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Résumé

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Hydrological History of the West Baray, Angkor, revealed through Palynological Analysis of Sediments from the West Mebon

En marge de ses spectaculaires monuments, Angkor, capitale du Cambodge ancien, se caractérise par un vaste réseau de canaux, de digues et de réservoirs. La fonction de cette infrastructure hydraulique et son rôle dans le déclin et l'abandon d'Angkor sont toujours sujets à débat. Cet article présente de nouvelles informations paléo-botaniques recueillies au Mebon occidental, un petit temple situé au centre du réservoir du Baray occidental. Le Mebon occidental est un endroit crucial pour saisir l'histoire hydraulique du Baray occidental et de son réseau de canaux et de digues qui recouvrent l'aire en amont, au nord et au nord-ouest. La connexion entre le Mebon et son Baray permet de considérer que le sédiment accumulé au Mebon a gardé la trace des plantes aquatiques qui s'y sont développées et de leur évolution en fonction des niveaux d'eau présents dans le Mebon, et donc dans le Baray. L'analyse palynologique indique une nette réduction du volume d'eau stocké dans le Baray occidental à partir de la fin du XIII^e siècle, reflétant peut-être un changement des techniques ou des capacités à stocker, à transporter et à utiliser l'eau. Que le Baray occidental ait eu des niveaux d'eau bas depuis le début du XIII^e jusqu'à la fin du XVI^e siècle présente des implications importantes pour le débat sur la fonction des grands Baray en particulier, et sur la Cité Hydraulique en général.

Abstract

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Hydrological History of the West Baray, Angkor, revealed through Palynological Analysis of Sediments from the West Mebon

In addition to its extraordinary monuments, the medieval Cambodian capital of Angkor is characterised by an extensive network of canals, embankments and reservoirs. The operation of this water management infrastructure, and its role in the demise and eventual abandonment of Angkor, is a topic of persistent debate. This paper presents new palaeo-botanical information from the West Mebon, a small water temple located within the West Baray reservoir. The West Mebon is a vital location in understanding the hydraulic history of the West Baray and the enormous web of canals and embankments that form its catchment to the north and northwest. Hydraulic connection between the Mebon and the surrounding baray means that the accumulated sediment within the Mebon preserves an archive of plant response to changing water levels within the Mebon, which acts as a proxy for water levels within the baray. Palynological analysis indicates a dramatic reduction in the volume of water brought into storage in the West Baray from the late 12th century, perhaps reflecting a change in the techniques or the capacity to store and transport water. The fact that the West Baray appears to have had low or minimal water levels for much of the period from the 13th to the late 16th century has important implications for the debate surrounding the purpose of the great barays.

Hydrological History of the West Baray, Angkor, revealed through Palynological Analysis of Sediments from the West Mebon

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Introduction

In 1979 B.Ph. Groslier recast Angkor as “*la cité hydraulique*”, recognising the important role of the network of canals, embankments and reservoirs in both the operation of the medieval Cambodian capital and its eventual demise as the seat of power. Recent mapping of the southern (Pottier, 1999) and northern (Evans, 2002) zones of Angkor has revealed, for the first time, the full aerial extent of the water management infrastructure, revealing it to be both massive and convoluted, covering an area of around 1,000 km² (Fletcher et al, 2003; Fig. 1). Indeed, the water management infrastructure is, arguably, Angkor’s defining characteristic. The function of the water management network, and its role in the demise and collapse of Angkor have been matters of persistent academic debate (Groslier, 1974; 1979; van Liere, 1980; Dumarçay, 1994; Bernon, 1997; Acker, 1998; Pottier, 2000a; Lustig, 2001; Fletcher *et al*, 2003). The history of the water management system, is thus potentially instructive as to the operation of the city itself.

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However, the corpus of epigraphic texts reveals little of the history of the water management infrastructure, or the changing priorities of the administration under successive kings in terms of water management (Jacques, 2001). Similarly, the stratigraphy and archaeology of the canals and embankments is only now being systematically investigated (Fletcher *et al.*, 2003).

The great reservoirs (*barays*) themselves record little evidence of the changing flux of water and sediment. Radiocarbon dating of sediment cores from the East Baray (Tsukawaki *et al.*, 1998) returned ages ranging from 2540 ± 110 ^{14}C yrs BP (160-180 cm below datum) to 11000 ± 200 ^{14}C yrs BP (260-280 cm below datum). Linear age interpolation from the uppermost age to the top of the stratigraphy suggests a net sedimentation of approximately 43 cm since the reservoir was built in the late 9th century AD. Recent excavations at the prehistoric site of Koh Ta Méas, some 1,300 m due west of the West Mebon within the West Baray, have demonstrated that the overlying *baray* sediment is no more than 30 cm thick in that part of the reservoir, suggesting that sedimentation played no role in reducing the capacity of the West Baray (Pottier *et al.*, 2004a, pp. 178-179). One consequence of this low net sedimentation within the great *barays* is that stratigraphic records of sediment accumulation, which are instructive as to the operation of the *barays* and the network of canals that function as their catchments, are difficult to resolve in sufficient detail, and are often highly disturbed by modern land use.

However, the West Mebon temple (Fig. 2 and 3), located in the centre of the West Baray, offers a unique opportunity to obtain a proxy record of water levels within the *barays* during Angkorian times. The precise permeability of the enclosure walls of the Mebon, which are presumed to be in keeping with Angkorian practice observed elsewhere and thus composed of sandstone and laterite capping a sand core, is unknown. However, even with relatively slow percolation of water through the walls and foundations of the Mebon, the water levels within the small basin enclosed by the West Mebon temple would be generally indicative of water levels within the West Baray, which is in turn sensitive to the operation of its catchment. Water levels in the Mebon determine the abundance and species composition of aquatic plant communities that grow within the basin. The changing composition of the aquatic flora is reflected by the contemporary sediment that accumulates within the basin, and in the assemblage of microscopic plant fossils (pollen, spores, algae and other plant microfossils) that are deposited in the sediment. It is possible, therefore, to exploit the record of changing water levels in the West Mebon basin to reconstruct the history of a large portion of Angkor's water management infrastructure.

Site description

The West Mebon temple is built on an artificial island in the centre of the West Baray reservoir. It is a square enclosure, approximately 100 m long on each side, and bounded by stone-covered embankments that support a sandstone wall, in turn punctuated by three towers on each side. A raised walkway 40 m long and 4.5 m

wide leads from the central tower on the eastern wall to a central platform measuring 9.65 m E-W and 8.65 m N-S (Glaize, 1944). Two stone-lined pits are located within this platform. It was in the westernmost of these two pits that the famous bronze statue of a reclining Vishnu was discovered (Glaize, December 1936). The top of the causeway and the surface of the central platform are approximately 1.5 m lower than the top of the enclosing embankment.

Dumarçay (1982; 2003, p. 52) suggested that the pits in the central platform of the Mebon were used to quantify the water level in the *baray*, although the mechanism for doing so has not been described precisely, nor discovered through excavation. The western pit is understood to be a well in the shape of an inverted linga which may have had an important symbolic function. In the bottom of the eastern pit a sacred deposit comprising a large ornate gold leaf, two smaller gold leaves, one amethyst crystal and two copper tubes was discovered in May 1944 (Glaize, 1944). However, research conducted by the joint Greater Angkor Project team (APSARA Department of Monuments and Archaeology, École Française d'Extrême-Orient and University of Sydney) in June 2005 indicates that the eastern pit is a later addition, comprising re-used blocks from the original enclosure wall and/or pavilions, and partially altering the masonry of the original structure in the western pit. The relationship of these alterations to the placement and burial of large pieces of the giant reclining Vishnu and the possible addition of the causeway has yet to be resolved.

The exact date of construction of the West Mebon is unknown but the style of the temple is suggestive of the middle to late 11th century (Baphuon style) (Glaize, 1963, pp. 274-275). An inscription in Sanskrit and Khmer (K922) was found at the site by Glaize in 1944. It appears to be a re-used pre-Angkorian text, poorly preserved and incomplete (Cœdès, 1954, p.71), and is of no value in dating the temple. Similarly, the age of the West Baray, with which the Mebon temple is assumed to be coeval, is not precisely known. It obviously post-dates the inscription K752 (1001-1002 AD), discovered in one of the small sanctuaries on the temple pyramid of Ak Yum, which was buried by the southern dyke of the West Baray during its construction (Cœdès 1953, p.59). However, in the absence of any later epigraphic reference – which also explains why it is the only *baray* in Angkor whose original name is still unknown - the West Baray is commonly and generally believed to be a mid-11th century construction, although Dumarçay suggested it may have been initiated by Suryavarman I and completed around 1015-1020 AD (Dumarçay, 1994, p. 377; 1998, p. 3).

Environmental setting and hydrology

The climate in the study area is monsoonal. The wet southwest monsoon is active from May to October, bringing on average approximately 88% of the annual rainfall (Kummu, 2003). The dry northeast monsoon normally begins in November and continues until April. Average annual rainfall in the main temple area is approximately 1,425 mm (Kummu, 2003). Ground water is easily accessible, and

fluctuates between depths of 0 and 5 m during the wet and dry season respectively (JSA 2002: p.301).

Since the 1940s the West Baray has been fed by water from Siem Reap River, and by rainfall. The water is diverted from the river immediately north-west of the East Baray and flows to the west along a modern channel that flows in the northern and north-western moat of the walled city of Angkor Thom before being redirected into the West Baray at its north-east corner. The water from the *baray* is partly used for irrigation purposes, controlled by another modern dam situated in the southern wall of the *baray*.

Water levels within the West Baray reflect the seasonal distribution of rainfall. Average monthly water levels within the West Baray fluctuate over a 3 m range between the average dry season minimum in May (a volume of approximately 15.38 million m³) and the average wet season maximum in November (approximately 49.19 million m³; Fig. 5a and 5b). These average monthly values mask the true variation in water levels and volumes, which can be up to 5.7 m in amplitude, a range in volume of 1.8–56.93 million m³. The net annual rainfall contribution to the West Baray's volume is approximately 7.7 million m³, or 16% of the average monthly wet season peak volume. Water levels within the West Baray are therefore predominantly controlled by the volume of discharge from its catchment, which currently covers a minimum area of approximately 240 km² and incorporates both natural channels and Angkorian canals, embankments and storages.

Water levels within the basin of the West Mebon temple appear to be slightly buffered from the variation apparent in the surrounding West Baray. Water is known to persist within the Mebon even in particularly dry seasons when the surrounding *baray* is dry (Fig. 3). This may be due to the mitigating influence of the floating vegetation mat on evaporative loss from the basin, or may indicate that the bed of the Mebon basin is slightly lower than the bed of the *baray*. Photographs taken in 1936 (Fig. 4), when the West Baray was dry, indicate that the Mebon basin remained clearly wet in parts.

Vegetation in the area is highly disturbed following millennia of land use. A small area of climax secondary semi-evergreen forest occurs to the east of the West Baray, within the bounds of the World Heritage park (Ashwell, 1993). *Barringtonia acutangula/Diospyros cambodiana* dominated swamp forest ('flooded forest') communities occur to the south as a fringe along the lakeward margin of the Tonle Sap lake floodplain (McDonald *et al.*, 1997). The landscape surrounding the West Baray is covered with both modern and remnant Angkorian-period bunded rice fields (Pottier, 1999). Currently, those parts of the bed of the West Baray exposed during the dry season are also used for rice and for cattle grazing. At present, the West Mebon basin itself is entirely overgrown by a thick fibrous mat of floating vegetation, characterised in particular by grasses and ferns. This mat rises and falls with the seasonal change in water levels in the West Baray.

Methods

A sediment core was collected in June 2004, west and slightly south of the central platform (Fig. 2), using a Kullenburg-type corer (Glew et al. 2001) operated from a floating platform. The full sedimentary sequence was not recovered, as the fibrous mat of vegetation floating above the sediment had to be removed by hand in order to allow the penetration of the core barrel. Cores were recovered using a hand-operated winch, and cut longitudinally to expose the stratigraphy. The organic content of the sediment was determined following Dean (1974; Loss-on-ignition – hereafter LOI – by combustion at 550°C for two hours). Sporopollenin was extracted from three samples (depths of 4-5 cm, 15-16 cm and 27-28 cm) using the procedure described by Brown et al. (1992) and sent for high-precision small-sample radiocarbon dating at the ANTARES facility (Fink et al, 2004; Zoppi et al, 2004; Hua et al, 2001). Radiocarbon dates were calibrated (Stuiver & Reimer, 1993, version 5.0) using the IntCal04 curve (Reimer et al, 2004).

Samples for pollen analysis were prepared following Berglund & Ralska-Jasiewiczowa (1986), and analysed using light microscopy at 400-1,000 x magnification. Absolute concentrations of palynomorphs and microscopic charcoal particles in the treated samples were calculated following Stockmarr (1971). Pollen and spore types were identified primarily by comparison with a reference collection, or by consultation with various morphological works (Tsukada, 1965; Huang, 1972, 1981; Raj & Saxena, 1966; Zhang et al, 1990; Maury et al, 1975). Terminology follows Punt et al. (1994). Pollen and spore data were classified as proportions, stratigraphically constrained, using Euclidean distance as the measure of dissimilarity (Grimm, 1987) in order to identify key boundaries in the sequence. Algae were identified by comparison with Yamagishi & Hirano (1973) and Baker & Fabbro (1999).

Results

Sedimentology and Chronology

Core WM/06/04/A is 68.2 cm in length, and comprises seven horizons (Fig. 6). Horizon 1 (0-9 cm depth) is a moist, black coloured (5YR 2.5/1) organic deposit, with a soft and crumbly texture and a diffuse (< 1.5 cm) lower boundary. Unit 2 (9-23.3 cm depth) is a dark olive-brown coloured (2.5Y 3/3) organic deposit, drier and more consolidated than the overlying sediments, with an acute (< 3 mm) wavy lower boundary. Horizon 3 (23.3-27.5 cm depth) is also a black (5YR 2.5/1) organic deposit, but drier and more consolidated than horizon 1, and with an abrupt (< 5 mm), wavy, lower boundary. Horizon 4 (27.5-33.6 cm) is grey (2.5Y 6/1), soft and slightly adhesive mineral mud, with few visible sand grains. The lower boundary is diffuse over 1-2 cm, and grades into horizon 5 (33.6-35 cm depth), which is a pale-red (10YR 6/2) sand with a loose, dry and crumbly texture. Horizon 6 (35-39 cm depth) is a light-grey sandy clay with a soft, wet consistency. It

has a diffuse and gradational contact with horizon 7 (39-68.2 cm depth), a dry, firmly textured light-grey (2.5Y 6/1) clay with a slightly plastic, adhesive texture. A few large (~ 1.5 cm diameter) mottles of light olive-brown (2.5Y 5/4) clay occur.

LOI₅₅₀ results (Fig. 6 and 7) indicate that sediments are predominantly mineral throughout, although organic material is a significant component above 27 cm depth (horizons 1-3), averaging 32.5% of the dry weight. Organic materials are most abundant within horizons 3 (23-26 cm depth) and 1 (0-9 cm depth), averaging 46 and 40% of the dry weight, respectively. The organic component of the sediments below 27 cm depth is very low, averaging 2% of the dry weight.

Accelerator Mass Spectrometry results (Table 1) reveal an internally consistent chronology for the core, with age increasing with depth. OZH583, which dates the transition from mineral substrate to organic infill at 27.5 cm depth, returned an age of 1040-1220 AD (2 σ range)⁹. OZH581 (4-5 cm depth) returned a date most probably from the 15th/16th centuries AD. Linear age interpolation to the top of the core indicates that sediment deposited after the 17th century was not recovered by the coring procedure. The chronological model used in Figures 6 and 8 is based on linear interpolation between the arithmetic mean of the 2 σ calibrated age range for each date.

Palynology

116 pollen and spore types were identified from 20 samples (Fig. 6). Preservation below 27 cm depth was poor and counting was abandoned at 31 cm depth. 29 unknown types were recorded, averaging < 2% of the total count for each sample. Total counts ranged from 152 to 1213, with an average of 338 specimens per sample.

Classification of the pollen and spore data is used here as a basis for description of the data. Microfossil concentrations are low in zone 1 (30-23 cm depth), averaging approximately 2,700 individuals/cm³. The non arboreal component of these samples is dominated by Poaceae (grasses) and Cyperaceae (sedges), with Chenopodiaceae/Amaranthaceae and *Nelumbo nucifera* also strongly represented. The most abundant arboreal types are *Celtis*, *Macaranga*, Combretaceae/Melastomataceae, *Pinus merkusii*, *Myrica* and Sapindaceae.

The transition to zone 2 (22-12 cm depth) marks a significant change in the character of the palynological assemblage. *Nelumbo nucifera*, which had previously characterised the aquatic flora, disappears temporarily from the record, reappearing

9. The interpretation of the calibrated age is problematic due to its coincidence with a 'plateau' in the IntCal04 calibration curve, centred around the turn of the 12th century AD, leading to several intersections with the curve at 1 σ and a wide (~ 180 yrs) probability range at 2 σ . The greatest proportion of the 1 σ probability (0.65) is represented by the date range 1152-1212 AD, which has a mean age in the late 12th century. However, a conservative approach is taken here, and the mean of the 2 σ range (ca. 1130 AD, early to mid 12th century), which incorporates all intersections with the calibration curve, is the basis for the interpretation presented here.

at and above 15 cm depth. In contrast, *Nymphoides* increases to become the most abundant aquatic plant within the assemblage. Poaceae and Cyperaceae remain the dominant non-arboreal pollen types. Several fern taxa appear for the first time at 19 cm depth, while Liliaceae pollen appears for the first time at 22 cm depth. Rutaceae - tribe Citreae, subtribe Balsamocitrinae *sensu* Grant et al (2000), probably *Feroniella lucida*, which is recorded in the Tonle Sap floodplain (McDonald et al, 1997) - and *Celtis* dominate the arboreal pollen assemblage, with several common taxa being present including *Macaranga*, Sapindaceae and *Uncaria*.

The pollen and spore assemblage in zone 3 (10-5 cm depth) is dominated by fern spores, particularly the psilate and verrucate variants of the monolete spore type, and the climbing fern *Stenochlaena palustris*. Poaceae and Cyperaceae are also strongly represented, with the latter having a markedly higher concentration of pollen grains in these sediments than in the previous zones. *Cassia* type is the most consistently represented of the arboreal pollen types, while Rutaceae, *Celtis*, Sapindaceae and *Uncaria* all reach maxima at 10 cm depth and decrease in abundance thereafter. Other common woody taxa include *Bombax* (*sensu* Tsukada, 1965), Combretaceae/Melastomataceae, *Flemingia* type, *Lithocarpus/Castanopsis*, *Macaranga*, Myrtaceae and Urticaceae/Moraceae (triporate). The sugar palm *Borassus flabellifer* appears for the first time in the record at 7.5 cm depth. Zone 4 (5-0 cm depth) is also dominated by ferns, grasses and sedges, and appears to have been isolated in the classification due to a very sharp peak in pollen concentrations at 5 cm depth, particularly among the ferns, aquatic plants and herbs (Cyperaceae, monolete psilate and verrucate types, Poaceae and *Stenochlaena palustris*). Arboreal pollen types are relatively poorly represented, the most abundant being *Celtis*, Myrtaceae, *Cassia* type, Sapindaceae and *Elaeocarpus*.

Sedimentary charcoal

Microscopic charcoal particle concentrations (Fig. 6), a crude proxy for overall fire activity predominately within the local area (Innes and Simmons, 2000), are relatively low in samples between 30 and 27 cm depth, equivalent to pollen zone 1, averaging ca. 267,000 particles/cm³ (rounded to the nearest thousand). Concentrations fall to an average value of ca. 93,000 particles/cm³ between 27-23 cm depth (equivalent to pollen zone 2), the lowest values in the entire sequence. Charcoal concentrations increase markedly above 22 cm depth, reaching an average of ca. 1,614,000 particles/cm³. The highest values are recorded at and above 7.5 cm depth, with an average of ca. 2,157,000 particles/cm³.

Algae and other micro-fossils

Three genera of the Chlorophyceae (*Coelastrum*, *Pediastrum*, *Tetraedron*) and one genus of the Cyanophyceae (*Gloeotrichia*) were observed in the pollen preparations (Fig. 7). A filamentous type was also observed (*Planktonema?*), but the individuals were too poorly preserved to be identified or enumerated with any confidence.

The planktonic *Tetraedron* is the most abundant genus throughout the sequence. Yamagishi and Hirano (1973) recorded nine species of *Tetraedron* in their survey of the Cambodian algal flora, which were variously recorded in planktonic and

epiphytic samples from the Tonle Sap lake and other water bodies, including “the ponds of Angkor Wat” (p. 61). Several species were observed in the West Mebon sediments, the most common being *T. minimum*. The representation of the genus peaks between 24 and 27 cm depth (an average concentration of 4.4 million individuals per cm³), and falls markedly above 23 cm depth, with a small peak at 15 cm depth. *Gloeotrichia* and *Coelastrum* (dominated by *C. polychordum*) have maxima at depths of 27 and 28 cm respectively. Thereafter *Gloeotrichia* is recorded at 7 and 12 cm depths only, whereas *Coelastrum* is not recorded in any other samples. *Pediastrum* (exclusively *P. duplex*) is present in trace amounts in samples at 24 and 25 cm depths, but is most abundant between 5 and 10 cm depth.

Leaf-spines of the aquatic vascular plant *Ceratophyllum* were also observed and enumerated. These were only recorded between 23 and 27 cm depth, with an average value of 1,750 individuals per cm³.

Discussion

The radiocarbon chronology and LOI data indicate that organic sediment began to accumulate within the West Mebon basin, represented by the transition from sedimentary horizon 4 to 3 at 27.5 cm depth, in the early to middle 12th century AD (OZH583, Table 1; see note 9). While the precise historical age of the West Mebon is unknown, this new radiocarbon age post-dates the *probable* date for the construction of the West Mebon by as much as a century. This discrepancy is either due to a lack of deposition in the pond during the first half century or so of its existence, or may be due to the cleaning out of the Mebon basin in the middle of the 12th century in order to increase or maintain its capacity, possibly associated with the major architectural and engineering developments of that century ascribed to Jayavarman VII. Occasional re-excavation of water features has been documented archaeologically at other sites in the Angkor complex such as Trapéang Phong (Bolle *in* Pottier *et al.*, 2004b, p. 29), and re-excavation of the West Mebon is not surprising given its function was clearly symbolic and ceremonial. Such an event would be consistent with a partial re-excavation of the Western Baray and the raising of its dike (Dumarçay, 1994, p. 377). Although archaeological evidence – unfortunately undatable – that appears to support this episode has been recorded during a recent excavation at Ak Yum (Llopis *in* Pottier, 2001, p. 27-28), it remains hypothetical and in any event may not have altered the water regime in the *baray*¹⁰. The relationship to the other structural modifications of the West Mebon, such as the reconfiguration of the central island, and/or the construction of the large earthen platform east of the temple, is as yet unclear. The occurrence of phytoplankton in the sediments below the organic infill implies water in the basin prior to its colonisation by higher plants, and may represent the earliest phase of the Mebon when sedimentation was dominated

10. Considering that re-excavated materials may have been used in the same manner as the original excavation – i.e. piled up to make a peripheral dike – the raising of the *baray*'s dike may have eventually increased its depth in some parts, but this does not automatically imply any significant increase of the water level in the *baray*, nor that the Mebon was at that time entirely submerged, as assumed by Dumarçay (1982, p. 103; 1994, p. 221).

by mineral material re-worked from the bed and newly built embankments. The diversity of pollen and spore types below 27.5 cm depth is low (an average of 10 taxa, compared with a maximum of 46 taxa at 5 cm depth). This, combined with the extremely low organic content of these sediments (2% of the dry weight of the sediment), suggests partial oxidisation of the sediment.

The development of predominantly organic sediment from 27.5 cm depth represents an increase in the supply of biomass to the sediment as a result of the colonisation of the Mebon by aquatic vascular plants. *Ceratophyllum* appears to have been the most significant of these, as its leaf-spines are abundantly preserved between 23 and 26 cm depth. *Ceratophyllum* is a non-rooted, fully submerged macrophyte with a preference for clear-water conditions and high phosphorous concentrations (Birks et al, 2001; Mjelde and Faafeng, 1997). The relatively low concentrations of phytoplankton fossils coincident with *Ceratophyllum* dominance may reflect the development of nutrient limitation as a result of aggressive foliar uptake of P by the local *Ceratophyllum* population, resulting in phytoplankton suppression (Lombardo & Cooke, 2003). These data imply that from the early to middle 12th century to around the end of the 12th century, the West Mebon held relatively deep, clear, standing water that supported an extensive community of submerged aquatic plants, particularly *Ceratophyllum* and *Utricularia*. The relatively strong representation of *Nelumbo* pollen, a plant adapted to insect pollination (Vogel & Hadacek, 2004) and which is normally under-represented in fossil pollen spectra, suggests that sacred lotus would have been an important component also. Curiously, one of the two small gold leaves from the ritual deposit found below the pavement of the eastern pit on the Mebon's central platform was inscribed with the word "lotus" (Cœdès quoted by Glaize, 1944). These data indicate that throughout the latter half of the 12th century the West Baray held sufficient water to surround the Mebon throughout the year.

Dramatic changes in the pollen and spore assemblages, charcoal concentrations, algae and sediments above 22 cm depth indicate markedly changed hydrological conditions within the Mebon and *baray* from the late 12th century AD. The disappearance of *Ceratophyllum* leaf-spines, the dramatic reduction of *Nelumbo nucifera* pollen, and the decline or disappearance of phytoplankton taxa (particularly *Tetraedron*), imply a marked fall in water levels within the Mebon. Given the lack of a direct inflow channel to the West Mebon the increased proportion of mineral material within the sediments is probably wind-blown material eroded from the exposed bed of the *baray*. Equally dramatic increases in the concentration of microscopic charcoal particles in the sediment may reflect burning associated with agriculture within the *baray* during the dry season, although it is not possible to define the source area for wind-blown charcoal particles with any precision. Taken together, these data indicate a clear change in the hydrology of the West Mebon in the late 12th century AD, consistent with a shift from the dominance of *baray* water towards a ground-water dominated regime, at least on a seasonal basis if not more permanently.

Such a marked fall in the volume of water brought into storage in the West Baray might be an indication of a change in the configuration of the ‘collector’ canals and embankments to the north and northwest, or a change in the function or use of the great *baray*. Dumarçay (1994, p. 221; 2003, pp. 57-58) claims that the system of water storage changed in the 13th century, moving from the use of large reservoirs to a greater reliance on canals and embankments for trapping and moving water across the landscape. One obvious implication of this would have been to reduce the volume of water flowing into the great reservoirs. Critically, Dumarçay (1982, p. 102; 2003, p. 62, and n. 18) claims that the West Baray was dry during the visit of the Chinese emissary Tcheou Ta-kouan (1296-1297 AD), citing Groslier (1973: 302, n. 1). However – ironically, given the assumed confusion over Tcheou Ta-kouan’s report concerning the location of the “bronze Buddha” in the “eastern lake” – Groslier was referring to the Eastern rather than the Western Baray (“Mais à son époque le Yaçodharatâtâka devait être asséché...”). Alternatively, based on epigraphic evidence for unprovenanced donations of rice to the Preah Khan temple, Lustig (2001) suggests that a greater reliance on taxation from the provinces from the 13th century made the great *baray* redundant, although she is necessarily cautious in her interpretation. A climatic explanation for the drying of the West Baray, such as a reduction in annual rainfall or an increase in seasonality, appears unlikely. While independent palaeoclimate data of adequate temporal resolution are not yet available for Cambodia, stable isotope records of temperature and rainfall from central China (Paulsen *et al.*, 2003) indicate that the 12th/13th centuries were periods of relatively wet and warm climate associated with the Medieval Warm Period. Finally, it is possible that new infrastructure ‘grafted’ to the *baray* may have contributed to the hydrological change apparent in the palynological data. In particular, the so-called south-west corner of “Goloupura” – probably a feature designed to connect the *baray* to the canal linking Angkor Vat to the lake Tonlé Sap (Pottier, 2000b, p. 102) – has a storage capacity of around 4.5 million m³ on its own, and may have deviated a significant part of the Western Baray waters to the Angkor Vat canal, which was eventually used for transportation. Interestingly, the supposed date for the creation of this infrastructure has become continuously younger, moving from the end of the 9th century to the mid-12th century (Groslier, 1979, p. 83) and then at least to the end of the 12th, if not the 13th century AD (Pottier, 2000b, p. 103). It is possible that the clear change in the hydrology of the West Mebon may place the construction of the south-west corner of “Goloupura” at the end of the 12th century AD.

The increased presence of fern spores in the sediment in the upper 15 cm of the sequence – from around the 14th century – reflects the progressive development of floating fern swamp within the Mebon. Similarly, the concentration of Cyperaceae pollen is high at and above 10 cm depth, and the first appearance at 7.5 cm depth of *Ludwigia* pollen, possibly *L. adscendens* or *L. hyssopifolia* (McDonald *et al.*, 1997), a marsh herb with a creeping growth habit, is also indicative of the full development of floating marsh within the Mebon. A stratigraphic boundary at 9 cm depth, around the mid-15th century, reflects a change in the type and amount of biomass accumulating in the basin, and marks the full development of a floating vegetation mat. The marked falls in the concentration of pollen from aquatic

plants such as *Nymphoides*, *Nelumbo nucifera*, and possibly Liliaceae, may reflect increased competition from invasive ferns, grasses and sedges.

These data suggest the progressive colonisation of the Mebon basin from the 14th century by aquatic ferns and herbs, which appear to have established a floating vegetation mat that completely closed over the basin by the middle of the 15th century AD. It is probable that this successional change within the local flora was driven by an increase in water levels within the West Mebon basin. The coincident reappearance of the algal taxa *Gloeotrichia* and *Pediastrum duplex* is also suggestive of higher water levels within the Mebon. The magnitude of this increase cannot be quantified, but the palynological assemblage does not indicate the renaissance of the 'full baray' conditions apparent in the 12th century.

The dryland flora coincident with these changes, dominated by *Cassia* type, *Bombax*, Rutaceae (*Feroniella?*), Urticaceae, Sapindaceae and *Flemingia*, is difficult to classify. These may have been components of a weedy secondary plant community growing immediately around the basin or on the earthen mound that abuts the east wall of the temple, or on the bed of the baray itself. The first appearance of the sugar palm *Borassus flabellifer* in the latter part of the 15th century, in addition to high sedimentary charcoal concentrations, may be indicative of some agricultural land use in the immediate vicinity from that time. Indeed, the small villages that were present on the bed of the baray in the early 20th century (Pottier & Dumarçay, 1993, Planche 1) were possibly founded at that time. Curiously, one of those villages, Phum Thnot, was named after the *Borassus* palm.

The presence of pollen from freshwater swamp forest trees such as *Barringtonia* and *Ilex cymosa* from around the 16th century (OZH581, Table 1) is indicative of the growth of large woody species within the Mebon basin. Indeed, photographs taken in the 1940s reveal that large trees had become established both on the bed of the basin and on the raised central platform. The fact that these plants had been allowed to grow to maturity implies that the Mebon was certainly not being maintained at that time.

Conclusion

The data presented here provide evidence for substantial changes in the operation of the West Baray throughout its history. Organic sedimentation within the West Mebon basin begins as much as a century after the probable construction of the monument, which may be a result of re-excavation of the basin in the early-middle 12th century, possibly associated with a period of architectural rejuvenation. From this time both the West Baray and its Mebon were full, and the Mebon basin would have carried relatively deep, clear, standing water, from which sacred lotus would have emerged. Toward the end of the 12th century, however, changes in the vegetation growing within the West Mebon basin indicate a sustained fall in water levels within the West Baray, possibly associated with changes in the operation of its catchment and/or the creation of new infrastructure for the alimentation of the Angkor Vat

canal. While the magnitude of this change cannot be quantified precisely, our data imply that the bed of the West Baray was at least partly exposed during the dry season, if not more permanently. Further changes seem to have occurred from the 14th century, with a colonisation of the basin by floating fern swamp, which perhaps developed in response to slightly higher and substantially more variable water levels within the West Baray.

The fact that the West Baray is unlikely to have served the purpose or purposes for which it was originally intended from the 13th century has important implications for the debate surrounding the function of the great *baray* at Angkor. This study emphasises the importance of adopting a diachronic model of use that reflects the continuous development of the water management system, rather than the fixed and contrasting models (functionalist versus ritualist) that have characterised, and to some extent retarded, the discourse to date.

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Lab. Code	Depth (cm)	$\delta^{13}\text{C}$ per mil	Percent modern (pMC) \pm 1 σ error	Radiocarbon age (^{14}C years BP \pm 1 σ)	Calibrated age range BP (2 σ 95.4% probability)	Calibrated age range AD (1 σ 68.2% probability)	Calibrated age range AD (2 σ 95.4% probability)
OZH581	4-5	-24.7	95.33 \pm 0.44	385 \pm 40	316 - 400 BP [0.38] 402 - 406 BP [0.007] 421 - 511 BP [0.61]	1447-1517 [0.76] 1594-1618 [0.24]	1439-1529 [0.61] 1544-1548 [0.007] 1550-1634 [0.38]
OZH582	15-16	-17.0	90.78 \pm 0.46	775 \pm 40	664-765 [1.00]	1225-1272 [1.00]	1185-1286 [1]
OZH583	27-28	-19.7	89.59 \pm 0.34	885 \pm 35	730-910 [1.00]	1051-1081 [0.29] 1127-1135 [0.06] 1152-1212 [0.65]	1040-1220 [1.00]

TABLE 1: Results of AMS radiocarbon dating of pollen samples from core WM/06/04/A. These ages were measured by accelerator mass spectrometry at the ANTARES facility (Hua et al, 2001; Fink et al, 2004). Radiocarbon dates are calibrated (Stuiver & Reimer, 1993, version 5.0) using the IntCal04 curve (Reimer et al, 2004). Ages are calibrated to years AD, representing 68.2% and 95.4% confidence levels respectively, and years BP (95.4% confidence only). Figures in square brackets indicate the proportion of the probability range represented by each intersection of the probability curve (thus, 1 is equal to either 68.2 or 95.4%). Measured $\delta^{13}\text{C}$ values relate solely to the graphite derived from the material used for radiocarbon measurement.

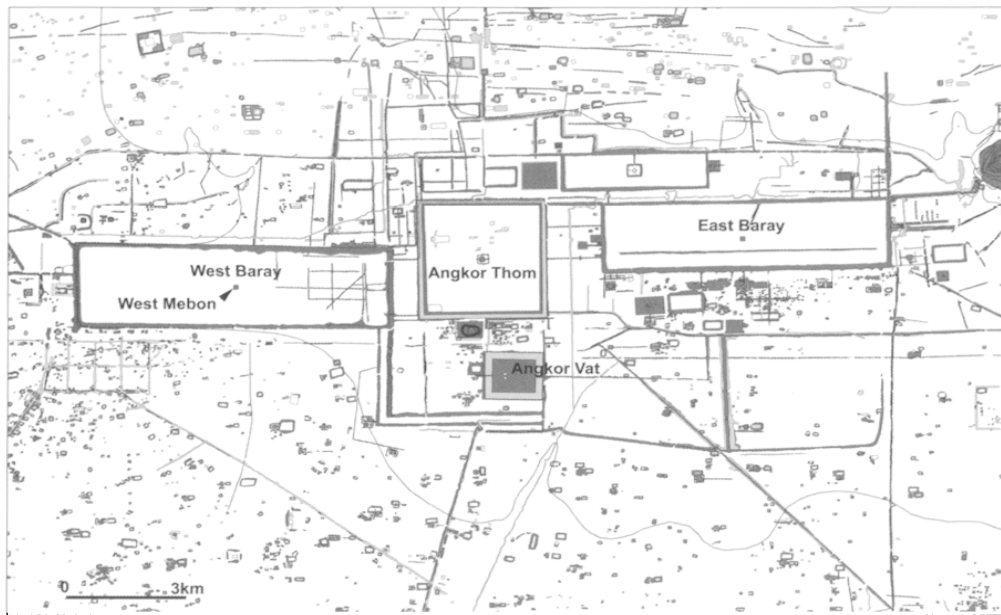


Fig. 1. Map of central Angkor, Cambodia, showing the location of the West Baray and the West Mebon.

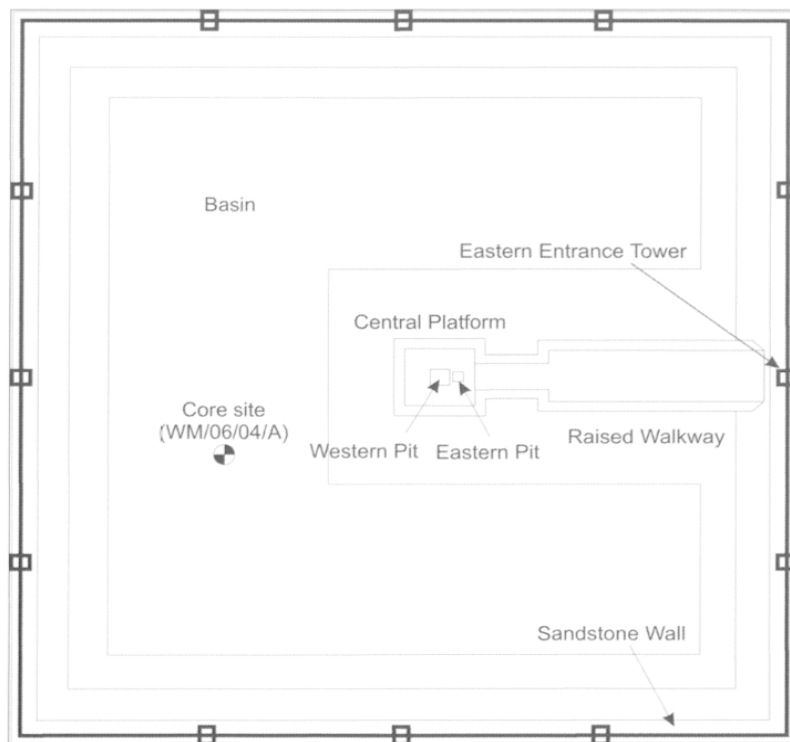


Fig. 2. Plan view of the West Mebon temple, showing major features and the core location, after Dumarçay (1982).



Fig. 3. Oblique low-level aerial photograph of the West Mebon temple and basin, looking north-east. The surrounding West Baray is dry due to a severe dry season, yet the Mebon basin retains sufficient water to support a verdant swamp flora. Photography by Christophe Pottier, May 2004.



Fig. 4. EFEO photo n°13752 CA3774, February 1936. Photograph of the West Mebon basin, taken immediately south the fully exposed central platform, looking west. Despite the basin being partly dry – enabling Lagisquet’s excavations around the platform to take place – the western part of the basin (in the background) clearly remains wet, supporting what appears to be a sedge-dominated swamp flora.

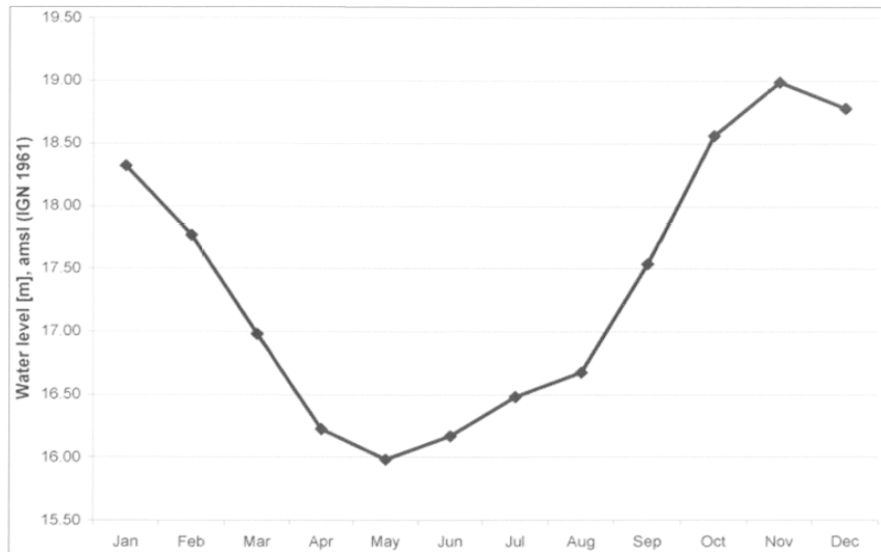


Fig. 5(a). Average monthly water height in the West Baray, 1992-2001 (Siem Reap Provincial Hydrology Department), corrected to IGN 1961 (Pottier 1993), IGN 1994 (Boldo and Barasz, 1994) and JICA 1997 (JICA, 1997) standards.

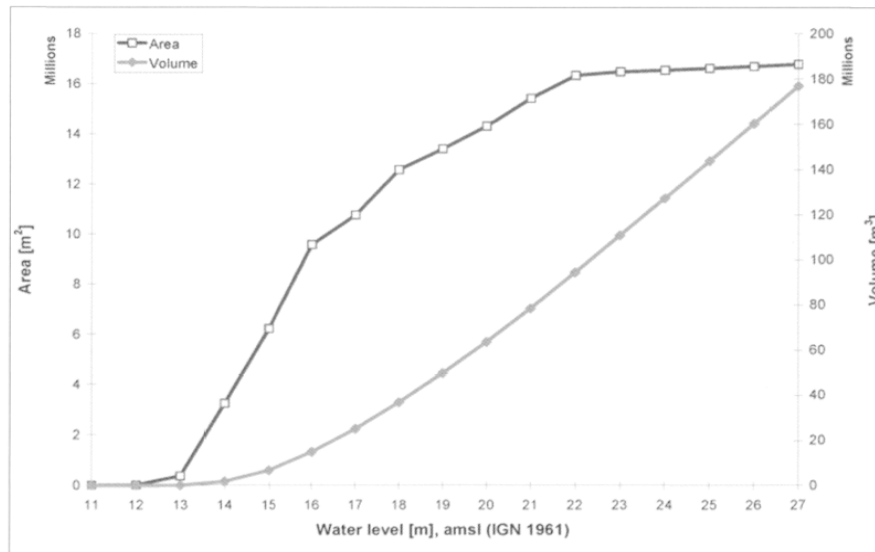


Fig. 5(b). Area/volume plot of water in the West Baray, based on a digital elevation model (DEM) that combines the TOPSAR elevation model and bathymetric survey data (IGN/FARK 1961, published in Pottier, 1993; Pl. 2-3). The DEM was used to calculate the volume-to-area water level curve using ArcGIS 8.3, which was then used to convert the water height within the baray (m AMSL) to volume (m³).

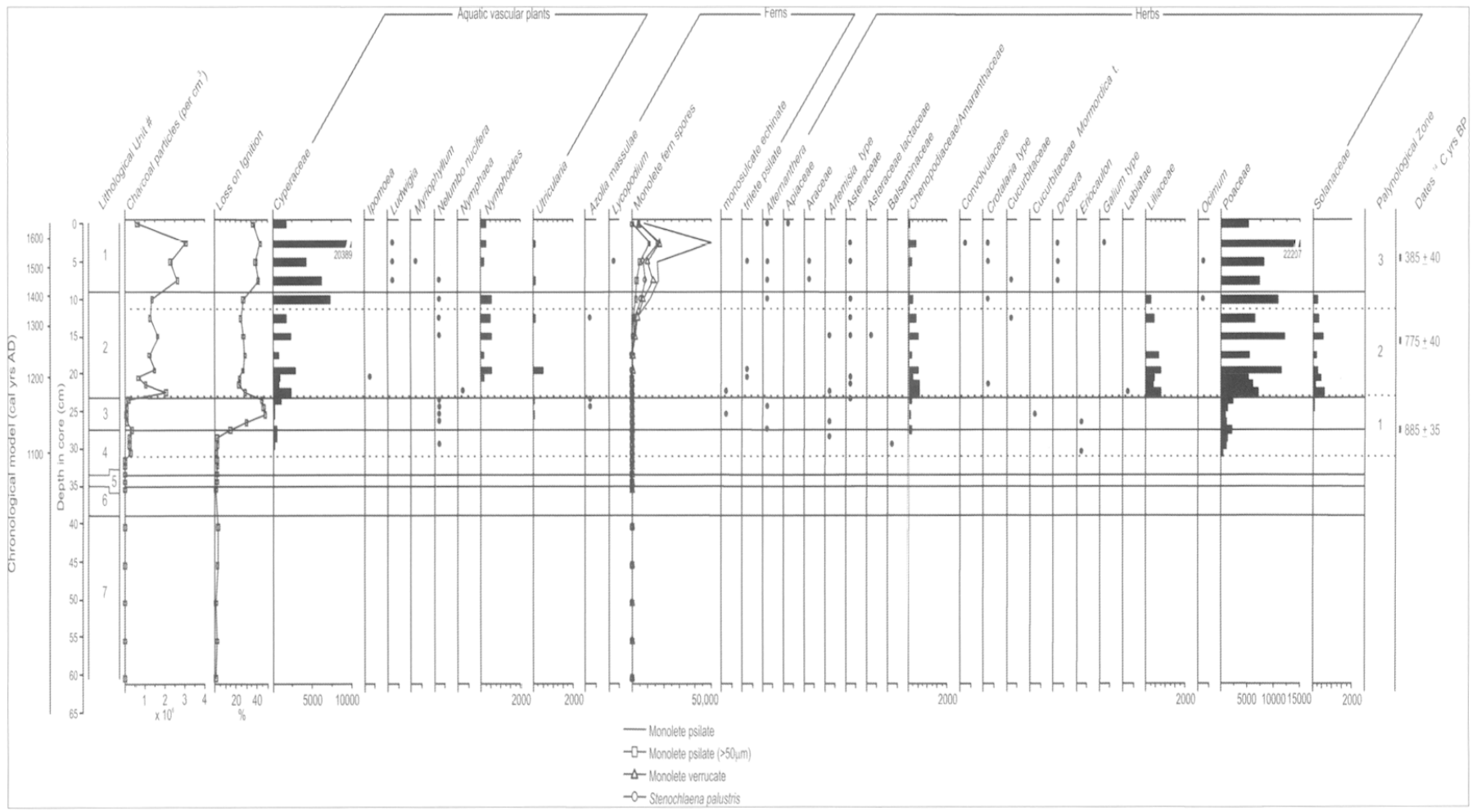


Fig. 6. PART I

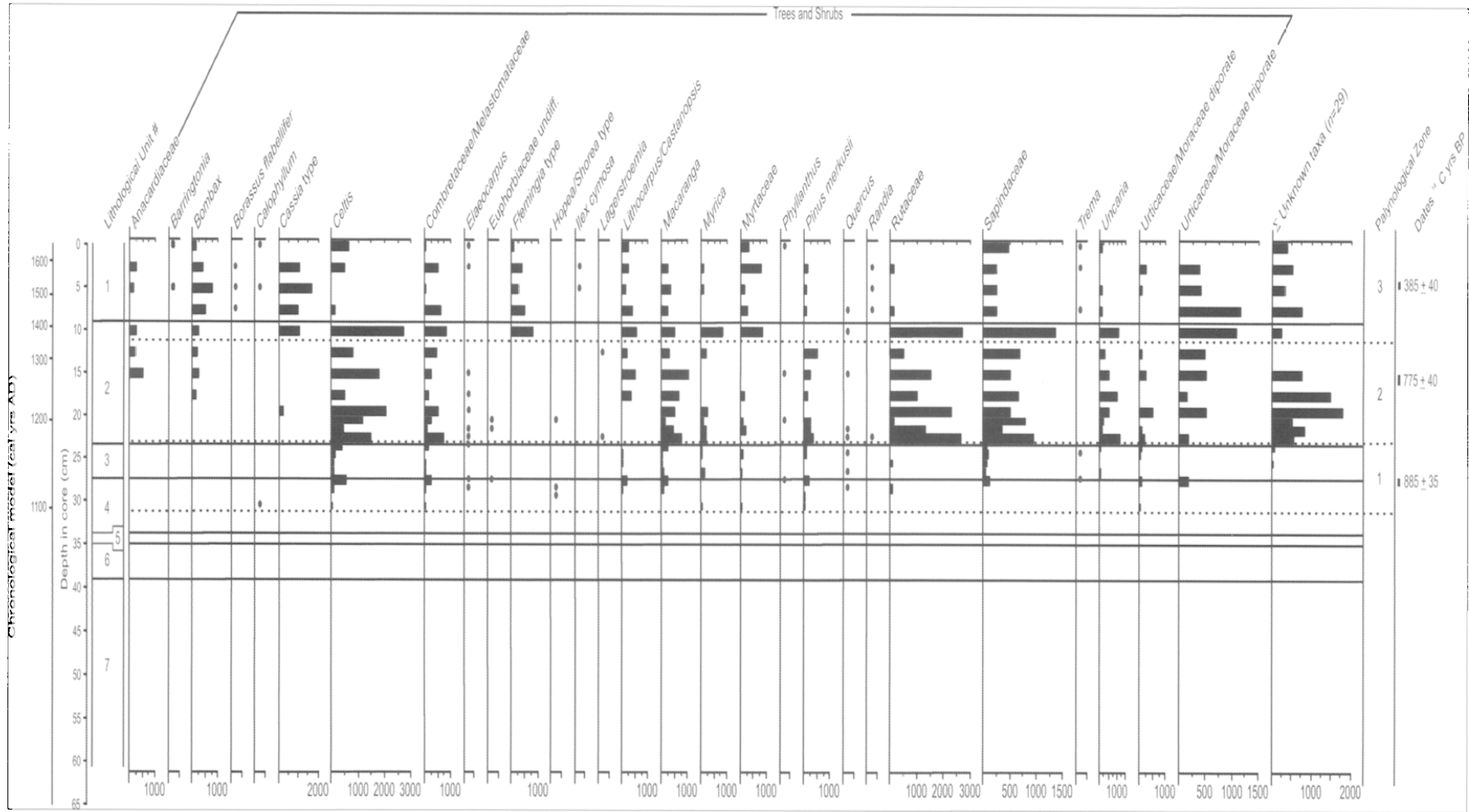


Fig. 6. PART II

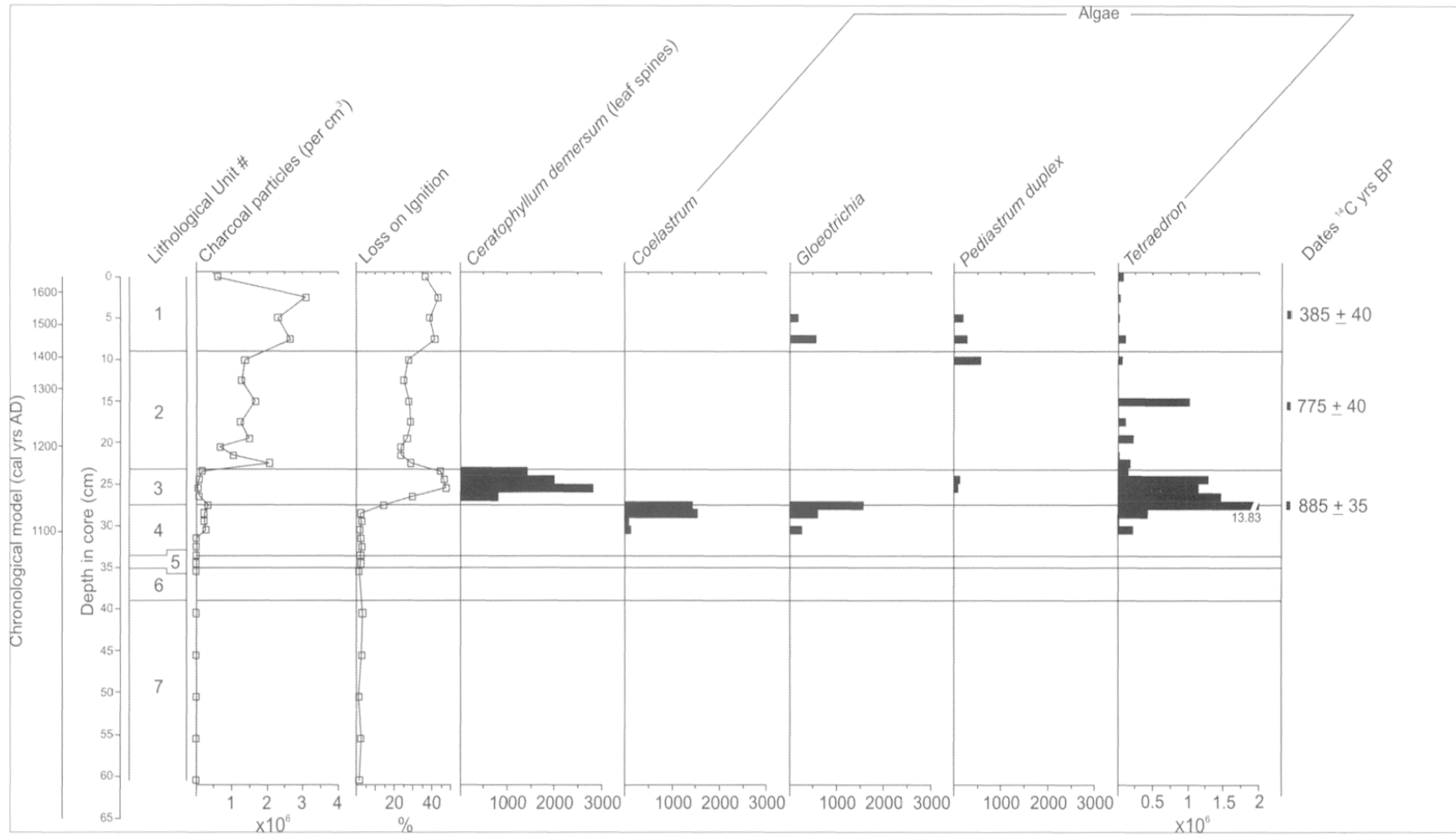


Fig. 7

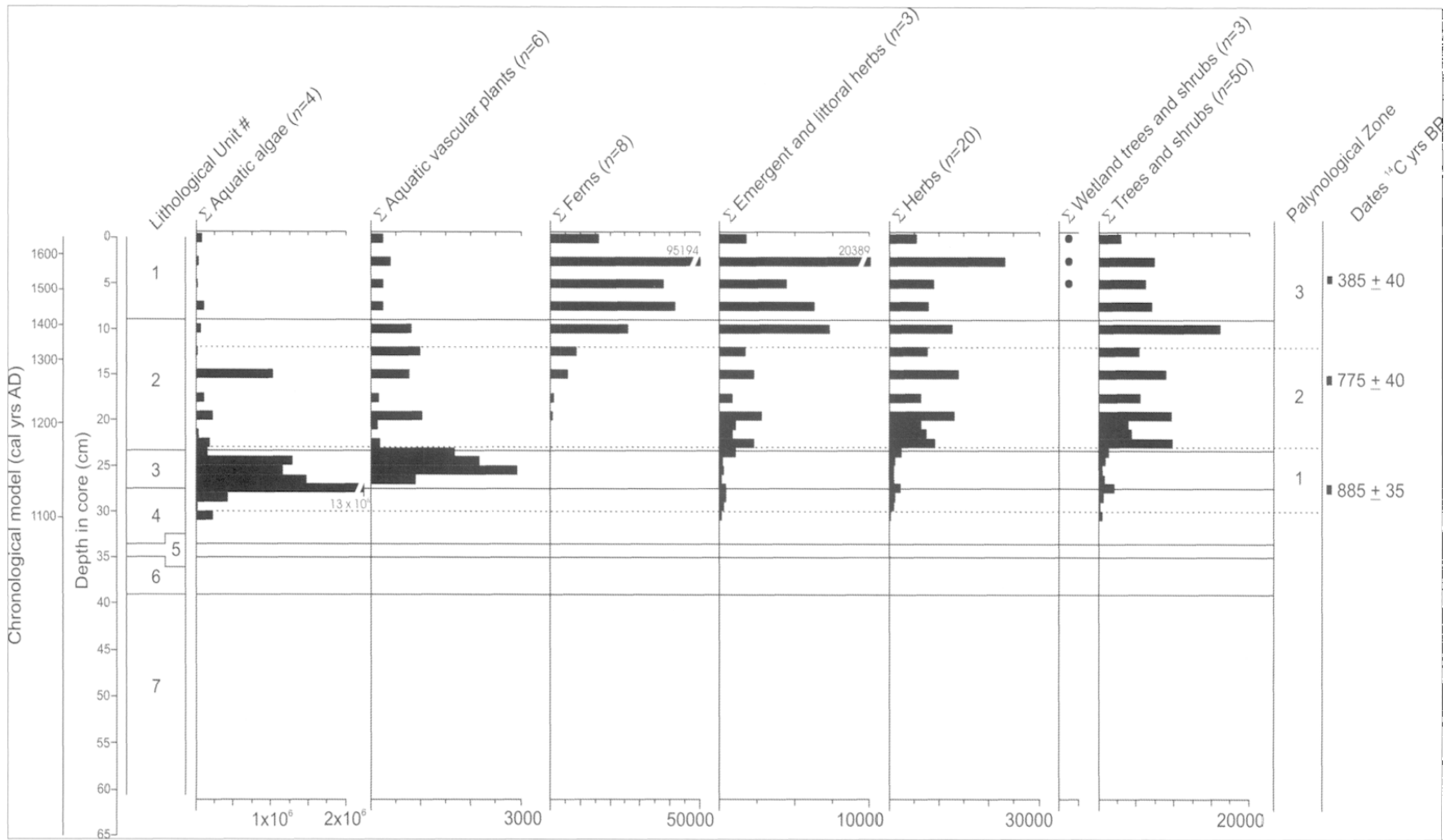


Fig. 8

Fig. 6. Plot of palynological (selected taxa only), lithological and chronological data from core WM/06/04/A against core depth. Pollen and spore types are expressed as a concentration of individuals per unit volume (cm^3). Closed circles indicate taxa which do not occur above 500 individuals per unit volume in any sample (a presence/absence value). The chronological model is based on linear interpolation between the mean of the 2σ calibrated age range (Table 1). Solid lines represent stratigraphic boundaries; dashed lines represent boundaries between palynological zones identified by classification (Grimm, 1987).

Fig. 7. Plot of algae and other microfossil data from core WM/06/04/A against depth. Taxa are expressed as concentrations per unit volume (cm^3). Solid lines represent stratigraphic boundaries. The chronological model is based on linear interpolation between the mean of the 2σ calibrated age range (Table 1).

Fig. 8. Plot of microfossil data from core WM/06/04/A, grouped according to habitat or plant type (unidentified taxa excluded). All groups are expressed as concentrations per unit volume (cm^3). Solid lines represent stratigraphic boundaries; dashed lines represent boundaries between palynological zones identified by classification (Grimm, 1987). Closed circles indicate taxa which do not occur above 500 individuals per unit volume in any sample (a presence/absence value). The chronological model is based on linear interpolation between the mean of the 2σ calibrated age range (Table 1).