Iron and fire: Geoarchaeological history of a Khmer peripheral centre during the decline of the Angkor Empire, Cambodia

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1. Introduction

At its height between the 11th and 13th centuries AD, the Khmer Empire extended across much of mainland Southeast Asia (Jacques and Lafond, 2004). The royal court and central administration resided in and around the city of Angkor, on the central plains to the north of the Tonle Sap Lake (Fig. 1). Large centres and regional settlements also developed across the area that demarcate their territories (Groslier, 1986, Groslier, 1980) and were linked to Angkor and one another by an extensive road and riverine transportation network (Hendrickson, 2011). The purpose of these provincial centres varied; many maintained civic-ceremonial functions, subsidiary to the central temples and administration of Angkor (Hall, 1985), some appear to be industrial or commercial (Welch, 1998, Hendrickson et al., 2013), while others represented strategic declarations of power (Groslier, 1973, Lustig et al., 2007, Hendrickson, 2010). All, however, existed as hubs for hinterland village groupings, often supplying the central administration with the resources and products of its region (Hall, 1985; Zhou, 2001, Lustig et al., 2007). Relative to the sprawling and ‘edgeless’ urbanism at Angkor (Evans et al., 2007), these secondary settlements contained well-defined urban and formal ritual spaces that are far more distinctive and more easily interpreted than the complex palimpsest of the capital (Evans, 2010, Evans et al., 2013).

The 15th century abandonment of Angkor by the royal court and its administration in favour of a succession of smaller cities in the southern river plains, marks the demise of the great inland agrarian empire that had endured officially since the 9th century. Investigations into this great transition in Southeast Asian history have, appropriately, focused on Angkor itself (Groslier, 1958, Groslier, 1979, Lustig et al., 2008, Buckley et al., 2010, Diamond, 2011). In contrast, the fate of provincial
settlements within the city-region network as Angkor began to fail has attracted relatively little attention, particularly in the Anglophone literature. This study therefore aims to begin addressing this lacuna, by providing an environmental history of Preah Khan of Kompong Svay (Preah Khan) – a peripheral centre with possible associations with industrial production located in the modern Preah Vihear province of Cambodia, approximately 100 km east of Angkor along one of the empire’s major transportation routes – in order to determine how this part of Angkor’s city-region responded to the demise of the capital.

Preah Khan, also known as Bakan, was the largest temple enclosure in the Khmer empire, at approximately 22 km² (Aymonier, 1900). According to the art-historical and epigraphic record, Preah Khan was founded in the 11th century AD, and remained important to the Khmer elite until at least the 13th century (Mauger, 1939). A later period of occupation is suggested by the construction of Preah Chatumukh, a tower depicting a standing Historical Buddha, and Theravada-Buddhist graffiti within the walls of the 2nd enclosure. Post-14th century AD Thai and blue-and-white ceramics in association with Post-Angkorian era metal production sites (see Hendrickson et al., 2013, Pryce et al., 2014) also suggests that the site was occupied and importing goods even as Angkor’s power waned.

The scale and duration of the building programme, the size of the enclosure, and the infrastructure along the roadway connecting it to Angkor, imply that Preah Khan was a vital resource for the Khmer elite. Groslier (1973) argued that Preah Khan was established as an eastern outpost to protect against potential Cham invaders based in modern day Vietnam. A more economically-focused interpretation by Hendrickson (2011) is that Preah Khan served as an entrepôt to gain access to the iron being produced to the east. Of all the Angkorian sites, Preah Khan has a unique historical association with iron. The site is approximately 31 km WNW of the iron ore deposits at Phnom Dek (‘Iron Mountain’) and the Kuay ethnic communities that belong to that area. The Kuay have been associated with iron smelting for centuries (Levy, 1943, Dupaigne, 1987) and only ceased producing the metal in the mid-20th century. The production of iron within the outer enclosure itself, while limited in scale, is anomalous to Preah Khan among all other Angkorian sites. Based on the recent dating of many of the slag concentrations inside the site it appears that this industrial activity occurred after the religious foundation of the city had ceased to function (Hendrickson et al., 2013, Pryce et al., 2014). The evidence of production in Preah Khan most likely reflects brief and opportunistic industrial activity.

To test these suggestions and gain a more detailed picture of the occupation and use of this site, we aim to investigate the geoarchaeological history of Preah Khan of Kompong Svay. Local environmental histories reconstructed from sediment cores retrieved from artificial reservoirs in the Angkor region have led to significant revisions of the established chronologies of these sites – in particular the timing of their construction, settlement and abandonment (see Penny et al., 2006) – and with this intent we focus on data collected from the baray (reservoir) at Preah Khan for this study. These results will also provide the first radiometric dates for the reservoir. With this data the timing of the baray’s construction within the context of the greater temple complex building programme, an understanding of the historical use and function of the baray, and how this may have changed through time, can be determined. Using these interpretations as proxies for

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**Fig. 1.** The location of Preah Khan of Kompong Svay, approximately 100 km east of the ancient city of Angkor. The proximity of Phnom Dek is also illustrated.
settlement occupation and function, a more complete history of this provincial outpost can be constructed.

2. Materials and methods

Here we utilise sediment that has accumulated in Preah Khan’s 3 km² baray (reservoir) (Fig. 3) as an archive of environmental and land-use change. Prior to the reactivation of the reservoir over the past decade for irrigation purposes, most of the baray was permanently or seasonally dry for, we presume, several centuries. The presence of a substantial canal on the bed of the baray, apparently linking Prasat Preah Stung to the central island temple of Preah Thkol (Hendrickson and Evans, in press), suggests that a large portion of the baray was dry even when it was occupied. In fact, it may never have operated at capacity. Oxidisation of the reservoir soil, changes induced in the soil column by seasonal variation in groundwater, and agricultural disturbance of the soil profile, make these materials unsuitable for analysis. A relatively deep basin at the eastern end of the reservoir, however, holds permanent water. Analysis of remote sensing images representing the period since 1945 indicates that, while the size of the water body varies over time (from 12.7 ha in 1945 to 51.1 ha in 2001), the basin does not dry out and may therefore provide a stable sink for material from the surrounding environment, and reducing conditions suitable for the preservation of organic material. The basin is fed primarily by groundwater, with surface flow channelled into the baray during the wet season via an inlet spanned by a laterite bridge at the northwestern corner of the reservoir (Hendrickson and Evans, in press).

Sampling sites within the permanent basin were established according to an a priori 50 × 50 m grid in a Geographic Information System using ArcGIS (see Fig. 3). Coordinates for each sampling station were uploaded to a handheld GPS as a series of waypoints. Water depth was recorded at each station, and a bathymetric model of the basin created by generating a triangular irregular network in ArcGIS. Sediment cores were obtained using a rope-operated percussion corer (Chambers and Cameron, 2001, Glew et al., 2001) operated from a floating platform.

Volume magnetic susceptibility of all cores was measured in the field using a Bartington MS2 meter with a MS2C 100-mm diameter loop sensor in order to determine any first-order correlations between cores across the basin (Dearing, 1994). The longest cores (Cores C1, B2 and A2), assumed to represent the highest rate of sediment accumulation within the basin and, therefore, offering the best temporal resolution, were returned to the University of Sydney for analysis. All remaining cores were split longitudinally in the field, logged (following Schnurrenberger et al., 2003), photographed and discarded.

The core selected for detailed analysis (C1) was split longitudinally in the laboratory, logged and photographed. The core was sliced into 1 cm thick slices and subsamples removed for loss-on-ignition (following Dean, 1974; Heiri et al., 2001), and particle size analysis (oxidisation with 5% w:v H₂O₂, de-flocculation with 5% w:v (NaPO₃)₆). Summary statistics for particle size data followed Folk and Ward (1957), using
geometric measures, and were calculated using Gradistat v8 (Blott and Pye, 2001).

Approximately 100-mg of freeze-dried sediment were homogenized for trace element quantification at 1-cm intervals. Trace elements were extracted in 6 mL of weak (1 N) HNO3 acid overnight at room temperature. This extraction procedure deliberately targets those elements weakly associated with organic matter and loosely bound to inorganic minerals. It does not extract more recalcitrant phases (i.e., contained within the mineral lattice; Grane et al., 1995; Gobeil et al., 2013). Elemental concentrations were measured using an Inductively Coupled Plasma Mass Spectrometer at the University of Alberta. Elemental accumulation rates (flux) were calculated as the product of elemental concentrations and sedimentation rate (g/m2/y).

Pre-industrial iron smelting required significant quantities of charcoal (up to 3:1 charcoal to iron ore required, according to Norbach (1997). Among the primary pollutants of this fuel is soot and particulate charcoal — generically, black carbon (BC). While many smelting systems were closed, increased quantity and size of furnaces will produce larger proportions of black charcoal. BC is highly durable in the environment, and preserves in soils and sediments over long periods of time (Herring, 1985, Scott, 2000). The abundance of macro- and microscopic BC in soils and sediments can, therefore, be used as a proxy for the occurrence of natural (Glasspool et al., 2004, Scott, 2009) and human-induced fire (Stanley and Bernhardt, 2010). However, separating the human activity signal from the natural fire regime has been a persistent challenge in the interpretation of charcoal records (Scott and Damblon, 2010). Reconstructions of past fire regimes rest on the relationship between the proximity of the source fire to the point of deposition, and the size of charcoal particles interred – that is, larger particles represent fires proximal to the point of deposition while smaller particles represent distal fires (see Duffin et al., 2008, and references therein).

The taphonomy of industrial BC is, however, more complex than BC produced by domestic or wild fire. In particular, the combustion of charcoal in an enclosed furnace means that small particles of ash and charcoal are not convected from the fire in the same way, or in the same volumes, as BC export from open fires. Equally, high temperatures (in excess of 1000 °C; Crew, 2013) and oxygen-rich combustion within the furnaces means that charcoal fuel is at least notionally – completed consumed. Given this, it seems probable that the BC signature of iron smelting is likely to be overwhelmed in the sedimentary record by the domestic fires of the people operating the furnaces.

Macroscopic charcoal extraction and analysis followed a modified protocol established by Stevenson and Haberle (2005). 1-cm3 samples taken at 2–3 cm intervals along the core, consistent with volume recommendations made by Caracail et al. (2001), were dispersed in 5% w:v (NaPO3)6 and mixed mechanically for at-least 4 h. Dispersed samples were then wet sieved through 250 μm and 106 μm mesh in order to separate size fractions that correspond to different, but overlapping catchment areas (see Clark, 1988). In this case, charcoal was separated into roughly local (∼250 μm), regional (106–250 μm) and extraregional (<106 μm) source areas.

Material retained in the two macrocharcoal size classes was transferred to a glass petri dish with 1 cm grid graph paper positioned beneath, and placed under a binocular microscope at 40× magnification. All charcoal fragments within the sample were counted by moving systematically from grid-square to grid-square. Results are expressed as absolute values (fragments per unit volume), which were then converted to influx values (particles cm−2 year−1) using the equation specified by Mooney and Tinner (2011) using a chronological model based on radiocarbon dating of the core.

Microscopic BC (<106 μm; BCμ) was concentrated by removing carbonate (HCl), silicates (HF) and non-charred organic carbon (wet oxidation using H2O2/NaOCl). Samples were mounted on glass microscope slides in glycerol and BC particles were counted under ×400
magnification. A known number of Lycopodium spores were added to the samples and were used to calculate the concentration of BC particles per unit volume of sediment (Stockmarr, 1971). Fire signals identified in charcoal records are composed of ‘background’ (long term, integrated combustion signal from the catchment landscape) (Clark and Royall, 1994, Clark and Royall, 1995) and ‘peaks’ (annual or inter-annual, often fires within the catchment, defined as being higher than long-term background signal) (Clark, 1990). ‘Background’ influx values representing ‘noise’ from distant (extra-regional) fires and secondary charcoal deposition were decomposed from peak abundances by calculating the residuals around the mean influx value. Positive deviations from the mean were then interpreted as peak fire signals.

Nine samples were selected for dating using AMS radiocarbon analysis (see Table 1) with material ranging from bulk or undifferentiated organic samples (“organic material” in Table 1), to unburnt wood fragments, and leaves and stems from aquatic plants (“macroplant material” in Table 1). Plant remains were isolated by wet sieving, while wood fragments were hand-picked under magnification from samples that had been freeze-dried. All samples were oven-dried before being submitted to ANSTO (Hua et al., 2001; Fink et al., 2004) and Beta Analytic for AMS14C analysis. The resulting radiocarbon ages were then calibrated to calendar AD years using the SHCal13 calibration curve (Hogg et al., 2013) with a no offset with Hendrickson et al. (2013). This regional offset for mainland Southeast Asia is a result of Northern and Southern Hemisphere air-mass mixing via the monsoon systems (Hua et al., 2004, Hua and Barbetti, 2007, Hua et al., 2012). The chronology of the sediment core was estimated using the P_Sequence deposition model of the OxCal v.4.2.3 programme, assuming a randomly variable deposition rate (Bronk Ramsey, 2008).

3. Results

3.1. Sedimentology and chronology

Eight cores (of the ten retrieved from the baray) were logged and correlated through stratigraphic and magnetic susceptibility analyses (Fig. 4). A recurring double peak in magnetic susceptibility profiles — perhaps indicating a significant erosion event in the catchment — indicates a general consistency in sedimentation across the basin. Core C1 (475601E 1481395N WGS84 48N) was the longest core recovered. Core C1 is 166.5 cm in length comprising 12 stratigraphic units (see Fig. 5). The basal Unit 1 (166.5–155 cm depth) is a greenish grey, slightly gravelly sandy mud with distinct and irregular dark greenish grey motles throughout the matrix and a clear planar upper boundary. Unit 2 (155–144 cm depth) is a greenish grey gleyed mud with a clear wavy upper boundary. Unit 3 (144–139 cm depth) is a greenish grey sandy mud with a clear wavy upper boundary. Unit 4 (139–113 cm depth) is a grey mud with a very abrupt planar upper boundary. Unit 5 (112.5–110 cm depth) is a yellow mud with a very abrupt planar upper boundary. Unit 6 (109.5–85 cm depth) is a light brownish grey mud with an abrupt planar upper boundary and many very fine plant fragments. Unit 7 (85–81 cm depth) is a dark grey mud grading to very poorly sorted, slightly gravelly sandy mud and contains a gradual planar to wavy upper boundary. Unit 8 (80.5–77 cm) is a greyish brown slightly gravelly mud with a clear planar upper boundary. Unit 9 (77–40 cm depth) is a light brownish grey mud to slightly gravelly sandy mud with many plant fragments and few fine roots throughout and a gradual planar upper boundary. Unit 10 (39.5–29 cm depth) is an olive brown organic mud with many small-large plant fragments, contains few fine roots throughout and contains an abrupt planar upper boundary. Unit 11 (29–3.2 cm depth) is a very dark greyish brown (sandy to slightly gravelly sandy organic mud with few fine roots throughout and contains a clear planar upper boundary. This is overlain by Unit 12 (3.2–0 cm depth), which is a dark greyish brown slightly gravelly sandy organic mud containing few fine roots throughout.

Radiocarbon results are given in Table 1, and reveal a number of temporal inversions, perhaps indicating some contamination with modern carbon during sample preparation. To identify outlying or otherwise anomalous dates, an outlier analysis (Bronk Ramsey, 2009) was performed in conjunction with the age-depth model in OxCal v.4.2.3. Of the full suite of samples, Beta-282654 (posterior 100%) and Beta-282654 (100%) were identified as outliers (most likely due to contamination with modern carbon). The final age-depth model, with outliers removed, is presented in Fig. 6. The overall sedimentation rate (on average 0.55 cm/year) is fast relative to rates observed in reservoirs at similar Angkor-period settlement sites, which range between 0.04 and 0.18 cm/year (see Penny et al., 2006, Penny et al., 2007). However, rates as high as 0.62 cm/year have been reported close to the wall of the West Baray at Angkor (Day et al., 2012), despite the low rates reported elsewhere in that reservoir (Penny et al., 2005), suggesting that high accumulation rates are strongly dependent upon material re-worked from the reservoir dykes and sediment focusing within the baray. At Preah Khan, bulk accumulation rates decline slightly after the late 14th century (40 cm depth), coincident with a sustained increase in organic material in the lake sediment, reflecting the expansion of aquatic plant communities within the reservoir. It seems likely that the development of extensive submerged and emergent swamp

<table>
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<th>Sample ID</th>
<th>Depth (cm)</th>
<th>Material dated</th>
<th>Radiocarbon age (14C years BP ± 1σ)</th>
<th>Modelled calibrated age range AD (2σ 95.4% probability)</th>
<th>Modelled median</th>
<th>Outlier?</th>
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<td>Beta-282652</td>
<td>10–11</td>
<td>Macroplant material</td>
<td>270 ± 40</td>
<td>1456–1582 [86.8%] 1628–1670 [8.6%] 1393–1450 [95.4%]</td>
<td>1524 No</td>
<td></td>
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<tr>
<td>Beta-282653</td>
<td>30–31</td>
<td>Macroplant material</td>
<td>520 ± 40</td>
<td>1393–1450 [95.4%] 1347–1394 [0.5%] 1339–1436 [1.0%]</td>
<td>1417 No</td>
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<tr>
<td>OZN549</td>
<td>31–33</td>
<td>Wood fragments</td>
<td>705 ± 40</td>
<td>1339–1345 [94.9%] 1339–1345 [94.9%] 1339–1345 [94.9%]</td>
<td>1398 No</td>
<td></td>
</tr>
<tr>
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<td>31–35</td>
<td>Organic material</td>
<td>593 ± 26</td>
<td>1339–1345 [94.9%] 1339–1345 [94.9%] 1339–1345 [94.9%]</td>
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<td></td>
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<tr>
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<td>35–36</td>
<td>Wood fragments</td>
<td>672 ± 69</td>
<td>1339–1345 [94.9%] 1339–1345 [94.9%] 1339–1345 [94.9%]</td>
<td>1394 No</td>
<td></td>
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<tr>
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<td>85–86</td>
<td>Plant material</td>
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<tr>
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Fig. 4. Lithologies and magnetic susceptibility readings of all cores collected from the baray at Preah Khan.

Fig. 5. Sedimentary characteristics of the stratigraphic layers of Core C1, plotted against modelled age (cal. AD) and depth.
generally decreased over time. Similar proportions of aluminium (Al), potassium (K), titanium (Ti) and scandium (Sc), has geological activities (Cooke and Bindler, 2015, and references therein). The covariance between lithogenic and trace metals from the same source, and that the relative influence of that source decreased as the baray aged. This is unlikely to reflect a shift in the depocentre of the basin, as it is largely dry, and we interpret these changes as a decrease in the volume of terrigenous material sequestered to the basin through time. This interpretation is supported by the concomitant increase in organic carbon. After this transition period (Stage 2) there appears to have been little input of terrestrial material, as the flux of most elements measured decreases dramatically (Fig. 7c).

3.3. Black carbon

Fig. 7b shows that background influx values for macroscopic charcoal were very low, especially for the >250 μm fraction (X = 3.04 cm−2/year−1; mode = 0). In such cases, statistical decomposition of the fire signal into ‘peaks’ derived from fire events in the local catchment and ‘noise’ (the result of low amplitude stochastic behaviour in fire regime and the taphonomy of charcoal) is not necessary (Higuera et al., 2011). Rather, variations above and below the long-term mean value – which we take here to represent the ‘background’ fire regime for each size class – were emphasized by re-plotting the data relative to that mean value (rather than absolute values with 0 as the arbitrary baseline).

The >250 μm charcoal fraction reveals a period of sustained fire activity in the local catchment during Stage 2 (the mid-late 14th century (from 48 to 37 cm depth)), as well as an earlier period of activity of lower intensity during part of Stage 1, between late-12th century and the early 13th century (138 cm depth). An additional single peak occurs in the early 14th century (73 cm depth). Similar patterns are apparent in the 106–250 μm charcoal fraction, with an initial increase in charcoal abundance at the late-12th century AD (from 138 cm depth), with the highest influx values occurring towards the end of Stage 1 and into Stage 2 (early to late 14th centuries AD (83 to 37 depths)).

Microcharcoal influx into the reservoir shows fairly sustained activity throughout the record. Variance from the mean indicates that regional fire activity is generally below the long-term average throughout the 12th to mid-14th centuries. Abrupt increases in regional fire activity are apparent, however, in the early 13th century (129 cm depth), late 13th century (90 to 73 cm depth), and early-14th centuries (56 cm depth). These peaks in regional fire activity are often coincident with peaks in macrocharcoal, suggesting a local catchment response to regional or extra-regional climate forcing.

4. Discussion

The chronology presented here suggests that construction of the baray occurred sometime during or shortly before the mid-12th century AD, and likely no earlier than the late 11th century AD. This result correlates well with stylistic dating of the monuments built upon its banks, which can be used to constrain the possible time period for the reservoir’s construction. The baray was clearly built prior to Prasat Stung, which is situated on top of the western edge of the baray dyke, and either prior to or contemporaneously with Preah Thkol, the island temple located in the centre of the basin. Both monuments were built in the style of Jayavarman VII and are hence associated with his reign between 1182 and 1218 AD (Mauger, 1939). Furthermore, Preah Damrei on the eastern outskirts of the baray, resembles closely the monument Kong Plok built on the eastern edge of the baray at Beng Mealea, a complex possibly associated with the reign of Suryavarman II (1113–1150 AD). Together this evidence suggests the baray construction was completed sometime towards the second half of the 12th century AD.

Human disturbance within the baray’s catchment appears to decrease in stages through the record presented here (Fig. 7a–c). In Stage 1 (between baray construction in the mid-12th century and the mid-14th century), above the underlying substrate and excavation spoil, the rate of sediment influx is relatively high and stable. Organic vegetation in the basin effectively reduced the flux of terrigenous material to the sediment by winnowing these materials from the water column.

3.2. Geochemistry

The flux of lithogenic elements into the basin (Fig. 7c), namely aluminium (Al), potassium (K), titanium (Ti) and scandium (Sc), has generally decreased over time. Similar profiles are evident for the trace metals analysed, including copper (Cu), zinc (Zn), arsenic (As) and lead (Pb). The flux of each element decreases over time after the construction of the baray. In addition, the flux of all elements appears to have declined in two stages; after fluctuating throughout the first two and half centuries levels generally decline in Stage 2 (the mid-14th century (48 cm depth)), and then again to the lowest levels in the record in Stage 3 (beginning late 14th to early 15th century (38 cm depth)) to the end of the record.

Changes in lithogenic elements reflect variability in the input of terrestrial material (Boyle, 2001). In contrast, trace metals can have both terrigenous and anthropogenic sources, including mining and metallurgical activities (Cooke and Bindler, 2015, and references therein). The covariance between lithogenic and trace metals fluxes within the baray core suggests the input of both groups of elements are derived

![Fig. 6. Age-depth model for Core C1, showing probability distributions for each radiocarbon-dated sample (excluding the two outliers, Beta-282654 and Beta-282655). The 1-sigma range of modelled values is shown in dark purple and the 2-sigma range is shown in light purple. Note that the age probability distributions for the boundary ages are modelled, and are not based on radiocarbon sampled material.](image-url)
Fig. 7. a–c: All palaeoenvironmental variables plotted against modelled calendar ages. The assumed year of Angkor abandonment by the royal court and elite is indicated in red. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
carbon is low, and the influx of lithogenic elements from the catchment to the baray is high relative to the rest of the record. The macrocharcoal record similarly remains low through this stage with only isolated incidences of local fire activity that also coincide with peaks in the microcharcoal record (suggesting that they may be the result of regional natural fire events rather than domestic or industrial burning). From the early 13th century, regular inputs of sediment, indicated by a higher accumulation rate and lithogenic element flux, along with the greater influx of trace metals into the basin, all suggest higher levels of human disturbance in the catchment, perhaps reflecting the continuing construction and maintenance of temple infrastructure by the Angkorian Khmer at the zenith of the Empire’s power. Colonizing swamp vegetation may have been actively removed from the baray during this period. Alternatively, higher levels of water turbidity, sustained by ongoing disturbance in the catchment and increased mineral input as evidenced by high lithogenic flux values during this period, may have suppressed macrophyte growth within the baray basin.

In Stage 2, between the mid-14th century and the late 14th century, the lithogenic input and trace metal flux decrease as organic carbon content increases. This is the period when the bulk of the macrocharcoal activity occurs in both size fractions, indicating a rise in local fire activity, presumably related to increased industrial and/or domestic wood fuel use at the site. The colonization of Angkorian temple moats by swamp vegetation, indicated by changes in pollen and spore assemblages and increases in organic carbon in the sediment, has been used to indicate a cessation of maintenance and, in some cases, the abandonment of the temple (Penny et al., 2006, 2007). The increased contribution of biomass to the sediment in the Preah Khan reservoir from the late 14th century may similarly reflect a lack of regular maintenance from this time, but these changes may equally reflect natural hydroseral vegetation succession within the baray.

In Stage 3, bulk accumulation rate, the influx of lithogenic elements and trace metals, and macrocharcoal fluxes, all decline to the lowest levels in the record, from the late 14th century to the end of the record, most probably in the late 15th century. This appears to represent the abandonment of Preah Khan as a viable settlement. Alternatively, it may also reflect the movement of industrial sites further away from the baray.

The results presented here appear to corroborate the findings of recent excavations conducted at Preah Khan. The record of local fire activity in Stage 2 of the record aligns with the results of Hendrickson et al. (2013), who found that periods of iron production inside the enclosure walls occurred during the 11th century but were most distinct between the late 13th and late 15th centuries AD. While the periods of peak fire activity coincide with the broad period of iron production within the enclosure, the fact that the peak probability of this industrial activity is offset from the succession of peaks in fire activity (Fig. 8) could reflect the position of the baray relative to the loci of production. Iron smelting localities within the temple enclosure varied considerably through time (Hendrickson et al., 2013). It is therefore possible that the particulate charcoal record is reflecting spatial changes in production, or domestic activity associated with production, rather than changes in the intensity of production or the size of the population over time.

To distinguish the confounding influence of climate on the fire record, we compared our charcoal record with two pan-regional proxy climate records (a tree-ring-based Palmer Drought Severity Index (PDSI)
record from the southern Vietnamese highlands (Buckley et al., 2010) and a stalagmite δ18O record from central-eastern India (Sinha et al., 2011, Berkelhammer et al., 2010)) (Fig. 8). This comparison reveals that periods of heightened local fire activity do in fact coincide with periods of prolonged drought, particularly at the turn of the 14th century and the period between the mid to late 14th century and early 15th century AD (the so-called Angkor I and Angkor II droughts: Buckley et al., 2010). However, the microscopic charcoal (regional) record lacks a particularly strong response during these periods, which would be expected if large wildfires had been prevalent during this time. This regional fire history, combined with the fact that periods of local fire activity coincide well with the archaeological evidence of iron production and possible occupation within the enclosure, suggests that these peaks in the macrocharcoal record represent episodes of human-induced fire activity coincident with, rather than resulting directly from, a changing climate. It is unclear if prolonged drought facilitated a cultural response that involved increased use of fire for domestic or industrial purposes.

The fact that human-induced fire activity in the local vicinity and industrial activity within Preah Khan both peak after Angkor’s power began to wane (14th to 15th century), but before the abandonment of the capital by the Khmer elite, suggests two main possibilities for the evolution of the use of the site and its relationship with the capital. While Stage 1 clearly represents Angkorian Khmer occupation and maintenance of the site, Stage 2 presents a less obvious picture. Either the increase in local burning is indicative of the continued use of the site by late-Angkor-period Khmer populations, or the informal and opportunistic use of the site perhaps by the iron-smelting groups following the departure of the Khmer and the contraction of territorial control. Given the sharp change in function of the site – from the apparent politico-religious and administrative purposes of the early history of the site (11th to 13th centuries AD) to one of brief and limited industrial iron production – the latter scenario seems most plausible. Furthermore, evidence of iron smelting, while restricted to the landscape external to the temple enclosure, intensifies in scale and distribution inside the complex only after the 13th century AD, and remains limited and sporadic relative to the activity evident in the surrounding landscape (see Hendrickson et al., 2013; Hendrickson and Evans, in press), suggesting opportunistic, rather than strategic shift in the use of this city. Whether Stage 2 represents late-Angkor-period Khmer repurposing of the site or the opportunistic use by forest-based minority groups, the apparent cessation of control by the political and economic elite based at Angkor appears to have occurred prior to the political abandonment of the capital in the early 15th century.

5. Conclusion

Overall it appears that the settlement narrative of Preah Khan is complex and warrants a renewed focus into its archaeological and art-historical record as well as further investigation into its environmental history. While stylistic dating of the temples indicates initial construction of the monuments began in the early 11th century AD, there appears to have been a delay in the construction of the baray by a century or more. The data presented here is coherent with the suggestions made by Groslier (1973) and Hendrickson et al. (2013) that Preah Khan may have been initially established for symbolic and administrative purposes, to establish power in a region strategically important to the Khmer in terms of access to resources and local smelting technology, and/or to mark the eastern extent of the empire. Increased focus on the environmental record – in particular the pollen record – would be beneficial to verify these hypotheses, as the absence of local fire activity during this time is not, alone, sufficient evidence for minimal domestic or industrial activity during Preah Khan’s early history. Questions remain regarding the control of this region prior to the 11th century, and whether trade relationships existed between Angkor and minority groups, such as the Kuay, existed long before the establishment of Preah Khan. If not, it remains to be seen where the Khmer sourced their iron during the early centuries of the empire. By the middle of the 14th century AD construction work had ceased across the Empire and Angkorian influence at Preah Khan waned or changed in purpose, as environmental, economic and political pressures mounted in the capital. The geoarchaeological history of this city does not present a clearly defined sequence of establishment, fluorescence and abandonment, but indicates that Preah Khan was utilised episodically, and appears focused on industrial purposes during and following the decline of the Angkorian capital.

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Appendix A. Supplementary data

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