Chinese Science Bulletin

ARTICLES

The records of coastline changes reflected by mangroves on the Sunda Shelf since the last 40 ka

WANG XiaoMei[1,2†], SUN XiangJun[3,2], WANG PinXian[2] & Karl Stattegger[4]

[1] Research Institute of Petroleum Exploration and Development, Beijing 100083, China;
[2] Key Laboratory of Marine Geology, Tongji University, Shanghai 200092, China;
[3] Institute of Botany, Chinese Academy of Sciences, Beijing 100093, China;
[4] Institute of Geosciences, University of Kiel, Olshausenstrasse 40, Kiel 24118, Germany

This paper presents a 40000-year-long high-resolution mangrove record from sediments of Core 18300, 18302 and 18323 on the continental shelf of the southern South China Sea and reconstructs the coastline changes on Sunda Shelf since the last 40000 years. In the period Marine Isotope 3, the old Sunda Shelf had low sea level, and it was partly exposed. Flourishing vegetations grew on the exposed old land. Mangroves developed along the coastline. On the Last Glacial Maximum, the sea level dropped greatly, coastline moved from inner shelf to outer shelf, the Old Sunda Land exposed further, and the lowering sea level induced the gradual disappearing of mangroves from the inner Sunda Shelf to the outer Sunda Shelf. And pioneer vegetation ferns covered the broadly exposed old land immediately. At the time of the last Deglaciation, sea level rose greatly, the coastline moved to the sea and the Sunda Shelf was drown again. Mangroves were emergent again from outer shelf to inner shelf and developed quickly.

Sunda Shelf, Mangroves, Marine Isotope 3, the Last Glacial Maximum, the Last Deglaciation

OCEANOLOGY

Sunda Shelf, also called "Great Asian Bank", the second largest continental shelf in the world, located in the southeast of semi-enclosed South China Sea. It is an important channel connecting the South China Sea and the Indian Ocean. During the Last Glacial Maximum, Borneo (up to 4101 m), Java (up to 3676 m) and Sumatra (up to 4101 m) were connected together to become the "Sunda Land"[1] (Figure 1) and it occupied 180 millions km^2, extends up to 800 km at its widest section, characterized by a very low gradient of 1∶9000, so a large quantity of terriclastics accumulated in this region both today and during the Last Glacial Maximum. Sunda Land, the most extensive land in the world beyond the polar region, was tectonically stable during the late Quaternary, the slopes of the shelf is small from the coast to the outer shelf, and a slight sea level change could cause a large shift of the shoreline and there were enough detrital material of terrigenous origin, especially the input of Old Sunda River, so large quantities of sediments were accumulated.

Sonne cruise 115 (December 1996—January 1997) got a lot of high resolution sedimental records along a transect across the Sunda Shelf covering the last 50000 years[2−7] and Hanebuth et al.[3] found the sea levels changed greatly since the last deglaciation, The reconstructions of the sea-level curves of global validity[8−12] also indicated there were several minor sea-level fluctuations during the past glacial cycle (Figure 1), but they do not resolve shorter variations and also show discrepancies of up to tens of meters during certain time intervals. So there are no detailed studies about the coastline

Received January 8, 2007; accepted May 23, 2007
doi: 10.1007/s11434-008-0278-5
†Corresponding author (email: chouxiaoya_77@yahoo.com.cn)
Supported by the National Key Basic Develop Research Program (Grant No. G2000078500)

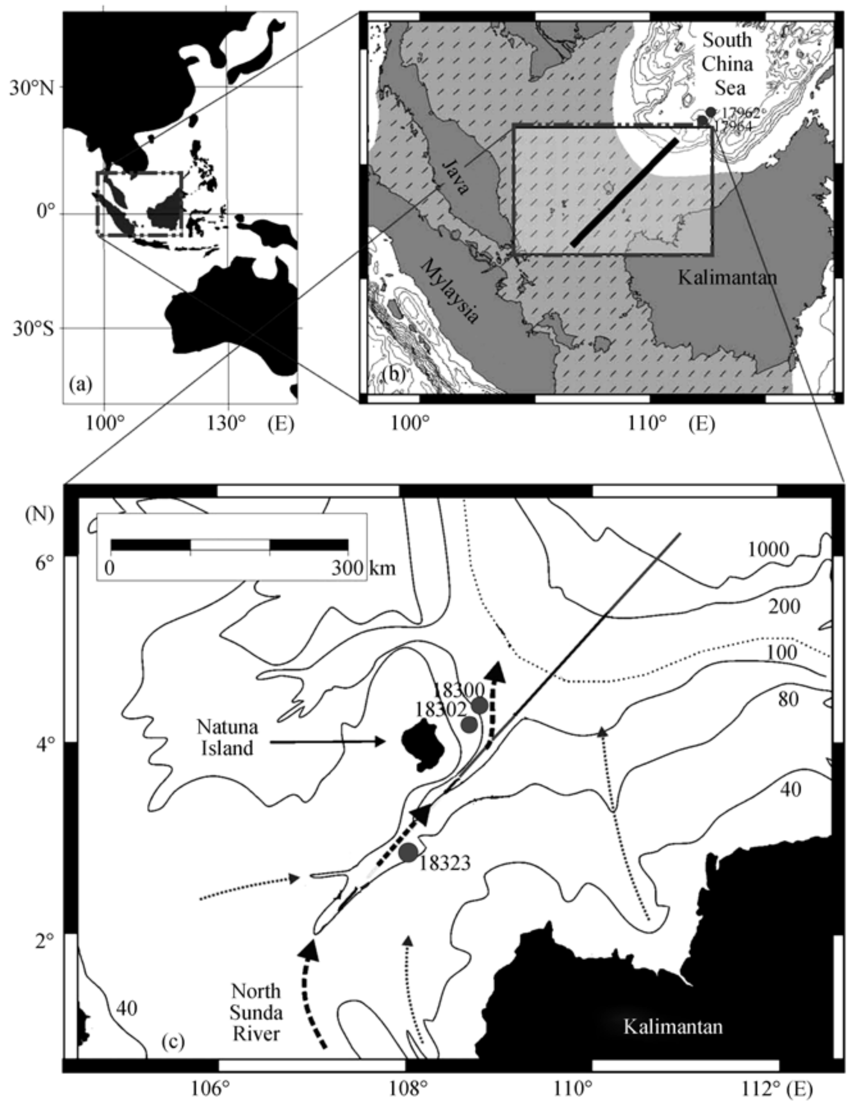

Figure 1 (a) The location of the studied area and cores; (b) SO115 transect on the Sunda Shelf (black line is the transect, grey refers to the exposed Sunda Land; (c) the locations of studied cores(Modified from Hanebuth et al.[7]).

changes since the Marine Isotope 3 in Sunda Shelf. Because mangroves most commonly found in the low energy coastline of tropical and subtropical area and periodically drown by sea water, it is a perfect indictor of coastline changes[13−18]. The main aim of this paper is to reveal coastline changes in the Sunda Shelf based on the high resolution mangroves records from the Sunda shelf.

1 Material and methods

The three sediment cores (Table 1; Figure 1), SONNE 18300(4°21′ N, 108°39′ E, 91m depth), 18302(4°09′ N, 108°34′ E, 83 m depth) and 18323 (2°47′ N, 107°53′ E, 92 m depth), discussed in this study were obtained during the R/V Sonne cruises 115 in December 1996－January 1997[2] along a transect following the paleo-valley of the North Sunda River and the bordering pa-

Table 1 The ages of the studied cores[a)]

Core number	Sample depth (cm)	Sampled material	AMS-^{14}C intercept (^{14}C a BP)
18300	60—62	Bulk, organic fibres	12440 ± 70
	206	Bulk, organic fibres	12650 ± 60
	400	Root	12580 ± 60
	590—592	Bulk, organic fibres	21490 ± 33
	879—881	Bulk, organic fibres	39210 ± 319
18302	85	Wood	11520 ± 55
	410	Peaty	12335 ± 60
	410	Arcoid bivalve	11660 ± 45
	590	Bulk, organic fibres	20160 ± 33
18323	190—192	Bulk, organic fibres	14180 ± 60
	380—382	Bulk, organic fibres	23460 ± 160
	534—536	Bulk, organic fibres	22810 ± 120

a) According to Hanebuth et al.[5]; Steinke et al.[19]

leo-river mouth down to the lower continental shelf. Each 10 mL in volume was collected at internals of 10 and 20 cm. All samples were prepared for pollen and spore analysis at Tongji University using hot hydrochloric and cold hydrofluoric acids to remove carbonates and silicates. Further to concentrate the pollen and spore, the material remaining after the acid reactions was washed through a 7 μm mesh in an ultrasonic basin bath. More than 200 pollen grains of land seed plants per sample were counted (excluding fern spores and pollen of aquatics). The pollen concentrations were calculated by the exotic pollen method (add 1 or 2 tablets of Lycopodium spores, and every tablets contains 10680 Lycopodium spores). The chronology is determined by AMS ^{14}C ages taken at the Leibniz-Laboratory.

2 Mangroves records in Palaeoecological sediments

The Mangroves in these three cores are mainly *Phizophora*, *Sonneratia* and a few *Bruguiera*.

2.1 Core 18300

The studied Station 18300 (7°11′ N, 112°5′ E) (Figure 1) located at the edge of entrenched valley. It was composed of different colors of mud and containing silt and organic layers (Table 2). From the 8.85 m core, 52 pollen samples were obtained at interval of 20 cm at 0—440 and 600—880 cm, 10 cm at 440—600 cm. The

Table 2 The lithology of Core 18300

Depth (cm)	Lithology
0—29	Grey mud containing silt
29—94	Calcareous deposit including slim organic layer
94—294	Dark grey mud with fractional wood
294—395	Organic mud
395—475	Olive grey mud
475—495	Gray green mud
495—795	Gray yellow mud
795—885	Gray green mud

(12650 ± 60) ^{14}C ka BP at 206 cm is improper according to the comparison results of pollen and spore of the studied three cores.

Marine Isotope Stage 3 (MIS 3) (8.8—6 m, about 39.2—22.1 ^{14}C ka BP) (Figure 2): Tree pollen is predominated (70%), in which, mangroves changed from 10% and 20%, Herbs, represented mainly by Cyperaceae and Poaceae, are 20%. Ferns spores (mainly *Cyathea* and *Gleichenia* and some trilete and monolete spores) occur in large numbers (40% of total pollen of land seed plants). The pollen concentrations are high in values. Last Glacial Maximum (LGM) (6—4.8 m; 22.1—16.3^{14}C ka BP): The differences are great compared to the last time. Tree pollen declined from 70% to 50%, in which, mangroves almost vanished completely. Herbs (mainly Poaceae) increased from 30% to 50%. Ferns exacerbated from 40% of land weed plants to 700%, and in which *Cyathea*, a kind of tropical tree ferns was the main element of ferns, and tree ferns inclines to live in a

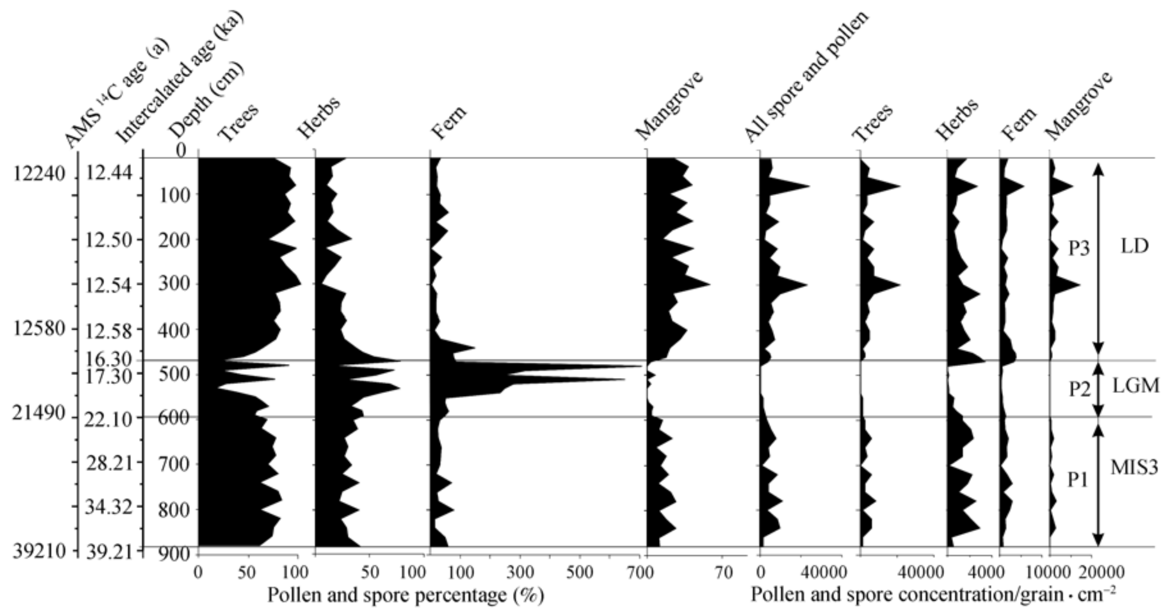

Figure 2 The pollen percentages and concentration of Tree, Herbs, Fern and Mangrove of Core 18300.

high humidity environment. The most striking characteristic is the prominently falling of pollen concentration. Last Deglaciation (of the last ice age) (LD) (4.8—0.4 m, 16.3—12.44 ^{14}C ka BP): Compared with the last time, trees declined to 70% from 50%, while herbs rose from 50% to 30%. Ferns decreased greatly to 60% of the land seed plant. In trees, mangrove rose remarkably to 40%—50% from lack of mangrove in the last time.

2.2 Core 18302

The studied Station 18302 (4°09′ N,108 °34′ E) (Figure 1) located at inner Sunda Shelf, From the 5.98 m core (Table 3), 41 pollen samples were obtained at interval of 20 cm at 0—400 cm and 10 cm at 400—598 cm. The ages at upper 85 cm is got by sedimental speed extrapolation. The age (11660±45) ^{14}C a BP at 410 cm got by Arcoid bivalve is too young, so abandon it.

Table 3 The lithology of Core 18302

Depth (cm)	Lithology
0—100	Grey arenaceous mud
100—296	Brown mud
296—400	Brown arenaceous mud
400—500	Brown mud containing organic material and lignite. There is disturbances at 430—433 and 445—450 cm
500—598	Mignonette mud

LGM (5.9—5.1m, about 20.16—16.3 ^{14}C ka BP) (Figure 3): Trees are dominanted at this time (50%—80%), and the percentage of herbs is 20%—50%. The content of mangroves increased gradually from bottom to top in this time. There were few mangroves from 20.16 to 18.1 ^{14}C ka BP, while from 18.1 to 16.3 ^{14}C ka BP the content of mangroves rose gently. And the content of fern changed greatly at this time, it is 400% of the content of land weed plants at the early time and declined to 100% at the later time. The pollen concentration was very low. The prominent characteristic of this time is there were some fresh water algae, Concentricystes, who incline to live in swamp and marsh environment. Early Last Deglaciation (of the last ice age) (5.1—4.1 m, about 16.3—12.4^{14}C ka BP): Trees increased and herbs decreased in this zone. Fern decreased greatly to 30% of the land seed plant from 100% of the last time. The most distinctly increased element in trees is mangrove, which increased greatly from 20% to 50%. The pollen concentration increased to several decades even several hundreds compared to LGM. Late Deglaciation (of the last ice age) (4.1—0 m, about 12.4—11^{14}C ka BP): There were no great changes compared to the early Last Deglaciation. Just the pollen concentration declined sharply to 1/10 of the last time.

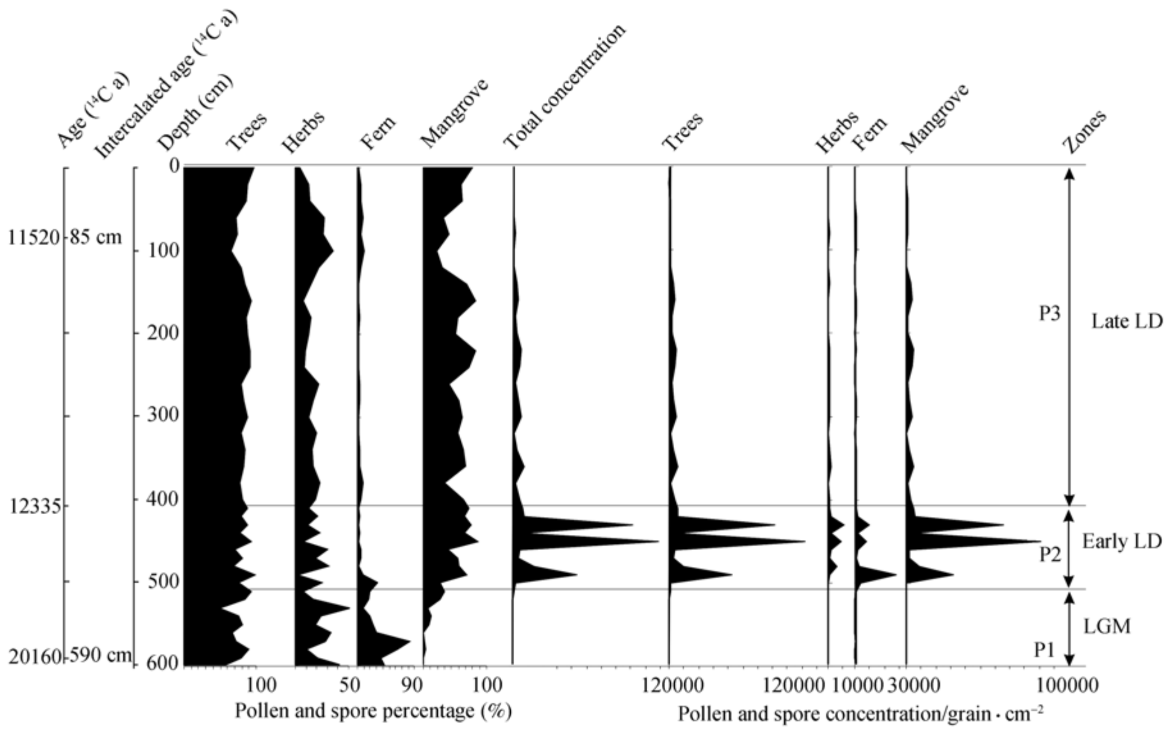

Figure 3 The pollen percentages and concentration of Tree, Herbs, Fern and Mangrove of Sonne 18302.

2.3 Core 18323

The studied Station 18323 (2°47′ N, 107°53′ E) (Figure 1) located at the inner Sunda Shelf, From the 5.4 m core (Table 4), 50 pollen samples were obtained. A soil horizon covered the top of the regressive deposits, so it was probably related to the land emergence during sea-level fall[20,21], which date from 20 to 23.5 ^{14}C ka BP[6], while at 380—382 cm, the deposits was soil, so the 22.81^{14}C ka BP at the depth of 534—536 cm is too young and abundant it. Just like Core 18302, the top age of this core is derived from extrapolations.

Table 4 The lithology of Core 18323

Depth (cm)	Lithology
0—197	Olive grey mud with organic and silt layers
197—397	Grey yellow mud with silt layers
397—540	Olive grey mud with silt layers

Marine Isotope Stage 3 (MIS 3) (5.4—3.8 m, about 31.27—23.46 ^{14}C ka BP): Tree pollen is predominated (exceed 80 %). Herbs (20% of the total trees and herbs pollen) chiefly comprised Cyperaceae and Poaceae. Ferns spores (mainly *Cyathea* and *Gleichenia* and many trilete and monolete spores) were 40 % of total pollen of land seed plants. In tree, mangrove occurred in very low content (just 8%). LGM (3.8—2.1 m, about 23.46—16.3 ^{14}C ka BP): The percentages of trees and herbs changed greatly, forming two peaks. But ferns (mainly *Cyathea*) occurred in large numbers in this time (150%—200% of the total land weed plants pollen). The most evident characteristic is that mangroves were almost completely disappeared. The pollen concentration reduced compared the last time. Early Deglaciation (2.1—1.1 m, 16.3—12.4 ^{14}C ka BP): All over this time, there were no big changes for the percentages of trees and herbs. Just in trees, mangroves rose to 30%. And the content of ferns fell to 40% of land weed plants. Late Deglaciation (1.1—0 m, 12.4 ^{14}C ka BP to Holocene): The only difference from early Deglaciation is the value of the pollen concentration, which reduced to 1/4 of the early Deglaciation.

3 Discussion

3.1 Marine Isotope 3 (MIS 3)

Deposits of the MIS 3 are preserved in two sediment cores, Core 18300 (39.2—22.1^{14}C ka BP) and Core 18323 (31.3—23.5^{14}C ka BP). In these two cores, pollen assemblages are quite similar in their composition and proportions, especially the similarity of the percentages and concentrations of mangroves and fern (Figures 2, 5, 4, 7). The abundant mangrove pollen and sediments of delta front in the two profiles from the continental shelf (18300 and 18323) indicates that they both should be located near the coast line.

According to the surface distribution of modern mangrove[20], we know the mangrove has high quantities near Borneo and declined towards the sea. The widely existence of mangroves in this area shows the living condition is the tropical and subtropical intertidal community and in some sense related to marine intertidal zones and periodically inundeated by the tides. But it was impossible, because the two profiles situated far away from each other, Core 18323 was in the inner shelf and Core 18300 in the outer shelf. So the reasonable explanation is that with dropping of the sea level, the inner shelf was already subaerially exposed and Core 18323 situated near the coastline, along which mangrove grow. But the outer shelf (from about sites 18323 to 18300) was still covered by shallow sea water. Core 18300 located in shallow and flat sea, at intertial zone. There was a small highland called Natuna Island which stood out of sea water. Along the small island mangroves survived, from which site 18300 received abundant mangrove pollen, although the site situated far away from the coastline of last glaciation (Figure 1). It is deduced that at that time only inner shelf were exposed from the sea water which was covered mainly by lowland rainforest. The lower montane rainforest seemed migrated from montane areas of the southern island down to the shelf and also became an important part of the glacial vegetation. The climate at that time should be cooler than the present day, but still very humid.

3.2 Last Glacial Maximum (LGM)

Pollen data of this period were obtained in all the 3 profiles (Core 18300, 18302 and 18323) from the shelf and all of them were swamp facies at this time.

Compared to MIS 3, the greatest changes are the content of mangroves, which declined to even diminish. Mangroves are now commonly found along the coast of the Malaysian Peninsula and adjacent islands, so the loss of mangrove indicates the receding of the coastline. The development of soil horizon, an important stratigraphic marker, formed on the top of the Regressive Unit[6], is

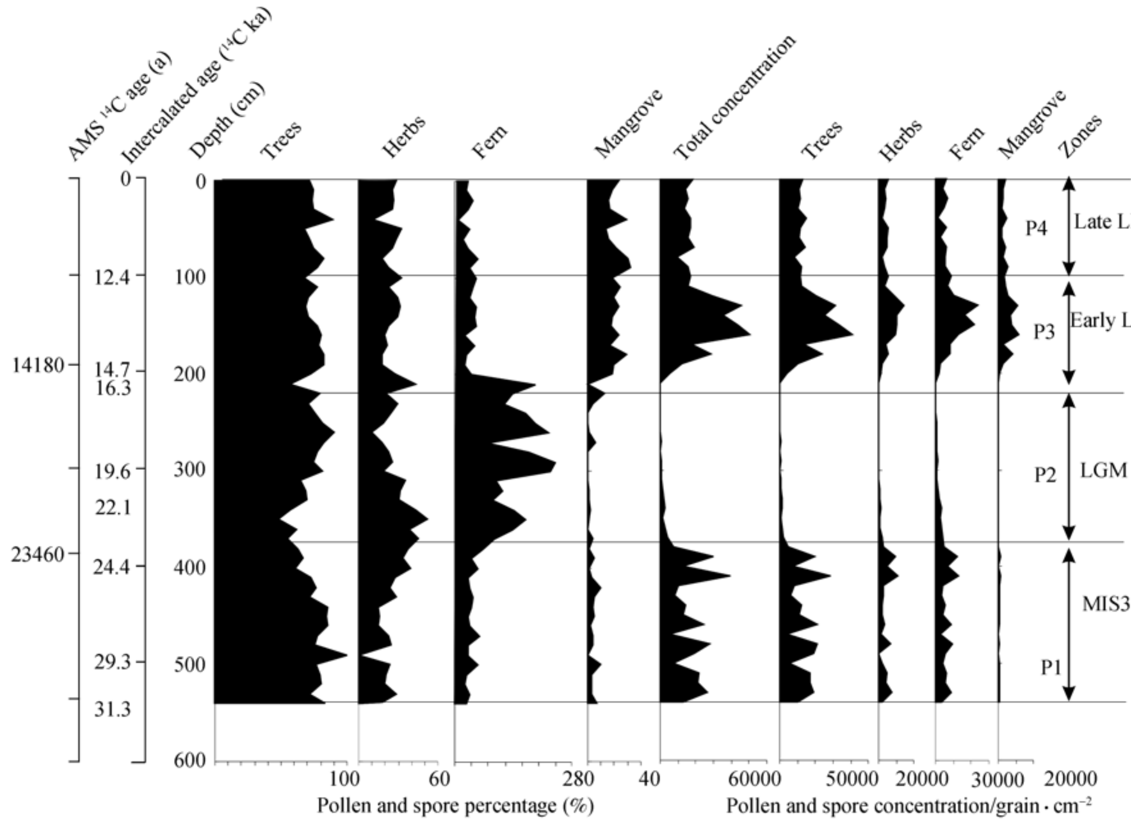

Figure 4 The pollen percentages and concentration of Tree, Herbs, Fern and Mangrove of Core 18323.

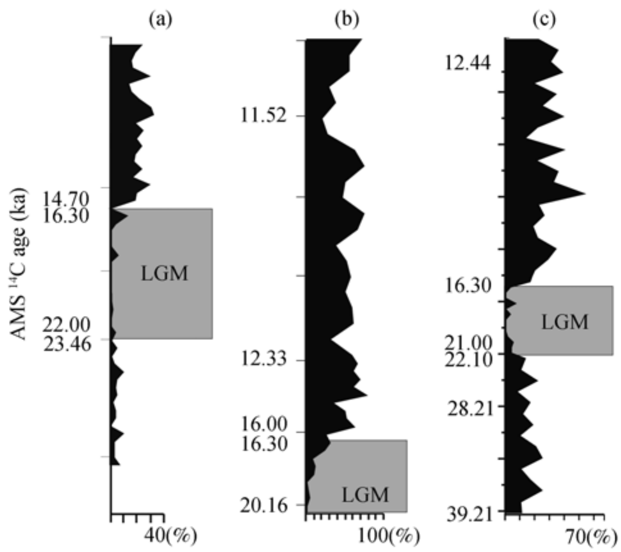

Figure 5 The percentages of mangroves at Sunda Shelf. (a) Dark grey shows LGM, light grey shows the disappearing time of mangroves.

also the proof of early land emergence during low sea-level in high glacial times. And foraminifers are completely lacking is also associated with land emergence[7]. This marshy soil facies covered an extent of the Sunda Shelf and adjacent regions[21,22], and incorporated parts of the underlying deposits. The low pollen concentration shows the pollen was transplanted to South China Sea through the Sunda River, and the high pollen influx in Core 17962 and 17964 in Sunda slope is the strong evidence[23,24].

From what cited above, we can speculate that during the LGM lowland rain forest and lower montane rainforest covered the exposed shelf and the upper montane rainforest periodically migrated down along the montane slopes of the southern islands. Along the North Sunda River developed marshy vegetation (plants of Cyperaceae and sedges etc.). Around these marshes distributed tree ferns (*Cyathea*) and palms etc. The climate deduced from the palaeovegetation should be cooler than the present day, but still humid. But the possibility of some declining precipitation was not excluded. Since the present climate is extremely humid, there could be a decrease in the total precipitation which the area receives, without necessarily being any recognizable effects on vegetation.

According to the disappearing time of mangroves, we can get the regressive processes of the coastline: Mangroves disappeared at 23^{14}C ka BP for Core 18323 (Figures 4, 5); while for Core 18302 mangroves disappeared at 20.16 ^{14}C ka BP (Figures 3, 5) and for Core 18300, mangroves disappeared at 21 ^{14}C ka BP (Figures 2, 5). So the coastline fell back to the place of the Core 18323 at 23 ^{14}C ka BP and to the place of the Core 18302 at 20.16^{14}C ka BP (Figure 7). Accompanying the great decreasing of mangroves, the content of fern increased greatly almost at the same time (Figure 6), which reflects a humid climate at that time.

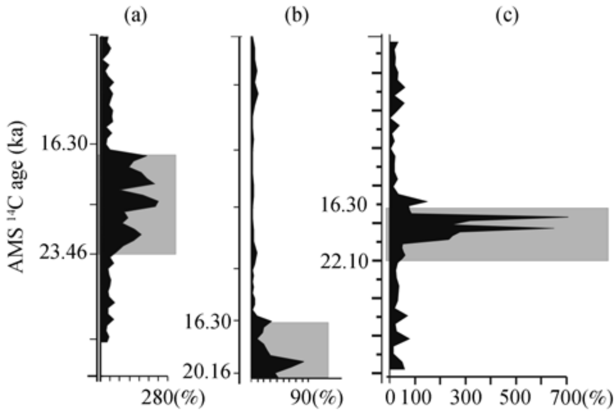

Figure 6 The diagram of the percentages of ferns in Sunda Shelf (dark grey shows LGM). (a) Core 18323; (b) Core 18302; (c) Core 18300.

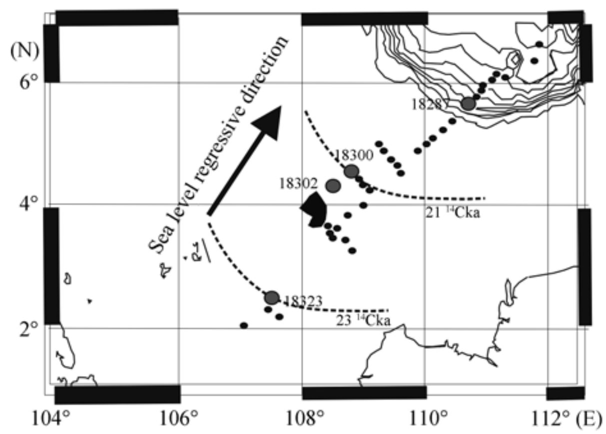

Figure 7 The sketch map of emergence time of the locations of the studied cores. Deduced from the disappearing time of mangroves at LGM; the black dots were the site of cores taken by Sonne 115; the black block is Natuna Island.

3.3 Last Deglaciation

During the Termination pollen records were discovered in all the three profiles and spanned from 16 ^{14}C ka BP to nearly Holocene. All profiles are very alike in pollen assemblages and are dominated by lowland rainforest and mangroves. The reappearing and quickly increasing of mangrove pollen upwards the profiles on the shelf indicate the raising of the sea level and submerging of the shelf. And the submergence of the shelf induced the living space of fern and herbs reduced. The emergence of dinoflagellae cyst, the increased content of water and decreased content of sand also confirmed the submergence of the Sunda Land[4]. And the sediment changed from land and sea facies to pure marine characteristics.

Based on the percentages of mangrove pollen in the three sites on the shelf, we deduced that the coastline reached to the site 18300 at 16.3 ^{14}C ka BP, then very quickly to the sites 18302 and 18313 at 16 ^{14}C ka BP and arrived to 18323 at ^{14}C ka BP (Figure 8).

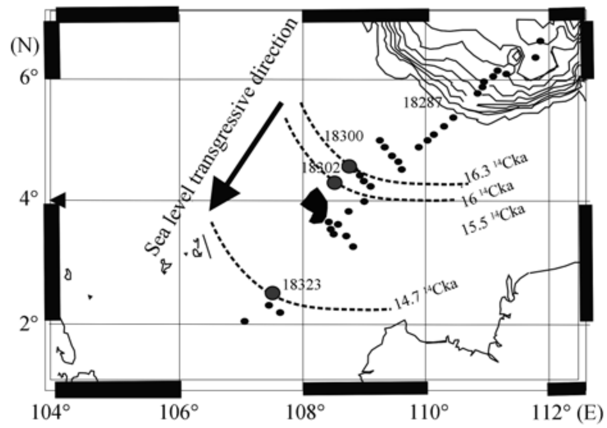

Figure 8 The sketch map of drown time of the locations of the studied cores. Deduced from the disappearing time of mangroves at deglaciation.

4 Conclusions

Through the high resolution mangrove records in the three cores in Sunda Shelf since the last 40 ka, we get the three conclusions:

(i) During the MIS 3, the sea level was low and Sunda Land was partly exposed. The emerged inner shelf was covered by lowland rainforest and low mountain forest. Mangroves grew along the coastline.

(ii) During the LGM, the mangroves gradually vanished from the shelf. The disappearance of mangrove shows the changes of shoreline from inner shelf to outer shelf and the emergence of Sunda Land. Fern grew on the exposed land.

(iii) In the last deglaciation, mangroves reappeared and subsequently developed swiftly in the shelf, indicating the shoreline move towards inner shelf again and the shelf is drowned again.

We thank Institute of Geosciences, University of Kiel for providing samples and Wu Guoxuan for his help in handling samples.

1 Tjia H D. The Sunda Shellf, Southeast Asia. Z Geomorph N E, 1980, 24(4): 405－427
2 Stattegger K, Kuhnt W, Wong H K, et al. Cruise Report SONNE115 "SUNDAFLUT". Sequence Stratigraphy, Late Pleistocene-Holocene Sea Level Fluctuations and High Resolution Record of the Post-Pleistocene Transgression on the Sunda Shelf. Berichte-Reports. Geologisch-Palaeontologisches Institut und Museum, Christian-Albrechts-Universitaet Kiel, 1997, 86: 1－211
3 Hanebuth T, Stattegger K, Grootes P M. Rapid flooding of the Sunda Shelf-a late-glacial sea-level record. Science, 2000, 288: 1033－1035[DOI]
4 Hanebuth T J J, Saito Y, Stattegger K. The stratigraphic architecture of the central Sunda Shelf (SE Asia) recorded by shallow-seismic surveying. Geo-Mar Lett, 2002, 22: 86－94[DOI]
5 Hanebuth T J J, Stattegger K. The stratigraphic evolution of the Sunda Shelf during the past fifty thousand years. In: Sidi F H, Nummedal D, Posamentier H W, et al, eds. Deltas of Southeast Asia and Vicinity-Sedimentol, Stratigra and Petroleum Geology. SEPM Special Publications, Tulsa, Oklahoma, 2003, 76: 189－200
6 Hanebuth T J J, Stattegger K, Schimanski A, et al. Late Pleistocene forced-regressive deposits on the Sunda Shelf (Southeast Asia). Mar Geol, 2003, 199: 139－157[DOI]
7 Hanebuth T J J, Stattegger K. Depositional sequences on a late leistocene-Holocene tropical siliciclastic shelf (Sunda Shelf, southeast Asia). J Asian Earth Sci, 2004, 23: 113－126[DOI]
8 Imbrie J, Hays J D, Martinson D G, et al. The orbital theory of Pleistocene climate: Support from a revised chronology of the marine $\delta^{18}O$ record. In: Berger A L, Imbrie J, Hays J D, et al, eds. Milankovich and Climate. (Part 1), Norwell, MA: Reidel Press, 1984. 269－305
9 Shackleton N J. Oxygen isotopes, ice volume and sea level. Quat Sci Rev, 1987, 6: 183－190
10 Bard E, Jouannic C, Hamelin B, et al. Pleistocene sea levels and tectonic uplift based on dating of corals from Sumba Island, Indonesia. Geophys Res Lett, 1996, 23: 1473－1476[DOI]
11 Chappell J, Omura A, Esat T, et al. Reconciliation of late Quaternary sea levels derived from coral terraces at Huon Peninsula with deep-sea oxygen isotope records. Earth Planet Sci Lett, 1996, 141: 227－236[DOI]
12 Chappell J. Sea level changes forced ice breakouts in the Last Glacial cycle: New results from coral terraces. Quat Sci Rev, 2002, 21: 1229－1240[DOI]
13 Zhang Q M, Sui Q Z, Zhang S Z, et al. Marine environmental indexes related to mangrove growth. Acta Ecol Sin, 2001, 21(9): 1427－1437
14 Fan H Q. The distribution of species of sessile defile animals of mangrove in Guangxi. Guang Xi Acad Sci Bull, Mangrove Paper Special, 1993
15 Tan X L, Zhang Q M. Mangrove Beaches' Accretion Rate and Effects of Relative Sea-Level Rise on Mangroves in China. Mar Sci Bull, 1997, 16(4): 29－35
16 Chen Y X. The environment ecological effect of Mangroves. Mar Environ Sci, 1995, 14(4): 51－56
17 Chen X Y, Lin P. Responses and roles of mangroves in China to global climate changes. Transactions Oceanol Limnol, 1999, 2: 11－17
18 Lu C Y, Lin P, Ye Y. Review on impact of global climate change on mangroves ecosystems and research countermeasure. Adv Earth Sci Rev, 1995, 10(4): 341－347
19 Steinke S. A high-resolution sea-surface temperature record from the tropical South China Sea (16500－3000 yr BP). Quat Res, 2001, 55: 352－362
20 Kawamura H. Marine palynological records in the southern South China Sea over the last 44 kyr. Dissertation for the Doctoral Degree. Kiel: Geologisch-Palaeontologisches Institut und Museum, Christian-Albrechts-Universitaet Kiel, 2002. 29－30
21 Biswas B. Quaternary changes in sea-level in the South China Sea. Geol Soc Malaysia Bull, 1973, 6: 229－256
22 Sinsakul, S. Late Quaternary geology of the Lower Central Plain, Thailand. J Asian Earth Sci, 2000, 18: 415－426[DOI]
23 Li X, Sun X J. Palynological records since last glacial maximum from a deep sea core in Southern South China Sea. Quat Sci, 1999, 6: 526－536
24 Sun X J, Li X, Luo Y L. Vegetation and Climate on the Sunda Shelf of the South China Sea During the Last Glaciation－Pollen Results from Station 17962. Acta Bot Sin, 2002, 44 (6): 746－752