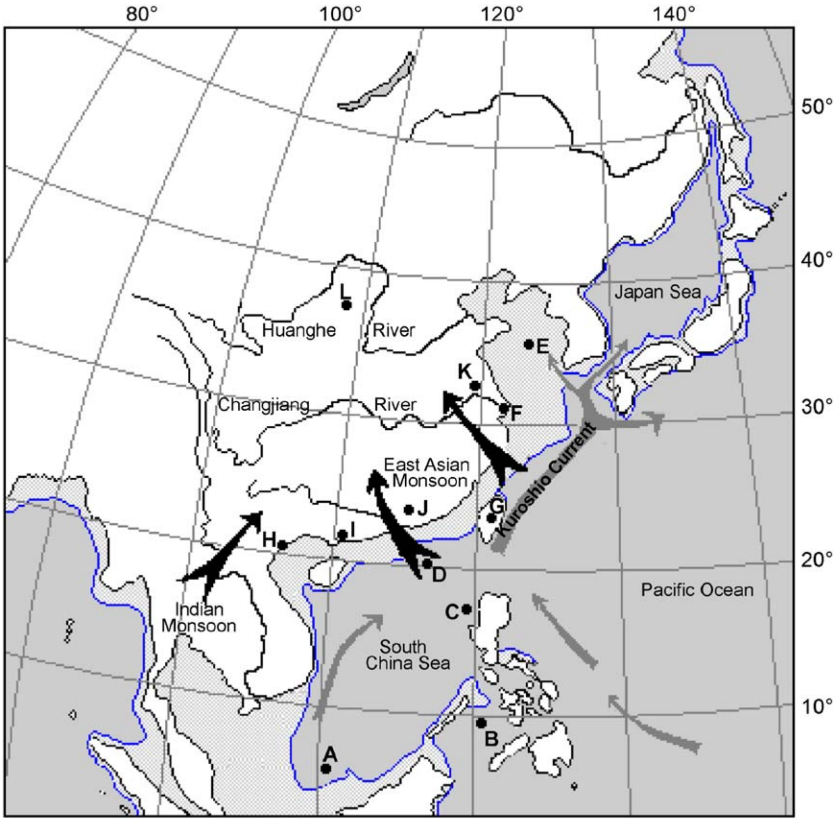


Fig. 10. Schematic map of the main Asian monsoons and currents with the locations of the core sites mentioned in comparing discussion on Younger Dryas cooling event (modified from Wang et al., 1999; Kim and Kucera, 2000; Kawahata and Ohshima, 2004; Mingram et al., 2004). A. Core 18287-3, South China Sea (Steinke and Kienast, 2001), B. MD97-2141, Sulu Sea (Kiefer and Kienast, 2005), C. Core17927-2, South China Sea (Wang et al., 1999), D. Core 17940, South China Sea (Sun and Li, 1999), E. CC02, Yellow Sea (Kim and Kucera, 2000), F. CM97, Changjiang delta (Yi et al., 2003), G. Toushe Lake, Taiwan (Huang et al., 1997), H. ND-1, Song Hong delta, Vietnam, I. Huguang Maar Lake D/F, South China (Mingram et al., 2004), J. Dahu Swamp, South China (Zhou et al., 2004), K. Hulu Cave (Wang et al., 2001), L. Midiwan (Zhou et al., 1999).

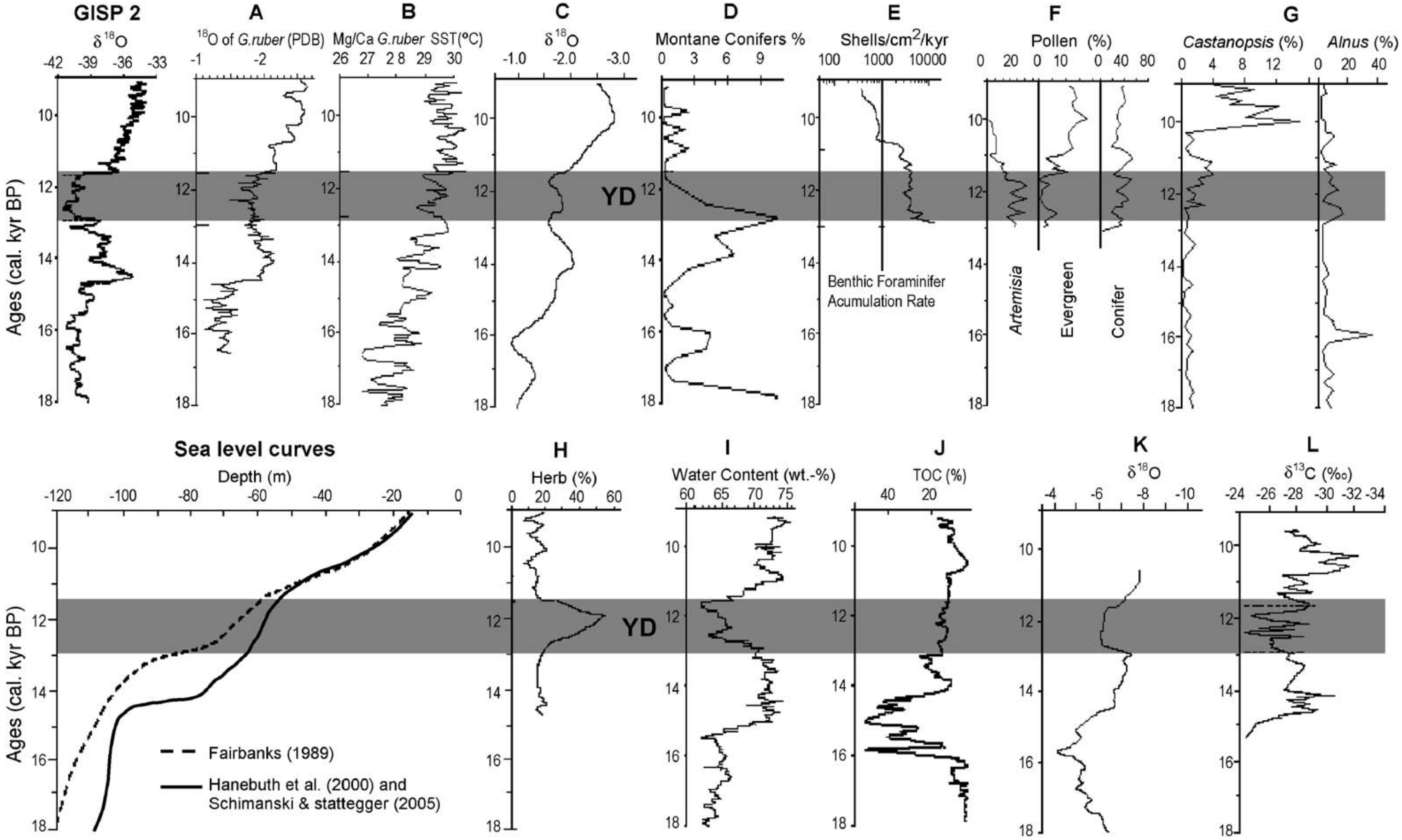


Fig. 11. Comparison on Younger Dryas cooling event recorded on the different sites in Asian monsoon areas and the sea level changes. YD: the Younger Dryas event. The time limit shown by ^{18}O proxy for GISP 2 ice core in Greenland (Stuiver et al., 1995) is regard as the ages of the onset and the end of Younger Dryas cooling event (12.9–11.6 cal. kyr BP). Sea level curves are from Fairbanks (1989), Hanebuth et al. (2000) and Schimanski and Stattegger (2005). A. Core 18287-3, South China Sea (Steinke and Kienast, 2001), B. MD97-2141, Sulu Sea (Kiefer and Kienast, 2005), C. Core17927-2, South China Sea (Wang et al., 1999), D.Core 17940, South China Sea (Sun and Li, 1999), E. CC02, Yellow Sea (Kim and Kucera, 2000), F. CM97, Changjiang delta (Yi et al., 2003), G. Toushe Lake, Taiwan (Huang et al., 1997), H. ND-1, Song Hong delta, Vietnam I. Huguang Maar Lake D/F, South China (Mingram et al., 2004), J. Dahu Swamp, South China (Zhou et al., 2004), K. Hulu Cave stalagmites (Wang et al., 2001), L. Midiwan (Zhou et al., 1999).

in the southwest to Japan, many more results both from marine and terrestrial sites show coherence with the North Atlantic data. For example, a southward migration of the cold Oyashio Current took place between 12.85 and 11.72 cal. yr BP (Chinzei et al., 1987); the Kuroshio Current began to reenter the Okinawa Trough at about 13 cal. yr BP (Ujiie et al., 2003); a high benthic foraminifer accumulation rate has been reported in the Yellow Sea during 12.9–11.75 cal. kyr BP (Fig. 11, site E) (Kim and Kucera, 2000); abundant *Artemisia* and coniferous taxa were present in the Changjiang delta during 13.0–11.7 cal. kyr BP (Fig. 11, site F) (Yi et al., 2003; Yi and Saito, 2004); cool-adapted vegetation, less *Castanopsis* and abundant *Alnus*, prevailed in central Taiwan (Fig. 11, site G) (Huang et al., 1997); and low δ^{18}O values are recorded in Hulu Cave stalagmites (Fig. 11, site K) (Wang et al., 2001). At the same time, a short climate oscillation has been also found in pollen data from the desert–loess transition belt of central China, for example, from Midiwan (Fig. 11, site L) (Zhou et al., 1996). This period corresponding with the Younger Dryas was not everywhere marked by a shift to continuous cold–dry conditions. The arid–semi-arid transition belt of China experienced a humid spell with strengthened summer monsoon conditions and an increase in precipitation, although the climate remained generally cold, correlated with a strong winter monsoon mainly controlled by orbital forcing (Zhou et al., 1996).

These comparisons confirm that the global climatic boundary conditions are probably the driving forces of East Asian monsoon variations. The reduction in solar insolation and the depression of the Asian continental snowline during the glacial period may have both increased the winter atmospheric pressure gradient, thus strengthening the winter monsoon, and decreased the summer atmospheric pressure gradient to weaken the summer monsoon (Huang et al., 1997). The consistent timings of the Younger Dryas and other phenomena widely recognized from tropical to temperate regions in Southeast and East Asia reviewed in our research indicate that the Asian monsoon and ocean environments are linked and were strongly influenced by the Younger Dryas event.

Following the Younger Dryas, slightly warmer and wetter conditions are demonstrated by the rapid increase in hardwood taxa and wetland herbs, corresponding to an increase in Asian monsoon precipitation (Morrill et al., 2003). After 10.9 cal. kyr BP, *Castanopsis* (*Lithocarpus*) and *Elaeocarpus* began to occupy relative high percentages, along with the semi-evergreen and tropical taxa dominated by increasing amounts of Datiscaceae, *Ficus* and Piperaceae, whereas the sedimentary environment remained unchanged. This pollen assemblage, even in this flood–tidal delta environment which is influenced by strengthened river transport, indicates a warming period during 10.9–9.4 cal. kyr BP. However, the vegetation was apparently very unstable, as indicated by frequent fluctuations of the composition of the pollen assemblage. The deciduous tropical taxa such as Datiscaceae and *Ficus* may indicate enhanced seasonality. At the beginning of the period, drought-tolerant herbs consisting mainly of *Artemisia* and *Chenopodium* began to decrease, but later they again rapidly increased. The low percentage of wetland/riparian taxa suggests dry conditions, although aquatic taxa such as *Acorus*, *Alocasia*, *Concentricytes*, *Myriophyllum* and Typhaceae increase. After 9.7 cal. kyr BP, *Artemisia* occurs only in small amounts and *Chenopodium* disappears, whereas the wetland/riparian taxa continue to increase. These characteristics indicate more humid conditions than before.

The period of 9.4–9.0 cal. kyr BP is characterized by another increase in temperate taxa, dominated by *Quercus* and coniferous species belonging to *Cryptomeria* and Taxodiaceae, as well as *Pinus*, *Castanea* and *Alnus*. In contrast, the tropical and subtropical taxa adapted to warm conditions such as *Castanopsis* (*Lithocarpus*) and *Elaeocarpus* become less abundant. Even semi-evergreen trees occur only sparsely. This change indicates a cooling period since the sedimentary environment kept unchanged as a flood–tidal delta.

During 9.0–6.5 cal. kyr BP, the pollen assemblages are mainly composed of *Castanopsis* (*Lithocarpus*), *Ficus*, Piperaceae and Datiscaceae, whose mother plants grow well in warm tropical and subtropical environments, as well as some *Dacrydium*, *Taxotrophis*, *Clausena*, *Trachycarpus*, *Elaeocarpus*, *Helicia* and *Allomorphia*, even in the delta sedimentary environment where the sediment almost completely derives from the river as allochthonous pollen. Thus, it is obviously a warm period, possibly corresponding to the climatic Optimum which has been widely reported in many studies (Hodell et al., 1991; Bush et al., 1992; Thompson et al., 1995; Islebe et al., 1996; Duplessy et al., 2001).

The content of allochthonous pollen is assumed to be unchanged since under the same delta sedimentary environment during the period 6.5–5.2 cal. kyr BP. However, the pollen assemblages are composed mainly of taxa of temperate broad-leaved trees such as *Quercus*, *Castanea* and *Rhus*, along with common *Castanopsis* (*Lithocarpus*), *Elaeocarpus*, *Helicia* and *Ficus*. The increase in coniferous trees belonging to *Cryptomeria*, Taxodiaceae and *Pinus*, along with the temperate broad-leaved trees such as *Alnus* and *Juglans*, distinctly shows a cooling climate. After a sediment hiatus, the present climate with a warm and wet character is shown during the period of 0.76–0 cal. kyr BP.

7. Conclusions

Pollen preserved in the delta area is possibly influenced by both climate change and the sedimentary environment evolution within river drainage area. Thus, it is necessary to distinguish the climate factor on pollen assemblages from sedimentary environment factor. The identified pollen in core ND-1 from the Song Hong delta is dominated by *Castanopsis* (*Lithocarpus*), *Elaeocarpus*, *Ficus*, Piperaceae and *Quercus*. High percentages of temperate taxa including conifers of *Dacrydium*, *Podocarpus*, *Pinus*, Cupressaceae, Txodiaceae and *Cryptomeria*, and some broad-leaved components of *Carpinus*, *Alnus*, *Juglans*, *Carya*, *Ulmus*, *Fagus*, *Ilex*, *Castanea*, *Quercus*, which mainly occur at high altitudes, is possibly associated with an altitudinal decline in the montane vegetation boundary. However, intensified river influence can also result in temperate group (allochthonous taxa) increase. After analyzing the magnitude of river influence on pollen assemblages during the sedimentary environment evolution, we extracted the climate information and used it to reconstruct climate change. A cooler climate during 14.5–10.9 cal. kyr BP than at present is indicated by a higher percentage of temperate types than at present under a similar river influence on floodplain as well as lagoon environment. A cooling event in the study area is recognized by abundant *Artemisia* associated with widely developed grasslands between 12.9 and 11.6 cal. kyr BP. This period corresponds to that of the Younger Dryas that has been reported from both terrestrial and marine records in regions influenced by the East Asian monsoon. After a warming period about 10.9–9.4 cal. kyr BP, a cooling period 9.4–9.0 cal. kyr BP is indicated by temperate taxa increasing without obvious river influence change in flood–tidal delta and tidal flat environments. Following a warming period 9.0–6.5 cal. kyr BP, which was shown by the tropical and subtropical taxa increasing even under intensified river influence, a cooling period, 6.5–5.2 cal. kyr BP, is indicated by the increase of temperate pollen such as *Cryptomeria*, *Alnus*, *Quercus*, and *Castanea*.

Acknowledgments

We thank Dr. S. Yi and Prof. K. F. Wang for critical and constructive comments. Prof. Y. L. Zhang, Dr. T. Saito, and Dr. H. Y. Lu are acknowledged for suggestions and corrections to the various plates and standard slides of modern pollen. Thanks are also due to Dr. Z. Y. Zhang, Dr. O. Abe, Mr. X. Q. Lu, and Mr. S. Lim for helpful suggestions on the manuscript. We also thank the editors and two reviewers for constructive comments on our manuscript.

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