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A broader view of collapse: Using palaeo-ecological techniques to reconstruct occupation dynamics across a networked society undergoing transformation

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Statement of Originality

This is to certify that to the best of my knowledge, the content of this thesis is my own work. This thesis has not been submitted for any degree or other purposes.

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Date:

Abstract

As a society evolves through varying levels of social complexity, it does so via the growth and fragmentation of networks. These networks can be both tangible (e.g. settlement, infrastructure) and intangible (e.g. socio-political, economic), and operate across multiple spatial scales. City networks, as an example, increasingly comprise our globalised landscape, and most social, political and economic systems today operate across these spatial frameworks. The organisational structure that these city networks develop over time reveals much about the way these networks function as well as their susceptibility to undergo dramatic change in the face of significant stress (such as severe climate change or economic/political disruption). When disruption in these networks occurs, the way these networks transform in time and space can also indicate the nature of the relationships that operated between the primary control centre and secondary cities within the network.

During the Angkor period, between the 9th and 15th centuries AD, the Khmer kingdom extended across the vast majority of Southeast Asia. Within this kingdom, a number of secondary cities and settlements were built and maintained for a variety of purposes, at the discretion of (or at least in association with) the kings who reigned predominantly from the cities of Angkor on the banks of the Tonle Sap. However, the location of the capital often shifted across space, and the ability of each ruler to extend or maintain territorial control across this city network varied. As such, the degree of integration between these Angkor-period cities and the centralisation of the king's control likely fluctuated through time.

Conventional scholarship places the apparent abandonment of Angkor to the mid-15th century AD, when the king and his court, as well as a substantial portion of the urban population, migrated south to cities in the region south of the Tonle Sap. This event traditionally marks the end of the Angkor period and a time of significant transformation in the kingdom, including the assumed abandonment of several key secondary centres throughout the Khmer city network. The timing of these supposed abandonments in relation to the capital has implications for understanding any precursor conditions that may have affected this transformation, including the level of network integration and centralisation of control that operated throughout the Khmer kingdom towards the end of the Angkor period.

Palaeoecological analysis (particularly the analysis of sedimentary, plant microfossil and charcoal remains) provides an innovative approach to reconstructing the occupation dynamics of a series of these secondary cities during the Angkor period and through the transition to the post-Angkor period. The results presented here significantly re-evaluate the conventional histories of two key secondary cities in the Khmer city network – Koh Ker and Preah Khan of Kompong Svay – which in the past have been largely based on inscription evidence and stylistic dating of temple architecture. Low (in regards to both abundance and variability) charcoal levels and the persistence of sparse, secondary forest suggests the maintenance of intensive agricultural land uses at both sites up until the mid-14th century AD. From this time, charcoal levels increase and become more variable, and swamp taxa markedly increase, suggesting a reduction in land use intensity and the cessation of Angkor-period water management techniques. The near abandonment of these centres ostensibly prior to the presumed political abandonment of

Angkor suggests a high degree of network integration and interdependence between Angkor and its secondary centres had been achieved by the end of the Angkor period.

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List of Abbreviations

ASL	**A**bove **S**ea **L**evel
BP	**B**efore **P**resent
CIDF	**C**entral **I**ndochina **D**ry **F**orest Ecoregion
DDF	**D**eciduous **D**ipterocarp **F**orest
EAM	**E**ast **A**sian **M**onsoon
EAq	**E**mergent **Aq**uatics
ENSO	**E**l-**N**iño **S**outhern **O**scillation
ERF	**E**xtra **R**egional **F**orest
IOD	**I**ndian **O**cean **D**ipole
ISM	**I**ndian **S**ummer **M**onsoon (South Asian Monsoon)
ITCZ	**I**nter-**T**ropical **C**onvergence **Z**one
KK	**K**oh **K**er
MDF	**M**ixed **D**eciduous **F**orest
PKKS	**P**reah **K**han of **K**ompong **S**vay
RiF	**Ri**parian **F**orest
SASDTF	**S**outh-east **A**sian **S**easonally **D**ry **T**ropical **F**orest ecoregion
SDTF	**S**easonally **D**ry **T**ropical and subtropical broadleaf **F**orest
SEDF	**S**emi-**E**vergreen **D**ry **F**orest
SeF	**Se**condary seasonally dry **F**orests
SIDEF	**S**outheastern **I**ndochina **D**ry **E**vergreen **F**orest ecoregion
SwF	**Sw**amp **F**orest
UC	**U**n**c**lassified

1 Introduction

"If Indo-China goes..."

"I know that record. Siam goes. Malaya goes. Indonesia goes. What does 'go' mean? If I believed in your God and another life, I'd bet my future harp against your golden crown that in five hundred years there may be no New York or London, but they'll be growing paddy in these fields, they'll be carrying their produce to market on long poles wearing their pointed hats. The small boys will be sitting on the buffaloes. I like the buffaloes, they don't like our smell, the smell of Europeans. And remember – from a buffalo's point of view you are a European too."

(Graham Greene, The Quiet American, p. 119).

1.1 The rise and fall of complex, networked civilisations

Modern society's trajectory of overall technological and economic advancement may foster the perception that growth is perpetual; that we exist in a world with indefinite end. It seems reasonable to assume that persistent technological progress, access to expanding knowledge bases, and newfound energy sources will continue to accommodate growing populations and push society towards increasing levels of organizational and infrastructural complexity. The building of societal complexity ostensibly presents as a hugely successful problem-solving tool, and in its initial stages encourages population surges, human health improvements, the development of social hierarchy, differentiation and specialisation of economic duties, higher degrees of social, political and economic integration, and greater information processing and exchange (Tainter 2006). However, the assumption that such developments are permanent or at least highly durable is incongruent with what we know of complex civilisations of the past, where constant growth and long-term (millennia-scale) stability was the exception, not the norm (Tainter 1988, Turchin and Nefedov 2009, Motesharrei et al. 2014). In the past, collapse or transformation (defined here as a substantial decline in urban and regional populations, a reduction in social complexity and territorial control, and the failure or restructure of economic and ideological systems (after Tainter 1988, Schwartz 2006, Sims 2006, Conlee 2006, Cowgill 1988, Eisenstadt 1988) occurred with remarkable regularity (see Tainter 1988, Diamond 2005 [2011], Yoffee and Cowgill 1988, and references therein). History suggests that complex civilization can simply be a peak stage of societal evolution (Flannery 1972, Schwartz 2006); that sophistication and complexity, once achieved, can, in fact, trigger instability and transformation (Tainter 1988, 2006).

As societies (both ancient and contemporary) develop towards such socio-political complexity, they do so as a result of the growth of networks (Flannery 1972, Castells 2002). These networks are both physical (e.g. tangible infrastructure and communication networks) and abstract (e.g. economic, political, or social networks), are connected by a select number of primary and numerous secondary activity hubs, and foster ceaseless and constantly mobile exchanges that operate over numerous spatial scales (Graham and Marvin 2001). In the modern era, such network development and interplay has been the dominant driving force behind the processes of globalization, and today these increasingly global-scale networks have become integrated to the extent that it is now difficult, if not impossible, to spatially differentiate between one society and the next (Cioffi-Revilla 2006). As such, the expansion of societal networks may have reached a practical threshold, and recent societal growth has come to manifest instead as increases in the density and complexity of these existing networks (Cioffi-Revilla 2006), with potential implications for societal stability (Tainter 1988, Flannery 1972). Given this association between network growth, social complexity, and societal stability, the insights produced by analysing the way in which a civilization has organized itself in both spatial and conceptual space (i.e. the physical and abstract networks upon which it depends), we may better understand both how it functions and the degree of complexity it has achieved. Furthermore, after such a level of complexity has been reached, by following the evolution of this spatial and conceptual organization during periods of heightened, and potentially fatal, disturbance (e.g. political, economic or environmental stress), we may also better understand how and why transformation occurs when it does. In other words, the response of a societal network to a particular disturbance at a particular time should elucidate much about the society in the general.

Such an approach engages with the fact that all civilisations exist as an interconnected network, and that the processes of transformation will therefore be both spatially and temporally interactive. As such, this thesis attempts to analyse a specific case study where it should be possible to discern these interactive processes of transformation – to see how a complex civilisation unravelled as a spatially constructed network. In doing so, this thesis poses several broad questions: what happens to the rest of the spatial settlement network when a major activity hub fails or relocates? And what can the fate of the wider network tell us about the preconditions and processes involved in the transformation? While this thesis will focus on one case study in history, by investigating the more abstract, structural processes at work during the decline of this civilisation we may be able to specify some generic forces that will be translatable to other contexts – in particular to understanding the resiliency of the networked, integrated settlement systems upon which the functioning of modern, industrial society depends.

1.2 The significance of the Khmer kingdom

The complex civilisation chosen as the focus of this thesis is the Khmer kingdom that dominated the Southeast Asian mainland between the 9th and 15th centuries AD. Over the course of several centuries, the Khmers built a vast agrarian society, using extensive hydraulic engineering techniques to overcome a host of environmental challenges. Governed largely from the resource-rich banks of the Tonle Sap, in the capital cities of Angkor, the Khmer constructed a dispersed agro-urban metropolis that became the hub of several networks, both tangible and intangible, that sustained the expanding kingdom. This region of capital centres consisted of numerous religious temple complexes around which village populations congregated, that were integrated together via the extensive hydraulic infrastructure and systems of ideological and economic exchange. These settlement patterns, land management techniques, and systems of incorporation were replicated in a network of secondary cities throughout the kingdom, eventually forming an extensive and highly integrated kingdom connected by networks operating at multiple scales. Congruent with the creation of these functional, spatial networks came the development of several components of socio-political complexity, such as a several-tiered social and political hierarchy, economic and craft specialisation, and military-led territorial expansion, so by the zenith of the kingdom's development a very high level of complexity had been achieved. Despite the success of this system, by the mid-15th century the political elite had abandoned their opulent capital – a move that ostensibly disrupted its political and economic networks, instigating the transformation of the kingdom and its loss of geographic and political dominance of mainland Southeast Asia (Dagens 2002).

Since this event, the mystery of the Khmer kingdom's dissolution has attracted significant scholarly interest. Numerous hypotheses for its transformation have been proposed, some that resonate strongly with contemporary issues of sustainable land and environmental management within a changing climate (e.g. Groslier 1979, 1986, Buckley et al. 2010). Few of these investigations have, however, sought to understand the inherent, structural reasons for the kingdom's vulnerability, nor to untangle the wider geographic or territorial space in which transformation unfolded. There has been an ongoing assumption that the political abandonment of Angkor instigated, or at least occurred concurrently with, a kingdom-wide 'urban diaspora' – the wholesale migration of urban populations from the majority of large Angkor-period cities toward settlements on the periphery of the kingdom, particularly in the region south of the Tonle Sap (see Lucero et al. 2015). This assumption, however, remains largely untested. Part of the issue has been the dearth of preserved archaeological and historical evidence from this pivotal period in Khmer history.

1.3 Traditional approaches to understanding the development and decline of the Khmer kingdom

Primarily, the history of the Khmers in mainland Southeast Asia has been uncovered using a combination of traditional historical and archaeological approaches. Interpretations of the written chronicles (e.g. Vickery 1998, Groslier 2006), inscriptions (e.g. Coedes 1937-1966, Lustig et al. 2007, Lustig 2009), the art-historical record (e.g. Thompson 1997), and material cultural remains (e.g. Pottier 1999, Pottier 2000, Fletcher et al. 2008, Stark 1998, Stark and Allen 1998, Malleret 1959-1963, Dumarcay and Courbin 1988, Evans et al. 2016) form the body of evidence used to decipher patterns of movement, land use and socio-political structure. Inferences of human occupation made from residual physical landscape formations, made infinitely more efficient through advancements in remotely sensed mapping technology, have also recently become influential (e.g. Evans et al. 2007, Evans 2010, Evans et al. 2013, Fletcher et al. 2003, Evans 2016, Evans and Fletcher 2015, Hawken 2011).

As necessary as these techniques are, they are not without issue, particularly in the Cambodian context. Historical records in the region, for example, are often heavily influenced by external superpowers, such as China and India (Vickery 1986), often adopt a propagandist tone, and can be strongly affected by the personal bias or the positionality of the interpreter (e.g. Indianised or colonial intellectual ideologies) (Stark 1998, Vickery 2000). Such records can also concentrate on the events within or affecting the capital centre, and ignore the city region that feeds it, and the fate of regional populations.

A focus on the inscription evidence can also be problematic. Firstly, such evidence presents a strong social bias, as the inscriptions written in the elite language of Sanskrit were written on stone, and thus survived more commonly than those written in Khmer, which were presumably inscribed into materials that perished rapidly in the tropical climate. Secondly, the inscriptions can present a temporal bias. For example, while the territorial extent of Khmer control can be effectively ascertained by mapping the distribution of royal-invested architecture and stone inscriptions (see Lustig et al. 2007), this type of evidence largely documents only the foundation (or reconsecration) of temples, and therefore tends to build models of occupation and population dynamics that are limited to stages of conquest and expansion. Crucially, in the wake of political or economic disruption, the construction of such physical, architectural evidence, as well as the maintenance of other historical texts, tends to become rare or non-existent (Schwartz 2006). As such, understanding Khmer history during its 15th century transformation requires the adoption of a broader, multi-disciplinary research approach.

Stark (1998), for example, has appealed for a more holistic approach to investigations of key historical transitions in Khmer society, arguing for the integration of archaeological and historical perspectives. This thesis argues that a palaeoecological approach should be added to this methodological milieu, especially considering the dependence of the Khmer on their challenging environment and the supposed role of deforestation, ecological deterioration and other pathological nature-culture relations in Angkor's decline (Buckley et al. 2010, Groslier 1979, 1986). Khmer settlements were characteristic blends of the physical and natural, with each city existing as complex mosaics of urban and agricultural land uses (Evans 2007, Hawken 2011, Gaucher 2002), to the point where Hawken (2011) has termed such urban transformation as 'artificial ecology', and Groslier (n.d.) has similarly said that "the city is the Khmer country" (quoted in Gaucher 2002, p.33). The mapping work of Evans et al. (2007) has reinforced these characterisations, revealing that the extent and scale of landscape modification in Khmer settlements, especially during the Angkor period, was exceptional, and therefore should be clearly evident in the palaeoecological record.

1.4 Reconstructing past landscapes – exploring settlement histories through the palaeoecological record

Humans impact the biophysical landscape in many discernable ways; they burn and clear the forests, cultivate agricultural crops, farm livestock, mine the land for metals and other minerals, and excavate waterways and reservoirs (Li et al. 2008). Evidence of these activities is preserved in sedimentary archives, which accumulate in depositional basins such as lakes, swamps and bogs (Last and Smol 2001, Smol et al. 2001). These natural archives capture changes in sedimentary characteristics, pollen and other botanical 'sub-fossil' assemblages, and micro- and macro-charcoal fluxes that, once constrained by radiometric dating techniques, can be used to infer human occupancy in the landscape and the changing nature of land use over time. Indeed the "landscape is a medal cast in the image of its people" (de la Blache 1913, quoted in Herbert and Matthews 2004, p.7).

Plant microfossil (i.e. palynomorphs, or pollen and spores) analyses constitute a particularly important component of these palaeoecological reconstructions, as plant microfossil assemblages reflect transitions in the local and regional flora and broader ecology through time. While such analyses have, for a long time, played a fundamental role in deciphering past trends in temperature and precipitation (Xu et al. 2010, Klemm et al. 2013, Peyron et al. 1998, Li et al. 2014, Maxwell 2001), this tool has also been an effective proxy for human impact and land use (Edwards 1999, Edwards and Macdonald 1991, Li et al. 2008, Andrieu-Ponel et al. 2000, Hannon and Bradshaw 2000). Applying the principles of ecological succession to vegetation changes evident in the pollen record allows for the identification of significant disturbances in the landscape and subsequent periods of recovery and rejuvenation. Li et al. (2008) has outlined a simple model describing the progression of five stages of human impact identifiable in the plant microfossil record (Figure **??**). Pioneering studies by Firbas (1937) and Iverson (1949) initially identified the value of palynological analysis to ethnographic research, however it took advancements in analytical techniques and improvements in the classification of anthropogenic crop and weed species for palynology to become instrumental in archaeological and anthropological research (Li et al. 2008).

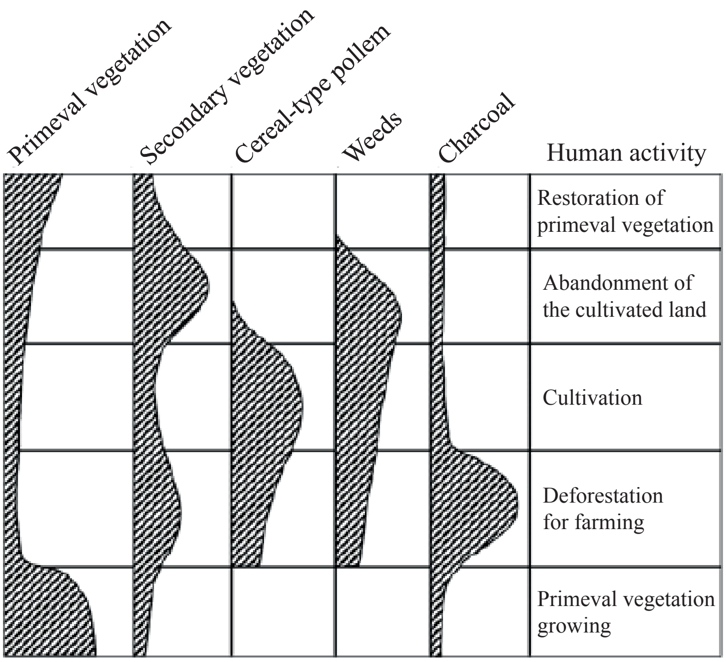


FIGURE 1.1: Expected progressive change in the preserved pollen spectra associated with deforestation of a pristine forest environment for agriculture. Source: Li et al. (2008).

Specifically, plant microfossil analyses utilise a range of indicators to identify human presence in prehistoric landscapes. Tracking declines in arboreal pollen is exceedingly common (e.g. Firbas 1937, Iverson 1949, Birks et al. 1988 and references therein, Hirons and Edwards 1986, White et al. 2004), as is identifying increases in pioneer plant species (e.g. Flenley 1988, Smith et al. 1989, Delacourt et al. 1986) or increased presence of pteridophytes (e.g. Liu and Qiu 1994). Additionally, the introduction of novel or agricultural plant species (e.g. corn, rice, wheat and vegetables) or weeds commonly associated with disturbed landscapes into the pollen record is also often used to indicate human presence and cultivation of the land (e.g. Penny 1999, Pope et al. 2001, Flenley 1988, Li et al. 2006, Maloney et al. 1989). Identifying the potential presence of crop species, while not indisputable (for example it is difficult, but not impossible to distinguish cereal pollen from wild pollen (Maloney 1990, Zeist 1984), and in many parts of Southeast Asia many species of cultivated rice, such as Oryza, grow wild in undisturbed marshland (Maxwell 1999)), is relatively straightforward as the vast majority of cultivated crops comprise species from a limited number of plant families, namely Poaceae, Solanaceae, Convolvulaceae, Umbelliferae, Amaryllidaceae, Cucurbitaceae, Leguminosae, Cannabidaceae, Cruciferae, and Rosaceae (Li et al. 2008). Finally, determining changes (usually a decline) in preserved pollen concentrations or influx (Yang et al. 2005, Whittington et al. 1991) and an increase in palynological richness (Birks and Line 1992) are techniques also employed. Birks and Line (1992) found that an increase in the heterogeneity of the landscape and hence diversity of botanical taxa in northern Europe resulted from human-induced activity, such as deforestation and cultivation. This result however, may not be as applicable to palynological studies in the tropics and subtropics, where the original biodiversity levels of the primary forest are often far higher than in those that dominate the northern latitudes.

However, the relationship between human landscape interference and vegetation succession is inherently complex, and is complicated by other influences, particularly climate (Penny

1999, Li et al. 2014, Novenko et al. 2016). As such, combining the plant microfossil record with numerous other proxies of landscape change can identify human activity more accurately (Li et al. 2008, 2014, Berglund 1991). Combinations of palynological, sedimentological, charcoal, palaeontological, archaeological, radiometric, tephrastratigraphical, geochemical and stable isotopic analyses can aid in deciphering the complex signal of human activity within the context of changing environmental constraints. The expedient use of such multi-proxy and multi-disciplinary techniques has revealed the timing of earliest human occupation (e.g. Antoine et al. 2015, 2016), settlement and migration dynamics (e.g. Cupillard et al. 2015, Vlaciky et al. 2013, Schmidt et al. 2011, Stančikaitė et al. 2013), local adaptation strategies employed during changing environmental conditions (e.g. Semah et al. 2016, Crombe et al. 2011), and the long-term impact of human activity on local ecology (e.g. Kershaw 1994, 1986, 1974) in various Pleistocene and early Holocene communities. These studies highlight that when multiple proxy variables present a complimentary picture of environmental change a more robust interpretation can be achieved. Where these proxy records diverge, this allows for the complexities and nuance inherent in landscape change resulting from human-environment interactions to be uncovered.

The vast majority of multiproxy research, however, is located in the temperate regions of the northern hemisphere. Equivalent research in tropical climates, and mainland Southeast Asia in particular, is significantly more limited (Maxwell 1999). Sediment records from several lake sites on the Khorat Plateau in northeastern Thailand have received particular attention, where multiproxy research spans two decades. Early studies used a preliminary pollen record, in conjunction with phytolith and charcoal records, and compared these records against local archaeological findings in an attempt to identify the onset and development of human occupation and intensive rice agriculture in the region (Penny et al. 1996). Building on this initial work, Kealhofer and Penny (1998), Penny (1999) and White et al. (2004) have used additional or revised plant microfossil data, and additionally compared these records against various climate proxy records (see Penny 1999), to help interpret the cause of vegetation disturbances and changes to burning regimes and agricultural plant species' abundances identified in the record. While these studies have equivocally attributed landscape-scale changes to human impact, particularly since the early Holocene, more recent research at these sites have utilised a suite of additional proxies (carbon content, isotopic data, geochemistry and biogenic silica) to focus increasingly on the climatic forcing of lake characteristics and its surrounding environment (Chawchai et al. 2013, 2015, 2016). Elsewhere on the mainland, palynological and charcoal studies in mangrove landscapes near the Gulf of Thailand have – similarly to the early NE Thailand research – interpreted abrupt increases in charcoal and Poaceae pollen as tentative evidence for the instigation of land clearance and rice cultivation in the region (Maloney 1991, Maloney et al. 1989).

However, while palaeoecological techniques have shown great utility in identifying human arrival and settlement in a landscape, evidence of human withdrawal from a settled environment, or significant and prolonged decreases in human population numbers, are less well understood in palaeoecological sequences. While Li et al.'s (2008) framework (Fig. 4.1) provides a theoretical basis, using ecological succession principles, for the identification of human abandonment of the landscape, this concept has been applied only minimally in the literature thus far (e.g. Bishop et al. 2003, Penny et al. 2006). In some cases, where a prehistoric society has relied predominantly on farming, if the land was marginal or poorly managed, soil fertility eventually depleted, to the point of weed infestation and crop failure (Li et al. 2008). In such an eventuality, communities would be forced to migrate to new regions and the fallow land would be left to rejuvenate (Li et al. 2008). In the Cambodian context, in those communities which employ swidden-agriculture techniques, land abandonment can be evidenced by a shift from mature dipterocarp forest to a degraded dipterocarp forest, where a dense layer of secondary shrubs and climbers proliferate throughout the understory (Boulbet 1979). For communities in landscapes more amenable to flooded and bunded field rice cultivation techniques, and where large, permanent water storage basins were present, land abandonment or repurpose can often present in the palaeoecological record as a transition through an initial phase of secondary forest expansion and regrowth taxa into a decline of charcoal production and local colonisation of floating vegetation and/or swamp communities (see Bishop et al. 2003). This type of evidence has been used to decipher periods of decline or reorganisation, and the abandonment of land management protocols common to the Angkorian period, in the Bakong temple district in the Rolous region (Penny et al. 2006) as well as in central Angkor (Penny et al. 2005). Such research is being used to re-evaluate conventional narratives of Khmer history, in particular revealing that the sequence of events surrounding the political abandonment of Angkor is likely more complex than previously assumed.

1.5 Study aims and thesis structure

In order to explore the transformation of networked society in the event of significant disturbance, this thesis aims to decipher the spatial response of a complex, networked civilisation following the abandonment of its social, political and economic centre. It has the following overarching aims:

- to determine the spatial dynamics of transformation in the broader city network of a complex society, following significant disruption in the network, for example the removal of an administrative or economic capital
- to explore what these dynamics reveal about how these city and settlement networks operated mechanistically, and what makes a complex, networked society vulnerable to collapse or transformation

In order to answer these overarching aims this thesis will endeavour to complete the following objectives:

- to reconstruct the palaeoecological histories of a series of peripheral cities within the broader Khmer kingdom, from the initial construction of each city, and throughout the kingdom's transition into the post-Angkor period surrounding the political abandonment of Angkor
- to infer population dynamics from these palaeoecological histories in order to determine the occupation history of each regional centre, and ascertain the timing of their abandonment, where possible, or any evidence of resiliency or reuse
- relate the spatial sequence of abandonment throughout the city network to the literature on the processes involved in societal transformation, in order to better understand the operation of the city network prior to the abandonment of the capital

The remainder of this thesis will be structured as follows; Chapter 2 will begin with a review of the literature regarding the development of networks in both past and present societies, and how these networks form a framework for the development of socio-political complexity. This chapter will also discuss how eventually this complexity can promote vulnerability to destabilisation and transformation or collapse, and how instances of social or material collapse have been traditionally approached in the literature. The chapter will conclude with an argument for a new approach to collapse and transformation studies and will outline, in more detail, the specific questions central to this thesis.

Chapter 3 will present an overview and analysis of the literature relating to the history of the Khmer kingdom as a complex, networked society. This history is largely the result of over a century of (predominantly French) scholarship in the region, and is predominantly based on analyses of historical text, temple inscriptions, art-historical interpretations of temple monuments, and various other archaeological investigations. The literature review will also present the sparse information we have regarding the transition of the kingdom into the "middle period" or post-Angkor period Cambodia and identify why this period is of importance in understanding the decline of complex civilizations in general.

Chapter 4 provides the historical and environmental context for each city analysed and its broader region. Chapter 5 outlines the numerous methodologies and materials employed in this thesis. Chapter 6 will present the results of the palaeoecological analysis for each peripheral city, and Chapter 7 will synthesise these results and integrate the histories of each peripheral city to construct a new narrative for the transformation of the Khmer kingdom, with a focus on the spatial dynamics of abandonment or reuse throughout the city network.

The final chapter, Chapter 8, will discuss this spatial sequence of city abandonment and kingdom transformation in the context of the theory introduced in Chapter 2, in an effort to elucidate the workings of the kingdom's city network and to identify possible precursors to collapse/transformation. The chapter will conclude with an overall summary of this thesis and identify opportunities for future research.

To clarify, references to the 'Khmer civilisation' throughout this thesis refer to the Ankgor-period Khmer kingdom, unless otherwise specified.

2 The growth and decline of complex civilization as a broad-scale, settlement network

2.1 Introduction

This chapter will provide a review of the literature relating to the evolution and stability of complex civilisations as networked systems. It will begin by describing the networks that exist in both the globalized landscape of the modern era, as well as those that existed in pre-industrial societies, in order to illustrate the dependency of urban sustainability on the maintenance of city (or settlement), communication, economic, and political networks. The chapter will then highlight the correspondence between network growth and the evolution of social, political and economic complexity and centralization that exists during the development of a civilization. Following this will be a discussion of how this concomitant development of socio-political complexity, network complexity and power centralization may have limits, in that a high degree of complexity may eventually induce conditional instability in the networked society. A review of the traditional city-scale, causal-mechanism approaches taken in studies of civilization 'collapse' will follow, along with a justification for a new approach. This new approach will need to better capture the population dynamics of the broader-scale city network prior to, during, and following the disruption of any sustaining communication, political or economic networks. Finally, the chapter will argue why past, networked societies are worthy of this kind of study, and will provide a chapter synthesis outlining the overall conceptual model that will be applied in subsequent chapters. Through the application of this new model, a greater understanding of the inherent vulnerability of city networks that exist within complex socio-political and infrastructural networks can be achieved.

Certain terminology used often in the chapter, and used interchangeably in the literature, first requires definition. Henceforth, 'settlement' will refer to any inhabited space at the village, town, city or city-state level, while 'settlement system' (the synonym of which is the 'networked society') will refer to the entire configuration of a civilization and its spatial configuration of settlements in conjunction with its many functional or institutional networks. 'Settlement network' refers to the physical, spatial configuration of individual settlements within a society, while 'city network' will refer to a network of only the larger settlements, namely the primary or primate city and its major secondary, satellite centres.

2.2 The contemporary landscape as a networked society

Networks appear frequently throughout nature and human society (Barabasi 2002, Aloy and Russell 2004, Boccaletti et al. 2006). As human individuals, we exist because of intricate networks of biochemical processes, we function as a result of complex and intertwined neural networks, and we work and cooperate within broad networks of social and utilitarian relationships. Networks upon which society depends can comprise tangible objects in Euclidean space, such as water and electric power grids, the Internet, or highway or subway systems. Alternatively, they can be more relational and abstract, such as acquaintance networks, collaborations between researchers, or power hierarchies. They can also incorporate both, as in the emerging 'enterprise networks', or in the 'networked city' paradigm (Castells 1996, 2002). As a result of their prevalence, particularly in the social sphere, the geography of networks has become the new social structure (Castells 1996, 2002), and as such it is becoming increasingly clear that understanding the world requires understanding networks.

An increased understanding of the geography of networks will be of particular utility to analyses of urban sustainability in our world of exploding megacities, sprawling urban agglomerations and conurbations, and 'global' or 'world cities' (Friedmann 1986, Sassen 1991 [2001], 1995). Cities (and nations) no longer exist in isolation, but rather function within expanding networks that operate within and across local, transregional and transnational scales (Gottmann 1990, Dematteis 1994, Castells 2002, Portnov and Schwartz 2009). As such, Marull et al. (2013) have remarked on the imperative to reframe sustainability policy, and the research that directs it, toward a new geographic scale – the level of the megaregion (or, in other words, a network of cities and their low-density hinterlands). Particularly in this Information Age, complex patterns of interaction are emerging, where traditional space and time constraints become increasingly irrelevant (Graham 1999). Maintenance of this new way of organising inhabited space will clearly require intimate knowledge of real-world network functioning.

2.2.1 Local and regional scale urban agglomerations

In the beginning of last century, a number of prominent urban scholars and philosophers, among them Patrick Geddes, H.G. Wells, Peter Kropotkin and Ebenezer Howard, predicted that the increasing centralization of the industrial metropolis, which was the dominant model of the city of the early 20th century, would start to reverse, in that the functions formerly monopolized by the metropolis would soon be shared by whole regions. These predictions soon became manifest, as the residential zones of cities and towns began to spill outward beyond the city centre, leaving a core business district surrounded by a suburban fringe (Gottmann 1961). This was simply the first phase of decentralisation, and its continuation has led to the decline (and sometimes renewal) of the original downtown and the growth of 'edge cities' or suburban CBDs (Garreau 1991, Ingram 1998). These peripheral economic hubs are created when back offices, corporate plazas, research and development and university campuses, retail centres, airports and logistics zones shift away from the centre until it becomes difficult to differentiate centre and periphery amongst the blanket of fragmented and interconnected business districts, industrial zones and high- and low-density neighbourhoods.

As a result, the 20th century has seen vast agglomerations of urban development and their peripheral settlements begin to eclipse large sections of the landscape (e.g. the "megalopolis" of the eastern US seaboard (Gottmann 1961), Randstad in northwestern Europe (Kloosterman and Lambregts 2001, Bontje and Burdack 2005), and the southern California 'metropolis' (Scott and Soja 1996, Dear and Flusty 1998). These expanding polycentric settlement networks have been further defined variously in the literature as agglomerations, conurbations, metropolitan areas and urban clusters, differentiated by the organisational and spatial structure of the networks they create (see Fig. 2.1i) (Portnov and Schwartz 2009). Often, where contiguous expansion is not possible or optimal, cities in such collectives have opted for more fragmented development by either parasitising other, pre-existing cities or developing new 'satellite' urban centres remote from their government or economic centre (Graham and Marvin 2001, Sieverts 2003, Hawken 2011), illustrating how the growth of (and interaction between) these city networks can occur across local and regional scales. Indeed, Taylor et al. (2010) have called for new processes to be recognised to explain these variable interactions: 'town-ness' for the relations that exist between a city and its local hinterland, and 'city-ness' to describe the more complex relationships that develop between cities of the broader city network.

In light of such transformation, a World Bank Report (Gill 2009) has recently called for the recognition of a new reality for today's urban environment – that of a 'portfolio of places', consisting of a linked urban continuum, beginning with the primary city at one end, and followed by a series of settlements of varying size (Hawken 2011). The seemingly boundless expansion and interconnectivity of these systems in the landscape has suggested to Richard Skeates (1997) a coming dawn of the "infinite city", where the traditional notion of a city as a "limited and bounded structure" is no longer relevant (p. 6). And while such grouping of interconnected cities may not be a particularly new phenomenon in urban history, it is the intensity, speed, power and reach of those connections that has come to change so dramatically in the last few decades or so (Castells 1996, Graham 1999, Wheeler et al. 2000, Graham 2002), creating new urban models that rely heavily on network utilisation.

2.2.2 Globalised networks

On a broader scale, vast global networks have also developed as individual cities and their local networks interact with larger centres and institutions further afield. The resulting global landscape presents a "system of relations which develop in a space of flows" (Dematteis 1994, p. 17), where cities are connected to multiple networks simultaneously, both physical and virtual, at a variety of levels that no longer conform to traditional hierarchical notions of scale (Sassen 1991 [2001], Graham 1999, Castells 2002). Some have argued that such a system can weaken the identity and autonomy of individual cities, as the strength of the overarching, multinational network/s they interact with (often dominated by large, well-branded commercial, political, religious or scientific organisations), overshadow any localised sense of place, worth and power (Dematteis 1988, 1994). Castells (2002) has similarly identified a new, transnational powerhouse existing at this upper level (that he has termed the "network state" (p. 552)), which he suggests comprises the network of national, regional, and local governments, NGOs and other international institutions under which most organisations and management authorities operate. Any links established to these regional or global networks can, however, be transitory or occasional, and thus seemingly unstable, and depend on both the internal and external dynamics at play (Dematteis 1994). And paradoxically, it is not the size or scale of the component in such a network that necessarily determines its functional significance. Instead it is actually the cities themselves within these networks that retain the most influence, on account of their relative intractability and specificity. As a geographically and materially constrained node in a fluid and unrooted global network, its reliable supply of specific and localised goods and services can increase the city in importance compared to the more regional players such as the overarching political state (Dematteis 1994, Storper 1997). In such a process, political legitimacy is diminished at the state level, and any amount that remains is often shifted to the city (Castells 2002). This suggests that, in the event of disruption or dissolution of overarching political or economic networks, the cities themselves may be likely to persist to a relative degree. Considering this, the functioning and sustainability of these highly populated centres will surely come to increasingly depend on an understanding of the dynamics of the networks in which each settlement exists.

The development of global city networks or the transformation to a megaregion is generally attributed to the growing and more geographically concentrated demand for water, energy, and other raw material resources (Galantay 1975), as well as accelerated improvements in transport and communication services in many post-industrial, globalised information societies (Graham 1999, Castells 2002). Practical spatial and material limits to the development of cities may also be responsible (see Fletcher 1995, 2012), evidenced by numerous megacities falling far short of their growth projections (Pearce 2006), as issues of overcrowding make it less viable to continue development within discrete city boundaries and more efficient to create new towns or establish relationships with cities beyond their borders (Fouchier 1998, Pearce 2006). These links build economic relationships between complementary centres, and encourage economic specialisations to emerge (Marull et al. 2013). The associated divisions of labour and shared innovation result in economic efficiency gains for all centres involved (Pred 1977, Camagni 2005). In addition to a merged economy, other social and natural phenomena, such as pollution and landscape conversion, become shared (or externalised) as a result of megaregion development (Marull et al. 2013). These shared economies are made possible by inter-urban technological infrastructure networks, comprising telecommunications, computing grids and convergent media modules, which allow interaction between centres that defies any geographic or time-zone disparity (Graham 1999).

An important consequence of these developments has been the shift in the role of today's dominant cities. These centres no longer simply dominate, or, for that matter, serve their hinterlands, but rather provide a physical location for the coordination of economic activities and function as an interdependent component of greater settlement systems. The concentration of communication infrastructure that is required for interaction between these coordination hubs leads to significant technological improvements in efficiency, innovation and resiliency, particularly at these hub locations (Graham 1999). Inevitably, this leads to increases in internal network complexity as well as the compounding of the dominance of these hubs over their less well-equipped neighbours (Graham 1999). Such regional dominance leads to greater competition on a global level and the ability to connect to ever-higher, planetary-scale networks (Graham 1999). The consequently enhanced reach engendered by these new connections demands even greater and more complex communication networks within and between these global hubs, thus generating a reflexive cycle of increasing network complexity at all scales. Given the dependence of these connector cities on their own internal and hugely complex infrastructure networks to maintain their position and effective operation within ever-increasingly complex global-scale networks, the long-term security and sustainability of such a 'networked society' is perhaps worthy of question.

2.3 Networked settlements of the past: patterns of growth in complex civilisations

Stepping back from the contemporary global landscape, networks are also evident (and somewhat easier to isolate) in the pre-industrial landscape, as many past societies have developed, simplistically, towards greater complexity in their evolution from bands, tribes and chiefdoms to complex states. While the social, economic, cultural and environmental drivers behind this kind of development in a complex society are highly variable (and often multivariate) (Adams 1966, Wright 1970, Flannery 1972, Allen 1997a, Flannery 1999), at least one commonality in the process is the evolution of a particular component structure – that of a network with nodes and linkages. Such network development is not static, but continual and dynamic, as more networks emerge at various scales over time and each network increases in complexity. The 'networked society' is not a new phenomenon.

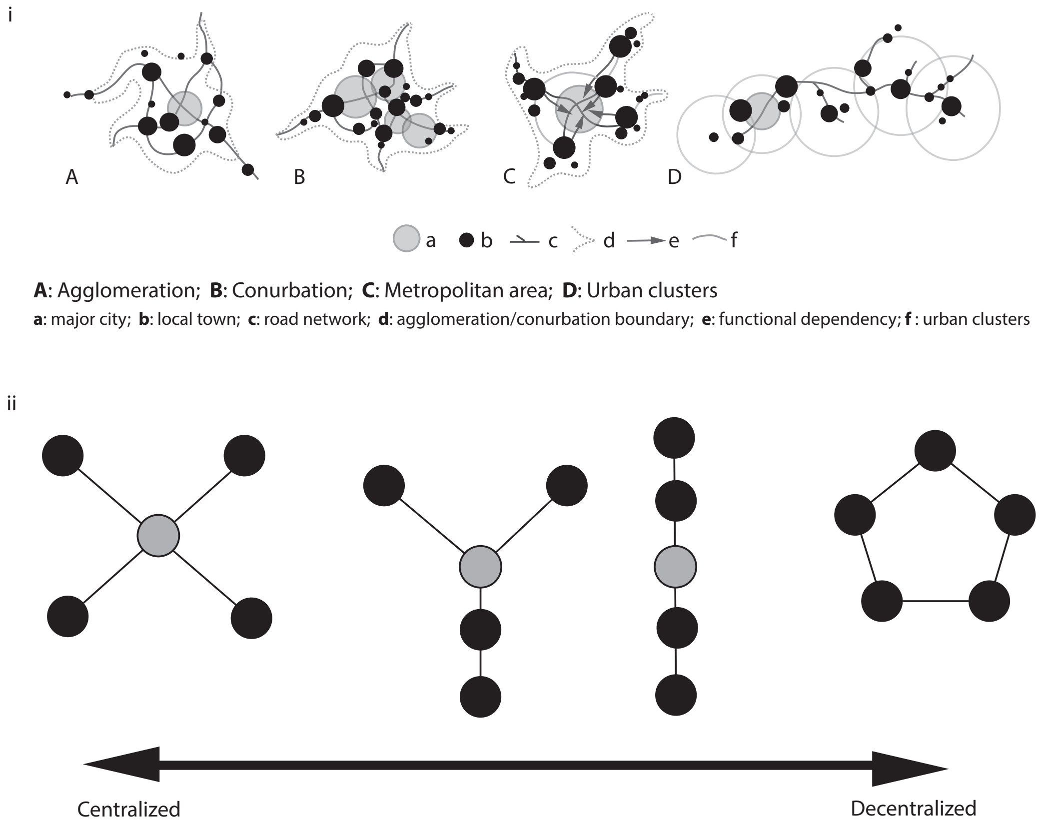


FIGURE 2.1: Examples of conceptual settlement network structures from the literature. **Top:** Portnov and Schwartz's (2009) conceptual diagrams of the various configurations developed by polycentric urban settlement concentrations. Each different structure eventuates as a result of contrasting developmental processes. **Bottom:** Borgatti et al.'s (2009) generalised network structures depicting the continuum of political centralisation. The most central node is illustrated in grey.

2.3.1 Components of the past networked societies

Within a networked society, the individual structural components of the network can take many forms. Nodes can be rest houses, shipping ports, resource and service hubs, individual actors, family or tribal units (Hage and Harary 1996, Schweizer 1997), agricultural sites (Tobler and Wineburg 1971, Smith 2005), small villages, ceremonial centres or large cities (Hendrickson 2007, Munson and Macri 2009, Hendrickson 2011); essentially any entity that accommodates or precipitates significant economic, political or social activity (Lowe and Moryadas 1975). These nodes maintain certain flexibility, however, and their significance or utilisation can transform over time, dictated by the changing needs of the evolving society (Hendrickson 2007).

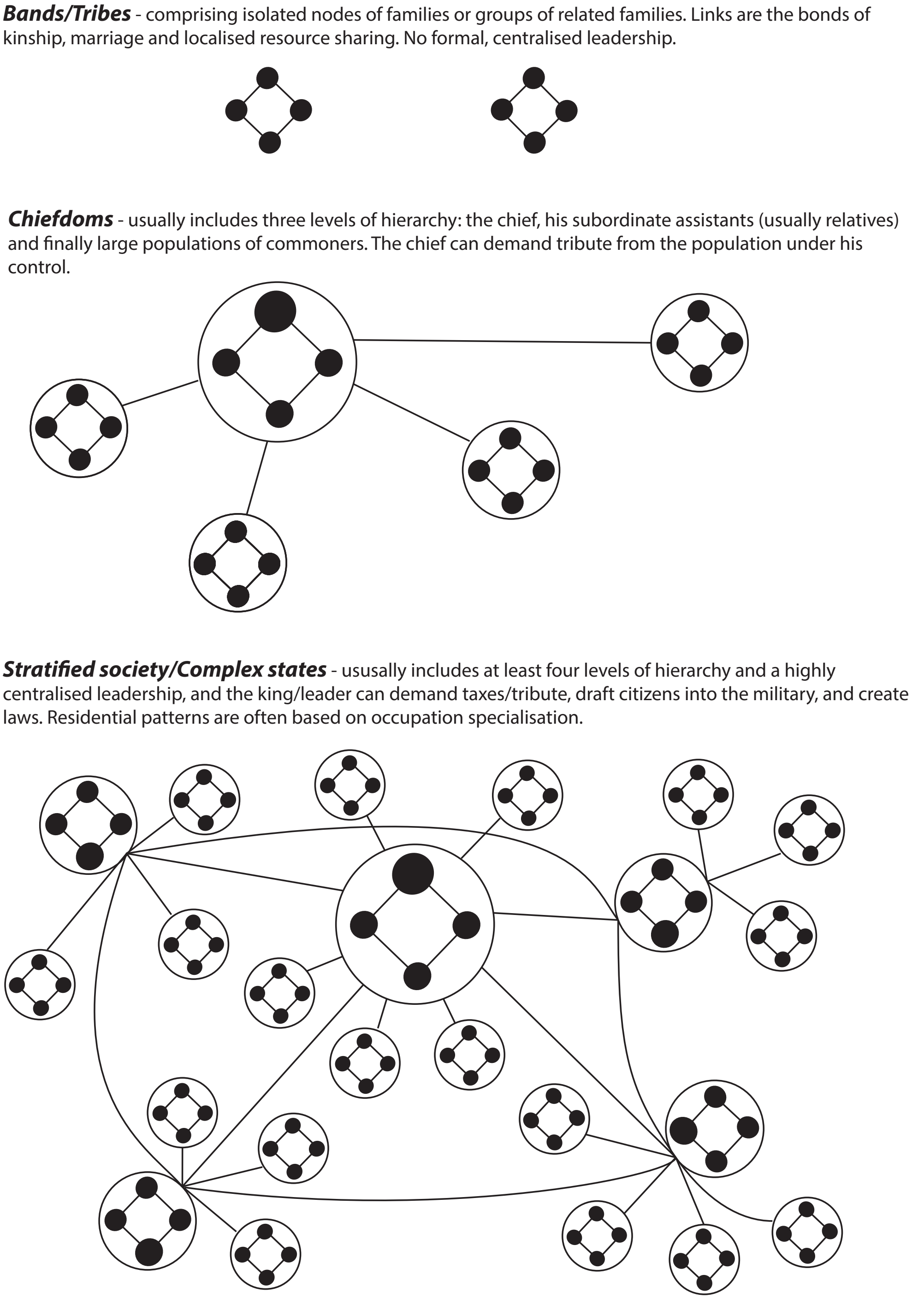
Linkages can be tangible or abstract, and can include the physical bridges that join two or more nodes together, usually manifesting in the pre-industrial landscape as roads or rivers and canals (Hendrickson 2007, 2011), or less tangible pathways, such as ocean trade routes which may be normative or customary. They can also exist as abstract relations, such as kinship ties, tribute demands or obligations, and ideological influence (Munson and Macri 2009). Regardless of their form, these linkages facilitate the transfer or sharing of material goods, services and information between the interlinked centres, and can be as transient or adaptable as the nodes they intersect (Lowe and Moryadas 1975).

Figure 2.2 shows a very simplified model of how these networks might grow through the process of socio-cultural evolution. Flannery (Flannery 1972, 1999) and Marcus and Flannery (1996) outline how most large, politically centralized states developed over time from a series of competing, smaller chiefdoms, as one among the series grew in power and united its neighbouring polities under its domain. How these chiefdoms or states themselves developed has been debated; where some believe early chiefdoms were the product of peaceful and theocratic redistribution networks (Service 1962, 1975), other models attribute chiefdom development to military conquests instigated by a large village polity and the incorporation of neighbouring villages under the leadership of a head chief (Wright 1984, Johnson 1988, 1988, Carneiro 1992, Anderson 1994). Following chiefdom development, any incidences of continued evolution towards a pristine state have been linked to the development of a bureaucracy, thus allowing for the expansion of territorial control (Wright 1977, Spencer 2010). Nonetheless, with each proceeding step, smaller, previously existing settlement networks may present as nodes in the larger-scale networks they join into during societal evolution, while potentially maintaining their internal proximity-based networks in the process. These new nodes may become important regional centres, as previous village-based networks are usurped and absorbed into more stratified socio-political networks (Sjoberg 1960), and provide an intermediary node linking small-scale villages back to the capital.

This process can develop in a relatively simple, linear fashion (Carneiro 1992) or can take a more cyclical course, where regional settlement agglomerations oscillate between simple, segregated, sub-chiefdoms and more complex, hierarchical groupings (Wright 1984, Johnson 1988, 1988, Anderson 1994). However, irrespective of the process, at each developmental stage, from isolated village through to interactive statehood, the interconnectivity of the network grows; individual polities create networks with surrounding polities, before creating or connecting into broader-scale networks if circumstances are conducive, and so on. This, of course, represents only one model of societal development, with an overall progression towards complexity and a clear pyramid of hierarchy, perhaps best suited to the development of isolated, dominant kingdoms. The historical record presents a litany of alternative cases, most notably the large Mycenaean polities, or the small city-states of the Aegean and the Cyclades, or the capitals of the Mayan Lowlands. These societies instead developed as a conjunction of interacting and roughly equally powerful entities in what Renfrew (1982) has labelled 'peer-polities' and Price (1977) calls 'clusters'. Despite this, the premise still stands that the majority of settlement systems develop some form of networked architecture in their progression toward greater complexity (e.g. Flannery 1972, Munson and Macri 2009).

2.3.2 The parallel growth of the settlement system and socio-political complexity and/or centralized control

Similar to the varied spatial patterns that develop in modern settlement clusters (Portnov and Schwartz 2009), the structural pattern created by these pre-industrial interconnected nodes and links varies according to the size, function, connectivity, and political structure characteristics of the society they represent (Taafe and Gauthier 1973, Robinson 1977). These network configurations can be instrumental in facilitating certain kinds of interactivity and reveal insights into socio-political structures and the level of centralized power operating in the network (Borgatti et al. 2009) (Fig. 2.1ii). For example, where a single node takes strong precedence over all others in a network, a radial or wheel structure will likely develop, and represents a social group with highly centralized power dynamics. Alternatively, in networks where the dominance of each node is more evenly distributed, the resulting structure may take the form of a grid or circle or something similar, and will represent a more decentralized group (Hendrickson 2007, Borgatti



Bands/Tribes - comprising isolated nodes of families or groups of related families. Links are the bonds of kinship, marriage and localised resource sharing. No formal, centralised leadership.

Chiefdoms - usually includes three levels of hierarchy: the chief, his subordinate assistants (usually relatives) and finally large populations of commoners. The chief can demand tribute from the population under his control.

Stratified society/Complex states - ususally includes at least four levels of hierarchy and a highly centralised leadership, and the king/leader can demand taxes/tribute, draft citizens into the military, and create laws. Residential patterns are often based on occupation specialisation.

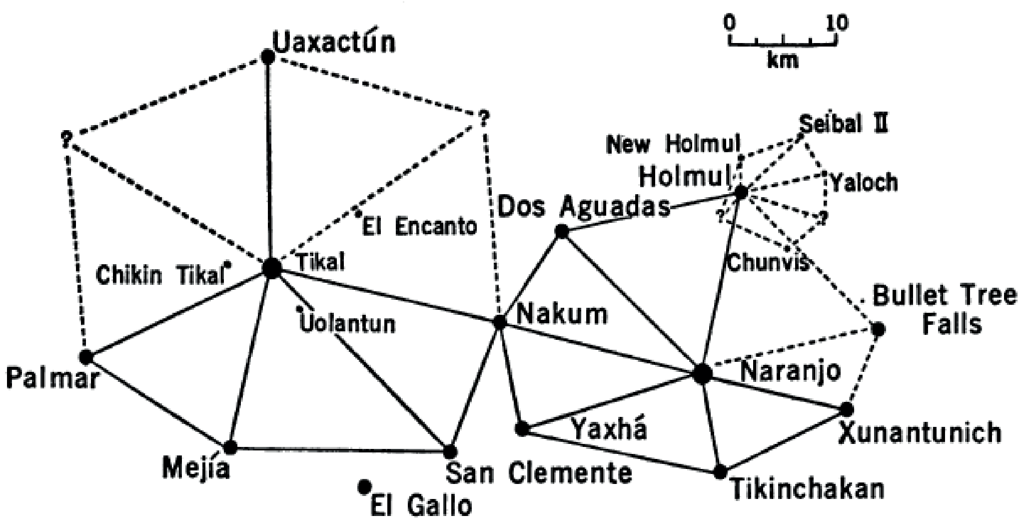
FIGURE 2.2: The conceptualised development of settlement networks in a pre-industrial society along the trajectory towards social complexity and centralised power.

et al. 2009). This demonstrates how merely a rudimentary reconstruction of the overarching network structure of a settlement can elucidate useful information regarding the nature of the society.

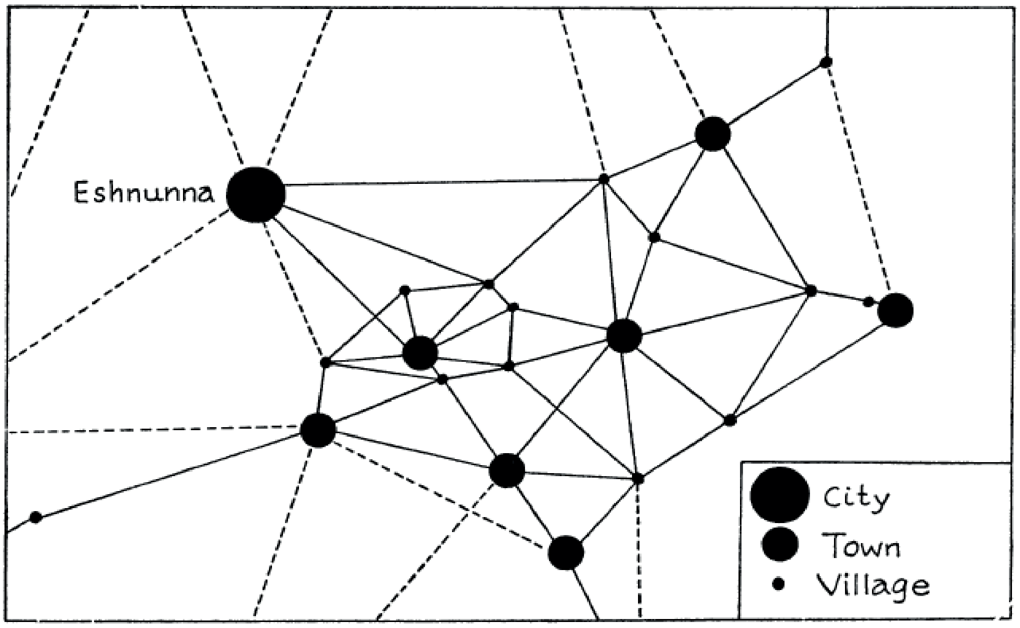
A potential corollary to the radial, centralised network structure is a hexagonal lattice model that developed predominantly in the 1970s literature to demonstrate socio-political centralization in the settlement configuration of ancient societies (e.g. Flannery 1972, Johnson 1972, Marcus 1973). These studies mapped the major population, political, and/or economic centres in conjunction with satellite, secondary centres of ancient Mayan and Mesopotamian civilisations, and found patterns in the placement and distance spacing of these settlement networks. In these cases, when (in certain, ideally flat areas) settlement configurations developed hexagonal (or, sometimes, rhomboidal) lattices in the landscape, with equidistant spacing between settlement nodes, this revealed that a fundamental shift had occurred in the evolution of the society (Johnson 1972, 1975, Folan et al. 1995). Such a shift represented the transformation of a simple society where considerations of terrain, water and resource accessibility, and defensibility determined the choice of settlement location, to a complex society where the settlement configuration was also influenced by access to economic, administrative or ceremonial service networks. As these settlement networks evolved from a heterogeneous, landscape- and resource-dependent configuration, settlement patterns gradually homogenized due to the increasing influence of overarching, landscape-independent (or less-dependent) service functions (see Fig. 2.3). Before the appearance of the hexagonal lattice city network, the society was likely loosely integrated and comprised a one- or two-tiered socio-political hierarchy, whereas the adoption of a systematic settlement configuration suggests the transition to a more integrated, complex polity with centralized control and three, four or even five levels of hierarchy (Johnson 1972).

An alternative method to predict socio-political hierarchy in a settlement network is the use of rank-size distributions (or site size hierarchies) (e.g. McAndrews et al. 1997, Duffy 2015 and references therein, Evans et al. 2016). This method assumes that plotting the size distributions of ranked cities within a society will produce a model that suggests the level of vertical and horizontal integration that exists between individual settlements (i.e. socio-political centralization and inter-settlement dependence). If the plot generates a log-normal distribution, this indicates that a single, politically dominant primate city exists and maintains a series of subordinate cities of decreasing size that interact with each below it (high levels of vertical and horizontal integration). If a concave distribution is created, this society also likely comprises a dominant, primate centre, but little interaction exists between it and subordinate settlements (high vertical and low horizontal integration). Finally, if the rank-size distribution takes on a convex shape, it is likely that each settlement in the society is relatively autonomous and maintains minimal socio-political interaction (low levels of vertical and horizontal integration). Berry (1964) additionally maintains that, while primate or concave distributions will be the more common (or natural) development, if a long period of urbanism persists in the society, eventually the log-normal distribution will appear.

Neither the lattice model nor the rank size approach has avoided criticism, however. The mathematics proposed in the hexagonal lattice model (in particular the equidistant spacing and angles created by the lattice) has been questioned (see Romanov et al. 1974), and the model's close coincidence with the tenets of Central Place Theory (Christaller 1933 [1966]), which eventually fell out of favour among urban geographers (see Taylor et al. 2010), has prevented its broad-scale adoption. Moreover, in many applications of the hexagonal lattice model, the explicit connections linking each settlement to each other are often poorly defined or based on limited epigraphic evidence, and appear to be dependent largely on proximity. The rank-size distribution model has also been criticized for assuming that complex hierarchical relationships can



Hexagonal lattice patterns in the structure of Mayan Lowland settlements (600-900 AD). Central nodes represent regional capitals, with secondary settlements organised around the periphery. How a tertiary-level hexagonal lattice may develop from a secondary settlement and its surrounding villages/hamlets is also shown. Links between settlements are based on royal marriage alliances. Diagram is reproduced from Joyce (1973).



Hexagonal and rhomboidal lattice patterns in the structure of settlements of the Early Dynastic I on the Diyālā Plains, Iraq. Links between settlements are assumed based on transport potential and stylistic similarities in artefact assemblages. Diagram is reproduced from Flannery (1972), and is based on the work of Johnson (1972).

FIGURE 2.3: Examples of hexagonal and rhomboidal lattice settlement network patterns.

be identified via a single variable such as settlement area or population size (Taylor et al. 2010 and references therein, Peterson and Drennan 2012, Duffy 2015), without also empirically identifying power relations between hierarchical tiers (Lukermann 1966, Taylor 1997). When only settlement size is taken into account, the centralization of political power can be overestimated (Duffy 2015).

Nonetheless, it remains broadly accepted that a basic spatial-hierarchical arrangement of settlements holds for most societies (Taylor et al. 2010), and can be indicative of socio-political evolution. However, it needs to be clarified that this arrangement only represents partial evidence of socio-political hierarchy and complexity. The main evidence demonstrated by these models, aside from the existence of a spatial hierarchy of settlements that maintain a relatively large, potentially functional nucleus city, is that there does appear to be a crucial point in the evolution of a society where settlement network patterns shift. At this time, the locations of individual settlements become less influenced by topographical or environmental constraints or favourability, and become increasingly selected based on their relation to a place of central administration or the needs of a centralized control. Such a transition implies (but does not, alone, prove) an increasing level of socio-political organization and more broad-scale, territorial control of a particular centralised power.

Once a radial or hexagonal settlement pattern has developed in a society, as an additional measure of socio-political complexity and power centralisation, the increasing complexity of each material and relational network emerging within a society as it moves along its evolutionary trajectory could be mapped. As the spatial scale of a society expands (i.e. as the spatial-hierarchical arrangement of settlements develops), and more nodes are added to the network, there should be a concomitant increase in opportunities for relational networks, which make use of these physical settlement networks. For example, as villages grow larger and more regionally important, they attain greater opportunities to develop or tap into broader trade networks (Chase-Dunn et al. 2006), or as a political centre expands its territorial domain it may need to instigate new ideological administration networks to maintain control (Spencer 2010). Figure 2.4 is a modified version of Flannery's (1972) depiction of the cultural evolution of societies, which outlines the types of societies in ascending order of socio-political complexity and their associated institutions. Added to this table are the possible new networks that may be introduced (and the old networks that may be sustained) at each level of socio-political complexity. Such a model illustrates the correspondence and interdependency that exists between network and socio-political complexity in societal evolution. Essentially, material/spatial and relational networks develop as the framework for the development of socio-political complexity, and hence the existence of both types of networks needs to be demonstrated.

2.3.3 The development of primate centres and their control of the network

As territory is expanded spatially and new networks are created, individual nodes can increase in importance relative to others in the settlement system. This is the development that settlement network structure theories (see above) rely on and can potentially demonstrate, because this imbalance is how social hierarchies develop during territorialisation, i.e. the organization of a settlement system. Consider, for example, that in a complex chiefdom, three levels of hierarchy exist – the chief, his related assistants, and the common villager (Flannery 1999). As territory expands during the transition to statehood and greater levels of socio-political complexity, a capital centre may develop and will assume a fourth hierarchical level (Wright and Johnson 1975). Such top-level, primate centres are then preferentially linked to other nodes in the settlement system. Political administrations within these primate centres will then seek to initiate new institutions and ideologies to accommodate the changing power relations between

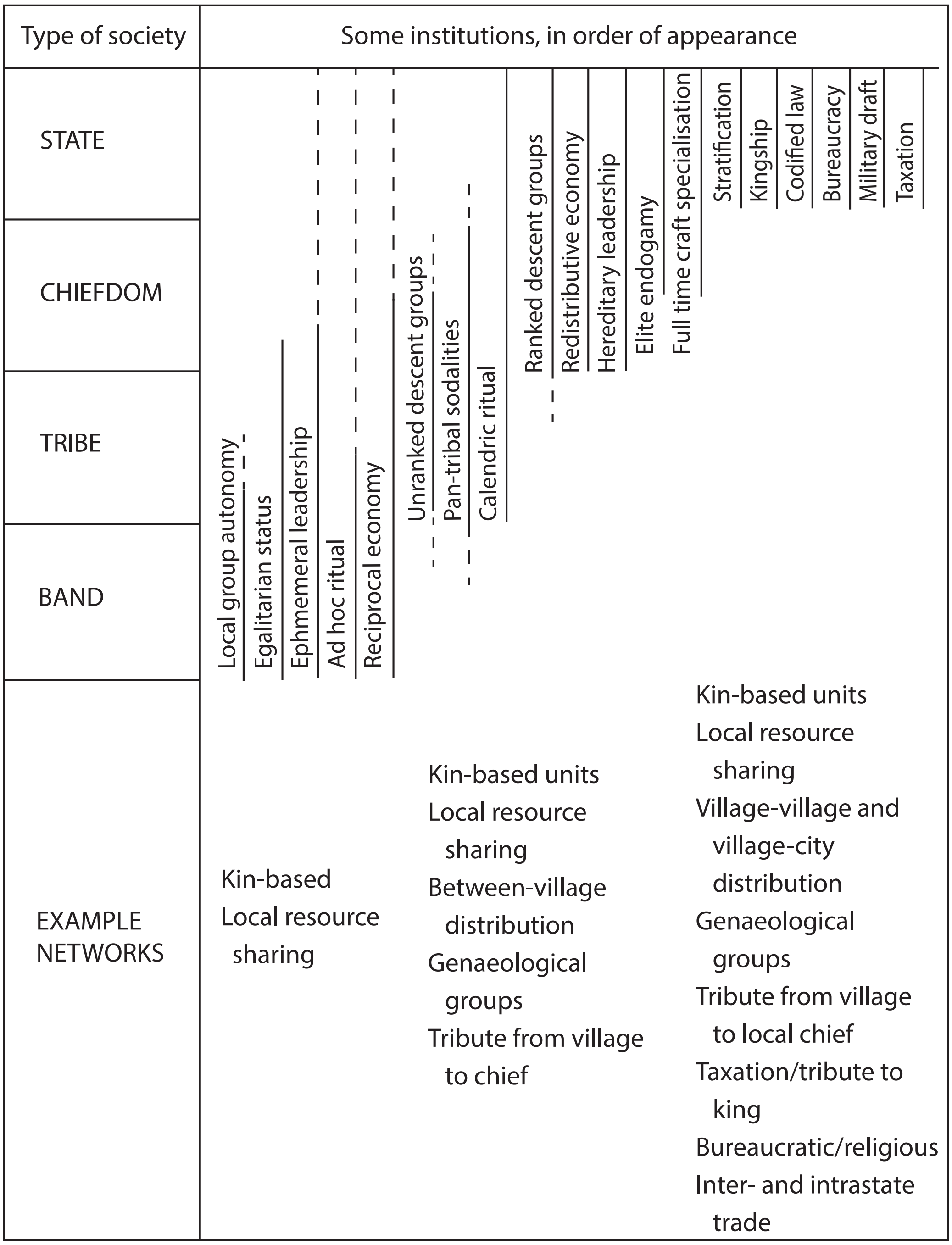


FIGURE 2.4: Potential networks that can develop in conjunction with socio-political complexity development. Modified from Flannery (1972).

nodes of different weighting and to administer over an expanding territory and resource base (Spencer 1998, Flannery 1999, 2010).

How, and to what extent, this administrative control is achieved depends largely on a variety of political, economic, military and ideological mechanisms disseminated via both physical and social networks. Economic power mechanisms usually relate to the networks created to administer and collect tribute levies or other taxes, or to control trade and labour forces (D'Altroy and Hastorf 1984). Political power is embodied in the relationship network created with officials and other elites who maintain peripheral settlements in the kingdom or empire. The strength of these connections can be variable, depending on pre-existing political arrangements, the susceptibility of the remote officials to subjugation, or the importance of the specific region to the elite (Sinopoli 1994), and could take the form of official appointments and resettlement, ideological or cultural authority, the bestowal of a spouse, or the presentation of prestige gifts (D'Altroy 1992, Sinopoli 1994, Yoffee 2005). While economic and political power relationships are generally considered the most effective for regional control (D'Altroy 1992), they are often utilized in conjunction with military (the maintenance of armies and defense infrastructure in strategic locations) and ideological (connections to deities or influential past rulers to legitimize the supreme power of the king and his court and the consequent social inequalities) mechanisms (Sinopoli 1994).

Such power relationships were imperative in settlement systems that were too large to control from a single central base. Territorialisation is managed by creating physical networks in space – with decentralized nodes established in regions strategically important for a particular control mechanism, usually near resource and production bases or heavily populated towns (Hendrickson 2007). Here, for example, political officials can be housed, human labour coordinated and mobilized, and tribute, taxes and resource surpluses stored and redistributed (Schreiber 2001). However, the practical efficacy of these networks at maintaining control over such vast territories is uncertain. For example, Chase-Dunn et al. (2006) argued that the actual level of control Mesopotamian leaders had over their periphery was limited, and Sutcliffe (Sutcliffe 1993) maintains that unilateral economic and social dominance of a major city over its periphery is untenable. It is possible that the level of control fluctuated with the needs of the capital, for example, during times of scarcity the elite may attempt to extract ever-greater amounts of resources from its subject groups, while in times of abundance they may allow local leaders more autonomy. The extent and level of centralised dominance may also depend on the current motivations of the elite, for instance whether or not they are in expansionist mode, or they may depend on the satisfaction of subordinate groups and the likelihood of revolt. Practical limitations, such as distance and the quality of transport and communication links, may also be an impediment (Sinopoli and Morrison 1995). In summary, whatever form it takes, centralised control of the network is rarely absolute, and is likely patchy in space and dynamic though time.

2.3.4 The territorial network as a settlement system

Economic control and ideological imposition is often not the sole outcome of such network development, however. While there is little doubt that primate cities provided a physical location for the coordination of the spatially extensive activities that allowed the settlement system to function as a whole, the idea of a dominant centre being serviced by its vassal communities (in a unilateral relationship) can be misleading. Instead of these networks creating fixed, autocratic links between the centre and its territories, Sutcliffe (Sutcliffe 1993) argues that these central political and administrative centres should instead be viewed as co-existing and functioning within "complex spatial systems" (p. 4), where both the capital and its outposts are dependent on each other, and both are dependent on the settlement system in general. System stability persists when the needs of both the core and its periphery are being met (Eisenstadt 1969). Thus the networks created for control purposes simply generate the backbone of a dynamic, interactive settlement system. This particular system integrates the physical networks (cities, villages, transport links, irrigation infrastructure etc.) with the relationship networks (economic, political, military, ideological or a combination of these) within a context of the geophysical landscape, climate and extra-regional socio-politics, to create the machine that sustains the society as a whole.

This concept of 'society as a system' has been presented, in a variety of ways, by innumerable scholars. Following Bertalanffy's (1968) initial classification of social science as the "science of social systems" (p. 195), undoubtedly the most influential work is that of the political economist Immanuel Wallerstein (Wallerstein 1974, 1979, 1987), who describes historical systems as 'complex systems' and believes that a conjunctive understanding of both the 'historic' as well as the 'systematic' is required to fully grasp world history. He famously categorized the various historical 'world-systems', based on the raw goods and materials production and exchange networks, that existed between culturally disparate societies (Wallerstein 1974) and strongly supported the idea that the relationship between a core polity or country (in this context a developed nation) and its periphery (a developing nation) was elemental in the generation of intersocietal systems (Wallerstein 1979). Underlying this body of work was his proposition that there are systemic laws, based on structural dynamics, which governed operation of these world-systems (Wallerstein 1987). These theories were closely echoed by other, largely political scientists, particularly Andre Gunder Frank (2004) with his 'theory of dependency' and John Crosby (1986 [2004]) with 'eco-colonialism', who both described situations when disruptions in power dynamics between a centre and its interconnected polities led to dramatic social, economic and ecological responses at a regional scale.

Joseph Tainter (1988) describes similar structural dynamics in societal-scale social systems, but introduces the idea that, during upward sociocultural evolution, each system response to change has the compounding effect of further increasing socio-political complexity (or the degree of network interconnectivity). Tainter explicitly defines the sociocultural evolution of a society as the "interlinking growth of several subsystems that comprise the society" (1988, p. 119), and therefore, as a society increases in complexity it does so as a system, and thus behaves like a system when change occurs. That is, when one or more interlinked components of the system are modified, the rest of the system responds accordingly. Each network is nested within the system to the degree where systemic interaction comes to depend on each component's connections to the network (Chase-Dunn and Grimes 1995). To illustrate, if an administration decides to increase agricultural output, change might be required in the farming facilities (such as the physical irrigation networks). To oversee these improvements, as well as to deal with the increased resource and distribution loads that eventuate, investments in bureaucratic and administrative personnel networks would occur in response. This would lead to increased populations or even the creation of new regional centres, followed by further increases in agricultural and resource extraction to support these population increases, plus potential increases in military assets to protect these growing regional centres. Such a picture also reveals the effect of positive feedbacks that can initiate unexpectedly as a result of the nonlinearity of system behavior (Fraser 2011). This may continue ad infinitum or until some limit or threshold is reached, at which point irreversible change and restructure across all tangible and intangible networks may then ensue (Tainter 1988, Bar-Yam 1992, Kauffman 1995, Fraser et al. 2003). Irrespective of the outcome however, at all points in the process, the system behaves as a whole.

Of course, human systems are more complicated than other systems in nature partly because of their inherent scope – indeed Bertalanffy (1968) evoked human history as the "widest possible application of the systems idea" (p. 195) – and partly because they are influenced by the complexity introduced by uniquely human behaviours such as purpose-based decision-making, extensive forethought, and the desire to extract meaning from life's pursuits (Straussfogel and Schilling 2009). Indeed the 'world-systems' models have been criticized for being too economically deterministic and thus failing to account for characteristic human behaviours and agency (Brumfield 1983, Flannery 1999). However, the settlement system/network society can still present an insightful and relatively predictable representation of a social system and say much about the overarching, universal processes at work (Aloy and Russell 2004), in large part due to one of the most distinguishing behaviours of systems – the tendency to self-organise without intent (Levin 1998). So while individual human components exhibit intent in their daily activities, and affect the system in doing so, the settlement system itself is committed to certain organizational laws and thus does not exhibit intent itself (Walker et al. 2004).

2.4 Linking network complexity to socio-political vulnerability

Peter M. Allen (1997b), in his analysis of cities and regions as internal dynamic and organizing systems, describes settlement systems as being naturally adaptable and 'resilient', however, he qualifies that this adaptability has its limits. While even substantial perturbations can have little effect on the stability of a system during its growth, the system can eventually reach a critical point where it becomes conditionally unstable, and small, chance fluctuations have the ability to cause networks to unravel, leading to significant declines in the connectivity and functioning of the system overall. Butzer (1980) attests to a similar vulnerability in centralised social systems, maintaining that overarching, nonproductive control structures can often overextend the subsystems that support it in order to meet short-term production goals. However, according to Butzer, under such highly centralised leadership, these production systems will inevitably deteriorate and cause system collapse. He adds the caveat that some of the advantages of complex civilisations, for example technology, administrative capabilities and resource exchange, can delay a society's arrival at this critical threshold of instability, until a point where a series of (often intersecting) internal and external events can destablise the weakened system and lead to decline.

Many other examples of complex societies with a heightened vulnerability to collapse exist in the literature. Joseph Tainter (1988, 2006) presented a thorough outline of why the continued development of complexity can eventually become problematic for a society. Tainter begins by accrediting the gradual development of social complexity to persistent and successful problem-solving, occurring at local and regional to international scales. These solutions are generally economic in nature, and so affect institutional and organizational networks, and are characteristically cumulative. They may include, for example, expanding the size or specialization of bureaucracies, increasing taxes, exploiting a new resource, expanding into new territory, investing in infrastructure, or improving the military (Tainter 1988). These demand higher allocations of personnel, greater amounts of information processing, higher capital costs, and greater integration of previously disparate organizational networks (Tainter 1998). Increasing or maintaining complexity is a problem-solving strategy applicable to various challenges, from maintaining status in the face of a hostile neighbour, to dealing with recurrent drought, or quelling civil or political unrest, and is ostensibly very effective. Over time, however, these increasingly complex institutional structures become more costly to maintain, and while initially these solutions may have resulted in a good return on investment (i.e. they solved the problem with minimal outlay), eventually returns diminished. A civilization may thrive on complexity, but complexity is a costly enterprise (economically and environmentally) (Batabyal and

Nijkamp 2009). Eventually a civilization may have no other choice (and Tainter emphasizes that this can be a conscious choice) but to transform and simplify through down-scaling and restructure (Tainter 1988, 2006).

Other researchers have also attempted to divorce a complex society's fate from its external circumstances and instead accredit instability to a society's inherent socio-political condition or structure. Rappaport (1977), Flannery (1972), and Dunning et al. (2012) have alluded to the idea that, as a settlement system grows and its subsystems and networks (be they material or relational) become more tightly interconnected and hierarchical, the inherent stability of the civilization will decline. This, they reason, is due to the self-sufficiency sacrifices that subsystems make when they become increasingly interlinked with the broader network and are forced to relinquish autonomy and specialize. With the consequent increases in interdependency between the component parts, losses in diversity and flexibility, and inertia within the material realm (Fletcher 1995), any disturbance will have ramifications that propagate throughout the system. Large nodes can become dependent on much smaller degree nodes in the network, increasing vulnerability further (Buldyrev et al. 2010, Barthelemy 2011). Moreover, when the effective functioning of the integrated settlement system depends on the control of a few (or a single) major city nodes, swathes of spatial area become vulnerable to the potential failure of that control (Buldyrev et al. 2010). Spatial dominance and close cooperation may be the hallmarks of a prosperous society, but there seems to be a limit, after which they may be the very traits that cause destabilisation, fragmentation or collapse.

2.5 The decline of socio-political complexity

2.5.1 The proliferation of 'collapse' studies

The collapse of complex societies has always held both popular and scholarly attention. However around the 1980s this attention accelerated, and since has barely lost momentum. This increased interest was largely a response to the long-held focus in archaeology and anthropology on the processes of growth and development of society, and the implication that the story of social evolution was over once complex civilization arose (Yoffee and Cowgill 1988). Collapse theorists sought to disprove this assumption. Among these investigations there are those that focused on the collapse episodes of single civilisations, while others compiled a variety of ill-fated histories and through comparison sought to find germane patterns in the narratives that track the demise of these grand, dominant societies.

Moreover, what the majority of collapse studies sought to achieve was the identification of the causal mechanisms responsible for collapse. The results have been manifold and diverse, and have led to intense debate (e.g. McAnany and Yoffee 2010). Enemy invasion and takeover was often cited in early works (e.g. Bury 1902 [1927], Briggs 1951, Bronson 1988), but more recently theories based on physical environmental variables and internal political dynamics have become prominent. Climate change, in particular, appears regularly. Numerous instances of collapse or transformation have been attributed to shifting climate patterns and the consequent impact this has on sustaining crop production systems (e.g. Bell 1971, Hodell et al. 1995, Gill 2000, Weiss and Bradley 2001, Peterson and Haug 2005, Buckley et al. 2010, Yamoah et al. 2017). Poor land and resource management has also been extensively cited (e.g. Groslier 1952, Abrams and Rue 1988, Wilkinson 1997, Shaw 2003), as have the social tensions generated by the over-centralisation of government and the ensuing injustices of a highly stratified society (e.g. McAnany 1995, Marcus 1998), while others assign blame to a destabilizing mix of multiple, interacting social, environmental, and economic factors (e.g. Chew 2006, Diamond 2009, Butzer 2012, Dunning et al. 2012, Turner and Sabloff 2012, Kaniewski et al. 2013).

The most well-known compilation works in this area sought to resolve some of this debate by using comparison to generate regional (or global) explanations for why collapse occurs when and where it does. In most cases however, these theses have simply reiterated the multi-causal hypothesis at greater length. Jared Diamond's (2005 [2011]) popular book isolates five major factors that he believes contribute to collapse, which he defines as a "drastic decrease in human population size and/or political/economic/social complexity, over a considerable area, for an extended time" (p. 3). These factors include environmental damage or degradation, climate change, hostile neighbours, reliance on friendly trade, and finally the success of the societal response to environmental problems. Diamond argues that an overall theme existed among the societies that he examined, namely that poor decision-making in the face of crises, particularly those that were recurrent or especially insidious, was at the core of why some societies failed where others did not. Such patterns of bad decisions at critical moments, Diamond maintained, gave the impression that collapse was a 'choice', or at least something that could be actively avoided if threats and their consequences were anticipated, understood, and effectively acted upon. Diamond's book received sustained criticism however, largely based on his implications that selfishness in decision-making (the 'tragedy of the commons' concept) is applicable to all cultures. Critics often further remarked on the irrelevancy of many of Diamond's arguments to our modern society, highlighting that problem-solving in the pre-industrial world was severely hindered by technological restraints that do not exist today (McAnany and Yoffee 2010).

Joseph Tainter's (1988) scrutiny of a collection of failed states produced a different, more specific hypothesis. While he too listed a litany of underlying mechanisms that work to destabilize a society, including, but not limited to, resource overuse, catastrophic events, ineffective crisis response, hostile invasions, relationships with other complex societies, social conflict and breakdowns, and the collision of unfortunate circumstances, his overarching thesis supports a fundamentally economic explanation to collapse (see section 2.5 above) – which he defines as a fundamental and pronounced decline in socio-political complexity taking place within two or three generations (p. 9). Tainter suggests that, particularly if governmental support from the general populace is waning, in the absence of governmental initiative, collapse becomes a statistical probability – increasingly likely over time as stress becomes insurmountable. He makes the caveat that such economically-induced collapse is not always assured in such circumstances, but will only occur when the society exists in a power vacuum. If not, the declining marginal returns scenario will likely serve to merely increase the vulnerability of the state to a much slower political decline or military takeover from a proximal regime.

What this body of work has been successful in accentuating is that socio-cultural evolution is not unidirectional; it continues beyond the achievement of complexity in pertinent ways. Societies do not continually expand as a general rule, and reaching complexity may instigate processes of instability as much as stability (Yoffee 2006). Collapse research has shown that the decline of socio-political complexity is clearly dependent on a wide variety of cultural, environmental, political and economic forces that, due to intrinsic differences in geographies and/or technological capacities (for example), will not be universal. While this means that comparative, diachronic studies are often avoided in favour of synchronic analyses of individual societies, both approaches contain inherent heuristic and practical value and should be (judiciously) embraced. Cross-cultural studies can identify possible patterns and repeating vulnerabilities that may be applicable to multiple, specific contexts (Trigger 2003, Yoffee 2005), while the specific case study approach can augment these multi-case studies, by supplying the thorough dissection of each society's complete evolution and history that is required for effective cross-cultural comparison. Moreover, only through such in-depth, focused analysis can some of the nuances of decline be uncovered.

However, it is the focal point most regularly adopted in these studies that has become somewhat stale; that is, the fixation on the social, political, physical environmental or cultural mechanisms that precipitate decline. Undue attention to these distinct and circumstantial factors, or 'context stresses', while vital, is a very mechanical, reductionist way of regarding and analyzing these scenarios (Allen 1997b). While this approach can decipher the various and changeable factors that influence the stability of a settlement system, it can conceivably ignore the workings of the system itself (i.e. the degree of settlement network integration and interdependency). While no amount of political and network stability can protect a society from truly calamitous events (such as severe and prolonged drought or other environmental disasters), it is a settlement system's internal, structural interplay that can buffer a society against less severe disturbances, and, importantly, determines a society's response to more serious events and/or socio-political decline (Kolata 2006, Sims 2006, Butzer 2012).

2.5.2 Reconsidering 'collapse': the spatial and temporal dynamics of socio-political network disruption

'Collapse' has been defined almost as many times as it has been studied. Most researchers, however, identify a number of broader processes that should take place in order to classify the decline of a civilization as a 'collapse'; the different opinions that surface mainly regard the pace and scale over which these processes occur. Socio-political declines generally need to be substantial, in that urban centres are either partially or completely abandoned, regional populations significantly diminished, complexity and extent of influence reduced, and economic and ideological institutions usually have failed or been reconstructed (Cowgill 1988, Eisenstadt 1988, Tainter 1988, Conlee 2006, Schwartz 2006, Sims 2006). Overall, collapse generally denotes the devolution of society from something "more complex and larger to something else that is less complex and smaller" (Yoffee 2006, p. 222), following the rupture of centralized power and the subsequent breakdown of relations between a capital and its peripheral regions (Sinopoli 1994). In line with Yoffee's definition above, Tainter (1988) testifies "collapse…is not a fall to some primordial chaos, but a return to the normal human condition of lower complexity" (p. 198).

Picturing 'collapse' as an endpoint to socio-cultural evolution can also be misleading, however. Often these evolutionary trajectories of societies were punctuated by multiple 'collapses' (Adams 1988, Yoffee 1988, Sinopoli 1994), as rulers of varying proficiency came and went, or circumstantial stresses lead to the fragmentation of settlement networks and the oscillation between different levels of sociocultural complexity (Marcus 1998). With each resurgence of socio-political hierarchies, however, new rulers were prone to significant recycling of the material remains and relationship networks, perhaps with utilitarian or ideological modifications (Smith 2005), lending a false sense of continuity to the society's development.

Overall, the central tenet of these arguments is that 'collapse', when it occurs, rarely occurs in totality (McAnany and Yoffee 2010). Usually, purported instances of total collapse are only apparent, and actually mask continuity in underlying populations, or spatial heterogeneity in the degree and timing of depopulation and institutional decline (Graffam 1992). More accurate definitions of collapse, which describe the transformation from complexity to simplicity, inherently imply that a residual population and a degree of societal structure will remain in the landscape (Marcus 1989, 1992). Sometimes, in subsequent generations, the society is able to regroup and return to the pursuit of regional dominance, while at other times they remain fragmented. At this point of final decline, the devolution of the settlement system – the severing of ties from an overarching control entity – may seem appealing to lower order subsystems. Especially if power at the highest level has been weakened in some respect, and regional population centres become free to establish or return to autonomy and self-sufficiency without retribution from above (Cooper 2006, Nichols and Weber 2006). Henceforth unable to reliably secure the necessary resources from its territory (Sinopoli 1994), the declining centralized institutions, in these situations, often abandon their bureaucratic systems and supporting infrastructure (Yoffee 2005). Therefore, 'collapse' more often than not, in reality denotes the restructuring of the institutions that connect and organize networks of settlements and populations (Nichols and Weber 2006), and while some institutions will fail (if they haven't already) as a result of this restructure, many others may survive (Yoffee 2006).

2.5.3 Beyond collapse: transformation following disruption

As such, it is becoming increasingly clear that studies into societies that experience disruption following disturbance need to expand their temporal and geographic scope. Until recently, the aftermath of 'collapse' had received limited attention, likely due to the persistent (but largely baseless) assertion that the post-collapse landscape is a culturally degraded one, and represents the dawn of a 'dark age' for the region (Kolata 2006, Schwartz 2006). There have, however, been some recent attempts to rectify this, some of which have been compiled in a volume edited by Glenn Schwartz and John Nichols (2006). This compendium reviews a variety of cases where 'collapsed' pre-industrial societies have undergone a period of regeneration or transformation. These authors found that post-collapse processes could be incredibly complicated and protracted, and could engender a range of outcomes, either the re-establishment of sociocultural complexity – either closely resembling that of the pre-collapse society (Bronson 2006), or as a transformed, but reminiscent, political, cultural or socially structured form (Conlee 2006, McEwan 2006, see also Isendahl and Smith 2013) – or the total abandonment of all that entailed the original complex state (see also Yoffee 1988, Sims 2006).

In Schwartz and Nichol's (2006) review a number of authors attempted to identify the precursor conditions that influenced the nature of transformation, post-disruption. The pathway a post-disruption society will follow, they argued, depends on a myriad of social, economic, political, cultural and environmental influences working on residual populations and institutions (Kolata 2006). Some of those influences were decidedly external, for instance, the opportunity (and wherewithal) to connect into new or existing international trade networks, while others were more internal, and politico-cultural. Elsewhere in the literature, researchers have attempted to explain the resurgence of a polity as being dependent on other external factors, for example favourable physical environmental conditions such as climate (Lieberman and Buckley 2012). However, isolating only one external variable such as this, among an array of influential variables, is likely to be highly problematic and result in the dissemination of misleading narratives, the kind that Flannery (1972, 1999) terms 'just-so' stories – liable to generate a relatively tidy argument for a particular case, but miss the nuances of what is, in most instances, a very complicated story, and hold little relevance to cases elsewhere in space and time.

Kolata (2006) attempts to instead capture the internal variables, as a component of these complicated narratives, in his theory of the nature and likelihood of transformation following disturbance or collapse. In those instances in history where social complexity is reestablished, and the reemerging polity returns as a "faithful copy" (Bronson 2006, p. 140) of its predecessor, he believes the strength and pervasiveness of legacy power principles, structures and relationships are responsible. In these cases, the pre-disruption society exercised control over its territories often through techniques of 'orthodoxy', which resulted in 'hegemony and sovereignty' relationships with subject populations. Here, state development and expansion had originally occurred through the establishment of direct control relations managed by a centralised government, through political, economic and/or military means. These state structures implemented tactics that, over time (multiple generations at least), culturally absorbed every facet of daily life for communities under their purview. These tactics could include powerful ideologies or the rule of law, which were spatially disseminated with the help of the extensive physical presence of prominent and symbolic religious and military infrastructure. These religious monuments were usually architecturally contiguous to those of the state capital, providing a constant and tangible link back to the system of sovereignty. Other examples could include enforced taxation or other revenue collection, seizure of local land or natural resources, or public displays of extreme punishment against insurgents. Of course, such centralised control required constant and costly administration and surveillance of sometimes defiant peripheral territories, but the physical remains of this administration, in addition to the written, oral or artistic records that was often the fruit of such administration, provided the familiar physical and cultural template upon which the transforming society could build (see also Bronson 2006). Kolata (2006) also believed that it was this long-term pervasion of state ideals and authority that fundamentally reshaped local cultures and value systems (not necessarily consumed, but at least became strongly hybridised with existing local ways and eventually naturalised) and provided a path of dependency for residual populations in the wake of state political or economic disruption.

Alternatively, there are cases where social complexity does not reemerge in the aftermath of state disruption or collapse. Instead, new, less centralised forms of independent socio-political and economic structures replace previous overarching systems (Sims 2006). Kolata (2006) suggests that such an outcome indicates that a different kind of state governance and structure had been prevalent in the pre-disruption society. This he termed 'hegemony without sovereignty', and proposed that in these states or empires territorial subjugation involved more indirect, soft-power methods. Political and social alliances, friendly trade, jointly acceptable tributary or patronage affiliations (Kolata 2006), or strategic and grandiose displays of wealth and military capabilities (Sahlins 2004) are some examples of the methods that could be employed, but irrespective of how central power manifested, control tactics were generally less autocratic and more demonstrative in nature. As such, the resulting influence on subject populations was less intrusive, less linked to the material landscape, and therefore less transformative. Subordinate populations in these societies may adopt certain practices advocated by their new leaders, or establish advantageous relationships with the political elite, but they will likely retain their local worldviews and cultural integrity. Distance from the grandeur of the capital and its inhabitants is important, so spatially this type of power is also less pervasive. However, the ongoing subversive threat of military takeover or social assimilation is usually strong enough to maintain a level of (surficial, at least) obedience and subjugation in territorial populations. Obviously, such power structures are far less logistical, are therefore less expensive, and require smaller centralized administration systems.

In the event of the breakdown on socio-political structures, however, the lack of physically prominent building blocks (i.e. symbolic and military infrastructure common in 'hegemony and sovereignty' societies) and meaningful cultural transformation in subject populations provides more flexible transformation pathways for the remaining people and systems. When new opportunities for social advancement or local community agency arise during periods of state decline, in the absence of rigid social and political structures, regional non-elite populations may be better placed to exploit them (see also Chase-Dunn and Hall 1997, Morris 2006). In doing so, they may remember the 'old' regimes as strangulating, and favour the creation of either a settlement collective, allowing more localised autonomy, or devolution into disparate and independent polities (see also Conlee 2006, McEwan 2006, Sims 2006). Having been able to maintain diversity in cultural and subsistence systems throughout the years of state control, they have the ability to found a less-complex society (or collection of polities) based on altered social relation systems, reinvented production and economic systems, and cultural plurality. Some aspects of the demised state may resound in the new institutions and structures (for example, the case of the regenerated southern Andes polities, who continued Inca-related farming methods following the removal of centralized authority (Graffam 1992)), but overall a fundamentally unrecognizable landscape emerges.

Finally, there are cases where complex, highly centralized civilisations have ostensibly disappeared, with or without reorganisation into smaller, autonomous settlements. A case observed by Yoffee (2006) is that of the Assyrian empire, which was the dominant superpower during the first millennium BC, but dissolved entirely a few centuries later. Yoffee argues that the Assyrian state progressively increased the centralisation of its control over this time, largely by marginalising local authorities, building the might of their military, expanding into new territory, and expelling conquered populations to the outskirts of the empire. These oppressive methods of control, however, were unsustainable, and when civil war engulfed the attention of leaders and the military, the oppressed raised a resistance, empowering Assyria's enemies to overtake its major cities and defeat the king and his military. The win removed the Assyrian government from power, but because the lower orders of elite – the traditional Assyrian nobility – had been usurped by military leaders and government officials, the entire hierarchical structure dissolved. Functional, cooperative relationships between the local, rural people and their traditional leaders had been corrupted, and so these populations, along with any non-Assyrian elite that remained, felt no impetus to regain Assyrian statehood and the structures that supported it. Therefore, the case can be made that a highly centralized state, one that in Kolata's (2006) terms maintains 'hegemony and sovereignty', can follow two divergent evolutionary pathways after a significant decline of complexity; either towards an ideologically-reprised, second-generation complex state, or towards near-total ideological and political abandonment.

More recently, research focused on the low-density, agrarian societies that prevailed in the tropical latitudes of the past has introduced an additional possible pathway – one that focuses on mobility and relocation as a form of transformation following institutional disruption (Lucero et al. 2015). These authors propose that in the wake of political destabilisation, the large, diffuse urban centres that acted as socio-political nuclei in these societies were largely abandoned, with populations establishing alternative centres in more compact communities on the peripheral regions of the territory. They describe this phenomenon as 'urban diaspora', and document its occurrence in Meso-America, South and Southeast Asia during the medieval period. In these cases, severe climate variability, at pertinent periods in the history of these settlements, destabilized political institutions and the infrastructure on which they depended, leading to large-scale transformations in the regional-scale settlement systems. While this study, once again, highlights the need to reframe 'collapse' episodes as transformations in socio-political structure, territorialisation, and settlement network configurations, care needs to be taken not to make assumptions regarding the dynamics of these changes. For example, in this particular study, the authors presented no evidence for the 'urban diaspora' in several key cities, nor did they consider the differences that may have occurred in the timing of abandonment between major settlements in the system, or the timing of resettlement in the peripheral regions. Also, the 'just so' explanation of climate as a single exogenous force acting to drive societies into transformation, while resonating strongly with contemporary concerns, should be viewed with extreme caution.

These nuances are important. Kolata (2006) and others have indicated that the spatial population dynamics at each interconnected city in regional settlement networks are vital for understanding the internal processes that lead to the 'collapse' or transformation (see also Adams

1978, van Buren 2000). For example, if secondary centres were abandoned prior to, or concomitant with the abandonment of the primate city/political centre, then this may indicate a waning of power in the territories in the lead up to destabilization, and high levels of power centralisation and interdependency within the city network (i.e. high vertical and horizontal network integration). Alternatively, if populations persisted for a significant period following abandonment of the political centre, this may indicate lower levels of interdependency and political centralization within the city network. The spatial patterning of transformation across city-networks, then, can reveal the nature of political control leading up to and during the transformation, and perhaps point to the reasons why the transformation occurred.

2.6 Shifting the focus and increasing the scale of inquiry

Increasing the scale of inquiry is therefore important, as only at a broader spatial scale can the regional variations in settlement response to disruption be captured. In many instances, transformation across a networked society can be protracted and asynchronous, which the Mayan 'collapse' narrative illustrates well. While Lucero et al. (2015) insinuate that populations in the southern plateau relocated to the northern lowlands following severe climate stress and the rupture of major political networks, others have described this narrative more as a case of relative persistence in regional centres (Robin 2001, Peterson and Haug 2005, Dunning et al. 2012). These studies document asynchronous population abandonment across the Mayan territories, with the abandonment of some regional sites being delayed by a century or more (Robin 2001, Dunning et al. 2012). How those more resilient settlements were utilised also varied, with some forsaking the renewal of sacred power institutions but maintaining agricultural use of the site (Lucero 2002, Sabloff 2007), while external, minority group populations overtook other settlements (Webster 2002)(Webster 2002).

The Mayan case study is also important for illustrating how regional variations can reveal significant insight into the circumstances that either led to decline or contributed to persistence. For example, the discovery that northern Mayan agricultural settlements positioned on the lowland Yucatán Peninsula outlasted their counterparts on the southern plateau confounded efforts to understand the decline of the society as a whole. As the decline of the Maya was, in large part, related to the southward shift of seasonal rain-belts, the fact that population decreases were most rapid on the southern plateau, where drought was less severe, seemed counter-intuitive (Peterson and Haug 2005). Subsequent spatial analysis revealed, however, the presence of groundwater reserves that, while extensive across the plateau, were only accessible to the lower-lying northern communities, thus increasing their ability to persist in the face of environmental stress relative to settlements further south (Peterson and Haug 2005, Dunning et al. 2012).

A particularly effective means of broadening the scale of analysis (both in terms of physical space and system detail) is by considering the society as a network of cities integrated by a broad-scale settlement system. The network society paradigm inherently demands an extension of the scope beyond the urban core in order to capture the dynamics of the lower-order settlement nodes that house the subsystems of the network. The settlement network approach will improve on other, geographically extensive approaches, such as the subdiscipline of settlement archaeology, which advocates studying the patterns of distribution of archaeological remains from site to site (Rouse 1972), as it will not only examine a broader spatial scale, but will also, importantly, consider the relationship (or interconnectivity/interdependency) that exists between the primate city and its secondary settlements.

2.7 The rationale behind studying past, rather than present, network societies

> *"Every thoughtful person who ponders the bureaucratic and technological pressures on ordinary life today must wonder whether it is possible for a society to strangle on its own complexities... Sensing that our own collective future is in jeopardy...we are hungry for historical analysis to help us imagine the direction events might take"*
>
> (Kenneth Baker, 1986. Treasures from the sacred well of the Mayas. San Francisco Examiner Review, Sunday January 12, p. 12)

2.7.1 Pre-industrial versus industrial society

Attempts to answer the 'big picture' questions posed by an investigation of this nature are, ironically, often better served by the smaller, more manageable sets of data presented by the remains of pre-industrial civilisations. Technological constraints of the past rendered global-scale connections more difficult, or at least slower and more geographically prescribed, and so networks of the past were more commonly contained within readily definable spatial boundaries. Critically, the processes that work to move a society through the various phases of growth, intensification, decline and transformation are more easily observable in the timescales available in the study of past civilisations than they might be in the monitoring of present societies in the midst of these processes. Such 'complete' timelines, or cycles, and spatially restrained data sets at least allow the researcher the impression of seeing the system as a spatial and temporal whole.

So while the civilisation systems of the past were relatively pristine and isolated (see World-Systems theory, Wallerstein 1979), they have now merged into one that is truly globalized (Cioffi-Revilla 2006). Today's urban landscapes are systems that incorporate networks, both abstract and tangible, that are multi-layered, multi-directional, are interactive over various scales, and are therefore extremely complex (Dematteis 1994). On the one hand, the spatial unit of administration is also becoming increasingly discordant with the associated political or corporate representation (Graham 1999, Alderson and Beckfield 2004), but local government institutions are becoming increasingly empowered through greater access to global-scale networks (Castells 2002). Contemporary trends towards increased liberalization, privatization and internationalization of telecommunication organisations have caused the degree of centralisation to rapidly increase in other subsystems, however, as globalized networks gradually splinter off from other local nodes – essentially linking global cities and bypassing most others (Graham 1999, Graham and Marvin 2001). As such, the traditional notions that cities, regions, states and empires correspond with spatial grades of bounded and contiguous territory is outdated and problematic in modern industrial society (Graham 1999, McCann and Acs 2011). What makes understanding networks so important – the increasing interconnectivity of today's urban landscape – is what makes it so difficult to study in the present context.

2.7.2 Types of past civilisations where clear identification of network components remains difficult

The low-density empires that emerged in tropical latitudes of the Earth during the first millennium AD represent a more difficult case for investigating the fate of networked societies. Unlike the 'traditional' bounded urban settlements familiar from early archaeological work in the Mediterranean and Southwest Asia, these vast, often imperial societies lacked a spatially discrete, highly populated city centre. Instead they were organised around large ceremonial complexes that centred on extensive agrarian hinterlands where the majority of the population lived and worked (Coe 1957). Fletcher (2009) refers to this settlement pattern as 'low-density, agrarian-based urbanism'.

Typically these societies consisted of a core complex where civic and ceremonial duties were performed and the elite and administrative personnel were housed. Often the core complex also contained agricultural land and workers, creating a nebulous divide between the urban and the rural. Beyond this central district sprawled the patchwork of rural landscapes and residential clusters, not dissimilar from modern-day neighbourhoods in industrialised, western societies, which congregated around subsidiary civic-ceremonial complexes (Coe 1957, Evans and Fletcher 2015, Chase et al. 2011, 2014). The homogeneity of the agricultural landscape, however, did not extend to the societal structure, as a number of features of an agrarian economy – in particular the generation and distribution of the surplus staple crop – produced structures that promoted a high degree of sociocultural complexity (Allen 1997a, Southall 1998). Core complexes were linked both internally and outward to their extensive hinterland and beyond into the broader city network through tangible networks of roads, causeways and canals and intangible networks of taxation and corvee labour (Hendrickson 2007). As a result, these multicentric territories became highly centralised and interconnected and functioned as urban landscapes despite the concentration on agricultural land-use and labour. This model of a polycentric, agricultural cityscape repeated itself, at various scales, multiple times throughout the landscape to create a vast, networked domain.

Of these cases, the Mayan society could be the most problematic, as it arguably presents the pinnacle of the diffuse, polycentric settlement pattern, where hierarchical networks may be difficult to define. Network linkages were predominantly intangible, and dominance rotated regularly between politically discrete nodes (Rice 2004, 2007). By the time the Maya came to dominate the Yucatan Peninsula in the Classic Period, settlements were littered throughout the landscape (Chase et al. 2014). These settlements varied vastly in size, from major 'urban' centres, smaller village groupings, to single kin-based settlements (Chase et al. 2014). Some stood relatively isolated as politically discrete units, while others were grouped together around dominant urban centres like Tikal and Carcol (Marcus 1973). Such variable degrees of integration throughout the landscape has inevitably created uncertainty surrounding the socio-political organization of the Maya, and thus the society has been varyingly referred to as a collection of autonomous 'city-states' (Mathews 1991, Grube 2000), regional states (Adams 1986, Chase and Chase 1998) and vast, totalitarian 'superstates' (Martin and Grube 1995, 2008).

Furthermore, the often intangible nature of geo-political links between some of the Mayan centres made these links seem tenuous; more assumed than real. However, researchers have demonstrated their existence empirically (Marcus 1973, Munson and Macri 2009). Munson and Macri (2009) examined the inscriptions on stone monuments and other material remains that detail or represent the relationships between these centres – relationships that ranged from the diplomatic, antagonistic, subordinate to familial, and could overlap through time to produce dynamic organizational networks. Their results show that diverse sociopolitical structures were operative in the Mayan culture throughout the Classic Period. With early spatial network research often inappropriately equating proximity to site interactivity (Bullard 1960, Johnson 1972), other more recent research has utilized changes in the distribution of archaeological markers to reasonably demarcate shifts in social hierarchies and the spatial territory controlled by certain polities (de Montmollin 1989, Kvamme 1990, Beekman 1996, LeCount 1999).

Despite the inherent difficulties, there are clearly markers definable in the cultural landscape that can define social and political interaction in these diffuse settlement systems. And, as these vast settlement systems of the ancient tropical latitudes provide a more promising prototype for the sprawling networks of cities and suburbs of the modern industrialised landscape (compared to the Western urban model (Fletcher 2009, 2010, 2012, Isendahl and Smith 2013)), they therefore should be targeted (or at least not avoided) in studies of the transformation that occurs in network societies following disturbance. In all instances where society is presented as a network it is undeniably a theoretical act, irrespective of its specific character. Numerous assumptions are always made, particularly regarding the nature and degree of interaction operating between linked nodes. Erroneous results can be avoided however, if careful consideration is taken to ensure the most appropriate network representation is selected for analysis (Butts 2009).

2.8 Chapter summary and conceptual model

Society comprises diverse socio-political, economic, urban and infrastructural networks that maintain the functioning of settlement systems, and operate over various spatial scales, particularly in the highly globalized urban landscape of the modern era. In past societies, it can also be readily seen how the growth of these networks in the settlement system provides the framework for the evolution of socio-cultural complexity, as a society develops from simple, isolated, autonomous village or tribal groupings toward highly centralized, socio-politically complex states.

As territory expands under a particular political power, spatial, city networks develop across the landscape, the configuration of which can, in part, reveal insights into socio-political structure and internal power dynamics. Integrating these settlement networks are relational (e.g. economic, political, and religious) networks, which are supported by, and often depend on, material infrastructural networks. As societies continue to develop over time, the degree of interconnectivity and complexity of these integrated settlement, infrastructural, and relational networks increases. This can lead to rigidity (lack of diversity and flexibility) in the system and a growing interdependence between secondary centres in the city network and the primary centre where the centralised power originates. Furthermore, research suggests that this strong association between network integration, centralized power relationships and socio-political complexity can create instability in a settlement system (Flannery 1972, Rappaport 1977, Tainter 1988, 2006). These authors maintain that a high degree of inherent complexity within a society can be pathological, and that a society can, therefore, approach limits to complexity (and by proxy network integration) in settlement system growth (see also Fletcher 1995).

In cases where this vulnerability intersects with some endogenous or exogenous force and some form of collapse or transformation occurs, there exists an opportunity to decipher more clearly the city network relationships and overall functioning of the preceding settlement system. Research (Kolata 2006) has suggested that the timing, nature and degree of the response of a society (particularly the peripheral or secondary centres in a settlement network) can be indicative of the level of integration (particularly vertical integration or centralization of power as well as inter-city dependency) that existed in the power networks prior to the disruption.

In order to achieve this, however, a new approach to ‘collapse’ studies is required. The spatial scale of inquiry needs to be broadened, by analyzing the response of the broader city network to disruption in the settlement system. Because, in cases where a substantial disruption occurs (for e.g. severe climate change) in the primate/capital centre or centralized power institution, high levels of network integration suggest that there should be a response in the interlinked, secondary centres throughout the city network. Research suggests that such settlement system-scale responses can be diverse, and can entail transformation to lower forms of complexity (Tainter 1988, 2006), urban and regional abandonment and relocation of populations (Lucero et al. 2015), persistence of populations and restructure of organizational networks (Culbert 1988), or total regional-scale abandonment of urban, political and ideological institutions (Yoffee 1988, Sims 2006). By increasing the spatial scale of analysis in the study of a transforming society, some of the assumptions regarding the fate of peripheral settlements and the level of interdependence that presumably exists between primate and secondary cities in a highly socio-politically complex society can be tested. Such an approach allows us to analyse more effectively the systemic pathologies that can develop by gaining ever-increasing levels of socio-political complexity, and the response of regional populations to the disruption or removal of integrative networks (political, economic, etc.) in the settlement system.

2.8.1 The specific questions

Therefore, in the case of a 'collapsed' or transformed society that was networked and highly centralised, two fundamental questions need to be asked:

- What was the response of secondary cities within the city network to disruption (i.e. failure or reorganisation of a centralised power networks) in the primate city? Did elite abandonment and depopulation in secondary centres occur prior to disruption in the primate city? Or did they persist at these secondary centres? Or was there an 'urban diaspora' in the secondary centres concomitant with the primate city?
- What do these population dynamics reveal about the relationships and interdependencies that existed between the primate city and its broader city network prior to collapse/transformation? How did these relationships affect the stability of the settlement system and its response to network disruption?

2.9 Chapter conclusion

This chapter has reviewed the literature pertaining to current and ancient networked societies, and how continued network creation and utilisation over time provides the framework for socio-cultural evolution. As society develops as a network, it therefore also declines as a network, and this calls for a new model for investigating the transformation of a society following disruption. This model should aim to reconstruct the dynamics of the city network, and test some of the assumptions that persist regarding the fate of the broader settlement system. Moving beyond the reductionist approach of models focused on the 'context stresses' associated with collapse and toward one that captures the broader, dynamic principles at work in a complex, networked society, without ignoring the more complex and multivariant inputs specific to each case, will be imperative to improving sustainability solutions for the modern, industrial, globally integrated landscape.

3 The Khmer civilisation as a case study: the evolution of a networked kingdom

3.1 Introduction

The Khmer civilisation provides an ideal case study to analyse the effect of network integration on the stability of a settlement system, as well as the broader spatial dynamics of transformation following disruption. Throughout its history the Khmer civilisation established numerous capital cities and secondary centres across their territory, in a settlement system that was linked via ideological, economic and infrastructural networks. By the height of this kingdom, between the 11th and 13th centuries AD, through increasing territorialisation and the enhanced power of the kings under the deveraja cult, the Khmer settlement network appears to have become increasingly integrated and administered by an increasingly centralised bureaucracy. By the mid-15th century AD however, this vast settlement network experienced significant disruption in the form of severe climate variability, infrastructural decline and the possible abandonment of major urban centres.

This chapter will provide a review of the literature on the history of the Khmer civilisation, particularly the research regarding its development from a collection of individual polities in pre-Angkor times, to its coalescence and eventual domination of mainland Southeast Asia, and finally through its transition to the post-Angkor period. The literature on this period of Cambodian history is extensive, and this chapter does not seek to provide an exhaustive recount, or to provide a detailed description of the region during this period (as this is provided elsewhere (see Briggs 1951, Higham 2001, Coe 2003, Chandler 2008)). Rather, this review will focus on two components of Khmer history: firstly, the Khmer kingdom's spatial, political and operational configuration as a city network and, secondly, the gaps in the literature regarding the occupation dynamics of the kingdom during and following the assumed 15th century political abandonment of the capital city of Angkor.

3.2 The evolution of the Khmer civilisation: an overview

The evolution of many past societies can be tracked through a process of fluorescence, fragmentation or collapse, followed by transformation or regeneration (Adams 1988, Yoffee 1988, Marcus 1998, Redman 2005, Nelson et al. 2006, Thompson and Turck 2009). Such cycles are evident in the occupational history of mainland Southeast Asia, and are particularly exemplified in the major ancient Southeast Asian settlements that dominated this region from the first millennium AD (Lieberman 2003, Stark 2006b). Archaeological remains, Chinese and indigenous historical documents allude to the development of three distinct, but overlapping and interacting polities in the region during this period (Stark and Allen 1998, Stark 2006b). The earliest of these polities occupied the Mekong Delta region, before populations migrated inland

and either established kingdoms or became subject to pre-existing ones (Pelliot 1903, Coedes 1968) on the seasonal floodplains on the northern edge of the Tonle Sap. Eventual coalescence and regional expansion of these independent polities formed a kingdom that, at its height between the 11th and 13th centuries AD, extended from the China Sea in the south, the Khorat Plateau in modern-day Thailand in the northwest, southern Laos in the northeast, and parts of modern-day Vietnam in the east (Jacques and Lafond 2004). While the earlier settlements on the Mekong River delta lacked unity and potentially spoke different languages (Hall 1955, Hall 1985, Thurgood 1999, Vickery 2003), threads of socio-political, architectural, ideological and (some) economic continuity have been identified both between this collection of earlier polities and the subsequent settlements that developed in the north (Coedes 1968, Groslier 1998, Vickery 1998, 2003, Stark 2006b, Lustig et al. 2007). As such, this level of cultural coherence has generally been considered sufficient evidence to assume this history marked the development sequence of the great Khmer civilization (Coedes 1968, Groslier 1998, Higham 2002, Stark 2006a).

3.3 The spatial dynamics of territorial control throughout the pre-Angkor and Angkor periods: the development of physical, settlement networks

3.3.1 Khmer settlement through space during the pre-Angkorian period (6th to 9th centuries AD)

Evidence for early port settlements (approximately 350 sites (Manguin 2014)) have been identified and excavated in the Mekong delta region (Malleret 1951, Groslier 1952, Malleret 1959, 1959-63, Stark et al. 1999, Stark 2006c), where a series of Khmer chiefdoms developed between (at least) the 1st and 7th centuries AD (Pelliot 1903, Coedes 1968, Hall 1985, Wolters 1999) (see map, Fig. 3.1). Recent radiocarbon dating of a major settlement of the region, Angkor Borei, however, indicates that pre-Angkorian Khmer occupation of this region could have begun as early as about 400-500 B.C. (Stark et al. 1999, Bishop et al. 2003, Bishop et al. 2004). Identified by Chinese traders as 'Funan', this complex collection of small, competing polities (Vickery 1986, Jacques 1990, Vickery 1998, Coe 2003) is believed to have been the crucible for the subsequent kingdom that eventually came to dominate the mainland (Groslier 1998) (Fig. 3.1). Chinese envoys who visited the region in the 3rd century AD described these settlements as containing "walled villages, palaces and dwellings" where "they devote themselves to agriculture" (Coedes 1968, p. 42). Evidence for both small (Pelliot 1903) and large-scale (Aymonier 1900) water infrastructure suggests these early populations engineered the marshy, tidal landscapes of the delta region, to render this 'realm wrested from the mud' (Aymonier 1900, Coedes 1968) suitable for agriculture, particularly the cultivation of rice (Stark 2006a and references therein).

Despite this development of rice agriculture and their position on the resource-rich Mekong River delta, the economies of the coastal entities of Funan predominantly benefited from their exposure to commercially important maritime trade routes (Hall 1985) and high-value non-timber forest products from the Cardamom Mountains (Groslier 1998). This placement enabled the maintenance of trade and diplomatic relations directly with both India and China throughout the state's history (Pelliot 1903, Miksic 2003), although the extent of these relationships is heavily contested (see le May 1964, Ray 1989, 1994, Vickery 1998, Smith 1999, Thi 2002). Throughout the Funan period, capital centres were often mobile in space (Stark 1998), reflecting the ephemeral power held by individual leaders of the time (Jacques 1979), although a consistent regional locus of power can be detected between the southern banks of the Tonle

Sap and the mouth of the Mekong River (Wheatley 1983). By the 7th century, however, the power of Funan apparently began to wane, and the region was abandoned by political leaders (although residual rural populations remained) (see Bishop et al. 2003) as political centres shifted northwards (Pelliot 1903, Coedes 1968, Hall 1985), ostensibly in order to participate in the burgeoning agrarian economies of the interior kingdoms of Chenla (Vickery 1998) (Fig. 3.1).

Chinese sources describe Chenla as a unified 'state', and document its rupture in the 7th century AD into two separate polities, Land Chenla and Water Chenla (Dupont 1943-1946, see also Vickery 1994). An interpretation of the inscriptions, however, suggest that the Chinese histories may have overstated their descriptions of Chenla (Wolters 1974, Vickery 1994), and according to Groslier (1998) this period was relatively unremarkable, as uncertainty and decentralised power characterized the region. Instead it has been suggested that spatially and economically modest polities, supported predominantly by subsistence agricultural economies, existed throughout the central and northern plains (Dupont 1943-1946, Groslier 1998). Vickery (1998) views this period differently, suggesting that by the 7th century Chenla had become, while not a 'state' per se, a large and complex chiefdom that oversaw vast, although potentially disconnected, territories from the coast of present-day Vietnam to the southern-eastern coast of present-day Thailand. Inscriptions created during the period 650-750 AD are among the most numerous in the entire pre-Angkorian and Angkorian periods (Lustig et al. 2007), suggesting substantial building works and economic organization during Funan's decline and into this period of supposed 'unremarkability' (Groslier 1998). As a comparison, the two other peaks in the production of inscriptions occurred during the early 10th to early 11th century under Yasovarman I's reign following his establishment of the capital at Angkor, and during the late 12th century during Jayavarman VII's famously prodigious building program (Lustig et al. 2007). This investment in architecture, as well as developments in art, and consistency in the language, content and style of inscriptions, is evidence of this region's stability and relative cohesion during this period (Briggs 1951, Coedes 1964, Vickery 1994, 1998).

Instability and fragmentation possibly followed in subsequent generations (Coedes 1968), where modest polities, controlling and exploiting only their immediate surrounds, persisted throughout the northern and central Cambodian plains (Groslier 1986). However, collective power in the region slowly grew, perhaps aided by the region's relative shelter from the growing maritime powers of the Indonesian archipelago (Groslier 1998). Ambitious leaders began utilizing political alliances and military force to expand their territory (O'Reilly 2007). Archaeological remains attributed to this period suggest that the provinces that encompass the low to middle catchments of the Mekong, from Ta Kao to Kratie, were the most densely occupied during this time (Groslier 1986). Significant sites were also located in the northeast, on the Siem Reap plain and in present-day northeastern Thailand, and a major capital of the early 7th century AD existed in the central Stoeng Sen valley (Groslier 1986).

From here, the conventional narrative describes a powerful ruler, Jayavarman II, in 802 AD, building on the political reorganisations undertaken by his predecessors, from his capital at Mount Mahendraparvata (Phnom Kulen) instituted the *devaraja* cult and declared himself the universal monarch or 'god-king' (Heine-Geldern 1942, Filliozat 1954, Higham 2001) over a now relatively unified territory. While this manoeuvre is traditionally referred to as the marking of the foundation of the Khmer kingdom that would dominate Southeast Asia's mainland and endure for the next six and a half centuries, it is based on a single inscription (K. 235) created in 1052 AD, over two centuries later, and found in the late 19th century (Aymonier 1901) at the Khmer temple of Sdok Kak Thom in present-day northeastern Thailand. Nonetheless, the relative paucity of historical data found between the 7th and 9th centuries has allowed this interpretation anchorage, and provided an opportune event to mark an apparently linear transition from the independent polities of Funan and Chenla, to integrated statehood. From this event forward, Jayavarman II's influence would continue in a number of forms, from the prevalence of the god-king and a specific Khmer royal lineage, to the endurance of his organizational practices and urban structures throughout the reign of all subsequent monarchs of the Angkor period.

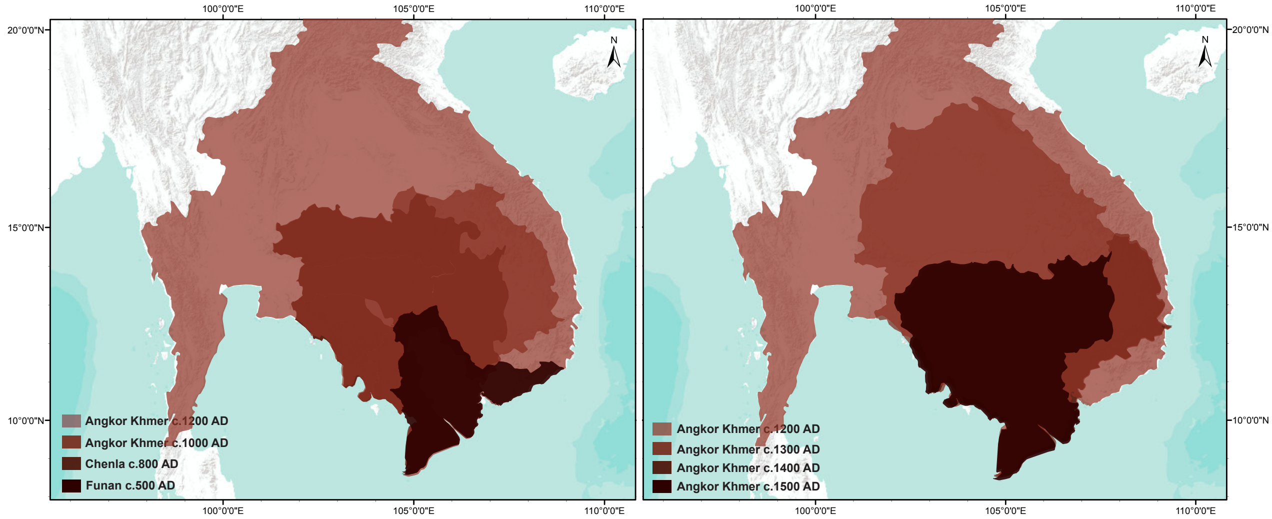


FIGURE 3.1: Map showing the varying extent of Khmer territory across the South-east Asian mainland between the 6th and 16th centuries AD. Data sourced and modified from the TimeMap Project, University of Sydney.

3.3.2 Expansion and consolidation during the Angkorian period (9th to 15th centuries AD)

During the Angkor period the capital relocated multiple times across the vast territory of the kingdom (Groslier 1986), but primarily the ruler and his royal court presided in a series of cities in the vicinity of the Tonle Sap, and most predominantly throughout the lake's northern central plains in the city of Angkor (Fig. 3.1). In the greater Angkor region alone, there were no fewer than seven capitals established between 9th and 12th centuries (Pottier 1999). The concentration of urban development in this region was doubtless due to its access to the water resources and fertile floodplains provided by the Tonle Sap lake system (Acker 2006). During the monsoon season, heavy rains cause the Mekong River to flood, which backflows into the Tonle Sap, causing the lake to swell to four-to-five times its dry-season area. This 'pulsing' system provides nutrients to the floodplain soils that surround the lake, making them ideal for intensive agricultural production. Furthermore, the highly productive flooded forests that line the extensive floodplains of the Tonle Sap provide breeding habitat for abundant fish and other aquatic species, making the Tonle Sap one of the most productive freshwater fisheries in the world (Lamberts 2006). Numerous river courses run from the north across this low-relief floodplain before entering the Tonle Sap system, and during the 10th and 11th centuries the proliferation of urban settlements generally remained focused along these natural watercourses and their navigable tributaries (Groslier 1986). Subsequent centuries saw further development and expansion, particularly throughout this northern realm as the preference for development on the central plains over the marshy delta regions of the south increased (Vickery 1998, Lustig et al. 2007). During this period the important Angkorian cities of Koh Ker, Banteay Chhmar, Preah Khan of Kompong Svay and Vat Phou were all founded north of greater Angkor, as were settlements in the Battambang and Prachinburi region to the west of the lake.

This period, however, was still characterized by alternating periods of consolidation and fragmentation of territory in addition to growth and expansion (Stark 2006b, Hendrickson 2007). In the early 9th century, several independent polities in southern Cambodia (Vickery 1998) and northwards up the Mekong (Wolters 1973) were consolidated or allied under the binding cult of the god-king (Wolters 1973). Territory that had been important to pre-Angkorian elite, located either on the south or southwest banks of the Tonle Sap, were also re-conquered (Coedes 1968, Wolters 1973, Vickery 1998), and capitals were established first at Mahendrapura on the Kulen Hills (Wolters 1973), and subsequently at Hariharalaya, near present-day Roluos on the northern banks of the Tonle Sap. In the late 9th century, the capital was once again relocated to a newly built city (built at the location of an existing settlement (see Higham and Thorsarat 2001)), referred to as Yasodharapura, which would become the base of political power for the most part of the next half century. Also at this time, control of the central Angkorian domain was consolidated through the installation of 100 wooden ashramas, some of which marked a territorial border that extended from Ba Phnom in the south, Vat Phu in modern-day Laos in the north, Tbhong Khmum in the east and Battambang to the west (Coedes 1932, Pottier 2003). In the mid-10th century, after a brief period of fragmentation, new territory was claimed from non-Khmer groups in the west, including the settlement of Lopburi, as well as the capital of Champa in the east (Hall 1975). At the same time, the re-modelling of existing and construction of new temples marked the reclamation of control in regions to the northeast of Angkor. This focus on the northeast region lasted throughout the mid- to late-10th century (Briggs 1951, Vickery 1985, Jacques and Lafond 2004).

Following another short period of regional disorder, the early-mid 11th century introduced an important escalation in Khmer control of regional territory (Hendrickson 2007). Further takeover of the territories of Luovo and Tambralinga in central and peninsula Thailand was achieved (de Mestier du Bourg 1970), as well as parts of the Malay Peninsula (Hall 1985), and power over provincial elites was strengthened in the central region (Briggs 1951, Jacques and Lafond 2004). The extent of central Angkorian territory at this point was marked by four linga positioned at each of the cardinal points: Vat Ek in the west, Preah Vihear in the north, Phnom Chisor in the south and Icanatirtha in the east, at an undetermined site on the banks of the Mekong (Jacques and Lafond 2004). This period also saw more substantial evidence of Angkorian control on the Khorat plateau, where dramatic changes occurred in settlement patterns and construction styles (Welch 1998). The remainder of the 11th century and into the turn of the 12th century was marked by destabilizing conflict, both internally and with the neighbouring Cham, Dai Viet and Chinese (Briggs 1951). In the early-mid 12th century political stability returned and allowed active expansion and consolidation to resume. Khmer control of the Thai peninsula was extended down toward Grahi and the Bay of Bandon, as well as north to the Myanmar border (Hall and Whitmore 1976, Mabbett 1978). Old territories east and north of Angkor, where substantial building works (both construction and renovation) were undertaken (Jacques and Lafond 2004), were reintegrated under the god-king's rule. An extensive building campaign was also launched in the capital of Angkor (Boisselier 1952) to further solidify control.

Disorder and political disintegration followed for a period once again (Briggs 1951, Coedes 1968), before the reign of Jayavarman VII and the period representing the height of Angkorian dominance of Southeast Asia began. In the late 12th-early 13th century a prodigious kingdom-wide building programme was initiated, which was to be continued by successive rulers. New building in the provincial sites of Banteay Chhmar, Vat Nokor, Ta Prohm Bati and additions to Phimai consolidated power in these regions (Cunin 2004), and 102 hospitals, of which 50 have been identified (Coedes 1940), and a proclaimed 121 resthouses (Coedes 1941 [1992]) were built throughout the territories in an effort to build rapport (Mabbett 1978) and expand Khmer territory (Hendrickson 2007). During this time Angkorian influence expanded further across the Malay Peninsula (Briggs 1951) and within Angkor's core territory itself, however it is unclear whether this represented actual seizure and infilling of non-contiguous territory or merely the addition of infrastructure into pre-existing, but empty, territory (Hendrickson 2007). From the middle of the 13th century the ambitions and achievements of the Angkorian leaders are far less evident in the landscape and inscription record (Jacques and Freeman 1997). Angkorian dominance of the region, however, was presumably maintained until at least the late 13th century, when a visiting Chinese diplomat, Zhou Daguan, described the Khmer domain as a thriving and prosperous kingdom that contained 90 (albeit unidentifiable) provinces (Zhou 2001).

Overall, during the Angkor period, spatial patterns of Khmer development tended to concentrate in areas optimal for religious temple construction and rice agriculture (Groslier 1986). As such, the vast plains and river valleys of central Cambodia, between the Tonle Sap in the south and the Mun River on the Khorat Plateau in the north, were heavily favoured by the Khmer, while the maritime coastline, the riparian zones of the Mekong River, swampy plains, dense forests, and regions of geographic relief were largely avoided (Groslier 1986). An exception to this, however, is the Kulen Mountain range, where early occupation of Khmer settlements were both more extensive and elaborate in arrangement (Evans et al. 2013a) and more intensive (Penny et al. 2014) than have been recognised in models of Khmer settlements from the Cambodian plains. In summary, regional Khmer dominance shifted vastly through time, and was only ever tenuous and loosely consolidated. Only a few remarkable leaders presented with the ability to effectively integrate control of the territories and expand into new geographic domain (Stark 2006b). Under such leadership however, the Khmer administered over a greater spatial area of the Southeast Asian mainland than any of its contemporaries (Stark 2006b).

3.3.3 The physical settlement network during the Angkorian period (9th to 15th centuries AD)

The administration of such a large spatial area was primarily coordinated from various centres within the greater Angkor region. While settlements on the central Cambodian plain during the pre-Angkorian period were largely restricted to specific environmental niches in the landscape (along river courses, for example), technological advancements, particularly in water infrastructure, gradually allowed for the development and occupation of more challenging environments (Groslier 1986). Such advancements in technology, specifically water capture, storage and distribution technology, particularly favoured expansion on the northern floodplain of the Tonle Sap, where the cities of Angkor would develop. By the Angkorian period, development in this region had become rapid and intense, as successive Khmer kings would construct new ceremonial temples and city complexes, including any associated infrastructure works, either within the framework of the existing built urban network (Evans and Fletcher 2015) or by partly demolishing or repurposing existing structures (for example, the temple of Ak Yom, which was buried by the construction of the West Baray (Pottier 2000)).

Each individual temple complex would then, for the most part, develop a peripheral landscape of residential villages that supported the needs of the temple and its elite. These villages and temple assemblages did not exist as isolated clusters, but instead functioned together as a polycentric urban administrative complex (Fletcher et al. 2003, Evans et al. 2007), and were linked components in a highly complex network of water channels and embankments (Groslier 1979). Fletcher and Pottier called this 'the Gossamer City' – a city defined more by its infrastructural networks than by its more famous religious architecture (Fletcher and Pottier 2002). Principally, these hydraulic networks redistributed water between regions of capture and diversion to storage locations, ameliorating the strongly seasonal climate of the area and allowing year-round agriculture (Groslier 1979, Fletcher et al. 2003, Fletcher et al. 2008, Kummu 2009), but also, in certain sections, would have been used for the transport of goods and information (Hendrickson 2007). Such iterative development saw the greater Angkor region, by the Angkorian period, become what Fletcher (2012) described as a "sprawling, almost monotonously self-similar [network of] suburbs" (p. 298), consisting of 22,000 km of rice-field embankments, over 4500 trapeang (small reservoirs), and in excess of 400 local temples (Hawken 2011). Mapping and survey work performed by Evans et al. (2007), building on the transformational work by Pottier (1999), have revealed that this city region extended across an area of more than 1000 km2 (and up to 3000 km2) – making it the largest known pre-industrial case of low-density, networked urbanism (see Fig. 3.2).

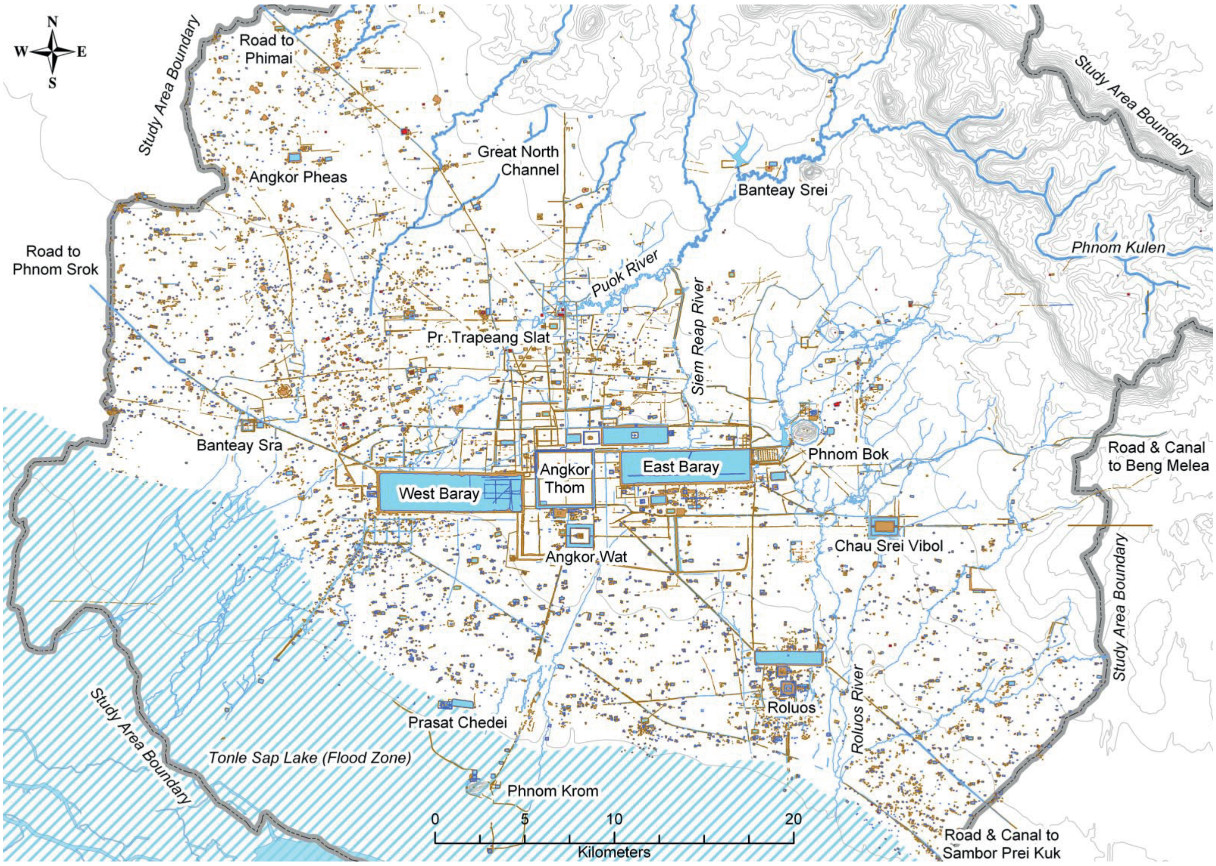


FIGURE 3.2: Archaeological map of Greater Angkor. Source: Evans et al. (2007).

While the settlement patterns and complex infrastructural networks that were created in the greater Angkor city landscape are now well understood, the settlement network that developed across the broader kingdom has received little scholarly attention until recently. Work by Hendrickson (2007) – building on the work of Aymonier (1900, 1901, 1904) and Lunet de Lajonquiere (1902, 1907, 1911) – has revealed the Angkorian kingdom as a system of cities, with Angkor as a highly connected node or hub in a network of arterial and tributary routes that connected primary Angkorian sites to each other and also to their surrounding areas (see also Hendrickson 2012). This is not to imply that the Khmer settlement system depended on this footprint of tangible network linkages, as Hendrickson (2007) suggests that this network of cities was integrated prior to the completion of the imperial road network. This transport network, Hendrickson (2007) proposes, was simply the framework within which the Angkorian administrative elite could orchestrate the operations required for the broader kingdom to function at its height, such as facilitating the increased movement of material goods and military personnel and equipment. The resources available from the core Angkor region, while relatively abundant, were not sufficient for the ongoing development of the expanding kingdom; additional goods needed to be sourced from further afield. Following the completion of this transport network, a large portion of temple settlements were connected to Angkor via this road network, or via the supplementary, but extensive, navigable river network (Hendrickson 2007).

In addition to the physical communication and transport networks linking the city network, the Khmer city network during the Angkor period was linked by religious ideology, architectural styles and settlement structure (Stark 2006b). This is largely how independent polities were integrated under Khmer control and new cities were established during periods of Angkorian expansion into uninhabited areas. The apparent long-term resiliency of this symbolic or ideological network is suggested by the multi-phase construction and modification evident at many cities in the kingdom (Evans 2016), for example Koh Ker, Preah Khan of Kompong Svay and Banteay Chhmar, where a series of kings, whether governing from Angkor or elsewhere, have contributed to the city's development over time (Jacques and Lafond 2004). Several inscriptions testify to the development of these networks, in their accounts of royal involvement in land assignments, explicitly linking these settlements to specific imperial and ideological influence (Lustig et al. 2007, see Table 3.1). This central influence further translated beyond mere loyalty – as royal land endowments came with agricultural tribute obligations for the recipient family and any descendants; the new village built upon the bestowed land would now be used to supply agricultural produce and corvee labour as the king required (Coe 1957, Jacob 1978). Such a system produced a strongly interconnected society, linked by both tangible land and fluvial networks and more abstract economic, labour and symbolic networks that were extensive and long-standing.

Figure 3.3 presents a map of the configuration of this city network, concentrating on the major secondary centres, as it likely existed at the height of the Khmer kingdom in the 11th-13th centuries AD. The capital, or primate city of Angkor is in the centre, and is surrounded by a number of important secondary centres. Table 3.1 outlines the list of secondary centres included in this network map, as well as the evidence for its association and importance to the rulers at Angkor (but not necessarily implying their control over these centres – see Lustig (2009)), and finally the physical (communication and transport) network that would have connected these centres to the primate city during the height of the kingdom. This map indicates that the city network within the Khmer kingdom, particularly during the Angkor period, formed a radial pattern in space (see Borgatti et al. 2009).

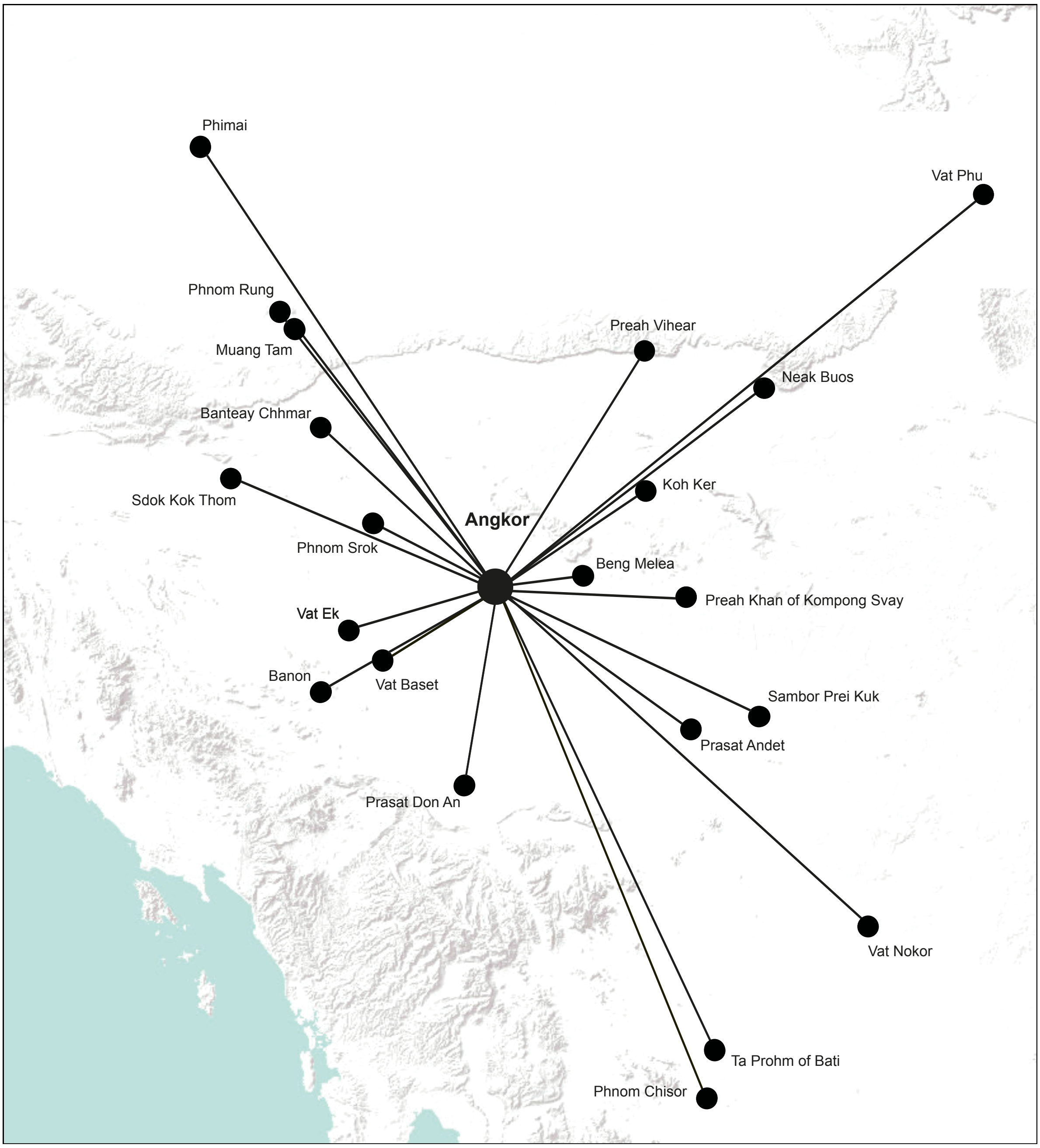


FIGURE 3.3: Map of the radial configuration of the city network operating in the Khmer kingdom at its height between the 11th and 13th centuries AD. Angkor sits in the centre, geographically, and also predominantly housed the political power during the Angkor period.

TABLE 3.1: List of secondary cities presumed to be operational during the Angkor period, taken from Hendrickson (2007). Includes evidence linking the secondary city to the capital of Angkor. Construction dimensions represent the perimeter of the temple enclosure. All temples were built in Angkor-period style architecture, and thus this evidence for association with the capital was not included. Distance to navigable river was measured from the corner of the enclosure closet to the water course.

Secondary city	**Evidence for importance and/or relation to Angkor**	**Transport/communication link to Ankgor**[1]
Beng Mealea	Located on Angkorian road network[1] Large temple enclosure (3737.3 m)[1] and *baray* construction (4294.9 m)[1]	Angkorian road Navigable river (1.6 km)
Preah Khan of Kompong Svay	Located on Angkorian road network[1] Large temple enclosure (18253.5 m)[1] and *baray* construction (7017.7 m)[1]	Angkorian road Navigable river (1.8 km)
Koh Ker	Large temple enclosure (895.7 m)[1] and *baray* construction (2809.7 m)[1] Inscription K.824 mentions King Jayavarman IV as a temple donor, inscription K.189 mentions a royal order of temple personnel	Navigable river (0.1 km)
Prasat Andet	Located on Angkorian road network[1] Large temple enclosure (1324.3 m)[1] and *baray* construction (1152.7 m)[1]	Angkorian road Navigable river (0.2 km)
Sambor Prei Kuk	Located on Angkorian road network[1] Large temple enclosure (3142.3 m)[1] construction	Angkorian road Navigable river (0.6 km)
Neak Buos	Large temple enclosure (268 m)[3] and *baray* construction (2295.6 m)[1]	Navigable river (1.4 km)
Preah Vihear	Large temple enclosure (160 m)[7] construction King Suryavarman I engraved above the doorway of the second entrance gateway of main temple[7]	Navigable river (1.0 km)
Vat Phu	Located on Angkorian road network[1] Large temple enclosure (1577 m)[1] construction Inscription K.367 mentions a royal edict regarding santuary management	Angkorian road Navigable river (1.3 km)
Prasat Don An	Large temple enclosure (1970.9 m)[1] and *baray* construction (3671.1.6 m)[1]	Navigable river (0.5 km)
Banon	Large temple enclosure (140 m)[2] and *baray* construction (3698.3 m)[1]	Navigable river (0.5 km)
Vat Baset	Large temple enclosure (1747.7 m)[1] and *baray* construction (1325.8 m)[1] The role of the ruler specified in inscriptions K.205, K.208 and K.447. Roles include land gifts/grants, title/honours/position grants, etc.	Navigable river (0.9 km)
Vat Ek	Large temple enclosure (668.8 m)[1] construction Guru of Suryavarman I named as temple founder in inscription K.211. Same inscription also specifies the role of the ruler in granting title/honours/position at the temple site	Navigable river (0.4 km)
Phnom Srok	Located on Angkorian road network[1] Large temple enclosure (4255.6 m)[1] construction	Angkorian road Navigable river (4.6 km)

Continued. . .

Secondary city	Evidence for importance and/or relation to Angkor	Transport/communication link to Ankgor[1]
Sdok Kok Thom	Located on Angkorian road network[1] Large temple enclosure (769 m)[1] and *baray* construction (1190.8 m)[1] Royal guru listed as temple founder in inscription K.235. The role of the ruler specified in inscriptions K.235 and K.1087. Roles include land/rice-fields/villages gifts/grants, title/honours/position grants, participation in religious ceremonies, granting immunities from tax/authorities, intervention in land disputes, etc.	Angkorian road Navigable river (3.4 km)
Banteay Chhmar	Large temple enclosure (3424.5 m)[1] and *baray* construction (4761 m)[1] Jayavarman VII named as temple founder in inscriptions K.226, K.227, K.592, K.696 and K.827	Navigable river (4.0 km)
Muang Tam	Located on Angkorian road network[1] Large temple enclosure (962.2 m)[1] and *baray* construction (2991.2 m)[1]	Angkorian road network Navigable river (0.4 km)
Phnom Rung	Located on Angkorian road network[1] Large temple enclosure (240 m)[5] and *baray* construction (2337.8 m)[1] Ruler informed of temple foundation and offered a share of the merit in inscription K.1068. Ruler also named or referred to in K.384	Angkorian road network Navigable river (1.5 km)
Phimai	Located on Angkorian road network[1] Large temple enclosure (3470.1 m)[1] and *baray* construction (4810.8 m)[1]	Angkorian road network Navigable river (0.8 km)
Vat Nokor (Banteay Prei Nokor)	Large temple enclosure (1594 m)[6] and *baray* construction (2742.3 m)[1] Jayavarman II believed to have settled in the city after establishing the *devaraja* cult on Mount Mahendra[7]	Navigable river (2.5 km)
Ta Prohm of Bati	Large temple enclosure (3430.6 m)[1] and *baray* construction (4613.3 m)[1] Role of ruler (granting of titles/honours/position) specified in inscription K.40	Navigable river (0.5 km)
Phnom Chisor	Large temple enclosure (180 m)[4] and *baray* construction (1167.6 m)[1] King Suryavarman I named as temple founder, and the role of the ruler (including land/personnel gifts/grants) also specified in inscription K.31. The ruler was named or referred to in K.34, and in K.33, an offer was made to the king to be involved in the temple foundation, and requests the king were made regarding land purchase and exclusive rights over land and foundations	Navigable river (1.7 km)

Sources:
1. Hendrickson (2007)
2. Aymonier (1901)
3. Lajonquiere (1901)
4. Aymonier (1900)
5. Aymonier (1999b)
6. Cunin (2004)
7. Jacques and Lafond (2004)

In line with the implications of Johnson (Johnson 1972, 1975) and Folan et al. (1995) (see section 2.3), there appears to have been progression in the evolution of Khmer society in association with the development of this radial pattern. During the Angkor period, the establishment of new centres, or the intensification or enlargement of pre-existing settlements, appears to be increasingly influenced by geo-political concerns or sacred organisation principles orchestrated by a central government. For example, at this time, an increasing number of settlements were built in the surrounding hinterland of the city of Angkor, or further afield as potentially strategic military outposts or resource acquisition centres, such as Preah Khan of Kompong Svay or Banteay Chhmar (Groslier 1986). Furthermore, in accordance with the religious ideology of the monarchy, four cardinal cities were built, to the north, south, east and west of the capital of Angkor, to house specific gods (Groslier 1986). Many of these locations, however, made little geographic sense beyond this geopolitical or sacred reasoning, often being removed from major watercourses and the fertile floodplains of the Mekong river system or the Tonle Sap. Instead, territorial expansion during the Angkorian period appears to have been guided less by environmental favourability, and more by the preoccupations of the central elite. This is largely because, as Groslier (1986) remarks, this heightened period of Khmer territorialisation occurred at a time when the Khmer were "religiously strong enough to reshape the [the landscape] according to their needs and ideas" (Groslier 1986, p. 286). Together, these developments provide preliminary evidence suggesting that this spatial network of cities was being operated by a high degree of centralised power during the 11th-13th centuries.

3.4 The development of socio-political complexity throughout the pre-Angkorian and Angkorian periods (both abstract and physical networks)

3.4.1 The precursor to centralised control: socio-political development through the pre-Angkorian period

Most scholars assume that, as the Khmer civilization developed from Funan to Chenla, the Khmer socio-political system grew increasingly complex. However, the nature and extent of socio-political complexity both between and within these pre-Angkorian period polities is difficult to discern (O'Reilly 2007). While Khmer documentary sources proclaim multigenerational political stability and cohesion, foreign records reveal episodes of political disintegration and conflict during the pre-Angkorian period (Stark 2006b). And while many prominent scholars of the period have argued against the legitimacy of these foreign representations (e.g. Vickery 1979, Wolters 1979, Vickery 1998), there is mounting agreement that, by at the least the mid first millennium AD, a relatively high level of socio-political complexity had been achieved in the Mekong lowlands. For the next few centuries, the degree of this complexity would fluctuate through alternating periods of growth and regression as seats of power and their associated territories shifted through space (Stark 2006b). Despite this variability, threads of consistent social, ideological and economic institutions remained woven throughout space and time (Wolters 1979, Vickery 1998, Lustig et al. 2007), and with the emergence of new political entities, innovations in governance systems often occurred (Stark 2006b), suggesting that an overall trend of increasing socio-political complexity and gradual state formation existed through this period (Vickery 1986).

A number of markers of social complexity existed during the Funan period (but likely appeared much earlier (Wheatley 1983, Higham 2002)), including the first kings, writing system, inscriptions, and urban cities (Stern 1927, 1938, Higham 2002). As an example of the latter, the arrangement of house mounds in a systematic grid pattern, indicative of urbanisation, has been recently uncovered at the pre-Angkor site of Sambor Prei Kuk (Evans 2016). The presence of engineered hydraulic systems within the cities of Funan (for example, canals linking Funan-era trading polities to each other and to maritime trading routes (Paris 1931, Evans and Traviglia 2012)) further alludes to growing urbanization pressures (Hawken 2011) and an agricultural revolution occurring throughout the Mekong Delta region (Groslier 1974), and suggests the ongoing production of an agricultural surplus, well above subsistence needs, and a burgeoning agricultural industry that was supplemented by aquaculture and craft production (Dega and Latinis 1996). The wealth derived from both international maritime trade and by agricultural surpluses (Hall 1982) would have encouraged the development of social hierarchies and thus a level of socio-political complexity (Vickery 1998, see also Chase-Dunn et al. 2006). A tax system may have been established, with Chinese sources describing payment in the form of gold, silver, pearls and perfumes (Coedes 1968).

Wheatley (1983) summarises the socio-political structure of the region as complex; more complex than a chiefdom, but less complex than a state. He claims that the consolidation of small chief-led polities had already begun prior to the pre-Angkorian period and that, by the first half of the 6th century AD, particularly powerful rulers had taken to appointing sons as rulers over subordinate chiefdoms. As such, there likely existed a three-tiered settlement hierarchy by the time of Funan – consisting of the capital, secondary towns of importance to the chiefs, and villages (Wheatley 1983, Vickery 1998, Miksic 2003). By the 7th century some inscriptions were referring to a number of social classes within each settlement, including agricultural workers, craft specialists, musicians, religious officials, local leaders and elite, and finally the chief or king (Vickery 1998). Such social and settlement stratification indicates a high degree of socio-political complexity had continued to develop in the polities of the Mekong Delta region by the middle of the first millennium AD.

The organization and specialization of labour, continual management and maintenance of water networks, and the planning necessary for both the production and distribution needs of large-scale agriculture, would have required a level of sophistication suggestive of a relatively high degree of centralized authority within Funan society (Dega and Latinis 1996). However, the nature of centralised rule within Funan society is somewhat ambiguous. While the Chinese referred to the Funanese leaders as kings, it is possible instead that, through cultural bias, wealthy chiefs of coastal trading cities may have appeared to the Chinese as kings (Vickery 1998). As such, there is a consensus that only relatively autonomous chiefs ruled predominantly among the collection of polities within the region (Jacques 1979, Wolters 1979, Wheatley 1983, Vickery 1998). The growth of any regional allegiances to particular chiefs would have been fluid, as each brokered differing levels of wealth and as individual success in warfare fluctuated through time (Hall 1982). Notions of statehood and kingship built on dynasties, according to Hall (1982), were non-indigenous concepts, and as such were only acquired gradually by the leaders of coastal entrepôts through sustained interaction with Indian and Chinese traders and diplomats. Any regional superiority eventually acquired by these leaders would have, however, been spatially restricted to their immediate surrounds and would have significantly diminished with distance inland (Vickery 1998). Overall, while the rule of kings or chiefs may not have been extensive spatially or temporally, it appears that 'Funan' consisted of a series of nucleated settlements containing at least some degree of centralised power, and maintained regional and extra-regional political or economic connections. This weakly integrated city network may, thus, represent the precursor to the more heavily integrated network of cities that would develop further inland in subsequent centuries.

During the shift in the locus of power north to inland plains of 'Chenla', land management techniques (Groslier 1998), religious ideology (Vickery 1998), and socio-political structure (Coedes 1968) were likely maintained. The move was potentially a response to the breakdown of maritime trade networks and the growth of the trading empire of Srivijaya on the Indonesion archipelago (Stark 2006b), and the opening of overland trade routes to central Vietnam and across central Asia (Hall 1985, Vickery 1998). Despite the mastery of agriculture and the interest in trade, the inscriptions of this period contain little information regarding economic markets, nor any system of tax collection (Vickery 1998). The northward shift is also purportedly coincident with the so-called 'Indianisation' of the region, represented by the appearance of Indic symbology and architecture (Manguin 2004), Brahmanism and greater social stratification (Vickery 1986) – the systems that may have provided the framework for the increasing centralization of socio-political structures in subsequent centuries. Rulers had also begun to coordinate claims of dynastic lineage that hearkened back to leaders of earlier southern Mekong polities (Coedes 1968). However, at this time political consolidation, while increasing from the 8th century onwards (Vickery 1998), remained spatially discrete. While polities in peripheral regions often claimed allegiance to a throne, they tended to preserve relative autonomy, retaining control over the appointment of local leadership (Wolters 1979, Vickery 1998). Each individual settlement maintained an engineered landscape of increasingly comprehensive irrigation networks, similar to those developed in the settlements of 'Funan', however regional integration of these networks would not occur for a few centuries yet (Hawken 2011). The inscriptions were also devoid of evidence for any centralized control over these infrastructure systems (Vickery 1998), despite the labour requirements and regional-level impacts of these works (for e.g. the diversion of rivers, etc.) (Than 1982).

3.4.2 The zenith of socio-political complexity and centralised control during the Angkor period (9th to 15th centuries AD)

From the 9th century onwards, with the dawn of the Angkor period, the social fabric and systems of operation that had begun to loosely incorporate the polities of the greater Angkor region – established previously in the pre-Angkorian landscape – grew in scale and complexity. State-level religious and economic control mechanisms became particularly important from the reign of Jayavarman II onwards, and worked in conjunction to sustain and cultivate the developing kingdom (Hall 1985). Subsequent kings continued to secure their legitimacy through an association with the matriarchal descendants of Jayavarman II, or the line of the god-king, under the rituals of the cult of devaraja (Coedes 1968). Such a system was likely very important as a catalyst for the development of very high levels of power centralisation that controlled vast territory during the Angkor period.

During the Angkor period, the religious and economic networks also became increasingly complex and centralised. Throughout the Khmer landscape, it was common for villages to be grouped together and assigned to maintain collective tribute obligations to local, elite family-owned temples and their associated cults (Coe 1957, Hall 1985, Hall 1992). Such a system was often established through the royal endowment of land (or by renovating and reassigning existing temple infrastructure) to prominent associates of the king, in an arrangement of mutual benefit (Ricklefs 1967). While the king maintained allies and subordinates in regional territories, the bestowed elite acquired religious merit and commanded de facto control centres for community-scale labour organisation and the administration of agricultural output, including any generated wealth (Lustig et al. 2007). As an example, upon consecration of the Ta Prohm temple group at Angkor, 3140 villages were assigned to it for support (in the form of produce donations and forced labour), equating to the service of an estimated 79,365 persons (Coe

1957). By the 10th and 11th centuries, however, top-down power over these networks purportedly intensified due to systematic increases in the integration of these nucleated settlements. Local 'kin' temples, owned generally by feudal families, were consolidated into hierarchical relationships with larger 'central' temples that were administered by representatives of the state (Sedov 1967, Hall 1985). As a result, local temple precincts became critical nodes in reinforced pyramidal bureaucratic networks (Hall 1992). Ostensibly, between the 11th and 13th centuries the Khmer economy grew increasingly reliant on the production generated by such taxation and tribute networks (Sedov 1978). Indeed, Coe (2003) describes the broader kingdom as an "immense revenue-gathering machine" (p. 150), with rice representing the primary, but not exclusive, economic unit (Mabbett and Chandler 1995). Lustig (2009), however, is critical of the extent to which redistribution of this revenue occurred (i.e. that the onward flow of taxation/tribute to the capital centre was minimal), and Miksic (2001) suggests that these kind of temple networks functioned more as a bureaucratic system rather than one of redistribution of revenue beyond the local level.

These temple systems were multipurpose, however, as they also existed as architectural and artistic representations of the king and his connection to the religious deities, and thus were tangible reminders of the king's universal power and legitimacy. Religious officials, such as the royal chaplain and various devout and knowledgeable men, commonly operated from these temple sites (Vickery 1985, Coe 2003). Crucially, the ideology embodied in these religious mechanisms blended indigenous folk beliefs with the hierarchical systems of Indic religions, to create an effective cult for the populace to follow (Hall 1976). While some argue that these ritual and symbolic links may have been more important than economic and political networks for maintaining subordinate territories in peripheral regions (Hall 1976), it was likely to have been the combination of these networks that was fundamental to the maintenance of centralised control throughout the Angkorian period. The tangible and intangible networks were interdependent; the establishment of religious symbols and personnel at these temple stations would have helped legitimise the centrally-established process of extracting economic goods and services from regional populations (see Yoffee 1988).

Other evidence for increasingly centralised control over the broader Khmer territory during the Angkorian period includes the increase in large-scale military action presented in the historical records between the 9th and 13th centuries (Hendrickson 2007), with militia likely comprising farm workers fulfilling corvee requirements (Mabbett 1978, Sedov 1978). Also, the amount of bureaucratic mechanisms disseminated throughout the kingdom increased, such as the appointments of elite representatives in strategic provinces, greater numbers of tax collectors and inspectors, and religious oversight officials having greater presence in important regional outposts (Vickery 1998, Hendrickson 2007). Additionally, the construction of the formalised imperial road system would have significantly enhanced direct communication and transport of goods between the capital and its provinces (Groslier 1986, Hendrickson 2011), and encouraged the growing politicisation of temple placement and purpose (Hall 1985, Kulke 1986).

However, the ascension toward greater socio-political complexity and territorial control is perhaps most acutely epitomized in the capital cities of the Angkor period, where extensive archaeological undertakings over the past several decades have revealed the progressive development of a vast and integrated settlement palimpsest, the spatial extent of which is unparalleled in the pre-industrial world (see Fletcher et al. 2003). Imprinted across a landscape of scattered Iron Age sites (Groslier 1979), and integrated with the relatively decentralized polities of the pre-Angkorian era, the greater Angkor region, over the course of half a millennium, developed into a highly engineered and interconnected metropolis (Evans 2007), potentially capable of supporting a populace of between 300,000 and 750,000 (Lustig 2001). The emergent landscape comprised a repetitive pattern of moated central temple precincts, satellite temple complexes, all interspersed with a relatively unstructured low-density distribution of ponds, village shrines, and irregularly shaped mounds that constituted the urban residential environment (Evans et al. 2013b). The distinction between urban and non-urban areas is ambiguous in archaeological maps of the city, and instead the urban landscape comprised an almost indistinguishable mix of rural-urban land-uses – compared by Fletcher (2009) to the desakota characteristic of low-density urban landscapes of contemporary Asian cities. These land use patterns continued on both sides of the temple city walls, and population densities within the enclosure were of very similar density to those outside the temple city limits (Evans et al. 2013b). This urban matrix continued to extend far beyond the walled temple enclosures (Evans and Fletcher 2015), now reaching previously isolated urban temples on the periphery, transforming them into nodes in an increasingly polynuclear agro-urban settlement landscape (Pottier 1999). The entire urban space was completely devoid of any clear demarcations defining any one urban zone from another (Evans et al. 2013b).

By the 11th century this urban landscape had become increasingly integrated through the development of an extensive system of water collection and redistribution. This is the point where expansionism was overtaken by settlement infill and intensification, at least in Angkor (Groslier 1979). Prior to the 9th century, hydraulic infrastructure provided dry season reprieve for pre-Angkor settlements in the region, however they were not of the same scale as at Angkor (Groslier 1974). Dramatic increases in the scale of these works during the Angkorian period saw Angkor develop into a 'hydraulic city', where previously isolated settlement clusters became increasingly integrated into a vast infrastructure network. Incremental additions and modifications to this hydraulic network fundamentally transformed the fluvial landscape, redefining subcatchments and creating new ones (Groslier 1979, Pottier 1999, Evans et al. 2007, Kummu 2009, Hawken 2011). This system was not the sole source of water for the Angkorian populace however, as small groundwater-fed ponds, or trapeang, were also dispersed throughout the greater Angkor area, particularly in close association with habitation structures (Pottier 1999, Evans 2002, Hawken 2011). This infrastructure, disconnected from the large-scale hydraulic system, was likely vitally important for local agriculture (Ebihara 1968) – even more so than the larger-capacity storage systems (Acker 1998)). While the barays were constructed from ground level using built-up embankments, the small and medium sized ponds were instead excavated deep into the watertable, and were thus less reliant on rainfall alone (Acker 1998). Additionally, these small and medium ponds likely operated under a separate level of management from that of the broader hydraulic system. Evans (2002) and Pottier (1999) show that there is very little spatial congruity in the patterning of these large- and small-scale hydraulic features; while barays were exceptionally large (up to 8km in length) and methodical in design, trapeang averaged only 140m by 70m (but were highly variable across space), and show archaeological signs of continual habitation. Labour requirements were therefore also very different, for example Pottier (2000) believes that the excavation of the West Baray in Angkor would have been the work of 150,000 labourers over the course of three months. So while the highly engineered and interconnected network of large-scale water reservoirs and connecting canals would have required a highly centralised bureaucracy to allocate labour for maintenance and to manage the distribution of water between reservoirs (Wittfogel 1953, Gaucher 2002), construction and management of the trapeang network would have been far less demanding. This non-correspondence between small- and large-scale operations represents divergent systems of hydraulic construction, organisation and control, one state-level and the other local and non-elite, which were largely independent from each other (Evans 2007, Hawken 2011). The emergence of this regional-scale hydraulic network, and its rapid and comprehensive increase in complexity from the 10th century onwards, marks an important transition toward a more centralised style of governance by the Khmer elite.

Further developments in urbanism are also evident during the Angkor period, including the proliferation of urban settlements and a shift in their settlement structure. To illustrate, between the reigns of Jayavarman IV (928-942 AD) and Suryvarman I (1002-1049), the number of urban areas (denoted as place names ending in –pura) listed in the epigraphy climbed from twelve to forty-seven (Hall 1976). Furthermore, within these cities the structure of agro-urban settlements was changing. Linear roadways and canals had begun to appear inside moated temple districts, altering the urban layout to more closely resemble modern-day city-blocks (Groslier 1979, Hawken 2011, Ichita et al. 2015, Stark et al. 2015, Evans 2016). This greater focus on structure carried over into the placement and size of other urban elements, such as ponds, mounds and shrines, within these city blocks. Together these changes produced an overall shift in the style of the general layout of these metropolitan settlement features, which Hawken (2011) has described and mapped in detail. Hawken describes first the evolution of the individual temple complexes, namely their shape, orientation and density throughout the landscape, and remarks on their heightened tendency toward cardinal alignment during the Angkor period (Pichard 2009) – a trend he supposes was directly related to the development and intensification of the 'hydraulic city'. From that time, concurrent shifts in landscape patterns, shaped by the rice field and residential development associated with these temples, mark a shift away from the predominantly radial and coaxial patterns of the pre-Angkor period and toward greater occurrences of cardinal patterns in settlement compounds. While the earlier patterns aligned more cohesively with the natural topography and drainage networks, reflexive traditions of land use, and egalitarian policies of water allocation (Johnston 2005), the later cardinal pattern, according to Hawken (2011), represents a settlement that transcends the limitations of the underlying landscape. Instead, he argues, cardinal patterns follow more sacred geometries that represent centralised structures of power. While it is so far unclear where or when this settlement pattern originated (see Evans and Fletcher 2015), the growing repetition of this pattern in urban form both within the Angkor metropolis and beyond (being recreated on a smaller scale elsewhere in regional settlements (Evans 2010, Evans and Fletcher 2015)), signals a growing coherence in urban planning, with an agenda that better accords with a settlement hierarchy. Along with the development of the 'hydraulic city', this evolution of settlement landscape signatures reveals a transition to greater socio-political complexity and centralisation of power during the Angkor period (Hawken 2011), at least within the greater Angkor region, however, as Wheatley (1983, p. 2) has remarked, "the structure of a city can be said to epitomise the pattern of society at large.".

This should not imply that such sovereign, centralized power was absolute during the Angkorian period, however, as royal control over the extended territory naturally wavered through time (Stark 2006b, Lustig 2009). Wittfogel (1953), in his discussion of Oriental despotism, insists that the historical societies of East Asia, characterised by the presence of great hydraulic infrastructure works, required centralised power structures, which were, almost without exception, autocratic in nature. However, in the case of the Khmer kingdom, the degree of this control, as well as how far it extended spatially, is uncertain. It is clear in the inscriptions and texts that certain powerful vassals of distant territories maintained a local status and influence that caused regular conflict with the central elite, and that land assignments often had suppressive intent (Hall 1985, Jacques and Lafond 2004). Lustig (2009) also argues at length that many of the regional centres throughout the kingdom continued to exercise substantial autonomy, at least with regard to local issues. Her systematic examination of the inscriptions potentially illustrates that the nature of some aspects of centralised control (particularly economic control) decreased with distance from the political capital, and at a point (in general about a day's travel away from the centre) highly centralised control gives way to a system of mutually beneficial relationships between the capital and regional elites. However, it is also clear that power structures during the Angkorian period reached a level of centralization that surpassed those reached by the kings or chiefs of earlier polities, and that several signatures of state-level socio-political complexity, and communication and political networks – vital to the integrity of the broader kingdom – had been maintained or intensified by the height of the Angkor period.

3.5 The disruption of the centralised control network and the transition to the post-Angkor period

In keeping with the characteristic nature of Khmer society, where migration and mobility of population centres was habitual (Stark 2006b, Ewington 2008), by (at the latest) the middle of the 15th century AD the Khmer king and his court had abandoned the grand, urban metropolis of Angkor in favour of cities in the Phnom Penh region to south and east (Dagens 2003). The timing of this migration remains ambiguous however, and has conventionally been linked to the Thai invasions of Angkor in 1431 AD (Coe 2003). Evidence for this is equivocal, however, and based on Thai and Cambodian chronicles that were constructed largely in the 18th and 19th centuries – over two centuries beyond the event itself, were written using chronologies of different origin and construction (Coe 2003), and likely contained inherent bias (with the Cambodian chronicles likely heavily influenced by the Thai) (Vickery 1979). Thus the reliability of this date has been questioned (Vickery 1979), and recent, preliminary evidence from sediment archives retrieved from the moat of Angkor Thom has suggested that the political abandonment, and shifting of the focus of settlement, may have occurred much earlier than 1431 AD, possibly in the mid-14th century AD (D. Penny, pers. comm.). Nonetheless, this event marks a major shift in Khmer history, particularly in regards to Khmer methods of territorialisation, which had been developing for the better part of a millennium prior to the political abandonment of Angkor. The building and dedication of monumental architecture had ceased by the end of the 13th century, and the final inscription, written in Sanskrit, the official language of the religious elite, was dated to 1327 AD (Coedes 1968). Groslier (1986) refers to the resettlement around the *Quatres-Bras*, or Four Rivers, as a return to geographic reality, where smaller-scale irrigation techniques, less reliant on large-scale storage and diversion systems, could be sufficient to maintain agricultural output in these cities whose economies were once again increasingly reliant on maritime trade.

However, various other reasons have also been proposed for the political abandonment of Angkor in the 15th century AD. Traditional explanations attributed this migration to either the Thai invasions Angkor in the 15th century AD, economic and resource exhaustion following the excessive building campaigns of the 12th and 13th centuries, and or state-level ideological progression away from Hinduism (Briggs 1951, Coedes 1968). Others have attributed regional trade dynamics, particularly shifting maritime commercial routes, as the driving force behind abandonment and resettlement (Hall and Whitmore 1976, Reid 1988, Higham 2002, Chandler 2008). However this model underplays the importance of overland trade for Southeast Asian mainland polities (Lieberman 1995) and potentially typifies the prejudice of colonial scholarship towards 'externalist' and trade-based historiography (Stark 1998, Lieberman 2003). Groslier has also suggested that unsustainable land management practices, over time, rendered the physical landscape less habitable (e.g. through sterilisation of the soil, excessive siltation of water management infrastructure, etc) (Groslier 1979). More recent palaeo-climate research, however, has revealed that mainland Southeast Asia experienced a series of severe droughts, interspersed by intense monsoon periods, in the 14th and 15th centuries AD (Buckley et al. 2010, Cook et al. 2010, Sinha et al. 2011). The severity of this climate variability would have had severe economic repercussions, which would have reverberated throughout the taxation and corvee labour networks. Following this, the ongoing expense of maintaining a socio-political network so deeply imbedded in the material realm (see Fletcher 2012) likely became increasingly untenable for the Angkor elite by the 15th century, having been weakened economically by decades of climate instability. This idea suggests that, in the face of a high degree of environmental stress, the nature of centralised socio-political control (i.e. its focus on territorialisation, the form and function of control networks, and the degree of centralisation) can provide limitations on the options for governmental response, and the effects of this response will propagate throughout the broader kingdom. What effect, for example, does this disruption in the primate city, and the control (economic, religious, communication, political etc) networks that support it, have on peripheral cities in the Angkor-period settlement network? Are they similarly abandoned? Or, alternatively does this transition involve fragmentation into a series of smaller, but still functional regional city settlements?

It is, however, this response of the broader kingdom to this supposed 15th century socio-political disruption that is missing from analyses of the transition into the post-Angkor period. Lucero et al. (2015), in their depiction of an 'urban diaspora' at this time, document the migration out of Angkor and into the cities across the southern margins of the kingdom, south of the Tonle Sap, but also suggest that a similar phenomenon occurred in several major secondary settlements throughout the kingdom. However, a lack of substantial evidence supporting these claims has been produced thus far, and in networked societies elsewhere (for e.g. the Maya civilisation), evidence has shown that the timing of urban centre depopulations, as well the processes responsible for those declines, can differ markedly across space and time (see section 2.7). In general, information on Khmer society at both the broader spatial scale during this transition period is very limited (see section 3.6).

3.6 Looking beyond Angkor: increasing the spatial scale of inquiry

The fate of residual populations in the post-Angkor period, or the 'middle period' (Thompson 1997), from the decline of Angkor in the mid-15th century to the establishment of the French Protectorate in 1863, is remarkably obscure in the annals of history. While written records have survived the Angkor period, on account of their inscription into stone, the archives of the middle period were written on more perishable materials. The transition from dominantly Hindu ideology to that of the Theravada Buddhism saw a refocus from the construction of temples made of brick and stone to more modest and transient architectural forms (however, while the final stone temple to be built at Angkor was dated to 1295 AD, the construction of wooden buildings had become prevalent in royal architecture several centuries prior to the 15th century political migration (see Groslier 1960, Cunin 2004, Ewington 2008). Furthermore, the accuracy of the chronicular record during the initial century and a half of the post-Angkor period has been questioned, with Vickery (1979) claiming the Cambodian chronicles were heavily influenced by the content of the chronicles composed by powerful neighbours. As a result, post-Angkor Cambodia plunged into an historical 'dark age' that may be more apparent than real.

From the meagre evidence that exists from this period, it appears that regional Cambodia had become a settlement landscape of relatively low population densities, likely only 10-20% as dense as those of the contemporaneous major Asian polities of China, Asia and Japan (Reid 1988). Rice-growing village habitation began restricting itself predominantly to the lowland corridors accessible to the coast (Lieberman 2003). The political capital continued to shift across space during the post-Angkor period (Ewington 2008), however the capital maintained a locus within the fertile environment of the present-day provinces of Prei Veng and Svay Rieng (Groslier 1986), in and around the confluence of the Mekong and the Tonle Sap. From this location, Laotian exports and abundant Cambodian resources from the Great Lakes area could be easily accessed, and the distribution of incoming products from China, India and the Indonesian Archipelago could be regulated (Lieberman 2003). With the capital located so far south, however, the king and his administration had become increasingly isolated from the kingdom's periphery (Chandler 2008). Throughout this time, the king and his elite retained relatively unstable levels of power, intermittently embattled by provincial revolts and dynastic disputes between competing factions either side of the Mekong, which continued up until the 18th century (Groslier 1986).

The characteristic movement of capitals throughout the kingdom, however, rarely coincided with a complete abandonment of each city itself, but rather resulted in a decrease in its political importance (Higham 2001, Coe 2003, Evans 2007). For example, archaeological investigations at the major Funan centre of Angkor Borei have revealed that the migration of rulers away from the Mekong Delta region did not result in urban abandonment, but rather a change in land use priorities and a reduction in population (Bishop et al. 2003). Following the king's migration from the Angkor capitals, many of the major temples remained connected to administrative networks and were continually bestowed with statuary, art and inscriptions (Dagens 2002). Indeed, Angkor Wat received additional artistic attention in 1577, and Portuguese reports attest to the brief return of the Khmer king and his court later in the 15th century, a move which was apparently accompanied by a repopulating of the city (Higham 2001, Dagens 2002, Groslier 2006). The account of Diogo Do Couto, the official Portuguese chronicler in Indo-China, bears secondary witness to this return to Angkor, based on the testimony of Antonio da Magdalena, who had visited Angkor in 1585 or 1586, and outlined that "the king who discovered this town had his palaces erected at enormous cost, and established his court there; he filled it with people from other towns in the Kingdom, and to them he gave lands and distributed hereditary domains for them to till the soil" (Groslier 2006, p. 55).

As such, Angkor Wat remained actively used in the centuries following the 'urban diaspora' as a prominent sacred site and pilgrimage destination for the Buddhist world, and likely housed smaller-scale village communities (Hawken 2011). This activity is recorded in forty inscriptions depicting the devout undertakings of an array of visitors between the 16th and 18th centuries AD (Thompson 1997, Groslier 2006). In 1866, the first photographs taken of Angkor Wat, by John Thompson, reveal a temple under vigilant care and upkeep, surrounded by a series of Buddhist habitations (Higham 2001). The idea that regions within Angkor were never completely vacated is further strengthened by the fact that the area continues to be inhabited to this day, in vestigial settlement configurations that substantially align with the skeletal remains of Angkor (Groslier 1974, Hawken 2011). Additionally, there is increasing evidence to suggest that the open land to the south and west remained populated and cultivated by the Khmer in the wake of royal exodus (Groslier 2006, Penny et al. 2006). Furthermore, substantial remodelling and the construction of the reclining Buddha at the Baphuon temple in the 16th century AD (Freeman and Jacques 1999) and the construction of the sitting Buddha at Phnom Bakheng in the late 17th or early 18th century AD (Jacques 2006) would have required substantial local work forces and some form of centralised control.

By the 16th century encroaching neighbours and contraction of Khmer territory ensured that any fragility in the sparsely populated periphery of the kingdom could be swiftly exploited by foreign powers (Lieberman 2003). Territorial contraction had begun on the central mainland even prior to the middle period, as western satellite cities – in fact the majority of northern Thailand and the peninsula – had been gradually taken back from the Khmer throughout the 13th century AD (Lieberman and Buckley 2012). This contraction continued throughout the ensuing centuries, although Cambodia was at times strong enough to resist and overcome invasions and even occasionally assault adjacent territory (Lieberman 2003 and references therein). However, by the late 18th and early 19th century, Siam had seized control of the provinces of

Battambang, Siam Reap (including Angkor) and Meloupreу in the north, and the Vietnamese had occupied Saigon and annexed much of the southern coast to Kampot, consequently severing Cambodian access to the sea and its maritime revenue (Lieberman 2003, Ewington 2008). Concurrently with Cambodia's spatial contraction, colonial powers in Europe were escalating and undergoing global-wide expansion. While many of these conquered regions would eventually return to Cambodian sovereignty, these 18th and 19th century invasions from both the east and the west had become increasingly unrelenting, and eventually led to intervention by the French. The resultant establishment of the French Protectorate over the remnants of the kingdom marked the end of the 'middle' period of Khmer history.

Despite the contraction of the kingdom of Angkor, the newly transitioned kingdom of Cambodia maintained social, economic and political relevance from the new centres south of the Tonle Sap, and as such remained one of the four major polities in Indo-China for several centuries following Angkor's political abandonment (Briggs 1951, Lieberman 2003). A number of aspects of this transitional period remain poorly understood however, in particular the occupation dynamics at the broader kingdom scale. Knowledge of the transition from the Angkor to post-Angkor period relies on the assumption that the 'urban diaspora' or migration from the Angkor-period cities to the 'middle period' cities south of the Tonle Sap was synchronous across the kingdom (see Lucero et al. 2015), despite very limited evidence of 15th century withdrawal from cities beyond the city of Angkor. What research into transformed societies has revealed is that the disruption of political networks can introduce new, potentially advantageous opportunities for peripheral settlements (Yoffee 2006), and that the responses of these settlements can vary significantly (Yoffee and Cowgill 1988 and references therein).

3.7 Chapter conclusion

The transformation of the Khmer kingdom, therefore, needs to be analysed on a broader spatial scale. Only through an analysis of the occupation dynamics of a set of major secondary cities throughout the Angkor-period city network can we test these assumptions of urban centre depopulations and migration south. Throughout the Angkor period the city of Angkor evolved into a very large, low-density primate city within a network of many large city centres, which were integrated via networks of temples linked by waterways and roads (Hendrickson 2010, 2011). Angkor became the base from which the king administered over a vast territory through highly centralised communication and ideological mechanisms (and somewhat centralised economic mechanisms), in line with Wheatley's (1983) and Friedmann's (1986) categorisation of the city (generically speaking) as a 'creator of effective space' and the "site of organisational foci of society, [which] contrives, prescribes, modulates, and disseminates order throughout the subsystems of that society" (Wheatley 1983, p. 9). Indeed, Lustig (2009, p. 158) has observed that, for the Khmer kingdom, "the concentrations of sites and their links suggest that the empire can be usefully viewed in terms of nodes and communication links, rather than held territory". The presumed 15th century abandonment of this political base and material network would have disrupted (but not removed) the king's administration networks, with ramifications for the interlinked secondary cities. As such, it is imperative to determine whether these secondary cities were similarly abandoned (see Lucero et al. 2015), or if the kingdom's broader city network instead became a set of independent or semi-independent, fragmented social and political subsystems operating within reconstructed spatial boundaries (Eisenstadt 1988). Determining the response of these secondary cities to this episode of disruption in centralised administration will provide a more nuanced understanding of the important transition from the Angkor period to the 'middle period' and reveal further insight into the relationships and interdependencies that operated between the major cities within the king's control network (see Kolata 2006) prior to the political abandonment of Angkor.

4 Environmental and site settings

4.1 Introduction

This chapter will begin with a justification of the sites selected for this analysis and present each site's individual history based on the available historical and archaeological records. The physical environmental setting of the central and northern plains of Cambodia (where the selected sites are located) will also be described as, in order to decipher the impact of anthropogenic disturbance on ecosystem structure and the broader physical landscape, a general environmental benchmark for the region needs to be established.

4.2 The selection of peripheral cities for analysis

This study will focus on three peripheral cities within Angkor's settlement network. The city sites - Preah Khan of Kompong Svay, Koh Ker and Banteay Chhmar (see Fig. 4.1) - were selected because they were all vital nodes in the Angkor socio-political network, represent occupation in relatively diverse physical environments, were spatially disparate but within stable Khmer control, represent both different and overlapping purposes (economic, religious, military, and/or political) for the Angkorian Khmer, and cover a variety of timescales of occupation.

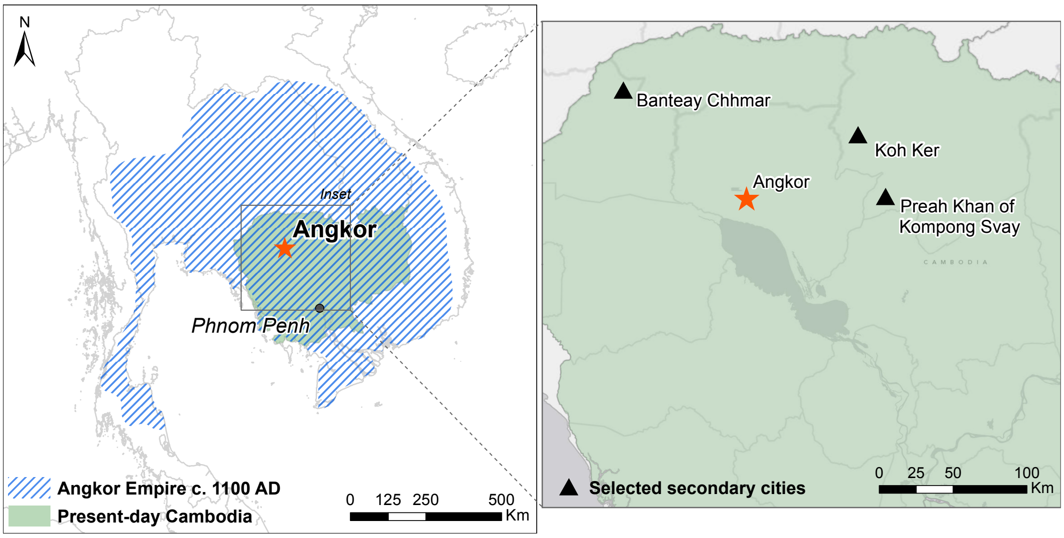


FIGURE 4.1: Map of the three cities selected for this study and their position within the larger context of the Empire at its height in the 12th century AD.

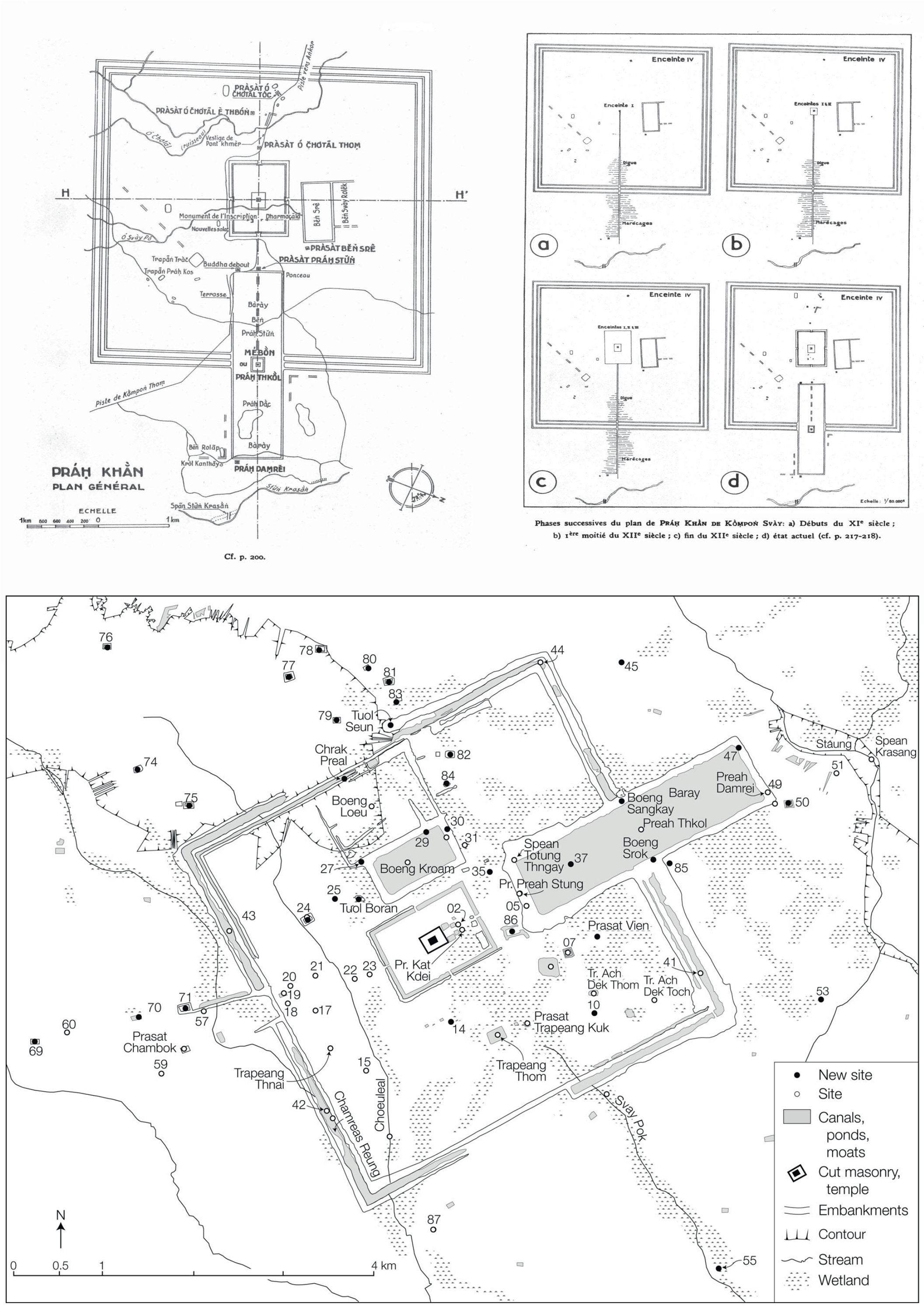
4.2.1 Preah Khan of Kompong Svay

Preah Khan of Kompong Svay, also known as Bakan, is a regional city situated approximately 100 km east of Angkor in the modern province of Preah Vihear. The city lies at the terminus of the East Road (Hendrickson 2007), where it meets the north-south flowing Staung River. Its position at this juncture connects the city directly to the capitals of Angkor and to numerous other provincial centres via the formalized road and navigable water networks (Hendrickson 2007). Although geographically isolated from the fertile alluvial soils and bountiful aquatic resources that sustained the densely populated cities on the banks of the Tonle Sap, Preah Khan presumably would have been positioned to source water from the Staung River (Hendrickson et al. 2010).

The existence of the city was initially documented by 19th century French explorers (Delaporte 1880, Moura 1882, Tissandier 1896), who identified a forest-shrouded temple complex comprising a central sanctuary surrounded by three concentric enclosures, within which numerous smaller temples, sculptures, accessory buildings, and basins were also built. By the turn of the 20th century, Aymonier (1900, 1901, 1904) and Lunet de Lajonquire (1902, 1907, 1911) had produced the first archaeological maps of the region. Subsequent aerial surveys performed by Golobeuw (1936) traced the extent of a previously unknown fourth outer enclosure (to be later measured at approximately 4.8 km by 4.8 km), making the Preah Khan temple complex nearly 23 km^2 and the largest rectilinear temple complex found in the Angkorian kingdom thus far (see Fig. 4.2).

Since this colonial-era mapping work, research at Preah Khan has been limited due to difficulties with site access and a scholastic preoccupation with sites in and around the capital of Angkor. An exception to this was the pivotal work by Henri Mauger, who produced a more detailed map of the complex in 1939 based on extensive ground surveys (see Fig. 4.2). Mauger noted the unusual north-eastern alignment of the complex, and using stylistic dating of the building works and one dated inscription (K. 161, from 1010 A.D. (Kern 1880)) found at the temple of Prasat Kat Kdei., Mauger suggested four phases of construction for the city, encompassing the reigns of several Angkorian kings; (1) the installation of the central sanctuary in conjunction with the inner (first) and, intriguingly, outer (fourth) enclosures sometime in the early 11th century, (2) the construction of the second enclosure during the first half of the 12th century, (3) the construction of the third fortified enclosure in laterite towards the end of the 12th century, and (4) the arrangement of the Baray together with the temples of Preah Stung and Preah Thkol, utilizing the earthen ramparts of the outer enclosure that had fallen into disrepair, perhaps in the early 13th century. This development sequence has since been reinterpreted by Jacques and Lafond (2004), however, who argue that the unfinished construction of the outer enclosure dates to sometime in the 14th or 15th centuries, during a period of heightened conflict with the western Siamese kingdom of Ayutthaya.

Debate concerning the function and occupation history of Preah Khan has been ongoing. Stylistic dating of the architectural works originally suggested use of the site between the 10th and 13th centuries (Mauger 1939). Subsequent archaeological work by Hendrickson et al. (2013) and Hendrickson and Evans (2015) indicate that occupation and use very likely extended beyond this period, and possibly well into the 17th century AD. While Groslier (1979) noted at Preah Khan a similar hydraulic suburb layout to other Angkorian cities, limited topographic indicators (such as house mounds, residential tanks, walled rice field systems etc.) and minimal ceramic remains found within or surrounding the temple complex have suggested that only small, possibly ephemeral populations ever persisted at this site (Hendrickson et al. 2015). However, recent airborne laser scanning results have revealed the presence of a clear urban grid within the central enclosure, and an extended, less uniform grid of lower density in the



Cf. p. 200.

Phases successives du plan de PRÁḤ KHẰN DE KỎṂPOṄ SVÀY: a) Débuts du XI^{e} siècle ; b) 1ère moitié du XII^{e} siècle ; c) fin du XII^{e} siècle ; d) état actuel (cf. p. 217-218).

FIGURE 4.2: Old and new archaeological maps of Preah Khan of Kompong Svay. **Top left:** Original temple complex map produced by Mauger (1939). **Top right:** Original sequence of construction for the temple complex produced by Mauger (1939). **Bottom:** Revised map of the temple complex and surrounds, modified from Hendrickson and Evans (2015). Number references can be found within Hendrickson and Evans (2015).

surrounding landscape (Evans 2016), suggesting that occupation patterns and population densities in fact closely resembled those of mid- and late-Angkorian settlements within the cities of Angkor.

The size and extent of the building works undertaken at this site imply a strong investment by the Angkor elite. To Groslier (1974), the timing of the city's foundation during the 11th century expansion period implies the city's original purpose was to accommodate the burgeoning populations of the cities on edge of the Tonle Sap. However, its placement at the eastern edge of the empire's extent also suggested to Groslier that Preah Khan may have instead been established as a staging point for Jayavarman VII during his ascension to kingship and as a strategic military outpost between the heartland of Angkor and their traditional enemies in Champa to the east (Groslier 1973).

Preah Khan also has an unusual historical association with iron production. The city is located approximately 31 km WNW of the region's largest iron ore deposit at Phnom Dek ('Iron Mountain'), and in proximity to the Kuay populations who have been associated with iron smelting for centuries (Levy 1943, Groslier 1986, Dupaigne 1987). Furthermore, a number of secondary roads leading from the city are directed toward an important copper source 8 km away at Phnom Pel (Hendrickson 2007). During his early explorations of the site, Aymonier (1900) found evidence of iron production between the 3rd and 4th enclosures and, while small in scale, this discovery remains anomalous among all other Angkorian sites, given that industrial work of this kind was not generally associated with sacred enclosures (Hendrickson et al. 2013). Following on from the suggestion that the exploitation of iron ore was prevalent in the region between the 9th and 13th centuries (ESCAP 2003), and building on the arguments of Groslier (1960-1970, and summarized in Jacques and Lafond 2004), Hendrickson (2010, 2011) and Hendrickson et al. (2013) have posited the alternative, more economically-focused idea that Preah Khan served as a production and distribution centre for the Khmer elite, to control the iron resources of the region that were important for continued expansion of the kingdom. However, radiocarbon dating of charcoal inclusions within these iron slag deposits places this industrial activity after the long and punctuated building program, suggesting that the religious function of the city may have ceased by the time the industrial activity occurred (Hendrickson et al. 2013, Pryce et al. 2014). As such, the evidence of iron production in this city most likely reflects brief and opportunistic industrial activity, rather than the strategic establishment as a trade outpost. Instead, Preah Khan of Kompong Svay is currently viewed as a symbolic expression of state power in a strategically important, resource-rich peripheral region of the kingdom (Hendrickson and Evans 2015), which contains a complex occupation and land use history (Evans 2016).

Overall, the high density of support infrastructure along the road connecting Angkor to Preah Khan (Stern 1965, Groslier 1973, Hendrickson 2011), its important association with iron ore resources (Aymonier 1900, Hendrickson et al. 2013, Pryce et al. 2014, Hendrickson and Evans 2015), the sheer size of the temple complex and extent and duration of the of building works, in addition to the evidence for high volumes of Angkor-period activity along the eastern road connecting this city to Angkor (Hendrickson 2007), strongly suggest that Preah Khan of Kompong Svay was one of the most important peripheral centres to the Angkor elite. As such, its occupation history represents a 'canary in the mine' for the disruption of centralised power in the network and its eventual devolution.

4.2.2 Koh Ker

Koh Ker remains one of the most intriguing cities of the Angkor period. Situated 80 km along the northeast royal road from central Angkor, this site was selected in 921-922 AD as the capital of the king Jayavarman IV following contention for the throne with Harshavarman I (Vickery 1986). It has also been posited that the capitals of Koh Ker and Angkor co-existed for a brief period, during the reign of Isanavarman II, which ended in 928 AD (Evans 2013, Uchida et al. 2014). Conventional historiography suggests that Koh Ker's occupation was fleeting, possibly lasting only 20 years until the death of Jayavarman IV in 940 or 941 AD (Coedes 1908, Parmentier 1939, Jacques and Lafond 2004). The capital subsequently returned to the Angkor region during the reign of Rajendravarman, after which time only a single inscription attributable to this king has been found at Koh Ker, and thus it was assumed that the city had been abandoned (Jacques and Lafond 2004).

The timing of the city's foundation remains cryptic, as there is no explicit record identifying Jayavarman IV as its founder (Jacques and Lafond 2004). As such, it is possible that construction of the city was initiated by a previous ruler, despite the fact that the vast majority of monuments and civil infrastructure within the temple complex have been attributed to Jayavarman IV (Jacques and Lafond 2004). While copious inscriptions have been found throughout the city, only a few include dates, most of which are later than 928 AD and therefore post-date Jayavarman IV's consecration (Jacques and Lafond 2004).

Archaeological research into the city of Koh Ker began with the colonial explorers Delaporte (1880) and Harmand (1879), and was continued by Aymonier (1900), Lunet de Lajonquiere (1902), Groslier (1926-1926) and Parmentier (1939). Following a long hiatus, largely due to colonial retreat, civil disturbances and a shift in research focus to the temple cities of Angkor, scholarly interest in Koh Ker was resumed by Jacques and Lafond (2004), Evans (2010, 2013, 2016), Mizoguch and Nakagawa (2011) and Uchida et al. (2014). Thus far, the remains of 76 temples have been documented across the 35km^2 complex (Uchida et al. 2014), in a layout that does not entirely conform to that of other Angkorian temple complexes (Jacques and Lafond 2004) (see Fig. 4.3). Among these monuments sits the largest temple mountain built by the Angkorian Khmer, a five-tiered stepped pyramid standing to the west end of the largest Koh Ker monument, Prasat Thom. According to Jacques (2004), the construction of Prasat Thom possibly began prior to Jayavarman IV's establishment as the capital in 921-922 AD, but received substantial enhancements during this king's tenure of the city. Southeast of Prasat Thom exists a large reservoir, with a north-south axis of approximately 1200 m and an east-west axis of approximately 600 m (Jacques and Lafond 2004, Uchida et al. 2014). The alignment of these three major features is not directly east-west, as in other major Angkorian temple complexes, but is instead shifted 14 degrees (Aymonier 1897), an adjustment that is generally considered to be an adaptation to the local topography (Jacques and Lafond 2004, Uchida et al. 2014). In the years following the construction of these major monuments and their associated structures, the axis of subsequent buildings became more regularly aligned east to west, a shift that Jacques (2004) tentatively proposes was a result of an increased number of influential Brahmins and clergy residing at Koh Ker following Jayavarman IV's consecration in 928 AD, who would have more strongly sought to maintain the religious architectural orientations.

The predominantly 10th century focus of the inscriptions, along with an architectural consistency throughout the building works, has suggested to many that development of the entire site occurred over a single twenty-year period (Aymonier 1900, Parmentier 1939, Chandler 2000, Jacques and Lafond 2004, Hendrickson 2007). During an early survey of the site, Lajonquiere (1902) documented that two groups of temples could be distinguished based on differences in orientation, implying that construction may have occurred in stages. This observation received

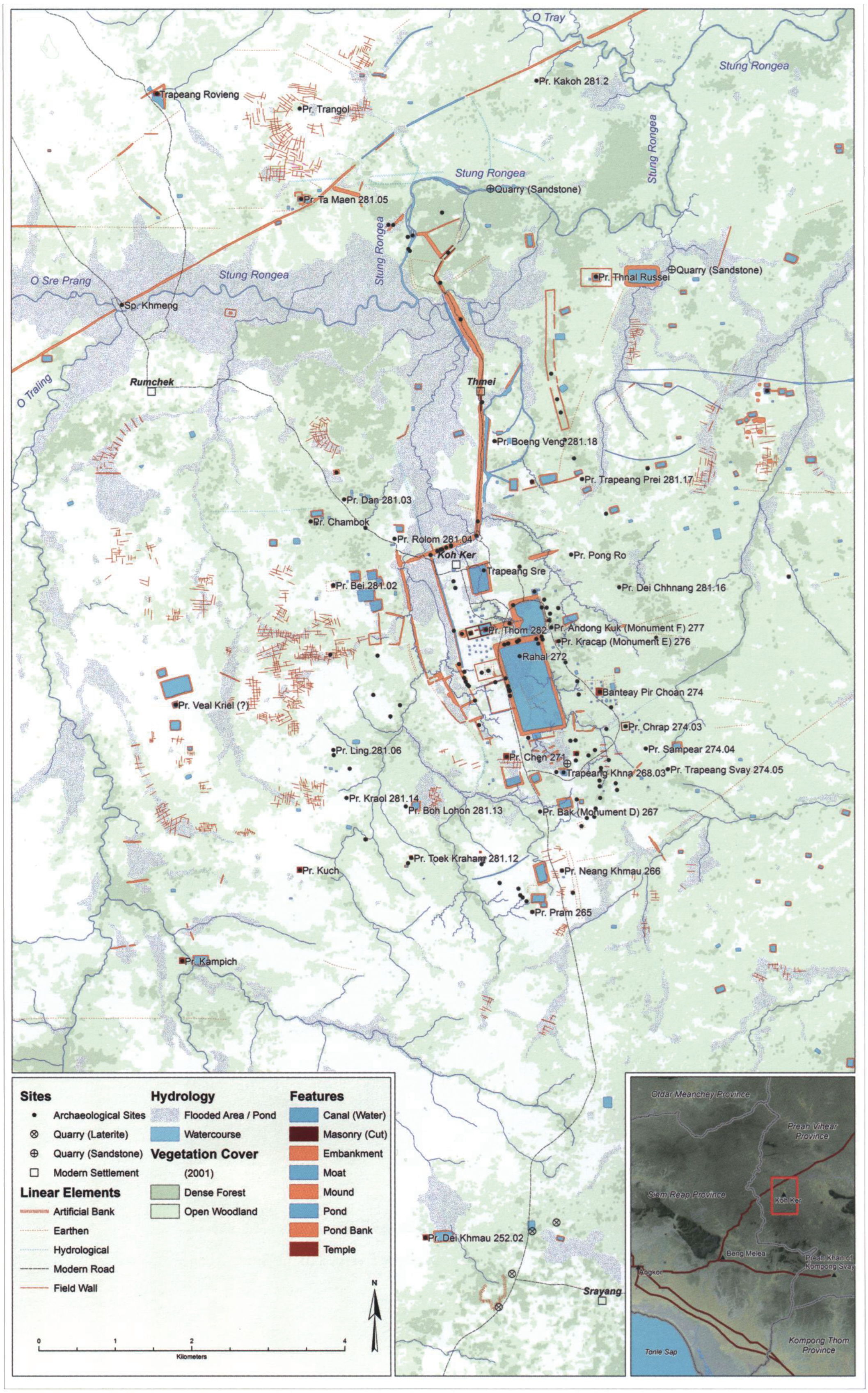


FIGURE 4.3: Archaeological map of Koh Ker and surrounds. Source: Evans (2013).

little traction until recently, however, when Uchida et al. (2014) used differences in laterite mineralogy and magnetic susceptibility to determine that the construction of the city did indeed progress in several separate phases. These researchers maintain that construction began with the brick sanctuaries, followed by those built of sandstone, with the final stages of construction making increasing use of laterite building materials, which were sourced over time from different regions. This research does not, however, identify the timing of each construction phase or the likelihood of continuity between each development sequence. A recent reappraisal of Prasat Andon Kuk as a hospital constructed during the late 12th century reign of Jayavarman VII (Jacques and Lafond 2004), along with two inscriptions (K. 674 from Prasat Dan and K. 682 from Prasat Thom) have suggested that at least some additional development occurred after the presumed abandonment of the city (Coedes 1937-1966). Furthermore, test excavations and pedestrian surveys conducted in 2006-2007 have revealed that repeated modifications were made to the baray (the Rahal) and that the central Koh Ker city region may have been inhabited sporadically since at least the pre-Angkor period (Ly et al. 2010). Ancient rice-field features found throughout areas where water naturally collects, as well as evidence for multiple concentric sites and their associated radial agricultural systems suggests that occupation in the Koh Ker region, in fact, potentially extends from the prehistoric period (Evans 2010). Field surveys and excavations also found concentrations of surface ceramics and stoneware that indicate intensive occupation of the city into the 12th and 13th centuries AD, and possibly occupation at Prasat Boh Lohong and Andong Preng into the 19th century AD (Ly et al. 2010, Belenyesy 2011, Ea 2011, Li 2011, Shimada 2011). Thus the history of construction, occupation and land use at Koh Ker remains largely ambiguous and is likely more complex and extensive than the presumed single twenty-year tenure.

Being remote from the bountiful natural resources supplied by the Tonle Sap ecosystem, the region surrounding Koh Ker has traditionally been considered poorly suited for the intensive rice agriculture characteristic of other Angkor-period cities. Freshwater availability is scarce and highly seasonal, and soils lack the nutrient-rich deposits of alluvium that make the Angkor region so productive (Parmentier 1939, Nesbitt 1997, Chandler 2000). Parmentier (quoted in Jacques and Lafond 2004, p. 107) described the city in 1939, thus:

> *"The region is now deserted and rather poor woodland, where sandstone and laterite break through the surface in broad patches. These sometimes extend over a considerable area, near the village of Srayang to the south on which Koh Ker depends. They are termed 'dance-halls of the elephants', considerable numbers of which still roam the region. The forest is quite impressive although rains are sparse. During the dry season it becomes impossible to follow the same roads as during the monsoon, because most of the natural or man-made ponds (trapeang) on which the pack-animals depend for their water are completely dried out".*

However, a closer analysis performed by Evans (2013) has refuted these claims that Koh Ker was inhospitable and unsuitable for intensive cultivation. Rainfall in the region is, at least in the contemporary landscape, 20-25% higher than the Angkor region (Nesbitt 1997), several potentially permanent water sources have been identified within walking distance of the city, and small water tanks would have been regularly capable of retaining water throughout the dry season, being excavated into the water table which in many areas is underlain by relatively impermeable sandstone (Evans 2013). Evidence remains in the landscape indicating bunded and walled rice field systems extended over approximately 40 km^2, and Evans' preliminary calculations suggest that agricultural production within the study area (i.e. < 8km and within a two-hour walk of Prasat Thom) may have been able to support populations of approximately 30,000 to 40,000 people.

Parmentier's (1939) original map of Koh Ker depicted a broad city settlement with poorly definable boundaries, comprising monuments, ponds, rice-fields, some water channels, a possible roadway and a collection of embankments. The scale and extent of the hydraulic works constructed at Koh Ker have more recently been mapped by Evans (2010, 2013, 2016), who clearly deciphered a significant network of hydraulic channels, stream diversions and damming structures, in addition to the numerous ponds and water tanks (at an overall density of approximately one pond per 0.8 km^2, see Evans (2013)) previously identified (Jacques and Lafond 2004). Evidence also exists for multiple stages of hydraulic development occurring, along with several subsequent adaptations and alterations within this networked water infrastructure (Evans 2010). Importantly, the scale of the dam in the north of the city is evidently comparable to the West Baray in Angkor, and would have potentially flooded between 4 and 5km^2 to a depth of 7m and provided a comprehensive dry season water resource (Evans 2013). Overall, this work indicates that substantial time, resources and manpower were expended on a water management system at Koh Ker that closely articulates broader Angkorian land and water management techniques, suggesting its importance and longevity as a city during the Angkor period at least.

The city of Koh Ker is a highly unique site. One of the few capitals to exist outside of the central Angkor district, understanding this city in more detail can potentially provide important insights into the mobility of Khmer kings, the nature and extent of their control, as well as the resiliency of cities peripheral to the fertile floodplains of Angkor following the departure of a king and his court. The fact that Koh Ker was chosen as a site for a king's capital, albeit for only a short period of time, suggests its relevance and significance to the broader Angkorian settlement network. The extent of temple construction, the size and grandeur of these monuments, and the presence of the ostentatious Prang temple pyramid speaks to Koh Ker's opulence and its place within a kingdom of growing prosperity. Determining the city's fate following the return of the capital to Angkor, as well as during the decline of imperial prosperity throughout the broader kingdom, will also help uncover the resiliency of major settlements during different successional stages of Khmer history. Recent research is overturning the previously accepted timeline of occupation for Koh Ker, and the city's possibly staggered construction sequence, and multi-period settlement and land use patterns suggest that its history and role within the Khmer kingdom is likely far more complex than assumed.

4.2.3 Banteay Chhmar

Banteay Chhmar, a modern name meaning 'Citadel of the Cats' (Briggs 1951), lies in the far northwest of Cambodia, at the foot of the Dangrek mountain range, approximately 100 km from the centre of Angkor and 25 km from the contemporary Thailand border. It is generally assumed that the city was either constructed or restored and chosen as a major Angkorian-period religious centre by the 12th century king and prodigious builder, Jayavarman VII (Jacques and Lafond 2004). Its remote location, general inaccessibility and the excessive looting of its sandstone artworks has limited any extensive archaeological work in this region thus far (Pottier 2004). However, prior to the city's desecration, numerous colonial scholars, including Aymonier (1900), Lajonquiere (1902, 1907, 1911), Parmentier (1936), Groslier (1935), de Coral Remusat (1951) and Coedes (1929) were able to document and analyse the city's numerous monuments and described their features, including their size, grandeur and extensive bas-reliefs, as unrivalled outside of Angkor Wat and the Bayon (Aymonier 1900). The few brief text engravings that have been preserved throughout the temple complex identify a number of deities and temple founders, however they have revealed little useful information on the monarchy of the time (Jacques and Lafond 2004). Potentially, the temple complex may have originally been the feudal holding of Jayavarman VII's paternal descendants (Jacques and Lafond 2004), however beyond this it remains unclear why Banteay Chhmar was important to the Khmer or why it was built in this locality.

The ancient Khmer word for this region was Ksac, which translates as 'sand' (Jacques and Lafond 2004), and illustrates well the dry and barren quality of Banteay Chhmar's landscape. Removed from major river sources and instead situated on a catchment boundary (Hendrickson 2007), widespread intensive agriculture would have been very difficult to maintain in this region. Nonetheless, Aymonier's (1900) original maps identify a large (1 km by 1.7 km) reservoir and more recent ground and aerial surveys performed by Pottier (2004), Richards (2007), Evans (2010, 2016) and Evans et al. (2011) have revealed a low-density pond-based settlement landscape characteristic of the Angkorian Khmers. However, while numerous intake canals and distribution channels have also been identified (Evans et al. 2011), Banteay Chhmar's water infrastructure network was not of a comparable scale to Angkor. Today the region is almost deserted, save small village populations in the surrounding commune (Hought et al. 2012) (see Fig. 4.4).

The city's regional location suggests that the predominant purpose of Banteay Chhmar was likely that of a strategically placed frontier stronghold (Higham 2001). Higham (2001) has posited that the outpost may have been commanded by Jayavarman VII's son, the crown prince Srindrakumaraputra or Indravarman, who is known for directing an apparently successful military campaign against Champa. The city's central sanctuary is dedicated to him, and four of his generals also have shrines built in their honour (Higham 2001). Whether or not this was the case, Coedes (1929) maintains that Banteay Chhmar was, at least, built as the funerary temple of the crown prince. Hendrickson (2007) has provided an alternative (or supplementary) suggestion for Banteay Chhmar's function as a settlement based on its position at the heart of the vast gold field known as Bo Sup Trup. He suggests that the city's separation from the royal road network may indicate that Banteay Chhmar's role in this area was focused on controlling direct access to this resource, in addition to its extraction and distribution via the less accessible, but still viable water network.

If Banteay Chhmar was, at some point, established as a military outpost, it is unlikely to have always served such a role, and occupation of the region appears to both pre- and post-date the reign of Jayavarman VII. Evidence for potentially Iron Age settlements exist throughout the local landscape (Richards 2007), and numerous scholars have attributed significant works in the city to the reigns of Jayavarman VII's predecessors. Groslier (1935) has suggested that at least a portion of the bas-relief carvings on the central temple may actually date to the earlier 12th century reign of Suryavarman II, while Parmentier (1936) believes that some may have been sculpted slightly later during the subsequent reign of Dharanidravarman II. For the most part however, the remaining structures and their features have been ascribed as constructions or renovations conducted by Jayavarman VII (Parmentier 1936, Remusat 1951). No evidence for occupation of the city following this period has been collected, however the modifications made to the infrastructure during the Khmer Rouge episode of the 1970s, along with the presence of minimal, current-day populations, potentially alludes to a settlement history that extends from the at least the turn of the first century right through to the modern day (Evans 2010).

The mystery of Banteay Chhmar provides an important opportunity to expand our knowledge of regional Khmer history, which has thus far been neglected, and to complement the analyses of Preah Khan of Kompong Svay and Koh Ker. Like those two provincial cities, Banteay Chhmar was located in a relatively hostile environment, and its fate following Angkor's abandonment will provide crucial insight into the operation of the settlement network during the Angkor period, and the degree of centralised control leading up to and following the devolution of the kingdom. Furthermore, the parallel roles (or purported roles) of both Preah Khan of

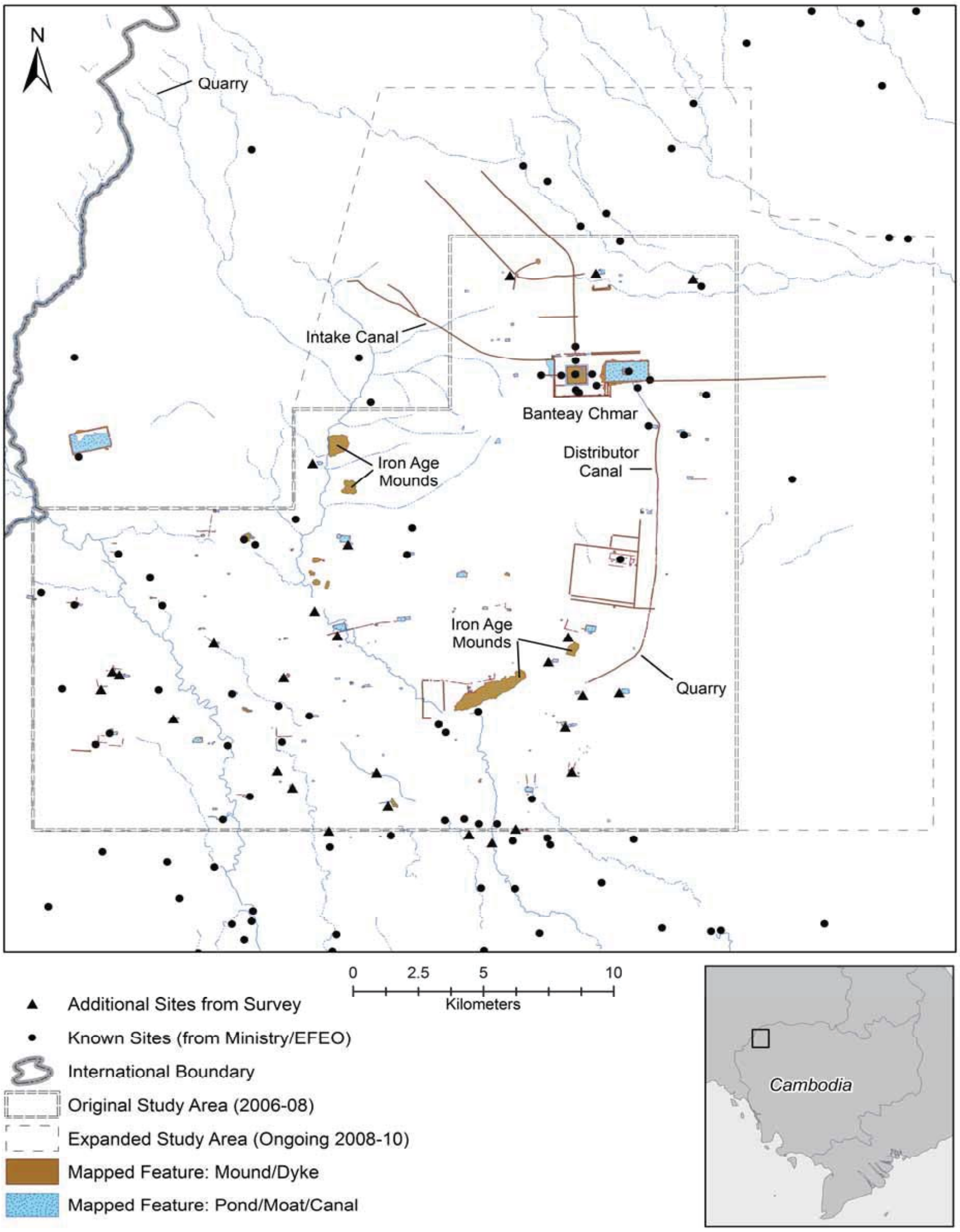


FIGURE 4.4: Preliminary archaeological map of Banteay Chhmar temple complex and surrounds. Source: Evans (2010).

Kompong Svay and Banteay Chhmar as military outposts on two opposing edges of the Khmer kingdom, both with clear access to a vital mineral resource, may reveal a greater understanding of the spatially disparate factors that can facilitate rejuvenation of regional populations following the decline of a major settlement hub.

4.3 The contemporary physical environmental setting

4.3.1 Climate

The three cities selected for analysis are all located within the northern plains of Cambodia. This region sits within the large basin of the Tonle Sap and Mekong River, bordered by several narrow coastal ranges in the south and the broader Dangrek Plateau in the north. Positioned in the tropical and subtropical latitudes and between the rainfall-generation systems of the Bay of Bengal and the South China Sea, the majority of Cambodia experiences a tropical savanna climate or tropical wet and dry climate (Köppen climate classification 1961). Rainfall in Preah Khan of Kompong Svay and Koh Ker is distinctly seasonal, with approximately 90% of annual totals (1400-2000 mm) (World Bank Climate Change Knowledge Portal 2017) falling during the wet season from May to October, when moisture-laden winds from the southwest are dominant (Wang and LinHo 2002). Banteay Chhmar, located further west in the Banteay Meanchey province, exists within a similarly seasonal climate, although is drier, receiving approximately 800-1400 mm of rain annually (World Bank Climate Change Knowledge Portal 2017). These totals are based on precipitation records from 1900-2012.

The seasonality characteristic of Cambodia is the result of the north-south migration of the Inter-tropical Convergence Zone (ITCZ) and the associated movement of monsoon systems across the region (Wang et al. 2003, Saha 2010). Cambodia, and much of mainland Southeast Asia, exists within the transition zone of the Indian Monsoon Systems in the west and the East Asian Monsoons in the east, where the cycles of these two climate systems intersect (Wang and LinHo 2002). This interaction provides greater complexity to mainland Southeast Asia's seasonality of rainfall and, as such, the region of study generally receives considerable variability in precipitation levels both within and between monsoon seasons (Yang and Lau 2006). Annual precipitation is generally bimodal, as each different monsoon system, and their various influences, shift across space and each, in turn, becomes more dominant over the area (Yang and Lau 2006). As a result, a 2-3 week break in monsoon rains generally occurs in the region during July (Maxwell 1999, Saha 2010). The intensity of each branch of the monsoon depends on coupled continent-to-ocean temperature gradients, which are usually greater in the east (between the cool Asian continent and the warm Pacific Ocean) (Wang and LinHo 2002), as well as their timing in association with either building or decaying El Nino/La Nina phases operating in the Pacific (Webster and Yang 1992, Wu et al. 2003). In addition to these monsoonal rains, tropical cyclones, often tracking from the eastern central Pacific Ocean in the east, can also contribute significantly to precipitation totals in the region (Saha 2010).

Pronounced levels of inter-annual and inter-decadal variability also typify these monsoon systems, and can be consequential for Southeast Asian economies that depend highly on agriculture (Goswami 2006, Yang and Lau 2006, Clift and Plumb 2008). One particularly unusual feature of the inter-annual variability of the Asian Monsoon is its tendency to exhibit quasi-biennial fluctuations in character (Shen and Lau 1995, Yang and Lau 2006), while the inter-decadal cycles display a periodicity of roughly 50-60 years (Goswami 2006). This multi-scalar temporal variability is largely due to the dynamic nature of other larger-scale climate systems with which the monsoons interact, such as the El-Nino Southern Oscillation, the Arctic Oscillation and the South Asian High, as well as the spatiality – both horizontally and vertically through the structure of the atmosphere – of the various operational components of these monsoon systems (Goswami 2006). Furthermore, variability is inherent in these monsoon systems given that they are driven predominantly by both local and regional-scale irregularities in land and sea surface temperatures (Yang and Lau 2006), and secondarily by snow and ice levels in Eurasia, soil moisture, vegetation coverage and the albedo of the Earth's surface, all of which vary considerably over multiple timescales (Saha 2010). Indeed, it is the highly variable nature of monsoon systems in this region, particularly their inter-annual and inter-decadal variability in strength, that may have both encouraged the fluorescence of agrarian societies initially in this region (Clift and Plumb 2008, Lieberman and Buckley 2012) and eventually led to their downfall (Buckley et al. 2010, Cook et al. 2010). This research illustrates how impactful these climate patterns are to anthropological systems in prehistoric Southeast Asia, particularly droughts associated with the weakening of the summer monsoon, which can often occur for decades at a time.

4.3.2 Geology, topography and soils

Cambodia's regional geology is characterized by its location on the Indochina terrane, within the Sundaland block, where the Eurasian, Pacific and Indian blocks converge (Daly et al. 1991, Metcalfe 2011). Basement complexes of Precambrian to Middle Palaeozoic age have undergone both contact and regional metamorphism and Late-Jurassic to early Cretaceous rifting resulting in the formation of vast structural depressions (Vysotsky et al. 1994). As such, all three cities are located across the extensive sedimentary basin that comprises the entire northern and central plains of Cambodia (Acker 1998, see Fig. 4.5).

Large Quaternary alluvial deposits stretch from the Dangrek Range and the adjoining Khorat Plateau in the north, to the Tonle Sap in the south and the Mekong River in the east, and are often underlain by a thick layer of lateritic clay (Acker 1998). The plain slopes gently from the northeast to the southwest (Acker 1998), and while several tablelands and outcrops rise abruptly throughout this region (Caro et al. 2010), elevations within this lowland plain are low, with an average altitude of 80-100 m, and generally not exceeding 500m above sea level (Caro and Im 2012, see Fig. 4.5). The highlands to the north and the west, as well as the isolated buttes, comprise almost uniform lithologies, predominantly consisting of the continentally-derived Lower-Middle Jurassic sandstones, siltstones and conglomerates known as the *Terrain Rouge* (due to the presence of iron oxides), which overlies the Upper Jurassic-Cretaceous claystones, siltstones, sandstones, and conglomerates known as *Grès supérieures* (Tien et al. 1991, Vysotsky et al. 1994, Sotham 1997). The upper, feldspathic sandstone horizons of these units are considered to be the dominant source of building and sculpture material during the Angkorian period (Delvert 1963, Uchida et al. 1995, Baptiste et al. 2001). Below these Jurassic to Cretaceous sandstone and claystone deposits lies the oldest stratigraphic formations of Cambodia, consisting mainly of either high-grade metamorphic gneiss, quartzite and amphibolites of Precambrian age, or the Devonian-Carboniferous suite comprising unmetamorphosed, but heavily folded, shale and sandstone (Vysotsky et al. 1994). Detailed descriptions of the stratigraphic formations comprising regional Cambodia are provided by Vysotsky et al. (1994).

More locally, Preah Khan of Kompong Svay sits within a broad and flat catchment bordered by outcropping sandstone hills ranging from approximately 150 m to 500 m in height (Contri 1972, Hendrickson and Evans 2015). This peneplain landscape comprises a mix of Triassic, Jurassic-Cretaceous and Quaternary alluvial deposits (Pryce et al. 2014, see Fig. 4.5). Exploitable iron oxide reserves can be found in the area between igneous (largely granite, andesite and rhyolite) intrusions and metamorphic hornfels (Christensen 2007, Carò and Douglas 2013). Dominant soil types in the region include acid lithosols, grey hydromorphics and plinthite podzols (Crocker 1962).

The region of Koh Ker consists of plateaus of Lower-Middle Triassic volcano sedimentary units, Lower-Upper Jurassic sedimentary units, with smaller Pliocene-Pleistocene basalts located 20-30 km from the city (Caro et al. 2010). Generally 2-3 m of loosely consolidated Jurassic sandstone exists below the soil layer (Moriai et al. 2002), which consists predominantly of acid lithosols (Crocker 1962). In the surrounding region, greyish black limestone deposits from the Upper Carboniferous are found to the north of Koh Ker, while intermediate extrusive igneous units are often overlain by Triassic rhyolitic tuffs in the area to the south (Caro et al. 2010). Several laterite outcrops exist immediately south of the collection of monuments of Koh Ker, from which much of the building material was sourced (Uchida et al. 2014). Overall, altitude varies little, ranging from 50-160 m above sea level.

Geological maps indicate that Banteay Chhmar sits within the geological province of the Battambang Plain, against the northern slope of a ridge that runs parallel to the Dangrek mountain range. The Battambang Plain consists of vast deposits of Quaternary period alluvium, bordered by outcropping sandstone and conglomerates, or Cretaceous-Paleocene formations known as the Upper Indosinias (Department of Potable Water Supply 2002). Some small deposits of Jurassic-Cretaceous sandstone also exist to the north of the city complex (ODC 2006b). Soil types in the region range from red-yellow podzols, grey hydromorphics, plinthite podzols, and acid lithosols (Crocker 1962). In general the geographic relief of the area is low, with altitudes ranging from 26-50 m above sea level.

4.3.3 Regional biogeography - forest types

All three cities sit within the Tropical and Sub-tropical Dry Broadleaf Forest Biome (henceforth referred to as Seasonally Dry Tropical Forest or SDTF), classified by Olson et al. (2001) as part of the World Wildlife Fund (WWF) global ecosystem assessment. Due to particularly high levels of endemism within the SDTF biome, floral characteristics within these forests differ greatly across the tropical realm, however they are usually defined collectively by their commonly semi-deciduous nature and their exposure to sharply seasonal rainfall regimes (Mooney et al. 1995, Werneck et al. 2011). Most examples of the SDTF biome are subjected to mean annual precipitations of < 1600 mm and at least five dry months per year (Miles et al. 2006, Werneck et al. 2011). Anomalies do exist however, especially in the SDTFs of Southeast Asia, where some examples of this biome receive up to 2300 mm of rainfall per year (Rundel and Boonpragob 1995) and others are more deciduous than semi-deciduous during drought periods (Ruangpanit 1995). Furthermore, it should also be noted that SDTF forest ecosystems commonly persist as diffuse mosaics with other biomes, in particular the tropical and subtropical grassland, savanna and shrubland (Menaut et al. 1995, Sampaio 1995, Prance 2006).

Within the broad biogeographic realm of the SDTF, two WWF-recognised terrestrial ecoregions, namely the Central Indochina dry forests (CIDF) and Southeastern Indochina dry evergreen forests (SIDEF), have developed as forest sub-units. The ranges of these forest units are delineated in Figure 4.6. The CIDF ecoregion extends across much of the central region of the Southeast Asian mainland, and within Cambodia is widespread throughout the northern, eastern and central plains (Wikramanayake et al. 2017a). In Cambodia, this forest type is often referred to as *forêt claire* (Wikramanayake et al. 2017a). Primarily it comprises deciduous trees, dominated by Dipterocarpeaceae species, and depending on the region often *Terminalia alata* (F.

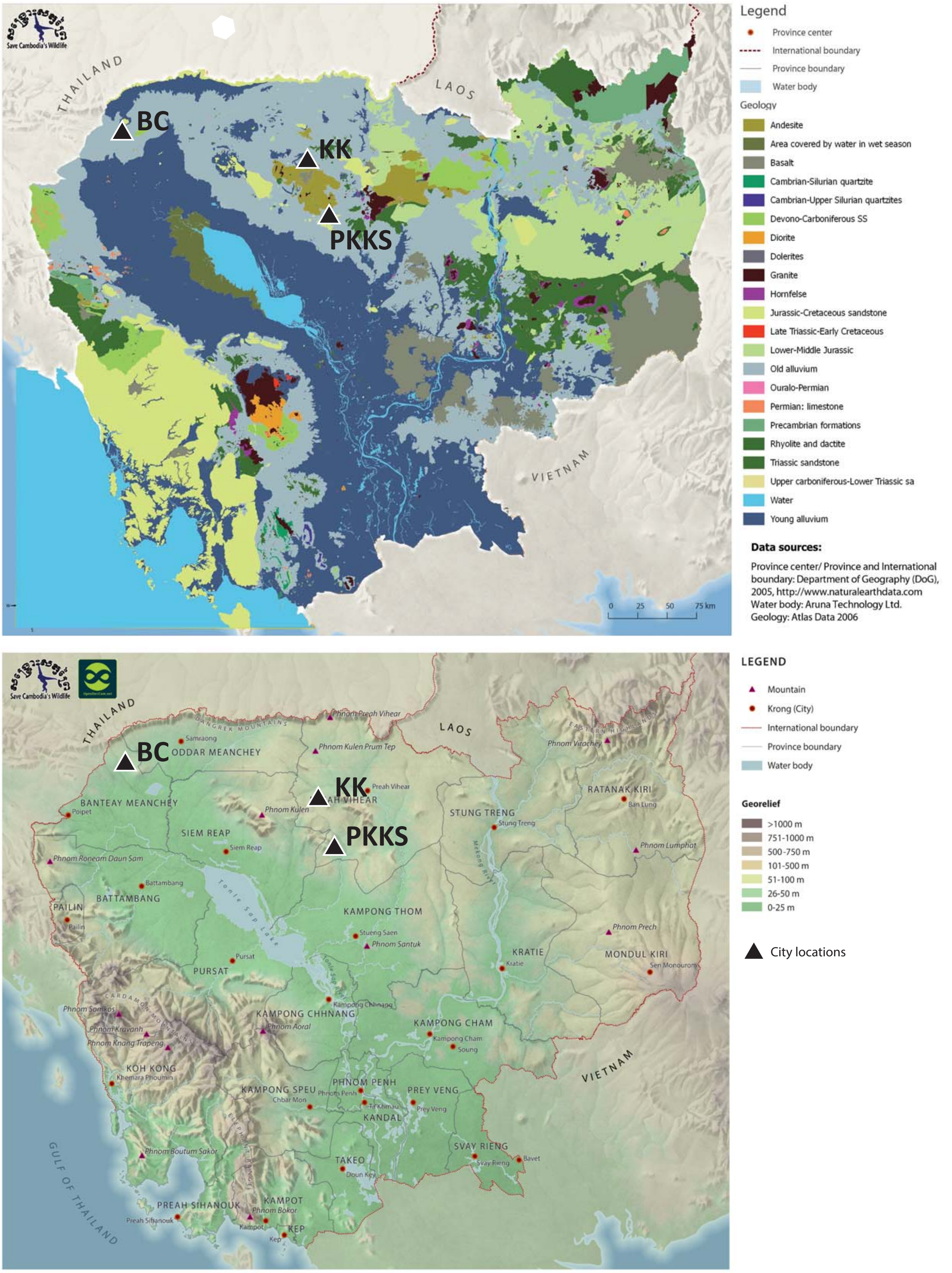


FIGURE 4.5: **Top:** Map of the geology of Cambodia, in relation to the three cities selected for analysis. Source: Open Development Cambodia (2006a). **Bottom:** Map of the geographical relief of Cambodia, also in relation to the selected cities. Source: Open Development Cambodia (2013).

Heyne ex Roth) and *Pinus merkusii* (Jungh & de Vries), that maintain either closed canopies or more open structure (50-80% cover) with a grassy understorey (Wikramanayake et al. 2017a). Small trees, such as *Pterocarpus macrocarpus* (Kurz), *Sindora siamensis* (Teijsm. ex Miq.) and *Xylia xylocarpa* (Roxb.), can also appear frequently (Wikramanayake et al. 2017a).

The second ecoregion, the SIDEF, is found throughout central north and northeastern Cambodia, with large tracts found particularly along the Cambodia-Thailand border, in regions subjected to more humid climates and reduced burning regimes, and which maintain soils with higher moisture-retention capacity compared to the CIDF (Wikramanayake et al. 2017b). Consequently, this ecoregion contains species that are comparatively less fire-tolerant and more drought sensitive than their CIDF counterparts. Wikramanayake et al. (2017b) concede that the ecoregion would be more accurately referred to as semi-evergreen, rather than evergreen, on account of substantial proportions of its canopy being deciduous during dry months. Overall, this ecoregion maintains both structural and floristic diversity, housing a richness of species endemic to mainland Southeast Asia (Wikramanayake et al. 2017b). The canopy is open and emergent species regularly include *Dipterocarpus alatus* (Roxb. ex G. Don), *D. costatus* (G. Don), *Shorea guiso* (Blume), *S. hypochra* (Hance), *Hopea odorata* (Roxb.), *Anisoptera costata* (Korth.), *Ficus spp.*, *Tetrameles nudiflora* (R. Br.) and *Heritiera javanica* (Kosterm.) (Wikramanayake et al. 2017b). Throughout the mid- and understory, bamboos, palms and lianas are often present.

For this study, vegetation landscapes found in the areas of study have been sub-classified further into specific forest types (see Table 4.1) in order to better identify local-scale occurrences of ecological succession within these broader-scale forest systems (Bunyavejchewin et al. 2011). Predominantly these sub-categories follow the nomenclature collated from specific forest type data presented by Hamilton (2016), Ruangpanit (1995), Neal (1967), Rundel and Boonpragob (1995), Bunyavejchewin et al. (2011) and Theilade et al. (2011). In instances where these authors diverged in the language used to classify forest types, nomenclature followed more closely that of Hamilton (2016), who favoured the usage of Bunyavejchewin et al. (2011). Within the CIDF ecoregion, the dry deciduous forest types predominate (Wikramanayake et al. 2017a). These include the deciduous dipterocarp forest (DDF) and the mixed deciduous forest (MDF) (Bunyavejchewin et al. 2011), both of which the presence of *Xylia xylocarpa* ((Roxb.) Taub.) is considered an indicator species (Tani et al. 2007).

DDF mainly occurs in the lowlands, however it can form composite landscapes with pine forest at higher elevations (Bunyavejchewin et al. 2011). Soils supporting this forest type are often poorly developed, sandy and lateritic (Santisuk 1988, Stott 1990), and thus not well-suited to extensive agriculture (Cooling 1968). The canopy of DDF is generally open, however the coverage densities can vary considerably depending on soil type, topographic relief, microclimate and fire regimes (Maxwell 1999). MDF similarly persists at low elevations and in similar climates, but its relative lack of dipterocarps and more diversity in its upper canopy differentiates it from the DDF (Bunyavejchewin et al. 2011). Moreover, as MDF develops in better developed, less acidic and marginally more fertile soils compared to DDF, and maintains greater abundances of highly valuable timber resources, it has consequentially experienced greater levels of human impact (Bunyavejchewin et al. 2011). Groundcover also tends to be more dense and diverse in the MDF type, typified by the abundance of herbaceous and shrubby species, particularly gingers and deciduous bamboo (Ruangpanit 1995). The leaves of MDF and DDF forest trees usually desiccate and fall in the early dry season (Williams et al. 2008), providing seasonal microclimates and leaf litter abundances that encourage periodic, low-intensity burns, and as such, many species common to dry deciduous forests have developed fire-resistant properties, such as thick bark layers and post-burn reproduction strategies (Stott et al. 1990, Bunyavejchewin et al. 2011).

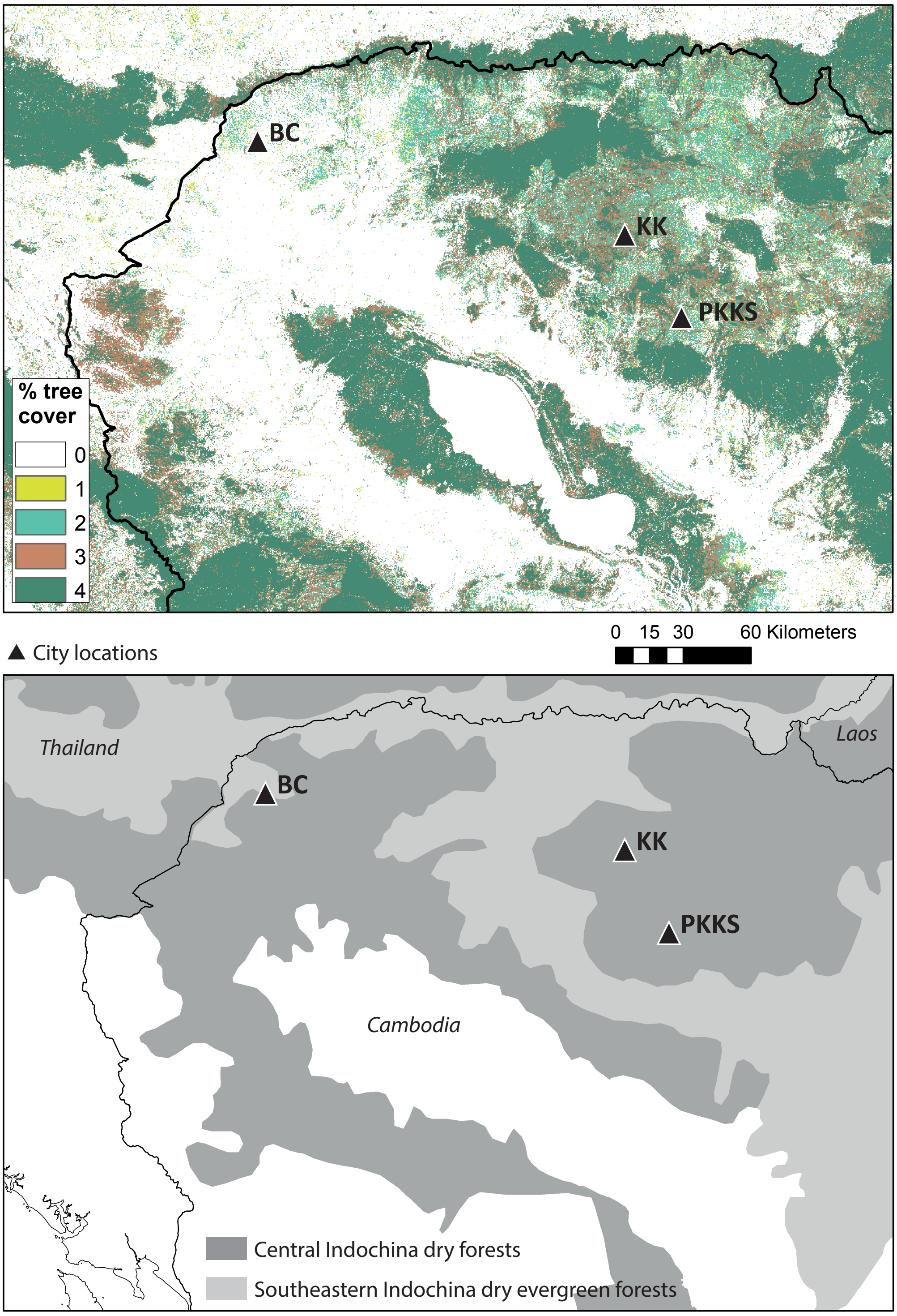


FIGURE 4.6: **Top:** Extent of tree cover remaining across the northwestern and north-central plains of Cambodia. Source: Open Development Cambodia (2000). **Bottom:** Current coverage of the two WWF-recognised terrestrial ecoregions comprising the Seasonally Dry Tropical Forest biome, in relation to the three cities selected for analysis. Source: Olson et al. (2001).

Alternatively, semi-evergreen dry forests (SEDF) are strongly associated with the SIDEF ecoregion, however often as a mosaic with the dry deciduous forest types (MacKinnon 1997, Wikramanayake et al. 2017b). SEDF generally contain greater floristic diversity than both DDF and MDF (Bunyavejchewin et al. 2011), and the presence of *Hopea odorata* (Roxb.) – a sought-after timber species – makes this forest type economically valuable (Bunyavejchewin et al. 2011). The canopy of SEDF is relatively closed, and usually dominated by evergreen dipterocarp species, alongside members of the Sapindaceae, Meliaceae, Annonaceae and Lauraceae families, while shrubby evergreen species from the Euphorbiaceae and Rubiaceae families largely comprise the understorey (Bunyavejchewin et al. 2011). As the name suggests, the SEDF forest type contains a mix of deciduous and non-deciduous vegetation, with the extent, timing and length of leaflessness varying considerably between species (Bunyavejchewin et al. 2011).

While swamp or flooded forests (SwF) exist primarily throughout the flooded zone of the Tonle Sap and along the Mekong River (MacKinnon 1997), they can persist along watercourses or in low-lying areas prone to saturation and water-retention throughout Cambodia (Theilade et al. 2011). In Cambodia, expressions of this ecosystem contain hydrophytic tree species, palms, and dense thickets of tree ferns and other pteridophytes (Theilade et al. 2011). Epiphytes are also common (Maxwell 1999). Many genera found within SwF overlap with those of the SEDF and dry dipterocarp forest types, however the species present in each type usually differ (Theilade et al. 2011). This array of forest types often occur together as highly granular patchworks within the terrestrial ecoregions (CIDF and SIDEF) outlined above (Bunyavejchewin et al. 2011), and can fluctuate between types (as well as total amounts of biomass) through wet and dry seasons (Ruangpanit 1995, Huete et al. 2008).

Herbaceous, emergent aquatic communities (EAq) that develop in open water bodies are the final vegetation type identified in this study. These plants can be either rooted submerged or emergent plants, or free floating plants that occur in stagnant lakes, ponds, reservoirs and early-stage swamp environments (Penny 1999). Often they develop into dense floating vegetation mats that can be up to one metre thick. It is expected that these local, aquatic species will be overrepresented in pollen records reconstructed from cores retrieved from such heavily colonized lake sites.

The suite of the aforementioned forest/vegetation types referred to here and in the results of this study is described in detail, including lists of common genera/species associated with each type, in Table 4.1. The lists of common species are predominantly based on surveys performed in each forest type, generally in Thailand, but also in central Cambodia. Where these have not been completed, species lists are based on palaeoecological studies undertaken in the Cambodian context (e.g. Penny 1999, Penny et al. 2006). Species identified within Thai forests that were not known to exist in Cambodia (as per Maxwell 1999, Dy Phon 2000) were excluded from the list.

TABLE 4.1: Ecological descriptions of the seven forest types classified and applied in this analysis. Includes information of the climate, geological, topographical and forest structure characteristics of each type, as well as a (non-exhaustive) list of the species commonly found in each forest structural component.

Forest type / vegetation assemblage	**Abbr.**	**Description**	**Common plants**		**Sources**
Deciduous dipterocarp forest	DDF	Open to nearly closed canopy (53-77% coverage) Low fertility soils Fire-adapted tree species (e.g. Dipterocarpaceae) Lowland (< 700-900 m ASL) Mean annual rainfall 1000-1500 mm, 5-7 dry months	**Canopy/mid-storey**: Dominated by Dipterocarpaceae genera (e.g. *Dipterocarpus obtusifolius* (Teijsm. ex Miq.), *D. tuberculatus* (Roxb.), *Hopea spp.*, *Shorea siamensis* (Miq.), *S. obtusa* (Wall. ex Blume)), but also includes *Careya sphoerica* (Roxb.), *Dalbergia cultrata* (Graham ex Benth.), *Dillenia obovata* ((Blume) Hoogland), *Irvingia malayana* (Oliv. ex Benn.), *Pterocarpus macrocarpus* (Kurz), *Quercus kerrii* (Craib.), *Sindora siamensis* (Teijsm. ex Miq.), *Strychnos nux-blanda* (A.W. Hill), *Terminalia* spp., *Xylia xylocarpa* ((Roxb.) Taub.)	**Understorey**: Poaceae genera, particularly *Imperata cylindrica* ((L.) Rausch), also *Aporusa sphoerosperma* (Gagnep.), *Corypha lecomtei* (Labill.), *Ixora* spp., *Phoenix acaulis* (Roxb.). *Cycas siamensis* (Miq.) is also widespread	Ruangpanit (1995) Neal (1967) Rundel and Boonpragob (1995) Bunyavejchewin et al. (2011) Tani et al. (2007) Maxwell (1999)

Continued…

Forest type / vegetation assemblage	Abbr.	Description	Common plants		Sources
Mixed deciduous forest	MDF	Closed canopy Mean annual rainfall 1400-1800 mm, 4-6 dry months Lowland (< 800 m ASL) Semi-deciduous (3-4 month periods) Deep, well-drained, loamy (calcareous or granitic) soils	**Canopy/mid-storey**: *Adina* sp., *Afzelia xylocarpa* ((Kurz) Craib), *Albizzia* spp., *Anogeissus acuminata* ((Roxb. ex DC.) Guill. & Perry), *Artocarpus sampor* (Gagnep.), *Azadirachta indica* (Ant. Juss.), *Bombax* sp., *Canarium subulatum* (Guillaumin), *Careya sphoerica* (Roxb.), *Cassia garretiana* (Craib.), *Dalbergia cultrata* (Graham ex Benth.), *D. nigrescens* (Kurz), *D. oliveri* (Gamble & Prain), *Dillenia* spp., *Diospyros* spp., *Garuga pinnata* (Roxb.), *Haldina cordifolia* ((Roxb.) Ridsdale), *Homalium tomentosum* ((Vent.) Benth.), *Hymenodictyon excelsum* (Wall.), *Irvingia malayana* (Oliv. ex Benn.), *Lagerstroemia* spp., *Leguminosae* spp., *Memecylon edule* (Roxb.), *Parinarium annamensis* (Hance), *Peltophorum dasyrrhachis* ((Miq.) Kurz), *Pterocarpus macrocarpus* (Kurz), *Schleichera oleosa* ((Lour.) Oken), *Sindora siamensis* (Teijsm. ex Miq.), *Spondias* spp., *Stereospermum chelonoides* ((non L.:Dop) DC.), *Eugenia/Syzgium* sp., *Tectona grandis* (L.f.), *Terminalia* spp., *Vitex pinnata* (L.), *Wrightia arborea* ((Dennst.) Mabb.), *Xylia xylocarpa* ((Roxb.) Taub.)	**Understorey**: Poaceae genera (the presence of bamboo can be diagnostic), also *Antidesma acidium* (Retz.), *A. ghaesembillia* (Gaertn.), *Bauhinia* spp., *Boesenbergia* sp., *Buchanania reticulata* (Hance), *Butea superba* (Roxb.), *Casearia grewiaeolia* (Vent.), *Cochlospermum gossypium* ((L.) Alston), *Colona auriculata* (Craib), *Congea tomentosa* (Roxb.), *Costus speciosus* ((D. Koenig) Sm.), *Cratoxylon formosum* ((Jack) Dyper), *C. prunifolium* (Dyer), *Croton* spp., *Curcuma* spp., *Desmodium* sp., *Gardenia angkoriensis* (Pit.), *G. philastrei* (Pierre ex Pit.), *Hibiscus* spp., *Ixora* sp., *Mallotus philippinensis* ((Lam.) Muell. Arg.), *Memecylon laevigatum* (Blume), *Millettia erythrocalyx* (Gagnep.), *Morinda* spp., *Phyllanthus emblica* (L.), *Randia tomentosa* (Wight & Arn.), *Streblus asper* (Lour.), *Zingiber* spp., small numbers of *Phoenix* spp. and *Calamus* spp.	Rundel and Boonpragob (1995) Richards (1952) Ruangpanit (1995) Bunyavejchewin et al. (2011) Maxwell (1999)

Continued…

Forest type / vegetation assemblage	Abbr.	Description	Common plants		Sources
Semi-evergreen dry forest	SEDF	Highland (700-1000 m ASL), or at lower elevations with higher moisture levels (e.g. moist valleys and ravines) Mean annual rainfall 1200-2000 mm, 4-6 dry months Moderately fertile soils, high moisture retention capacity	**Canopy/mid-storey**: *Anistoptera* spp., *Baccaurea ramiflora* (Lour.), *Carallia brachiata* ((Lour.) Merr.), *Celtis* sp., *Dehaasia cuneata* (Blume), *Dipterocarpus alatus* (Roxb. ex G. Don), *D. costatus* (C.F. Gaertn), *D. dyeri* (Pierre), *D. turbinatus* (C.F. Gaertn), *Duabanga grandiflora* ((Roxb. ex DC.) Walp.), *Elaeocarpus* spp., *Erythrophleum succirubrum* (Gagnep.), *Hopea ferrea* (Laness.), *H. odorata* (Roxb.), *H. pierrei* (Hance), *Hydnocarpus ilicifolia* (King), *Irvingia malayana* (Oliv. ex Benn.), *Lagerstroemia calyculata* (Kurz), *Litsea vang* (Lecomte), *Mangifera indica* (L.), *Mesua ferrea* (L.), *Pterocymbium javanicum* ((R. Br.) Kosterm.), *Pterospermum diversifolium* (Blume), *Shorea thorelii* (Pierre ex Laness.), *Sindora siamensis* (Teijsm. ex Miq.), *Tetrameles nudiflora* (R. Br.), *Trema tomentosa* ((Roxb.) Hara), *Wrightia arborea* ((Dennst.) Mabb.), *W. pubescens* (R. Br.)	**Understorey**: *Dimocarpus longan* (Lour.), *Uncaria homomalla* (Miq.), *Wrightia annamensis* (Eberh. & Dubard)	Bunyavejchewin et al. (2011) Maxwell (1999)

Continued…

Forest type / vegetation assemblage	Abbr.	Description	Common plants		Sources
Riparian/Gallery forest	RiF	Alongside streams and at the intersection where the watertable rises to meet the ground surface	**Canopy/mid-storey**: Similar to SEDF, additional species include *Acacia harmandiana* ((Pierre) Gagnep.), *Alangium* sp., *Barringtonia acutangula* ((L. Gaertn.), *Crateva magna* ((Lour.) DC.), *Crudia chrysantha* ((Pierre) Schum.), *Cynometra dongnaiensis* (Pierre), *Diospyros helferi* (C.B. Clarke), *Dipterocarpus alatus* (Roxb.), *Eugenia cambodiana* (Gagnep.), *Ficus* spp., *Hopea odorata* (Roxb.), *Hydnocarpus anthelminticus* (Pierre ex Laness.), *Nauclea orientalis* ((L.) L.), *Pterospermum diversifolium* (Blume), *Sterculia foetida* (L.), *Strychnos* sp., *Terminalia bialata* ((Roxb.) Steud.), *Xanthophyllum glaucum* (Wall.)	**Understorey**: *Anogeissus rivularis* ((Gagnep.) Lecomte), *Artabotrys* sp., *Combretum quadrangulare* (Kurz), *C. trifoliatum* (Vent.), *Cordia obliqua* (Willd.), *Gmelina asiatica* (L.), *Mallotus* spp., *Morinda persicaefolia* (Ham.), *Uncaria homomalla* (Miq.)	Bunyavejchewin et al. (2011) Maxwell (1999)
Swamp forest	SwF	Lowland (50-100 m ASL) Sandy alluvial soils or permanently moist peat Mean annual rainfall is variable, SwF common in regions receiving 1600-2200 mm Irregular canopy and dense understorey	**Canopy/mid-storey**: *Baccaurea* sp., *Barrongtonia acuminata* (Korth.), *Callophyllum* spp., *Cleistanthus tomentosus* (Hance), *Diospyros cambodiana* (Lecomte), *Elaeocarpus* spp., *Eugenia* spp., *Euonymus* sp., *Fagraea racemosa* (Jack ex. Wall), *Ficus* spp., *Garcinia* sp., *Irvingia malayana* (Oliv. ex Benn.), *Litsea* spp., *Livistona saribus* ((Lour.) Merr. ex A. Chev.), *Macaranga triloba* ((Reinw. ex Blume) Muell. Arg.), *Melaleuca cajuputi* (Roxb.), *Memecylon* sp., *Myristica iners* (Blume), *Parinarium annamensis* (Hance), *Shorea guiso* ((Blanco) Blume), *Sterculia foetida* (L.), *Terminalia cambodiana* (Gagnep.)	**Understorey**: *Areca* spp., *Calamus* spp., *Cibotium barometz* ((L.) J. Sm.), Cyperaceae, particularly *Mapania* sp. and *Hypolythrum* sp., *Homalium brevidens* (Gagnep.), *Licuala* spp., *Livistonia cochinchinensis* (Mart.), *Mallotus nisopodus* (Gagnep.), *Nepenthes* spp., *Pternandra caerulescens* (Jack), *Stenochlaena palustris* ((Burm f.) Bedd.), *Streblus asper* (Lour.), *Urticularia aurea* (Lour.)	Theilade et al. (2011) Tani et al. (2007) Yoshiki et al. (2007) Maxwell (1999)

Continued…

Forest type / vegetation assemblage	Abbr.	Description	Common plants		Sources
Secondary forest	SeF	Variable conditions	**Canopy/mid-storey**: *Albizzia* sp., *Butea monosperma* ((Lam.) Taub.), *Careya sphoerica* (Roxb.), *Dehaasia cuneata* (Blume), *Diospyros filipendula* (Pierre ex Lecomte), *D. hermaphroditica* ((Zoll.) Bakh.), *Dipterocarpus intricatus* (Dyer), *Elaeocarpus* spp., *Eugenia* sp., *Hopea* sp., *Lagerstroemia* spp., *Madhuca elliptica* ((Dubard) H.J. Lam), *Oroxylum indicum* ((L.) Kurz.), *Parinarium annamensis* (Hance), *Peltophorum dasyrachis* ((Miq.) Kurz), *P. ferrugineum* (Benth.), *Shorea roxburghii* (G. Don), *Sindora* sp., *Strychnos* sp., *Terminalia triptera* (Stapf), *Trema* spp., *Vatica* sp., *Vitex* sp., *Xylia xylocarpa* ((Roxb.) Taub.)	**Understorey**: Poaceae species, *Antidesma ghaesembillia* (Gaertn.), *Aporusa* sp., *Bauhinia* sp., *Colona* sp., *Combretum quadrangulare* (Kurz.), *Connarus cochinchinensis* ((Baill.) Pierre), *Cratoxylum* spp., *Croton oblongifolius* (Roxb.), *Croton* sp., *Curcuma domestica* (Valeton), *Gardenia philastrei* (Pierre ex Pit.), *Grewia tomentosa* (Juss.), *Lepisanthes* sp., *Macaranga* spp., *Mallotus* spp., *Memecylon edule* (Roxb.), *Wrightia religiosa* ((Teijsm. & Binn.) Benth.), *Zizyphus cambodiana* (Pierre)	Ruangpanit (1995) Maxwell (1999)
Emergent aquatics	EAq	Open, stagnant water bodies Often exists as a herbaceous swamp (floating vegetation mat) of varying density	Poaceae genera, Cyperaceae genera, *Hydrocera trifolia* ((L.) Wight & Arn.), *Hydrocharis dubia* (Blume), *Ipomoea aquatica* (Forssk.), *Nelumbo nucifera* (Gaertn.), *Ludwigia adscendens* ((L.) Hara), *Ludwigia* spp., *Nymphaea lotus* (L.), *Nymphoides hydrophylla* ((Lour.) Kuntze), *N. indica* ((L.) Kuntze), *Salvinia cucullata* (Roxb.)	Penny (1999) Penny (2006) Dy Phon (2000)	

4.3.4 Regional biogeography - forest disturbance

The nature and composition of SDTF landscapes are being continually shaped and re-shaped over time via both natural and anthropogenic disturbances (Bunyavejchewin et al. 2011, Dale 2011). SDTF communities provide numerous exploitable resources for rural and urban communities, and as such local populations can have discernable impacts on the ecology of this biome (McShea and Davies 2011). While livestock fodder, supplementary food products, medicines, building materials, oils and resins are all regularly sourced from dry tropical forests by local populations (Stott 1990, Murali et al. 1996), collecting wood fuel for commercial (charcoal production) and residential (cooking and heating) is the overwhelming (80%) purpose of resource extraction from these forests (Murphy and Lugo 1986).

Additionally, land management through the use of fire is a further important ecological impact induced by local communities, and has been occurring for at least 2500 years (Maxwell 2004). In regions where the SDTF biome persists, fire is utilised to clear the land for agriculture, burn waste products, maintain forest habitat structure, and encourage the growth of livestock fodder and other exploitable forest products (MacInnes 2011). Given the relatively low biomass of SDTF, it takes less effort to burn and clear for agriculture, and is thus often targeted over wetter forest types (Martinez-Yrizar 1995). Often, divisions are made between the purposes of fire use that depends on the specific type of forest available. For example, Maxwell (2004) found that in denser forests, fire use was preferentially utilized for swidden agriculture, while in relatively open forests fire was used more often to maintain an open, grassy understory.

In cases where SDTF landscapes have been subjected to ecosystem disturbance, recovery tends to occur only over relatively long timescales, particularly regarding the old-growth or climax species within these systems (Derroire et al. 2016). Such recovery, however, depends on the degree and scale of disturbance, as well as the specific functional characteristics of the local SDTF species (Turner et al. 1998, Kennard and Putz 2005, Otterstrom et al. 2006, Dale 2011, Derroire et al. 2016). Furthermore, when disturbances are combined or are particularly severe, unprecedented ecological states can be reached in the landscape (Dale 2011). In the case of widespread anthropogenic disturbance, such as selective logging practices or land clearance for agriculture, recovery is liable to be protracted and potentially incomplete, possibly leading to fundamental shifts in local ecosystem development (Ruangpanit 1995, Dale 2011).

In the contemporary landscape, MDF landscapes that have been fragmented or degraded by human activity – through either increases in logging or burning – become particularly susceptible to invasion by introduced weed species such as *Chromolaena odorata* ((L.) R.M King & H. Rob.) (Bunyavejchewin et al. 2011), before secondary forests (SeF) resembling the deciduous dipterocarp forest, savanna or savanna woodlands comprising canopies and mid-stories dominated by Shorea and Dipterocarpus, with also pioneer species such as *Trema angustifolia* (Blume) and Euphorbiaceae species (particularly *Mallotus* spp. *Macaranga* spp.) (Santisuk 1988, Ruangpanit 1995), and understories of fire-tolerant woody shrubs, dwarf palms, cycads and grasses often eventually emerge (Vidal 1960, Boulbet 1982, Stott 1990, Rundel and Boonpragob 1995) (see Table 4.1 for a more comprehensive list of common SeF species). In fact, given the lengthy and pronounced dry seasons characteristic of these forest ecosystems, they maintain a long-associated and very strong relationship with fire, and it has been purported that the dry dipterocarp forest types (DDF and MDF) may potentially be a fire-adapted successional ecosystem that has evolved from previous semi-evergreen or evergreen forest in response to prolonged increases in anthropogenic burning (Wikramanayake et al. 2017a). Others have described cases in which MDF and DDF communities have supplanted SEDFs following severe windstorms (Baker et al. 2005). In regions where human-induced burning practices become particularly sustained and intense, grasslands, dominated by *Imperata cylindrica* ((L.) Räusch.) or *Arundinaria* spp., often invade the landscape (MacKinnon 1997). Alternatively, in cases where fire is instead suppressed for significant periods of time, which often occurs in regions of growing population densities or in forests managed for timber resources (Bunyavejchewin et al. 2011), mixed deciduous forests (MDF) can succeed toward the dry semi-evergreen or evergreen forest type (SEDF) (Ruangpanit 1995, MacKinnon 1997).

4.3.5 Local biogeography and land use

Today the landscape surrounding Banteay Chhmar, Koh Ker and Preah Khan of Kompong Svay consists of a patchy assortment of land-cover, but is dominated by deciduous forest and woodlands. Figure 4.7 illustrates the variety of terrestrial vegetation types and land uses, and their distribution, within the broader region of each city. Due to extensive land clearance (see Fig. 4.6), much of these forests are now a mosaic of secondary formations, particularly around Banteay Chhmar (Hought et al. 2012) where rain-fed rice paddy fields are a prominent component of the landscape. A large patch of evergreen, broadleaf forest (resembling the SEDF forest type) also persists to the southwest of the temple complex, while tracts of dry deciduous forest and mixed evergreen and deciduous forest types remain in the southeast (Hought et al. 2012).

Vegetation and land use patterns surrounding Koh Ker and Preah Khan of Kompong Svay comprise less rice paddy fields than Banteay Chhmar and greater overall proportions of contiguous deciduous forest (Fig. 4.7). Given the proximity of these cities to local watercourses, riparian forest types are also more prevalent in the regions surrounding these cities compared to Banteay Chhmar. In the area immediately surrounding the main Koh Ker temples, a few paddy fields remain while other previously agricultural fields have been abandoned and have transitioned to grasslands (see Fig. 4.7). Within the regional matrix of deciduous forest, numerous patches of mixed evergreen and deciduous forest types remain scattered around Koh Ker, while substantial pockets of evergreen, broad-leaf forest remain around Preah Khan of Kompong Svay.

4.4 Chapter conclusion

This chapter has described the history of the individual cities chosen for this analysis and established their relevance within the settlement network. The physical setting of each city has been described, providing a background environmental context for this research. In particular, the contemporary forest types and land uses predominant at each site have been outlined in detail.

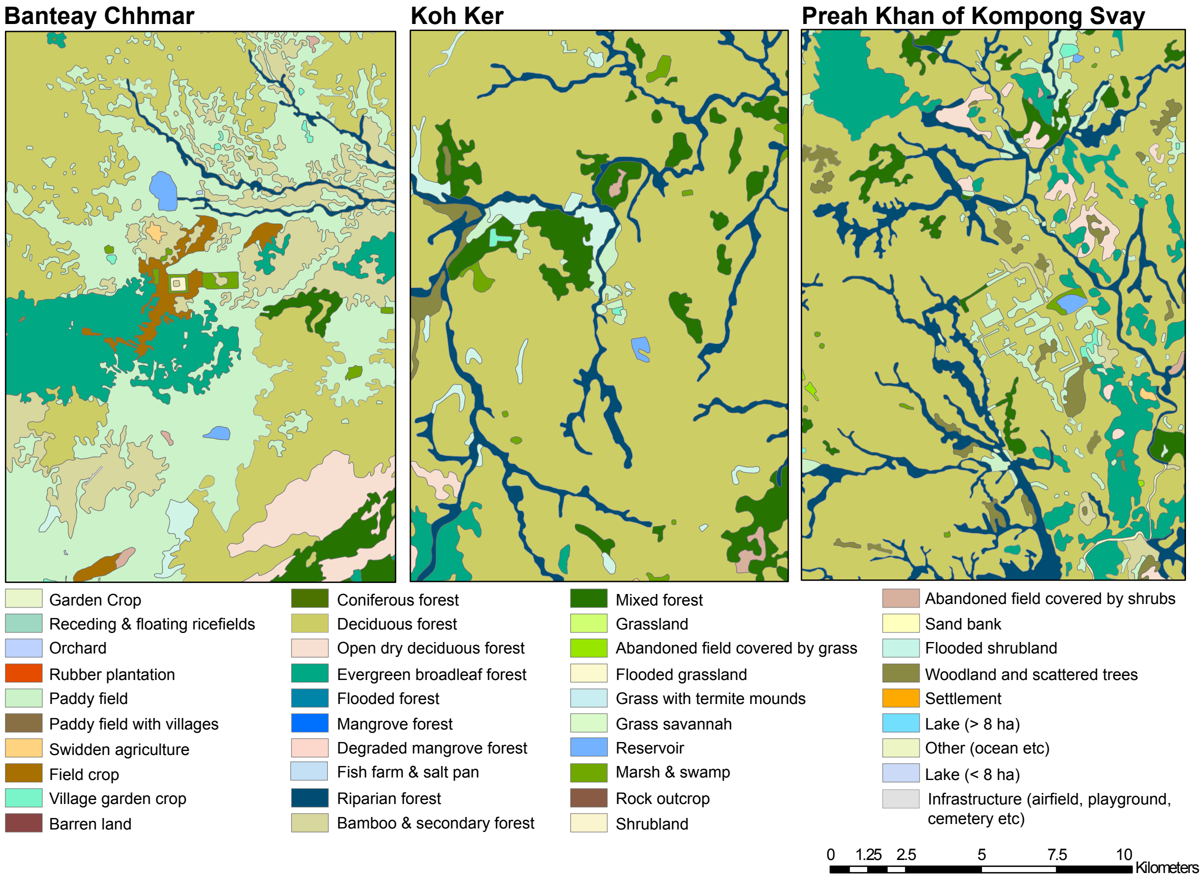


FIGURE 4.7: Maps illustrating the coverage of various land cover and use types (50K data) in the surrounding regions of each city selected for analysis. Source: JICA (2002).

5 Method and materials

5.1 Introduction

This chapter will detail the specific methods used, and the materials under analysis, including the various environmental proxies utilised. As outlined in the preceding chapters, in order to determine how a settlement network responds to a significant disturbance, a reconstruction of the occupation dynamics operating at a series of peripheral settlements is required. Such an analysis requires a detailed reconstruction of the land use history and evolving functionality of each settlement, which can infer population change and the nature of centralised control in the settlement network over time.

5.2 Coring and in-field analyses

The palaeoecological record is most effectively reconstructed from sediment sequestered to depositional basins such as lakes and peat bogs deposits. When palaeoecological analyses are used for deciphering human occupation histories, depositional basins within close vicinity to important archaeological sites provide ideal archives, as long as relatively high and continuous sedimentation can be demonstrated, and the necessary conditions exist for the preservation of organic material over long time periods (Li et al. 2008). These sedimentary archives may be better placed to capture the complex intermittency of human presence in the landscape through time and, if multiple archives exist, can also capture the patchiness of human disturbance in the local landscape through space.

As such, a variety of depositional basins with permanent water within or proximal to each of the city sites were selected for sediment sampling, including temple moats, small reservoirs (*trapeangs*), large reservoirs (*barays*), and a possible quarry (see Table 5.1). The size of each basin varied, however most were relatively small in area (with maximum diameters ranging from approximately 32 to 1600 m). It should be noted that larger receiving basins record an environmental signal - particularly a vegetation signal – from a larger catchment area, reflecting a regional source, than will a small basin, which will tend to record local processes (Prentice 1985, 1988, Jackson and Wong 1994, Sugita 1994, Jackson and Lyford 1999, Sugita 2007). As such, Li et al. (2008) recommends, for palaeoecological analyses attempting to reconstruct human impact proximal to the sampling site, that small basins (i.e. less than 100 m in diameter) should be selected for coring. In this study, multiple water bodies (of varying sizes) were cored in each city site, in order to maximize the chances of retrieving a sediment core suitable for analysis (Figure 5.1).

For the sake of clarity, each city in the data set will be referred to as a ‘city site’, each depositional basin selected for sampling as a ‘basin’, while each location within the basin selected for coring will be referred to as a ‘coring location’.

TABLE 5.1: List of sediment cores retrieved from a variety of coring sites across the three cities selected for analysis. Coordinates are in 48N WGS84 UTM. Note: Water depths should be applied cautiously - often difficult to determine due to fuzzy sediment-water interface and interference with vegetation/debris on floor.

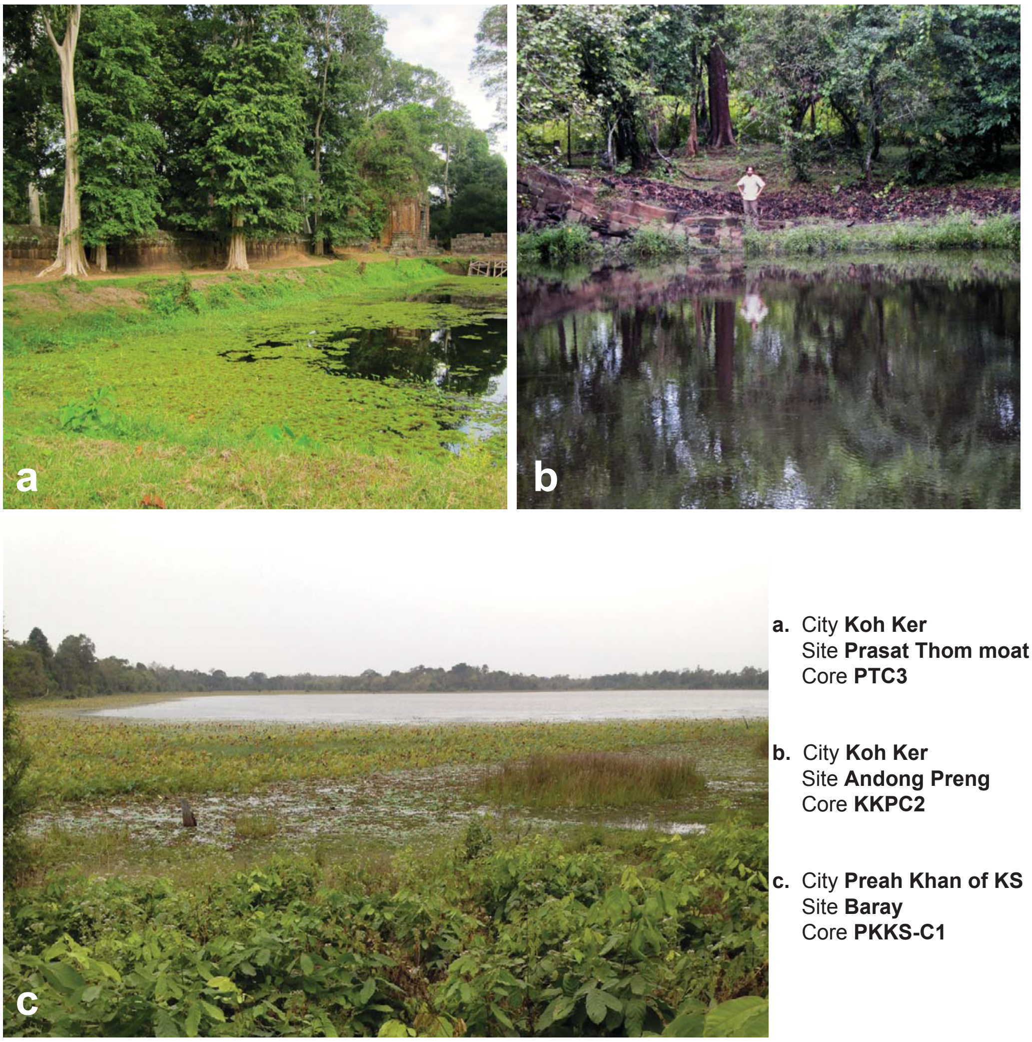
City	**Water basin type**	**Core ID**	**Coordinates**	**Length (m)**	**Basin diameter**	**Water depth (m) (approx.)**	**Notes**
Preah Khan of Kompong Svay	Large water reservoir (*Baray*)	A1	N 475592 E 1483991	0.71	Max. 1050 m	4.50	Heavy macrophyte growth
		A2	N 475795 E 1484004	0.98		4.20	Clear water, no visible macrophytes
		A3	N 475998 E 1484001	0.76		5.30	Edge of herb swamp encroachment, dominated by *Nelumbo nucifera*
		B1	N 475400 E 1483802	0.96		5.20	Clear water
		B2	N 475600 E 1483803	1.48		5.20	Clear water
		B3	N 475799 E 1483792	0.69		4.80	Clear water
		B4	N 476005 E 1483803	0.66		5.80	Clear water
		B5	N 476191 E 1483792	1.22		5.15	Clear water
		C1	N 475601 E 1483600	1.665		4.25	Very dense growth of Ceratophyllum at approximately 2 m depth, or about 1-2 m above sediment surface
		C2	N 475807 E 1483600	0.90		4.20	

Continued. . .

City	Water basin type	Core ID	Coordinates	Length (m)	Basin diameter	Water depth (m) (approx.)	Notes
Koh Ker	Temple moat (Prasat Thom)	PTC1	N 450225 E 1523902	1.29	Moat is 32 m wide	1.43	Light amount of floating vegetation (mainly water hyacinth and rat's ears)
		PTC2	N 450173 E 1523895	1.65		2.47	33.7cm void between above approximately 0.57m. Core split and void removed. Light amount of floating vegetation (mainly water hyacinth and rat's ears)
		PTC3	N 450124 E 1523879	2.29		3.02	Light amount of floating vegetation (mainly water hyacinth and rat's ears). Site is 331 ft a.s.l.
		PTC4	N 450246 E 1523806	1.25		1.80	Heavily vegetated (approx. 95% coverage, less dense on shoreline) with floating mat of ferns and aquatic plants that was roughly half a metre thick and grew to heights of 0.5-1.5m. Lost about the top 10-15cm of sediment.
Koh Ker	Quarry site (Trapeang Khnar)	KKQC1	N 450527 E 1521867	0.45	Max. 200 m	3.58	Three cores together should capture entire depth sequence. Very heavily vegetated with floating mat of ferns, pitcher plants etc - 0.5-2m tall. Started coring at 58cm.
		KKQC2	As above	2.43		As above	
		KKQC3	As above	0.37		As above	
Koh Ker	Royal Palace reservoir (Andong Preng)	KKPC1	N 450217 E 1523289	0.78	Max. 40 m	3.65	Site regularly cleared/disturbed - was used as a camp for CMAC workers in the area. Fishing (?) net in nearby tree. Possibly hit the bottom of the reservoir with this core.
		KKPC2	N 450215 E 1523296	0.69		3.50	
		KKPC3 (short core)	N 450217 E 1523289	0.21		3.65	Short core taken to capture sediment-water interface and very top layers of sediment. Retrieved close to C1. Leafy/twiggy layer at approx. 11-15cm.
Banteay Chhmar	Temple moat (Banteay Chhmar)	No core recovered	N 294468 E 1556002	N/A	Moat is 65 m wide	2.60	Colonised with floating mat of grasses, sedges, ferns and other aquatic plants
		BCMNE	N 295244 E 1556768	0.22		2.60	Colonised with floating mat of grasses, sedges, ferns and other aquatic plants
		No core recovered	N 294445 E 1556733	N/A		Not recorded	Colonised with floating mat of grasses, sedges, ferns and other aquatic plants

Continued…

City	Water basin type	Core ID	Coordinates	Length (m)	Basin diameter	Water depth (m) (approx.)	Notes
Banteay Chhmar	Large reservoir (Boeung Choeng Krours *baray*)	No core recovered	N 294537 E 1560590	N/A	Max. 1600 m	Not recorded	Remnant tree stumps scattered throughout
Banteay Chhmar	Reservoir (Sra Rean)	BCSR	N 295050 E 1556592	0.47	Max. 40 m	2.00	Colonised with floating mat of grasses, sedges, ferns and other aquatic plants
Banteay Chhmar	Large reservoir (Banteay Chhmar *baray*)	No core recovered	N 297439 E 1556808	N/A	Max. 1600 m, not completely inundated	Not recorded	



a. City **Koh Ker**
Site **Prasat Thom moat**
Core **PTC3**

b. City **Koh Ker**
Site **Andong Preng**
Core **KKPC2**

c. City **Preah Khan of KS**
Site **Baray**
Core **PKKS-C1**

FIGURE 5.1: Example photos of the types of water basins selected for coring. These three locations represent the coring sites for the three sediment cores eventually selected for detailed analysis.

Coring locations were established in either the approximate centre of the basin or, for the large basin at the PKKS city site, by determining a basic bathymetry of the basin. Research investigating differences between pollen capture in sediment cores taken from central and marginal zones of lakes and bogs (Edwards and McIntosh 1988, Whittington 1991) found that higher abundances of cereal-type pollen grains are deposited on the water basin edge, compared to the centre. Little spatial variation, however, was found in the deposition of anthropogenic weed pollen (Whittington 1991). Janssen (1966) illustrated that local and regional pollen was also captured differentially across water basins, with marginal zones being dominated by local pollen and central zones by regional species, and aquatic plant contributions overwhelmed what local pollen portion did exist in the centre of the lake. Grass pollen, however, is often better represented in central regions (Tolonen 1986). However, these studies refer to large water bodies in the northern hemisphere where wind pollinated flora dominate, and have not been tested in the tropics. As such, the basins sampled in this research are likely to be too small for these effects to be particularly pronounced. Furthermore, given their location within regions of heavy and long-tern human impact, the central regions of these water bodies are most likely to be the least disturbed, particularly by domesticated animals and livestock.

Coordinates for each coring location were recorded using a Trimble Nomad GPS receiver using ArcPad 10.0. Water depth was recorded at each coring site using a weighted measuring tape. Sediment cores were obtained using a rope-operated percussion corer (see Chambers and Cameron 2001, Glew et al. 2001 for more detail on this configuration and operation of this equipment) and a rigid A-frame over a 'moon pool' in the centre of the craft through which the coring device is lowered (Fig. 5.2). The sediment samples were collected by driving 2-3 m lengths of 60 mm diameter PVC pipe (55 mm internal diameter), with the basal end sharpened for ease of penetration, into the sediment. Samples were recovered by hand or with the assistance of a hand-operated vehicle winch. Upon recovery cores were divided into one-metre lengths using a pipe cutter, then capped and labeled for exportation to the University of Sydney. Using a small gravity corer, short cores (i.e. < 50 cm) (see Renberg and Hansson 2008) were also obtained to capture the recent sediment at the water-sediment interface, which was frequently disturbed during the percussion coring process. Short cores were extruded on site using a screw-extruder into 0.5 or 1.0 cm thick slices, normally to a depth of 20 cm.

FIGURE 5.2: Coring platform, including two adjacent inflatable boats, aluminium platform and constructed aluminium frame. The percussion corer was subsequently suspended from the u-bolt below the apex of the frame.

5.2.1 Preah Khan of Kompong Svay

Coring in PKKS was concentrated in the large baray associated with the central temple complex (Fig. 5.3), and was the largest site (in terms of area) sampled in this research. A bathymetric model of the basin was created by measuring a series of water depths in conjunction with a total survey station positioned on the southeast corner of the baray, and then generating a triangular irregular network in ArcGIS version 10.1. The unusual depth (deeper than other similar reservoirs in Angkor), steep sides and irregular shape of the basin suggest that the baray was constructed around a pre-existing depression, possibly an oxbow lake or river palaeochannel (Hendrickson et al. 2010). If this is the case, the north-western end of the reservoir is perhaps being replenished by a permanent groundwater source, which may explain why this section of the reservoir has maintained permanent water over at least several decades, and most likely several centuries.

Coring locations across the basin were established according to an a priori 50x50 m grid in a Geographic Information System, also using ArcGIS version 10.1. In total, 10 sediment cores were collected (see Table 5.1 and Fig. 5.3). In this case where multiple cores were retrieved from several locations within a single basin, each core was correlated to ensure a section representative of the basin stratigraphy had been acquired. First-order correlation was achieved through in-field volume magnetic susceptibility comparisons, using a Bartington MS2 meter with a MS2C 100-mm diameter loop sensor (Dearing 1994). Presuming that the longest core would represent the highest rate of sediment accumulation within the basin and, therefore, offering the best temporal resolution, core C1 (measuring 1.665 m, see Table 5.1) was shipped back to the University of Sydney for further analysis. All remaining cores were split longitudinally in the field, logged (following a modified version of the Schnurrenberger method but later converted to Schnurrenberger et al. 2003), photographed and discarded (see Appendix A).

5.2.2 Koh Ker

Three basins were selected for coring at Koh Ker. Unfortunately, the main reservoir associated with the central temple complex (Rahal) was completely dry and appears to have been for some time. Sedimentation rates were therefore assumed to be low, and the oxidization or organic material – including the environmental proxies targeted here – probable. Instead, basins selected for coring included the moat surrounding the central, largest temple (Prasat Thom), a possible quarry (Trapeang Khnar), and a small reservoir (Andong Preng) that may have originally been associated with the Royal Palace (see Evans 2013) (Fig. 5.4).

Four coring locations were established at Prasat Thom – one in each corner (NW, N, NE and SE) of the moat, and a single core was taken from each coring location. The floating coring platform was moved into position and anchored using a rope that was attached to trees on either side of the moat. The southern portion of the moat was overgrown with swamp vegetation that, in places, is developing toward true swamp forest community. Here, a thick (circa 35-40 cm) floating mat of vegetation precluded direct access to the water column. In this case the piston corer was carried out onto the swamp surface and deployed through a hole cut in the floating vegetation mat. Surface sediment proved to be too unconsolidated for recovery with the micro-gravity corer, and thus no samples were recovered using this instrument in all four coring locations. The moat was between 1.43 and 3.02 m deep, and deepened significantly toward the west. Today the moat is greater than 30 m in width, however Jacques and Lafond (2004) have noted that during the Angkor period it would have been far narrower. In total, four cores were recovered from the moat site, the longest being PTC3 from the northwest corner (2.29 m long). Siliclastic sediment (clay, silt, sand) was recovered in the base of PTC3 and PTC4, indicating full recovery of the moat fill through to the natural substrate.

Trapeang Khnar is a small basin, possibly an abandoned quarry site, heavily overgrown with a very thick (circa 80 cm thick or more) mat of floating vegetation. The vegetation consists of undisturbed, mature swamp species dominated by *Nepenthes* spp. (pitcher plants). Mature swamp forest exists in patches on the northern margin of the basin, where *Syzgium/Eugenia* spp. are present (Theilade et al. 2011). The piston corer was carried out onto the swamp surface, and

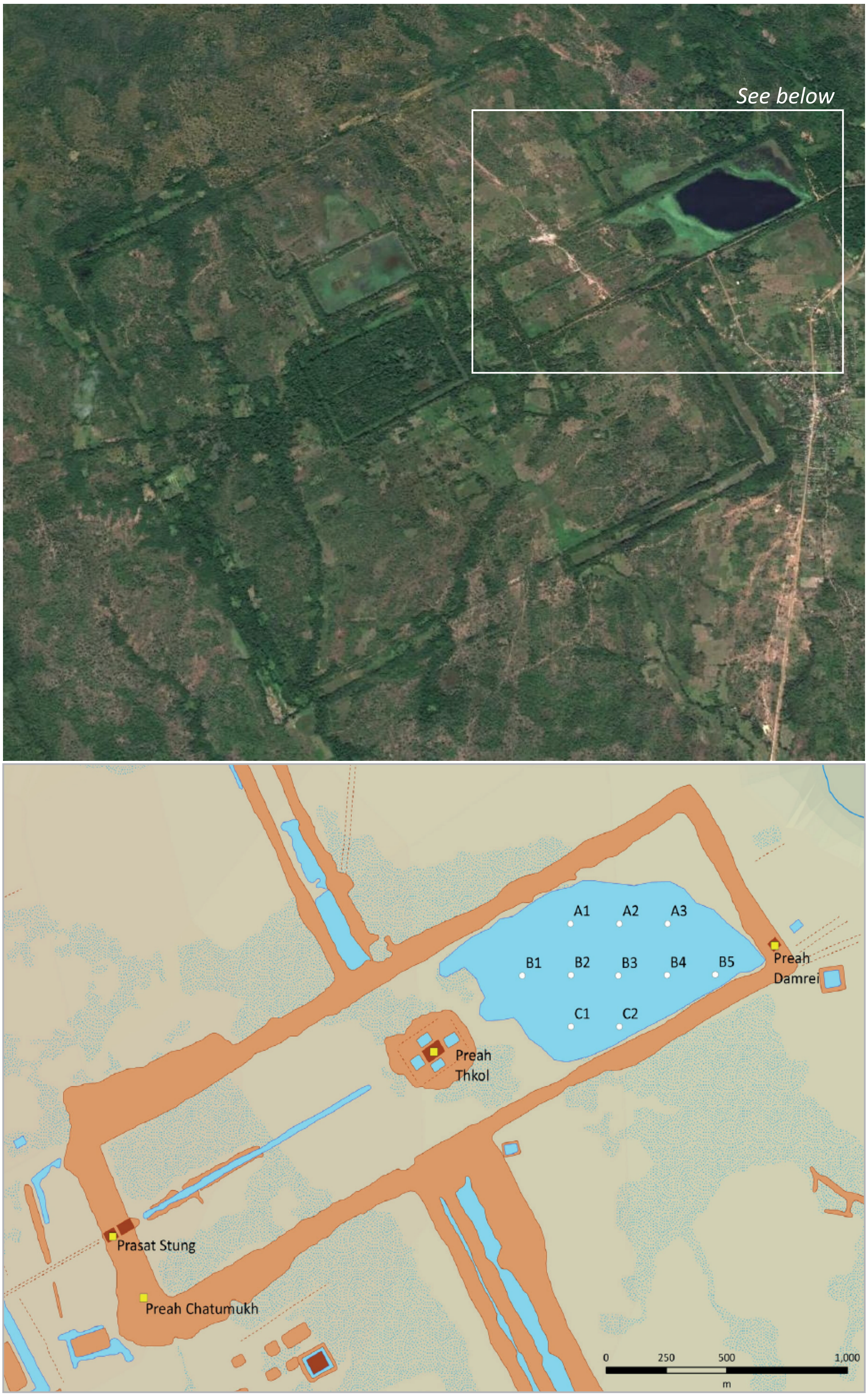


FIGURE 5.3: Coring locations at Preah Khan of Kompong Svay. Top image source: Google Earth. Bottom GIS map courtesy of D. Evans.

deployed through a series of holes cut in the vegetation mat. Three cores were collected, the longest of which was KKQC2 at 2.43 m (terminating approximately 6.81 m below the swamp surface). Each core was retrieved from the same coring hole, in an attempt to capture successive segments of the same sediment column. KKQC3 captured the basal sediment, which was siliclastic. Damage to the cutting head of the core barrel, observed after recovery, suggests further penetration was prevented by sandstone bedrock.

Andong Preng is a deep, steeply sided basin faced on all sides with sandstone steps. The facing has slumped on the western side, but the basin is otherwise remarkably well preserved. As with other enclosed basins, a vegetation mat had colonized the site but had been removed recently to expose the water surface. Two cores (KKPC1 and KKPC2) were taken, adjacent to one another, in the centre of the basin. A third core was taken using the micro-piston corer (KKPC3) and was extruded on site. The coring platform was anchored by tethering it to a rope attached to the exposed roots of large trees growing on the banks. KKPC1 contained clay mineral sediment in its basal layer, implying that full recovery of the basin fill was achieved for only this core. Details of all cores from all three basins are presented in Table 5.1.

5.2.3 Banteay Chhmar

Overall, six basins were selected for sampling across the Banteay Chhmar temple complex and its surrounding region (Fig. 5.5). Firstly, three coring locations were established in the moat of Banteay Chhmar, including the NW, NE and SE corners. Swamp vegetation was well established on the moat in all quadrants except the SW corner, which has been recently cleared of vegetation and dredged. It is thus assumed that the SW section of moat has been cleared, or re-flooded, in the past several decades. In the NE corner, this floating vegetation community consisted predominantly of grasses, sedges and ferns and lacked the species indicative of a more mature swamp community. The floating mat of vegetation made manoeuvring the floating platform into the centre of the moat difficult, and therefore the piston corer was instead carried out onto the swamp surface and deployed through a hole cut in the floating vegetation mat. Surface vegetation proved too thick for penetration with the micro-gravity corer, and no samples were recovered using that instrument.

Secondly, the Boeung Choeng Krours baray was selected for coring. This large reservoir lies approximately 3.3km north of the Banteay Chhmar temple complex. Remotely sensed imagery indicates that the lake has been permanently inundated with water for at least the past half century, since the conversion of the extensive Angkor-era embankment running north-south into a dam wall during the Khmer Rouge period (Evans 2010). Remnant tree stumps scattered throughout the lake suggest that it was likely a forest or savannah landscape that is now permanently flooded. As such, we cannot be sure that the lake has been inundated from the Angkor period, however satellite imagery indicates that the region in the centre of the present-day dam, to the west of the north-south embankment and to the north of the east-west embankment is the most likely to be permanently water-logged. Coring was, therefore, concentrated in this region. To test the suitability of this site for coring, a test core was recovered from over the side of the one of the inflatable boats using the mini-gravity corer. As the top 20cm of the lake floor consisted of the basal clay sediments, this basin was abandoned for this stage in the project. The sample recovered was logged and discarded in the field.

A similar exploratory method was employed in the north-eastern corner of the *baray* associated with the Banteay Chhmar temple, in order to test the likelihood of the recovery of a substantial sediment core. As with the Boeung Choeng Krours baray, the sample recovered by the mini-gravity corer, consisting predominantly of basal clay sediments, suggested that either very little

FIGURE 5.4: Coring locations at or near Koh Ker. Background image source: Google Earth.

eroded sediment had accumulated over time in this basin, or that it had been excavated in the recent past. The sample recovered was once again discarded in the field, without being logged.

Finally, the Sra Rean reservoir, which lies in the NE corner of the Banteay Chhmar temple complex, was selected as a basin for coring. The reservoir consists of a small basin surrounded by a moat (approximately 10-15 m wide). As with other enclosed basins, a vegetation mat has colonized the site and consisted predominantly of grasses, sedges and ferns – indicative of an early stage swamp vegetation community. The first attempt at coring within the centre of the basin recovered a 47 cm core, mainly consisting of basal clays. The second attempt failed, as the force of piston corer penetrating the clay substrate caused the PVC core to break during the coring process. Overall, only two very small (see Table 5.1) clay-dominated cores were collected from Banteay Chhmar. These were packaged whole, labelled and shipped to the University of Sydney.

5.3 Core logging and sampling

Cores selected for analysis were split longitudinally in the laboratory at the University of Sydney. Cuts were made down the entire length of opposite sides of the PVC core barrel using a circular saw. Cuts were made only to the depth of the thickness of the PVC pipe (2.5 mm) to ensure that the sediment was not disturbed. The core halves were separated by inserting metal or plastic spatulas at right angles to the angle of insertion (assumed to be 0°), and along an assumed 90° bedding plane, to prevent contamination of sediment between bedding planes. The spatulas were inserted progressively and contiguously down the core, with particular care given to cleaning the spatulas between each insertion. Once split into two halves, the surface of each core half was cleaned by gently scraping away the exposed surfaces in the direction of the bedding plane to ensure any sediment contamination was eliminated and the stratigraphy was clear for logging and photography. One half of each core was selected for magnetic susceptibility scanning (see below) and archived at 3°C, while the remaining half (referred to henceforth as the "working" split-core) was logged, photographed, sealed and refrigerated until sub-sampling could commence.

The PKKS-C1 core was logged during an earlier stage of the project, and was logged using a protocal modified from SSDS (2017). Logging protocol for both Koh Ker cores (PTC3 and KKPC2) followed that of Schnurrenberger et al. (2003). The terminology used in the SSDS (2017) protocol was later translated into terminology used in the Schnurrenberger et al. (2003) method for consistency (see glossary in Appendix A). While both the Schnurrenberger et al. (2003) and the Troels-Smith (1955) protocols would have been suitable to employ here, due to their similar applicability for organic-rich sedimentary environments as well as their emphasis on describing the sedimentary components, the Schnurrenberger et al. (2003) method utilises terminology that is more readily understood by non-specialists and, as such, is being increasingly utilised in studies outside the temperate northern hemisphere (e.g. Conroy et al. 2008, Creutz et al. 2016, Prospere et al. 2016, Sahoo et al. 2016). The resulting logs were plotted using Strater (version 3.0) (Golden Software 2012). Copies of the stratigraphic logs and smear slide logs are provided in Appendix A. Because the PKKS-C1 stratigraphy was logged during an earlier project and under a different (but comparable) method, smear slide analysis was not undertaken for this core.

Following logging and photography, each working split was subsampled into contiguous 1 cm slices (approximately 11.88 cm^3), cut parallel to the assumed bedding plane, before being further subsampled volumetrically using a modified 5 cc plastic syringe for the analytical

FIGURE 5.5: Coring locations at Banteay Chhmar and surrounds. Background image source: Google Earth.

techniques described below. Subsamples were kept in zip-lock bags and refrigerated while awaiting the proceeding stages of analysis.

5.4 Dating and age-depth modeling

Radiocarbon analysis was the dating method preferred here, given the expected time period of sediment accumulation (roughly the last 1300 years) and the abundance of organic material present throughout the cores retrieved. Radiocarbon dating of organic material has made particular contribution to our knowledge of the history of Angkor (see Zoppi et al. 2004, Penny et al. 2006, Penny et al. 2007, Day et al. 2012, Hendrickson et al. 2013), and has often refined or remodeled traditional temporal sequences of temple complex development and function in Angkor and in regional centres, which had previously relied on dated inscription evidence and stylistic interpretations of monumental architecture (e.g. Stern 1927, Parmentier 1939, Coral Remusat 1940, Groslier 1966, Jacques and Lafond 2004). Radiocarbon dating of preserved organic remains has so far permitted the reevaluation of the duration of Angkor's occupation (Zoppi et al. 2004, Penny et al. 2007), identified the timing of the introduction of particular construction and urban design techniques (Zoppi et al. 2004), and helped identify the timing of industrial activity and the occupation and land use within peripheral city centres (Hendrickson et al. 2013).

For Preah Khan of Kompong Svay, only the longest of the sample set of ten cores was selected for analysis. At Koh Ker, the longest cores from each of the three basins, from a total sample set of ten cores, were selected for exploratory radiocarbon dating. To help select the most appropriate of these cores for further analysis, 'bookend' or 'range-finder' radiocarbon dates were attained initially from these selected cores to determine the period each core represented. The most suitable cores (i.e. greatest time coverage and best likelihood of a conclusive chronology being constructed) were then selected for further dating and analysis, which included PTC3 from the moat of Prasat Thom and KKPC2 from Andong Preng. The final cores selected from all city sites included C1 (Preah Khan of Kompong Svay), PTC3 and KKPC2 (Koh Ker), while no cores were selected for further analysis from Banteay Chhmar (see section 6.2 in Results chapter).

Material appropriate for radiocarbon dating, ranging from bulk or undifferentiated organic or sapropelic mud samples, to unburnt wood fragments, and macroscopic leaves and stems from aquatic plants, was selected from deposits throughout each core chosen for analysis (see Table 5.2). The number of samples selected for absolute dating for each core varied between two and nine, depending on the length of the core and complexity of the stratigraphy. In total, 37 samples were extracted and submitted for AMS radiocarbon dating across the seven cores representing three coring locations from two city sites. Macroscopic plant remains, such as leaf fragments, were isolated by wet sieving with deionised water through a pre-washed steel hand sieve, while wood fragments were hand-picked under low magnification from samples that had been freeze-dried using a Labconco 77535 Freeze Dry system. Bulk sediment samples were extracted from the centre of the core using a scalpel that had been washed in deionised water. Samples that were retrieved from highly organic layers (such as peat) were also pretreated with potassium hydroxide (10% KOH w:v) to remove any contamination by modern humic acids (Hammond et al. 1991). All samples were oven-dried at 60°C overnight before being submitted to the laboratory for AMS ^{14}C analysis. More specific information for each selected sample, including depth, material, laboratory and sample codes can be found in Table 5.2.

All samples submitted for dating were subjected to acid-base-acid (or acid-alkali-acid; AAA) pre-treatment by the laboratory, and processed and measured using the Accelerator Mass Spectroscopy (AMS) method (see Nelson et al. 1977, Elmore and Phillips 1987). AMS differs from traditional radiocarbon dating in that it directly measures the proportion of the number of carbon-14 atoms, relative to carbon-13 or carbon-12 atoms, through the detection of each atom's specific atomic weight (Bowman 1990). The conventional radiocarbon ages obtained were then calibrated to calendar AD years using the SHCal13 calibration curve (Hogg et al. 2013) with an offset of -21 ± 6 years (Hua et al. 2004), consistent with other studies performed in this region (e.g. 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).

5.4.1 Age-depth model

Age-depth models are fundamental to palaeoecological studies (Parnell et al. 2011). Using a range of statistical methods to extrapolate between dated levels throughout the core, they establish an age-depth relationship to provide an estimated age for non-dated levels. Final chronologies were modelled in the Bacon software package (Blaauw and Christen 2011), using R (R Development Core Team 2013) as an interface. Bacon utilises Bayesian statistics to construct age-depth relationships based on the interpolation of sediment accumulation rates between absolutely dated levels throughout the core. The models are constrained by prior information ('priors') about the stratigraphy and its expected rates of accumulation, supplied by the user. The mean accumulation rate was set from a basic calculation of overall accumulation rates using linear interpolation between top and bottom weighted mean calibrated radiocarbon dates. In general, other model parameters such as accumulation shape, the reported age range probability, and student-t values were kept at the default settings.

'Outlying' or anomalous radiocarbon dates were not identified statistically and manually removed prior to the analysis, as Bacon is capable of identifying or accommodating outliers (and the general 'scatter' inherent in the error distributions of ^{14}C data) through the use of a student-t distribution with heavy tails (wider than the Normal distribution models) during the error modelling process (Christen and Perez 2009). Weighted-mean ages derived from the model were used to place results in a temporal context.

TABLE 5.2: Details for the 37 organic samples submitted for radiocarbon dating analysis.

City	**Coring site**	**Core ID**	**Depth (cm)** ***Top***	**Depth (cm)** ***Bottom***	**Material description**	**Laboratory**	**Lab ID**
Preah Khan of Kompong Svay	Baray	PKKS-C1	10	11	Macroplant material	Beta-Analytic	282652
			30	31	Macroplant material		282653
			31	33	Wood fragments	ANSTO	OZN549
			31	35	Organic material		OZN553
			35	36	Wood fragments		OZN550
			85	86	Plant material	Beta-Analytic	282654
			86	88	Organic material	ANSTO	OZN552
			130	135	Wood fragments		OZN551
			140	141	Plant material	Beta-Analytic	282655
Koh Ker	Trapeang Khnar	KKQC1	4	7	Wood fragment	DirectAMS	D-AMS 006493
Koh Ker	Trapeang Khnar	KKQC2	43.5	47.5	Macrophyte fragment	DirectAMS	D-AMS 007104
			62.5	63.5	Organic mud		D-AMS 007105
			103	103	Macrophyte fragment		D-AMS 006494
			129	130	Organic mud		D-AMS 007107
			185	186	Organic mud		D-AMS 007108
			275	276	Organic mud		D-AMS 007106
			281	282	Sapropel with macrophyte fragments		D-AMS 006495
			282	283	Sapropel with macrophyte fragments		D-AMS 006496
Koh Ker	Andong Preng	KKPC1	11	15	Woody twig	DirectAMS	D-AMS 006497
			63	64	Peat with macrophyte fragments		D-AMS 006498
Koh Ker	Andong Preng	KKPC2	10	11	Organic mud	DirectAMS	D-AMS 007109
			19	20	Sediment (humates)		D-AMS 018422
			28	29	Organic mud		D-AMS 008223
			46	47	Peat		D-AMS 008224
			51	52	Twig fragments		D-AMS 018423
			60	61	Peat		D-AMS 007110

Continued…

City	**Coring site**	**Core ID**	**Depth (cm)** ***Top***	**Depth (cm)** ***Bottom***	**Material description**	**Laboratory**	**Lab ID**
Koh Ker	Prasat Thom	PTC3	10	18	Leaf	DirectAMS	D-AMS 006499
			95	96	Peat		D-AMS 006500
			111	112	Peat		D-AMS 006501
			125	126	Peat		D-AMS 007111
			173	174	Organic mud		D-AMS 007112
			181	184	Leaf fragment		D-AMS 006502
			213	214	Sapropel		D-AMS 006503
Koh Ker	Prasat Thom	PTC4	21	22	Peat	DirectAMS	D-AMS 007113
			64	65	Organic mud		D-AMS 007114
			118	119	Organic mud		D-AMS 007115
			121	122	Organic mud		D-AMS 007116

5.5 Physico-chemical analyses

5.5.1 Magnetic susceptibility

Approximating the abundance of the magnetic minerals in sediments and soils, attained through measuring a deposit's magnetic susceptibility, indicates changing erosional processes and sediment sources, and enables cross-correlation of cores from the same and/or different sites (Thompson et al. 1980, Dearing 1991, 1999, Nowaczyk 2001). A material's magnetic susceptibility is measured by temporarily exposing the sample to a low-level magnetic field generating a small magnetization response (Nowaczyk 2001). The sign and strength of the magnetisation response reflects the composition of the material at the atomic level, and the abundance of small ferri- and ferromagnetic minerals in the material. The magnetic volume susceptibility κ then serves as a proportional factor for the magnetic field H and sample's temporary magnetisation M as follows (Gale and Hoare 1991 [2011], Nowaczyk 2001):

$$M = \kappa H \tag{5.1}$$

Magnetic susceptibility of all cores was measured either in the field (see section 5.2) or in the laboratory using a Bartington MS3 magnetic susceptibility meter fitted with a MS2E surface scanning sensor, operated using Bartsoft software. Following core splitting, the archive-splits were sealed with plastic film (to prevent sediment adhering to the sensor surface) and manually guided below the surface scanning sensor, with measurements taken every 10 mm. Each measurement was taken 3-5 times, with a sampling duration of 5 seconds and air 'blanks' between each set (automatic drift correction was set to 'on' in Bartsoft), so that the relative precision could be calculated. All measurements taken in the laboratory (i.e. cores PTC3 and KKPC2) were expressed as the mean value of the sample set, in dimensionless SI units, with a one standard deviation range. For the PKKS core, where measurements were taken in the field using a low resolution loop scanner, multiple measurements were not made and therefore errors could not be calculated (although correction for background magnetism still occurred by subtracting an 'air' measurement from the sample measurement). All results were plotted using the C2 software program (version 1.7.6) (Juggins 2014) for use in the correlative, multi-proxy analysis and presentation.

5.5.2 Particle size analysis

Particle size analysis an essential method for characterising the lithology of regolith materials and changes in the particle-size distribution of lake sediment deposits can be indicative of changes in a catchment's environment and, in particular, the timing and degree of human-induced disturbances and modifications to the surrounding landscape (Flenley 1988). Binford (1983), for example, found direct correlations between increases of finer particles being delivered to lake basins and human populations in the Guatamalan lowlands during the Mayan Period. Additionally, particle size analysis can be used as a supplementary method of describing textural characteristics during core logging (section 5.3) (Gale and Hoare 1991 [2011]). As such, the textural descriptions in the final stratigraphic log results were refined by particle size analyses (referring to the 'textural group' description provided by the Gradistat program v8 (Blott and Pye 2001).

During subsampling of the sediment cores, approximately 0.5 cm^3 of sediment (0.8 to 1.0 g wet) was taken from samples at 2 cm resolution, and placed inside labelled, 50 ml centrifuge tubes. Organic material was oxidised using dilute hydrogen peroxide (H_2O_2, 35% w:v). Approximately 2 ml was added to test the degree of reactivity of each sample. Once the initial reaction had subsided and the sample was relatively stable, 30 ml of hydrogen peroxide was added and all samples were placed in a hot water bath (set to 70°C). Additional H_2O_2 was added iteratively until no further reactions were observed. Samples containing particularly high levels of organic material required up to 8 or 9 treatments.

Samples were then deflocculated by adding 30 ml of sodium hexametaphosphate ($(NaPO_3)_6$, 5% w:v) dispersant and mechanically mixed using a rotating mixer for 2-4 hours (Gale and Hoare 1991 [2011]). The grain size distribution of each sample was then measured using laser diffraction spectrometry undertaken with a Malvern Mastersizer 2000 equipped with a Hydro G dispersion unit. Each sample was initially subjected to 20 seconds of sonication within the dispersion unit in order to break up any remaining flocs. Three replicate measurements were taken for every sample and the mean and standard deviation was utilised for the final analysis. Statistical analysis followed Folk and Ward (1957), with summary statistics calculated using Gradistat v8 (Blott and Pye 2001), and using the Folk and Ward (μm) output.

5.5.3 Moisture content, organic content, dry bulk density and mineral accumulation rate

The identification of environmental impacts from human activity in the landscape can be further gleaned through additional parameters that describe the physical characteristics of the sediment archive. These include moisture content, organic content, dry bulk density and mineral accumulation rate. Determining the organic content of sediment deposits is fundamental to understanding changes in bulk accumulation rates, as increases in organic accumulation can be indicative of a number of changing processes in the environment. Increases in organic content within sediment deposits can be indicative of high levels of erosion in the catchment, as high organic deposition can be the result of direct increases in the erosion of organic particulates, as well as indirect processes, such as increases in aquatic ecosystem growth as a result of surges of bioproductivity due to greater inputs of mineral and nutrient-laden terrigenous material (Gale and Hoare 1991 [2011], Ludwig et al. 1996). However, increases in autochthonous organic matter deposition can also cause increases in lake sedimentation irrespective of changes in erosion regimes (Dearing and Jones 2003). For example, lower water levels in the basin, caused by either climate changes or human manipulation, can increase nutrient availability and enhance aquatic productivity (Gale and Hoare 1991 [2011]). Decreases in organic content, on the other hand, can be indicative of either lower levels of overall erosion in the catchment, the reduction of available plant matter available for erosion, or the removal or harvest of aquatic plants by local populations (Gale and Hoare 1991 [2011]). In excavated cultural basins, changes in organic material are often due predominantly to autochthonous/endogenous processes, often reflecting early vegetation successional changes associated with the cessation of direct management of water bodies (e.g. Penny et al. 2006).

Dry bulk density and mineral accumulation rates are also an important component in the calculation of the patterns and rates of bulk sediment accumulation within the basin, as they can more directly reflect higher levels of erosive activity in the surrounding landscape (Edwards and Whittington 2001, Dearing and Jones 2003). Forest clearance and agricultural activities destabilise soils and release them for transport into the lake basin, and therefore higher rates of sedimentation can signal soil destabilisation and changes in land use in the catchment (Turkelboom et al. 1997, Penny and Kealhofer 2005). Alternatively, lower levels of sedimentation can result from not only diminished erosive activity in the catchment, but also from increased aquatic productivity in the water basin, where greater densities of aquatic vegetation can winnow out sediments entering the basin (Lowe and Walker 1997).

Subsampled sediments from the working split-core (i.e. the remaining sediment retained after all other subsamples had been removed from the 1 cm slice) were analysed for moisture content, organic content and dry bulk density through a loss-on-ignition procedure (following Dean 1974, and a modified version of Bengtsson and Enell 1986). Firstly, 10 cm^3 of wet sediment was sampled from the core using 10 cm^3 cylindrical plastic pots (designed for the Bartington MS2B Dual Frequency Magnetic Susceptibility Meter (Dearing 1999)), transferred to a pre-fired and pre-weighed crucible and weighed again. These samples were then dried for 14 hours at 105°C (Hakanson and Jansson 1983). Each sample was then re-weighed to determine the loss of mass, taken to be equivalent to the percentage water content of the sample. Each sample was then crushed using a mortar and pestle and the resulting volume measured (usually 3-5 ml) using 10 cm^3 cylindrical plastic pots with measured and marked volume increments, before being transferred back into the labelled crucible. Samples were then placed inside a furnace set to 550°C (Heiri et al. 2001). After two hours the samples were cooled to room temperature and re-weighed once more, giving the loss of mass resulting from the ignition or organic carbon. Finally, percentage moisture content (equation 5.2), dry bulk density (equation 5.3), mineral bulk density (equation 5.4), percentage organic content (equation 5.5) and mineral accumulation rate (equation 5.6) were calculated using the following formulas (modified from Bengtsson and Enell 1986, Gale and Hoare 1991 [2011]):

$$W = \frac{W_{\mathrm{W}}}{W_{\mathrm{f}}} \times 100 \tag{5.2}$$

Where: W = moisture content (%); W_{W} = water weight (g); W_{f} = fresh sediment weight (g)

$$\rho_{\mathrm{dry}} = \frac{W_{\mathrm{S}}}{V} \tag{5.3}$$

Where: ρ_{dry} = dry bulk density (g cm^{-3}); W_{S} = dry sediment weight (g); V = volume (cm^3)

$$\rho_{\mathrm{mineral}} = \rho_{\mathrm{dry}} \times \frac{100 - OC}{100} \tag{5.4}$$

Where: ρ_{mineral} = mineral bulk density (g cm^{-3}); ρ_{dry} = dry bulk density (g cm^{-3}); OC = organic content (%)

$$OC = \frac{W_{\mathrm{s}} - W_{\mathrm{a}}}{W_{\mathrm{s}}} \times 100 \tag{5.5}$$

Where: OC = organic content (%); W_{a} = ash weight (g); W_{s} = dry sediment weight (g)

$$A_{\mathrm{m}} = \frac{\rho_{\mathrm{mineral}}}{A_{\mathrm{b}}} \tag{5.6}$$

Where: A_{m} = mineral accumulation rate g cm^{-2} yr^{-1}; ρ_{mineral} = mineral bulk density (g cm^{-3}); A_{b} = bulk accumulation rate g cm^{-2} yr^{-1}

Statistical analysis of the suite of physio-chemical parameters, including determining the mean, standard deviation, and the degree of correlation between variables (Pearson's *r*) was performed in Microsoft Excel (2013) using the Analysis Toolpak Add-in package.

5.6 Charcoal analysis

The combustion and burning of carbonaceous material (wood, coal, oil etc) in the landscape produces large quantities of soot and particulate charcoal, or more generically, black carbon (BC) (Schmidt and Noack 2000, Braadbaart and Poole 2008, Scott 2010). During the charring process, biomass undergoes structural and chemical changes that render it relatively inert (Bustin and Guo 1999) and thus charcoal can remain preserved in soils and sediments over geological timescales (Herring 1985, Scott 2000). The abundance of micro- and macroscopic charcoal in soils and sediments of lakes and mires (see Patterson et al. 1987) 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) over several spatial and temporal scales, modulated by a complex taphonomy (Scott 2010, Scott and Damblon 2010).

While naturally occurring wildfires are predominantly the result of lightning strikes, additional, but less common ignition sources can include volcanic activity, meteorite strikes, spontaneous combustion and sparking resulting from rock fall (Cope and Chaloner 1980). The sources of human-induced fires, however, are more variable and can be attributable to forest clearance, slash-and-burn cultivation, metallurgy, backfires, bonfires and domestic burning (Flenley 1988, Galop et al. 2002, Granstrom and Niklasson 2008, Bal et al. 2011). These anthropogenic mechanisms influence many components of the fire regime, including burn intervals, spatial and seasonal distribution of fires, and fire intensity (Granstrom and Niklasson 2008). However, separating the human activity signal from the natural fire regime has been a persistent challenge in the interpretation of charcoal records in human occupied landscapes (Scott and Damblon 2010). When combined with pollen and other microfossil studies (Penny and Kealhofer 2005, Penny et al. 2006, Bal et al. 2011) and/or compared against long-term climate records for the region (Swetnam 1996, Power et al. 2013), however, a reasonably robust record of land-cover and land-use change, controlled for the influence of a fluctuating climate, can be obtained (see section 5.8).

Further challenges remain in the interpretation of charcoal records, primarily due to the variable nature of source fires and taphonomic processes (ie. transport and dispersal processes). The type and quantity of particulate charcoal released during a fire event depends on the intensity and duration of the fire, the fuel load and vegetation type available and/or selected, local meteorology, and the characteristics of the substrate and ground cover (Schmidt and Noack 2000 and references therein, Asouti and Austin 2005). Once released, charcoal is initially entrained within the convective column and wind-transported from its source or re-worked subsequently and deposited by water erosion, with the degree of dispersal being generally dependent on size of the charcoal fraction (Higuera et al. 2007 and references therein). Fire signals interpreted from charcoal records are therefore composed of a series of 'peak' fire signals associated with specific proximal fire events or periods during which numerous specific proximal fire events occur, superimposed over 'background' levels. This 'background' record, then, represents the long-term, distal, integrated combustion signal from the regional landscape (Clark and Royall 1994, 1995). 'Peaks' indicate annual or inter-annual fires, often occurring within the catchment, and are defined as being higher in amplitude than the long-term background signal (Clark 1990), calculated here as the mean charcoal influx over the reconstructed record (see Analysis below).

5.6.1 Laboratory protocol – extraction techniques

Macroscopic charcoal extraction and analysis followed a modified protocol established by Stevenson and Haberle (2005). 2 cm^3 samples taken at 2-3 cm intervals along the core, consistent with volume recommendations made by Carcaillet et al. (2001), were dispersed in 5% w:v $(NaPO_3)_6$ and mixed mechanically for at least 4 hours. 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, on account of their high settling velocities (Tolonen 1986, Patterson et al. 1987), while smaller particles represent distal fires (Clark and Royall 1995, Schmidt and Noack 2000, Duffin et al. 2008 and references therein). As such, dispersed samples were then wet sieved through 250 μm and 106 μm mesh in order to separate size fractions that correspond to (ie. were sourced from) different, but overlapping catchment scales (see Clark 1988). In this case, charcoal was separated into roughly local (> 250 μm), local-regional (106-250 μm) and extraregional (microscopic charcoal - < 106 μm) source areas. Low wind velocities most readily lift charcoal particles between 130 and 150 μm, but these particles do not travel great distances (Clark 1988). Clark (1988) found that charcoal particles with a diameter > 100 μm were deposited between approximately 30 m and 10 km from the source of origin, depending on the height of convection. While microscopic charcoal (often referred to in the literature as 'pollen slide' charcoal) is usually considered to be 5-20 μm (Patterson et al. 1987) or at least < 50 μm (Clark and Royall 1995), 106 μm was selected as the threshold here so as not to exclude potentially important pollen grains that are regularly greater than 50 μm (such as larger grass and cereal grains, and some important aquatic species such as *Nelumbo nucifera*).

Microscopic charcoal (<106 μm; BC_μ) was isolated by digesting carbonate (HCl 10% w:v), silicates (HF 48% w:v) and non-charred organic carbon (wet oxidisation using H_2O_2/NaOCl). As both BC_μ and pollen extractions were prepared together, for more detail see Section 5.7. Samples were mounted on glass microscope slides in glycerol and BC_μ particles were counted under 400 x magnification. A known number of Lycopodium spores (Department of Geology, Lund University; Batch # 1031) were added to the samples and were used to calculate the influx of BC_μ particles per unit volume of sediment (Stockmarr 1971, Maher 1981), see Analysis below.

5.6.2 Analysis – counting and statistical methods

Microscopic charcoal was counted prior to pollen analysis. After placing the pollen slides beneath a Zeiss Axioskop II light microscope at x 400 magnification, BC_μ particles were counted using a hand-held counter clicker. Slides were manoeuvred along transects, and all BC_μ particles and Lycopodium marker spores were counted within each successive field-of-view, until 25 marker spores were tallied. Uncertainty was estimated by calculating the total standard deviation of these charcoal counts. Raw BC_μ counts were converted into influx values (particles cm^{-2} $year^{-1}$) using the following formula (Maher 1981):

$$BC_\mu influx = \frac{SRM}{V} \tag{5.7}$$

Where: S = sedimentation rate (cm yr^{-1}); R = the ration of pollen to marker spores counted; M = the number of marker spores added to the sample; and V = the volume of the sediment sample.

For the two macroscopic charcoal size classes, the material retained in the sieves was transferred to a glass petri dish for counting. The petri dish was placed over 1 cm grid graph paper, with each grid-square being individually numbered, and positioned beneath a binocular microscope at 40 x magnification. Once settled, the entire sample was counted. Charcoal fragments were counted by moving systematically from grid-square to grid-square. Results were converted from absolute values (fragments per unit volume) to influx values (particles cm^{-2} $year^{-1}$) using the method specified in Mooney and Tinner (2011), with the sedimentation rate calculated from the chronological model built from radiocarbon dates (see section 5.4). Uncertainty associated with experimental counting error was estimated by replicating (six times) one count of each macrocharcoal size class and calculating the relative standard deviation of those replicates, which was then applied to all other counts. Uncertainty associated with sedimentation rates calculated from modelled radiocarbon chronologies and used for calculating charcoal influx rates provides a source of unknown error.

For all size classes, 'background' influx values representing 'noise' from distant (extra-regional) fires and secondary charcoal deposition were decomposed from peak fluxes by calculating the residuals around the mean value for the period of record. Relatively high positive deviations from the mean were then interpreted as peak fire signals. Numerical peak-detection, such as the use of the CharAnalysis statistical program (Higuera et al. 2009), was unnecessary for this data given its relatively low resolution and non-continuous nature (samples were taken at every 2-3 cm). Furthermore, the fact that the majority of water bodies sampled were small ponds or moats, the charcoal was separated into three size classes, as well as the low background charcoal levels (regularly '0' in the macrocharcoal size class) and relatively short temporal window covered by the data (less than 1000 years), also meant that statistical separation of 'peaks' from the 'noise' was not necessary beyond this relatively simple method. As such, the long-term mean value is considered a sufficient representation of the background fire regime in this data set.

5.7 Plant microfossil analysis

5.7.1 Laboratory protocol- extraction techniques

The method of pollen and spore extraction employed here followed the standard procedure outlined in Faegri and Iverson (1989). Following sieving for macroscopic charcoal (see section 5.6), the < 106 μm fraction was placed inside labelled 15 ml polythene centrifuge tubes. The wet sediment was disaggregated by adding 10 ml of chemical dispersant (10% potassium hydroxide (KOH)), and heating in a hot water bath for approximately one hour. This step also aids in the pre-treatment process by releasing pollen-staining tannins and initiating the breakdown of cellulose structures. Samples were then checked for significant clumping using the vortex mixer, and where visible clumping persisted, the KOH step was repeated. Once sufficiently dispersed, samples were washed with distilled (DI) water, centrifuged and decanted. This final step was repeated until the supernatant ran relatively clear.

Carbonates were removed by treatment with hydrochloric acid (HCl 10% w:v). Before this step commenced however, one tablet of exotic marker spores (*Lycopodium clavatum* spores, Batch #1031, concentration of 20,848 ± 691.4 marker grains per tablet) was added to each sample. This step allowed for the concentration of palynomorphs to be determined in addition to absolute and relative abundances (Maher 1981). Initially only 1 ml of HCl was added to each sample and placed in a gently boiling hot water bath, primarily to test for the reactivity of each sample to the addition of acid, but also to help dissolve the spore tablet. Any excessive foaming was controlled by diluting the sample with a few drops of DI water. After the reaction had sufficiently subsided, an extra 5 ml of HCl was added to each sample and all were heated for 20 minutes. Samples were then, once again, washed using DI water, centrifuged and decanted.

Silicates were then digested in a hydrofluoric acid (HF 48% w:v) solution. Approximately 6 ml was added to each sample and all were mixed using the vortex mixer. The rack of samples was then transferred to an actively boiling water bath and left to react. Samples were stirred again using the vortex mixer after roughly 30 minutes and taken out of the bath after one hour. Samples were left to cool, then centrifuged before the acid was decanted into a labeled waste bottle. If any mineral material remained visible at the base of the centrifuge tube, the sample was subjected to a second HF treatment. Approximately 6 ml of HCl (10% w:v) was then added to each sample to disperse any remaining siliceous colloidal clumps that may have formed during the HF treatment (Faegri and Iversen 1989). Samples were stirred and gently heated in a warm water bath for 3-5 minutes. One DI water-wash completed this step.

Acid hydrolysis (acetolysis) treatment of the samples proceeded next. This step eliminates most of the remaining, extraneous organic matter, removes non-sporopollenin tissues, and stains the pollen and spore grains a golden yellow colour to enhance visibility of wall-texture and surface patterns under the microscope. As acetolysis only occurs effectively at 100°C (Heck and Cushing 2010), the water bath was pre-heated prior to the commencement of this step. The acetolysis mixture also reacts explosively with water, thus washing with approximately 6 ml of glacial acetic acid (CH_3COOH) initially dehydrated each sample. The acetolysis mixture was then prepared; it consists of glacial acetic anhydride ($(CH_3CO)_2O$) and concentrated sulfuric acid (H_2SO_4) in a ratio of 9:1. Approximately 6 ml of this mixture was added to each sample and the samples placed into the actively boiling water bath for no more than 2 minutes to avoid damaging the microfossils. The samples were then centrifuged and the supernatant decanted into a labeled acid waste container. Approximately 6 ml of glacial acetic acid was added before the samples were mixed, centrifuged, and decanted once again. The samples were then washed with DI water.

Finally, samples were transferred to labeled 1.5 ml vials and mixed gently but thoroughly with enough glycerol to maintain adequate dilution of the sample – normally approximately 0.5-1 ml. To mount samples onto glass slides, one drop of the thoroughly mixed sample was placed in the centre of a labeled slide using a fine pipette and placed on a hot plate set to 60°C. Several drops of pre-melted paraffin wax were then added to the slide using a glass rod, surrounding the sample, and a glass cover slip placed gently on top. Once the wax had surrounded the sample the slide was removed from the heat so that the wax solidified and permanently trapped the sample.

5.7.2 Analysis - classification and counting

A reference sample collection of known Cambodian pollen genera and/or species (determined from Phon 2000) was collated prior to sample counting. A relative paucity of information is available on the morphology of pollen and spores specific to Cambodia, which made this preparatory task vital. Sample reference photos and descriptions were collated from a variety of sources, namely the Australasian Pollen and Spore Atlas (Australian National University 2016), the physical collection of which is housed at the Australian National University (who also maintain an online database, see http://apsa.anu.edu.au), David Roubik and Jorge Patino's (2003) collection of pollen from Barro Colorado Island (available online through the Smithsonian Tropical Research Institute (http://stri.si.edu/sites/roubik)), Andrew Maxwell's (1999) PhD thesis on the pollen record of northeastern Cambodia, Dan Penny's (1998) PhD thesis and reference compilation of pollen from the dry deciduous and semi-evergreen forests of north-east Thailand from the collection at Rijksherbariam/Hortus Botanicus in Leiden, the Netherlands.

Of the final suite of prepared slides, the initial round of palynomorph counting included only those samples from approximately 10 cm intervals down the core. If greater resolution was deemed necessary following the initial round of palynomorph counting, then additional samples were selected at intervals of roughly 3-5 cm, paying particular attention to sections of the core where the greatest rate of change was apparently occurring. Plant microfossils at each selected depth were identified and counted under a Zeiss Axioskop II light microscope fitted with an AxioCam HRc camera at x 400 magnification. A total of approximately 300 palynomorphs, including at least 100 arboreal taxa, was the target for a sample to be included in the pollen record. If the count fell short following the inspection of 5 slides, the depth was discounted from the analysis. Where possible, a replacement, proximal depth was selected and analysed.

Classification of palynomorph specimens occurred at the species level where morphological preservation and taxonomic distinctiveness permitted, and particularly when a vouchered reference specimen was available for comparison. In most cases, however, taxa were identified at the level of genera, families or super-familial taxonomic groups. Unknown pollen grains (i.e. those not identifiable from the reference collection described above) were described using the terminology of Huang (1972) and Punt et al. (2007), photographed and assigned a classification for reference should they reoccur. These grains were then visually compared against genera known to exist in Cambodia from Huang's (1972) pollen opus of Taiwan. Photographs of example specimens for the most frequently encountered (top 99%) pollen and spore types are provided in Figures 5.6 to 5.8. Details of each specimen, including their major morphological traits, are provided in Table 5.3. Where the identification of a species or genus was not conclusive, the classification was assigned the one of the following qualifiers, either 'cf.' (for comparable form) or 'sf.' (for similar form). Those classifications assigned 'cf.' had highly comparable pollen morphology to the species or genus identified, however either minor differences were evident of the species/genus identified represented taxa that were unlikely to be found in this region. Those assigned 'sf.' had pollen morphology in which many, but not all, of the characteristics of that particular genus/species could be identified.

TABLE 5.3: Detail descriptions of the top 99% of pollen and spore specimens encountered, including the vegetation assemblages each described specimen has been assigned for this analysis. Terminology follows that of Huang (1972) and Punt et al. (2007). Photo codes refer to pollen photos provided in Figure 5.7.

Family	**Genus, species / descriptor**	**Pollen class**	**Polar shape**	**Equatorial shape**	**Size (μm)**	**Aperture**	**Surface**	**Photo code**	**Forest type / habitat**	**Veg. assem.**	**Source** Morph. Ecology
Adoxaceae	*Viburnum* cf.	Tricolporate	Circular	Subprolate to suboblate	15-20 x 18-22	Pores round	Reticulate	1a-b	ERF, SeF	ERF, anthro.	g. a.
Anacardiaceae	Undif.	Tricolporate	Circular to angular	Prolate to subspheroidal	18-49 x 18-41	Pores transversally elliptic or transversally parallel; colpi usually as long as P axis	Reticulate, striate, striato-reticulate or granulate	N/A	UC	UC	h. N/A
Aquifolliaceae	*Ilex*	Tricolporate	Circular-lobate to interangular	Subprolate to lobate	14-22 x 12-18	Pores round, transversally elliptic or transversally parallel	Bacculate-clavate but with less pronounced features near colpi	2a-b	SwF, SEDF	Pre-dist., post-dist.	h., c. b.
Arecaceae	Undif.	Monocolpate (monosulcate)	Subspheroidal to spheroidal	Subspheroidal to spheroidal	Various	Sulci very long	Psilate, scabrate, echinate, granulate	3 (e.g.)	DDF, MDF, SwF, Cult.	Pre-dist., anthro., post-dist.	h. c., d., e., f.
Asteraceae	echinate	Tricolporate	Circular to circular-lobate	Oblate-spheroidal to prolate-spheroidal	13-47 x 13-45	Pores usually round	Echinate	4	SeF	Anthro.	h. b.
Asteraceae	*Artemisia* cf.	Tricolporate	Circular to circular-lobate	Subspheroidal	20-25 x 18-26	Pores transversally elliptic; colpi 14-21 x 2-6 μm	Sexine short rugulate; tectum usually scabrate	5a-b	SeF	Anthro.	h. b.

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Family	**Genus, species / descriptor**	**Pollen class**	**Polar shape**	**Equatorial shape**	**Size (μm)**	**Aperture**	**Surface**	**Photo code**	**Forest type / habitat**	**Veg. assem.**	**Source** Morph. Ecology
Asteraceae	fenestrate / lophate		Circular	Suboblate to spheroidal	19-25 x 18-26	Poral lacuna 4-7 x 5-11 μm	Exine often echinolophate	6a-b	SeF	Anthro.	h. b.
Betulaceae	*Betula* cf.	Triporate	Circular to angular	Oblate to oblate-spheroidal	Approx. 18-20 diam.	Pores vestibulum type	Tectum psialte; sexine faintly striato-reticulate	7	ERF	ERF	h., g. g.
Blechnaceae	*Stenochlaena palustris*	Monolete	Roughly circular	Elliptical, bean-shaped	Approx. 20 x 33 x 25	Single laesura	Bacculate	8	SwF	Anthro., post-dist.	c. c., b.
Bombacaceae	*Bombax*	Tricolporate	Inter-semi-lobate to inter-subangular	Peroblate to suboblate	Approx. 40-60 x 40-60	Colpi short, pores club type	Reticulate	9	MDF, SeF	Pre-dist., anthro.	h. c., b., f.
Caryophyllaceae	Undif.	Pantoporate	Circular	Spheroidal	21-50 diam.	Pores circular to elliptic >2 μm wide	Rugulate	10 (e.g.)	ERF or SeF	Anthro.	h. b.
Chenopodiaceae / Amarantheaceae	Undif.	Pantoporate	Circular	Spheroidal	Approx. 12-30 diam.	Pores round	Usually granulate	11	SeF	Anthro.	h. c., b.
Adoxaceae	*Viburnum* cf.	Tricolporate	Circular	Subprolate to suboblate	15-20 x 18-22	Pores round	Reticulate	1a-b	ERF, SeF	ERF, anthro.	g. a.
Combretaceae / Melastomaceae	Undif.	6-colapte, triporate	(hexi-)semi-lobate	Subprolate	Varies, approx. 10-30 diam.	Small pores, usually not annulate	Psilate	12a-d (e.g.)	DDF, SEDF, MDF, SwF, SeF	Pre-dist., anthro., post-dist.	h. c., b.
Costaceae	*Costus speciosus*	Inaperturate	Elliptical	Spheroidal to subspheroidal	68-80	N/A	Granulate with nery large gemmae (5 μm)	13	SwF	Post-dist.	i. j.

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Family	**Genus, species / descriptor**	**Pollen class**	**Polar shape**	**Equatorial shape**	**Size (μm)**	**Aperture**	**Surface**	**Photo code**	**Forest type / habitat**	**Veg. assem.**	**Source** Morph. Ecology
Cyperaceae	Undif.	1-4-aperturate	Rectangular, subspheroidal or triangular	Obovoidal	Usually >20 μm	Indistinct, range from pores to furrows, indicated by a change in exine texture	Tectum usually psilate; sexine usually granulate	14a-b	SwF, RiF, EAq, DDF	Pre-dist., post-dist.	h., c. c., b., f.
Datisaceae / Elaeocarpaceae	*Tetremeles* / *Elaeocarpus*	Tricolporate	Sub-circular or semi-angular	Spherical	8-13 x 8-12	Indistinct pores only apparent as small notches in equatorial view	Psilate	15	MDF, SEDF, SwF, SeF	Pre-dist., post-dist.	c. b., c., d.
Dennstaedtiaceae	*Pteridium*	Trilete	Semi-lobate	Elliptical	28-34 x 21-27	Three laesura, extending more than half of radius	Psilate to scabrate	16	SwF	Anthro., post-dist.	g. b.
Dipterocarpaceae	*Hopea* / *Shorea*	Tricolporate	Circular	Spheroidal to suboblate	Approx. 15-25 x 20-28	Colpi long, with splits clean and fairly narrow, but sometimes splayed	Micro-reticulate	17	SeF, SEDF, DDF, RiF, SwF	Pre-dist., anthro.	c. c., e., k.
Dipterocarpaceae	*Dipterocarpus*	Tricolpate	Circular to circular-lobate	Spheroidal	Approx. 50-60 x 48-52	Colpi narrow, sometimes splayed	Micro-reticulate	18	SEDF, DDF	Pre-dist.	c. c., e.
Ebanaceae	*Diospyros*	Tricolporate	Inter-hexagonal to subangular	Prolate to oblate-spheroidal	Approx. 25-40 x 21-30	Colpi long, pores common or drop type	Psilate to scabrate	19a-b	SeF, MDF, SwF	Pre-dist., anthro.	h. c., f., b., d.

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Family	**Genus, species / descriptor**	**Pollen class**	**Polar shape**	**Equatorial shape**	**Size (μm)**	**Aperture**	**Surface**	**Photo code**	**Forest type / habitat**	**Veg. assem.**	**Source** Morph. Ecology
Euphorbiaceae	*Macaranga / Mallotus*	Tricolporate	Circular to semi-angular	Sub-spheroidal to suboblate, characteristically flattened at the pores in equatorial view	Wide size range, approx. 12-39 diam.	Distinct transverse parallel furrow; narrow, short colpi	Psilate to scabrate	20a-b	SeF, MDF, SwF, RiF	Anthro.	c. c., f., b., d.
Euphorbiaceae	Undif.	Usually tricolporate	Circular, circular-lobate or inter-semi-angular	Suboblate to prolate	Wide size range	Colpi varying in length; pores usually transversally parallel, however some are transversally elliptic or circular	Usually granulate or reticulate	N/A	SeF, MDF, DDF	Pre-dist., anthro.	h. c., f.
Fagaceae	*Lithocarpus / Castanopsis*	Tricolporate	Circular-lobate	Perprolate	12-15 x 8-10	Pores small, transversally parallel or transversally elliptic	Psilate	21	MDF	Pre-dist.	c. e., b., c.
Fagaceae	*Quercus* cf.	Tricolporate	Subcircular	Spheroidal to subprolate	27-34 x 20-30	Pore indistinct; colpus endexine has distinctive kink at the equator	Scabrate	22a-b	ERF	ERF	c. e., c.
Gutteriferae	*Cratoxylum*	Tricolporate or tricolpate	Circular	Oblate	Approx. 16-23 diam.	Pores round, where present	Granulate-scabrate or reticulate	23a-b	MDF, SeF	Pre-dist., Anthro.	i. c., f.

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Family	**Genus, species / descriptor**	**Pollen class**	**Polar shape**	**Equatorial shape**	**Size (μm)**	**Aperture**	**Surface**	**Photo code**	**Forest type / habitat**	**Veg. assem.**	**Source** Morph. Ecology
Hamamelidaceae	*Altingia*	5-(panto)-porate	Circular	Spheroidal	Approx. 17-30 diam.	Pores circular-elliptic	Reticulate, with sculpturing elements evident on pore membranes	24	ERF	ERF	g. l. b.
Juglandaceae	*Engelhardtia*	Triporate	Semi-angular or circular	Subspheroidal	Approx. 18-23 diam.	Pores small, atrium type	Granulate	25	SeF	Anthro.	h., c. c.
Leguminosae	*Intsia*	Tricolporate	Inter-angular	Prolate	36-51 x 48-57	Pores circular to elongate	Coarsely reticulate	26	ERF	ERF g. b.	
Lythraceae	*Lagerstroemia*	Tricolporate	Circular or inter-semi angular; ornate p. view is diagnostic	Subprolate	38-43 x 28-38	Pores circular and distinct	Granulate to scabrate	27a-b	MDF, SEDF, SeF	Pre-dist., anthro.	c. c., f., k.
Lythraceae	*Rotala*	3-4colporate	Circular or inter-semi angular	Prolate to subprolate	16-22 x 12-17	Pores drop type	Psilate to granulate	28a-b	MDF, EAq	Anthro.	h. m., p.
Meliaceae	*Aglaia*	Tricolporate	Semi-angular	Prolate	13-17 x 10-13	Colpi distinctly short; pores transversally elliptic	Psilate to granulate	29a-b	SEDF, SwF	Pre-dist.	h. c., b.
Menyanthaceae	*Nymphoides*	Parasyncolpate	Angular to semi-angular	Oblate	17-21 x 25-30		Scabrate	30	EAq	Anthro.	g. b.
Mimosoidae / Legumino.	*Acacia / Albizzia*	Polyad, 16 grains			At least 36-65 diam.		Psilate to granulate	31	MDF, SeF, RiF	Pre-dist., anthro.	h. b., f., c.

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Family	**Genus, species / descriptor**	**Pollen class**	**Polar shape**	**Equatorial shape**	**Size (μm)**	**Aperture**	**Surface**	**Photo code**	**Forest type / habitat**	**Veg. assem.**	**Source** Morph. Ecology
Moraceae	*Ficus*	Di- or triporate	Cigar-shape, triangular, but mostly elliptical with one side slightly bulging	Circular	5-10 x 7-13	Pores small, common type, circular and indistinct	Psilate	32	SwF, RiF	Post-dist.	c. c., d.
Myricaceae	*Myrica*	Triporate	Circular	Spheroidal	14-18 x 17-22	Pores round, prominantly apsidate	Granulate	33a-b	RiF, SwF	Post-dist.	c. c.
Myrtaceae	*Eugenia*	Tricolporate; syncolpate	Semi-angular, angular or semi-lobate	Oblate to peroblate	Equatorial axis < 14	Indistinct pores	Psilate to granulate	34	MDF, RiF, SeF, SwF (Predominantly SwF, RiF)	Post-dist.	c. d., n., c.
Myrtaceae	Undif. (includes *Eucalyptus*)	Tricolporate; syncolpate	Semi-angular, angular or semi-lobate	Oblate to peroblate	10-12 x 15-19	Pores round or transversally elliptic	Granulate to scabrate	35 (e.g.)	UC	UC	c. N/A
Nelumbonaceae	*Nelumbo nucifera*	Tricolpate	Circular	Subprolate	40-60 x 44-58	Colpi long (greater than two-thirds the length of the P axis) and 2-3 μm wide	Verrucate, visible columella	36a-b EAq	Anthro.	h., g. b.	
Nephrolepidaceae	*Nephrolepis* cf.	Monolete	Roughly circular	Elliptical, bean-shaped	Varies, approx. 12 x 18 x 10 - 25 x 40 x 20	Single laesura	Rugulate, psilate	37	SwF	Post-dist.	c., g. c.
Pandanaceae	*Pandanus*	Monoporate or monolete	Subspheroidal to spheroidal		Usually < 20 diam.		Echinate	38	SeF, RiF, SwF	Anthro., post-dist.	l., h. c., b.

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Family	**Genus, species / descriptor**	**Pollen class**	**Polar shape**	**Equatorial shape**	**Size (μm)**	**Aperture**	**Surface**	**Photo code**	**Forest type / habitat**	**Veg. assem.**	**Source** Morph. Ecology
Pinaceae	*Pinus*	Vesiculate	Elliptical	Bilateral / Bisaccate	Approx. 35-50 x 30-50 x 35-45 for the corpus		Sacs coarsely reticulate; corpus psilate-microreticulate; distinct difference in ornamentation between cap and rest of corpus	39a-b	ERF	ERF	h., c. c.
Poaceae	Undif.	Monoporate	Usually circular	Spheroidal	Usually > 20 diam.	Pores distinct, drop type, circular and annulate	Tectum psilate; sexine psilate-granulate	40	DDF, MDF, SeF	Pre-dist., anthro.	c. f., c., k.
Podocarpaceae	*Podocarpus* / *Dacrydium*	Vesiculate	Spherical-elliptical	Bi-trilateral / Bi-trisaccate	Approx. 25-40 x 25-45 x 25-40 for the corpus	Tectum with scabrate processes; sexine reticulate		41	ERF	ERF	h. b.
Rhamnaceae	*Zizyphus* sf.	Tricolporate	Subangular	Subprolate to suboblate	13-20 x 13-20	Pores are small and round	Psilate to finely-reticulate	42a-b	SeF	Anthro.	Modified from c., h. c.
Rhamnaceae / Sapindaceae cf.	Type 1	Tricolporate	Subangular to semi-angular	Oblate to spheroidal	Approx. 11-15 x 11-15	Pores appear transversally elliptic or rectangular	Psilate	43a-b	UC	UC / possibly anthro.	h, c. c.
Rhamnaceae / Sapindaceae cf.	Type 2	Tricolporate	Subangular to semi-angular	Subprolate to prolate	Approx. 12-15 x 12-18	Pores are round or longitudinally elliptic	Psilate	44a-b	UC	UC / possibly anthro.	h., c. c.

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Family	**Genus, species / descriptor**	**Pollen class**	**Polar shape**	**Equatorial shape**	**Size (μm)**	**Aperture**	**Surface**	**Photo code**	**Forest type / habitat**	**Veg. assem.**	**Source** Morph. Ecology
Rubiaceae	*Uncaria* / *Wendlandia*	Tricolporate	Semi-angular or circular-lobate	Suboblate to subprolate	10-17 x 9-15	Pore common type, longitudinally or transversally ellptic or circular, distinctly annulate	Reticulate	45a-b	SwF	Post-dist.	h. b.
Rubiaceae	*Adina* / *Nauclea* cf.	Tricolporate	Semi-angular to circular	Oblate to spheroidal	11-13 x 11-13	Pores circular and distinctly annulate	Psilate-granulate	46a-b	MDF, RiF	Pre-dist.	Modified from c. c.
Rubiaceae	*Neonauclea* / *Randia* cf.	Tricolporate (or triporate)	Circular	Suboblate to subprolate	Approx. 18-25 x 18-25	Pores round or longitudinally elliptic and distinctly annulate	Finely reticulate	47a-b	MDF	Pre-dist.	Modified from h. c.
Rutaceae	*Clausena* / *Zanthoxylum*	Tricolporate	Circular to circular-lobate or semi-angular	Prolate	Approx. 20-28 x 13-28	Pores common type, transversally parallel or rectangle	Reticulate, sometimes with bacculate processes	48a-b	SeF	Anthro.	h. b.
Sapindaceae	*Schleichera oleosa*	Tricolporoidate - syncolpate	Semi-angular	Prolate	27 x 19	Colpi long, tips acute, pores round	Striate	49	SeF, SwF, MDF	Post-dist.	o. c., k.
Schisandraceae	*Schisandra*	3-6-colpate	Circular	Oblate	15-22 x 23-30	Colpi monopolar convergent	Lopho-reticulate	50 (e.g.)	ERF	ERF	h. h.
Simaroubaceae	*Irvingia*	Tricolporate	Semi-lobate	Spheroidal	16-21 x 16-20	Pores usually indistinct, colpi fairly short	Psilate-granulate	51a-b	DDF, MDF, SEDF, SwF, SeF	Pre-dist., anthro., post-dist.	c. c., d., k.
Ulmaceae	*Celtis* cf.	3-4-porate	Circular	Sub-spheroidal	20-30 diam.	Pores round, globe type / annulate	Psilate-granulate	52	ERF	ERF	Modified from h. c.
Ulmaceae	*Trema*	Diporate, or triporate	Spherical-elliptic	Spherical to suboblate	12-15 x 12-17	Pores circular and distinctly annulate	Scabrate to verrucate	53	SEDF, MDF, SeF	Anthro.	c. c., f.

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Family	**Genus, species / descriptor**	**Pollen class**	**Polar shape**	**Equatorial shape**	**Size (μm)**	**Aperture**	**Surface**	**Photo code**	**Forest type / habitat**	**Veg. assem.**	**Source** Morph. Ecology
Umbrelliferae cf.	Undif.	Tricolporate	Inter-subangular or circular-lobate	Usually prolate to perprolate	Usually < approx. 14-20 x 7-15	Pores usually drop type and transversally elliptic	Usually granulate	54a-b (e.g.)	UC	UC	Modified from h. N/A
Urticaceae / Moraceae	Diporate / triporate undif.	Di- or triporate	Circular	Spherical	7-11 diam.	Pores small, indistinct, circular and non-annulate	Granulate	55	SEDF, SeF	Pre-dist., anthro.	c. c.
Vitaceae	*Vitis* cf.	Tricolporate	Inter-hexagonal	Subprolate		Round pores	Finely reticulate	56a-b	SeF, Cult.	Anthro.	N/A b.
C3P3 reticulate prolate				Prolate			Reticulate	57	UC	UC	N/A N/A
Tiny 4-colpate / colporate	psilate	4-porate / colporate	Circular	Prolate	5-6 x 7-9	Pores indistinct if present	Psilate	58a-b	UC	UC	N/A N/A
Tiny 4-colpate / colporate	reticulate	4-porate / colporate	Circular	Prolate to prolate-spheroidal	9-11 x 10-13	Pores round, if discernable / present	Reticulate	59a-b	UC	UC	N/A N/A

Sources:

a. Winkworth and Donoghue (2005)
b. Dy Phon (2000)
c. Maxwell (1999)
d. Theilade et al. (2011)
e. Rundel and Boonpragob (1995)
f. Ruangpanit (1995)
g. ANU (2016)
h. Huang (1972)
i. Jones and Pearce (2005)
j. Engel and Phummai (2008)
k. Bunyavejchewin et al. (2011)
l. Maloney (1991)
m. Quamar and Chauhan (2011)
n. Morley (1987)
o. Kailas et al. (2016)
p. Graham et al. (2011)

5.7.3 Analysis - data presentation and statistical methods

Following the identification and counting of microfossil taxa, all identified taxa were separated into either primary (i.e. arboreal and woody shrub) or secondary (i.e. herbaceous/wetland) taxon groups. Counts of plant microfossils were then converted to relative abundances (i.e. percentage of either arboreal or herbaceous taxa pollen sums). While most taxa that had been identified only to family level, for example Poaceae, Cyperaceae, and Chenopodiaceae / Amarantheaceae, could be classified (as a whole family) as either arboreal or herbaeous taxa, the relative abundances of some families that contained both arboreal and herbaceous species, as well as those taxa identified by a descriptor (e.g. 'tricolpate spheroidal verrucate'), were calculated as a percentage of the overall pollen sum. Relative abundances, instead of absolute abundances, were plotted because the pollen percentage method is the most reliable when pollen deposition is irregular through the sediment archive (Berglund and Ralska-Jasiewiczowa 1986). Pollen percentages were plotted stratigraphically using the software package C2 version 1.7.6 (Juggins 2014). Statistical analysis involved a constrained hierarchical cluster analysis (see Appendix B), which aided in the determination of major transitions in the pollen record down the core. This analysis was performed in the free-source statistical program R (R Core Team 2013) using the packages 'rioja' version 0.9.6 (Juggins 2012) and 'vegan' version 2.2.1 (Oksanen et al. 2015), employing the coniss method and a Euclidean distance method. All of the pollen data was included in this analysis and the number of cluster groups plotted was identified using the broken stick model.

An additional analysis followed this initial analysis on the pollen data in order to help identify and interpret changes in land use and occupation intensity of each city site through time. This analysis involved further classifying the pollen data in two stages. Firstly, each taxon was classified according to its commonly associated vegetation assemblage or habitat. Information on the vegetation assemblage or habitat each taxon is generally found in was derived from a variety of environmental studies in the region, predominantly Maxwell (1999), Dy Phon (2000), Theilade et al. (2011), Ruangpanit (1995), Engel and Phummai (2008), Winkworth and Donoghue (2005), Rundel and Boonpragob (1995), Quamar and Chauhan (2011), Graham et al. (2011), Bunyavejchewin et al. (2011) and Morley (1987) (see Table 5.3). Ultimately, all taxa identified to genera or species level were assigned to either one or several of the following vegetation assemblages common to the lowland Cambodian river plains: Semi-Evergreen Dry Forest (SEDF), Mixed Deciduous Forest (MDF), Deciduous Dipterocarp Forest (DDF), Riparian Forest (RiF), Swamp Forest (SwF) (which includes pteridophytes and other herbaceous aquatics that colonise the swamp forest understory), Emergent Aquatics (EAq) (those species commonly found in open-water environments) and Secondary (Disturbance) Forest (SeF) (see Table 4.1 for more detail on the characteristics of these forest types/vegetation assemblages). Taxa not found in the surrounding environs of these study sites (for e.g. highland environments throughout Cambodia or elsewhere in Southeast Asia) were classified as Extra-regional Forest (ERF). A few taxa notable for their cultivation uses were also classified as Cultivated (Cult.). Clearly, as taxa are highly likely to exist in multiple forest types, multiple classifications were often assigned (see Tables 4.1 and 5.3).

For the second stage of this analysis, where possible each vegetation assemblage outlined above was designated as being most closely associated with either 'pre-disturbance', 'anthropogenic', or 'post-disturbance' landscapes, appropriate for the environmental context of the chosen sites. Broadly speaking, the species found predominantly in SEDF, MDF and DDF were considered 'pre-disturbance' (given the local biogeography, see section 4.4), while SeF and EAq were considered 'anthropogenic', given the extent of landscape disturbance and forest clearance that occurred during the Angkor period (Groslier 1979), as well as the introduction and modification of water features that was common practice in Khmer temple cities (Groslier 1979, Fletcher

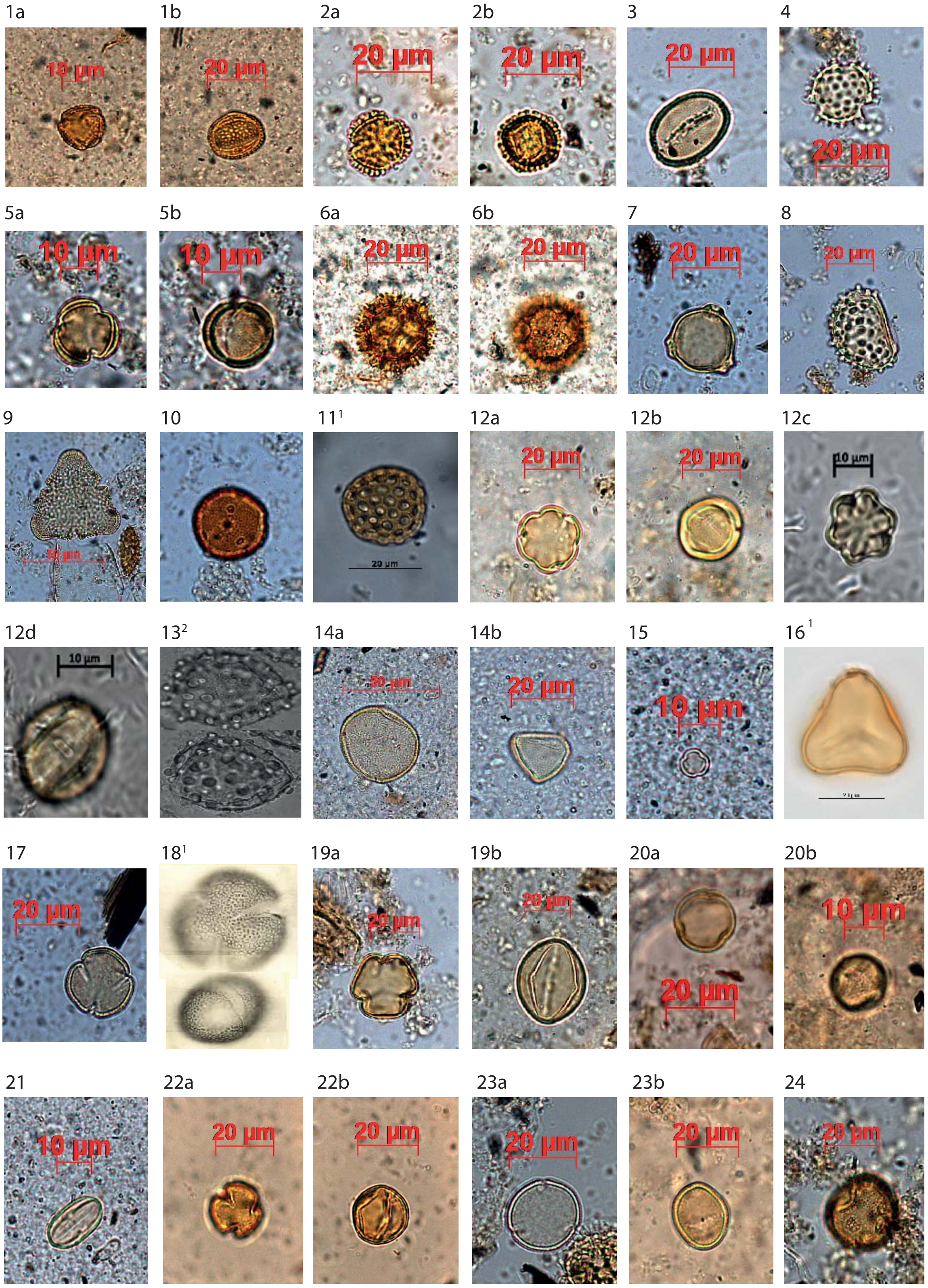

FIGURE 5.6: Plate 1: Photo examples of the top 99% of pollen and spore specimens encountered in this analysis. Number codes refer to Photo codes in Table 5.3. In general, photos were taken by the author or provided courtesy of R. Hamilton. Sources for those photos collected from elsewhere are specified.

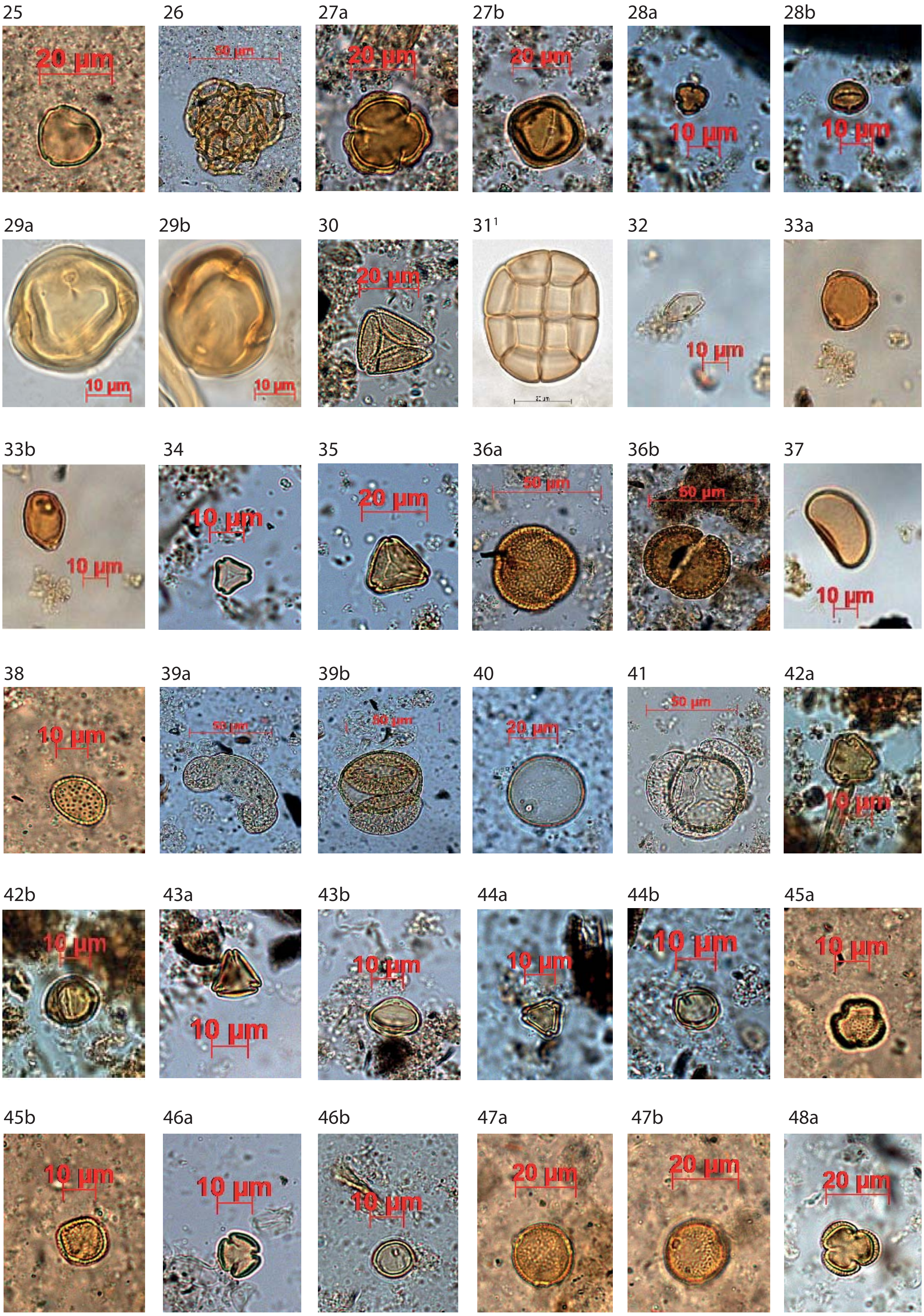

FIGURE 5.7: Plate 2: Photo examples of the top 99% of pollen and spore specimens encountered in this analysis. Number codes refer to Photo codes in Table 5.3. In general, photos were taken by the author or provided courtesy of R. Hamilton. Sources for those photos collected from elsewhere are specified.

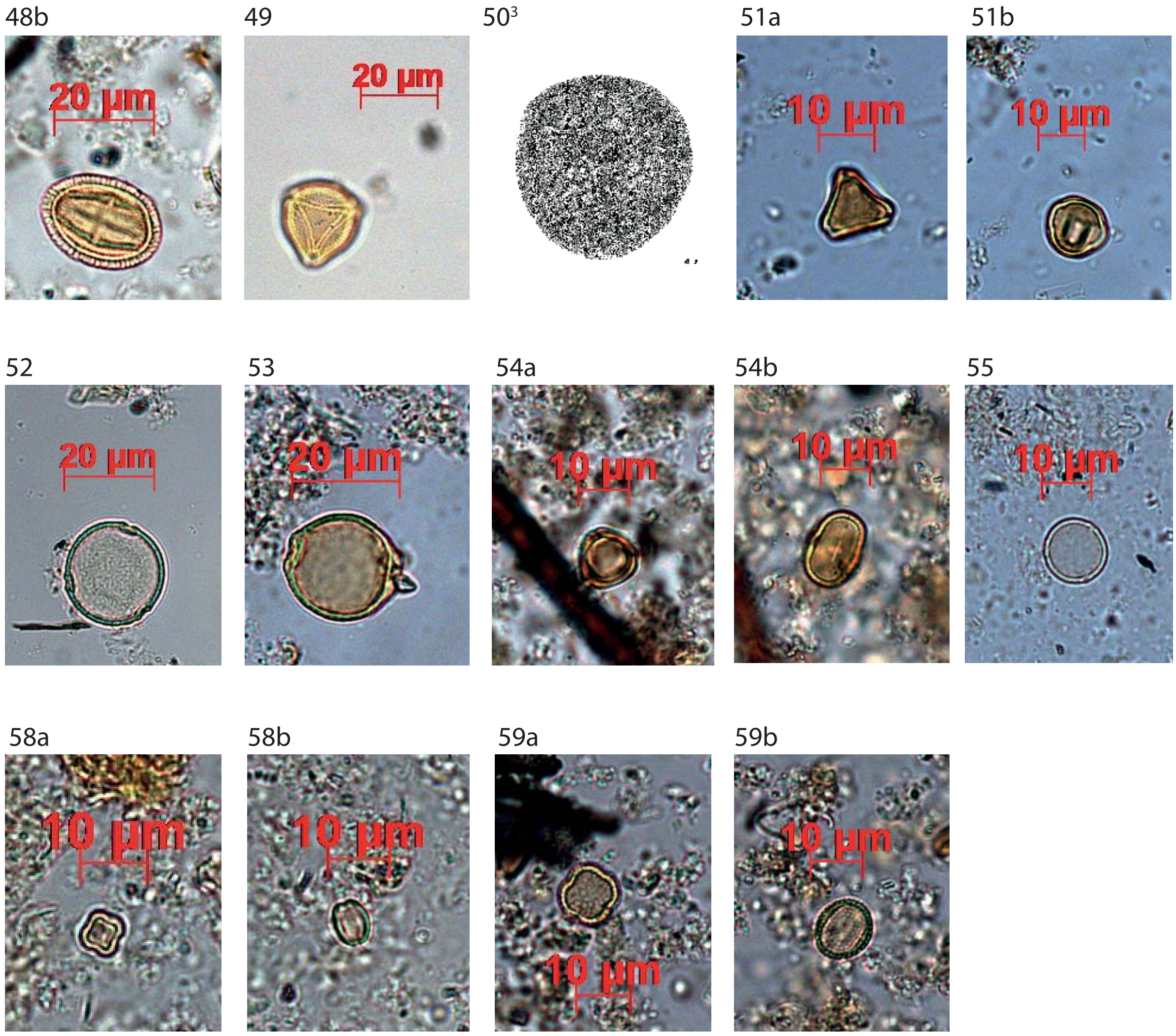

Photo sources:

1. Australasian Pollen and Spore Atlas (ANU 2016)
2. Jones and Pearce (2005), p.165
3. Huang (1972), Plate 143

FIGURE 5.8: Plate 3: Photo examples of the top 99% of pollen and spore specimens encountered in this analysis. Number codes refer to Photo codes in Table 5.3. In general, photos were taken by the author or provided courtesy of R. Hamilton. Sources for those photos collected from elsewhere are specified.

et al. 2003, Fletcher et al. 2008, Kummu 2009, see also section 3.4 and 3.5). During periods of occupation, these water-bodies were maintained (i.e. cleared of encroaching littoral vegetation, so that often only those floating aquatic macrophytes (for e.g. *Nymphoides* or *Nelumbo nucifera* remained (Penny et al. 2006, Day et al. 2012). Finally, SwF was considered as 'post-disturbance', as the abandoned water features, particularly the large *baray*, regularly transitioned into swamp forest communities in many Angkorian sites (from direct observation during field work; see also Bishop et al. 2003, Penny et al. 2006, 2007). Grouping the vegetation assemblages in this way allowed for the identification of ecological succession processes occurring in the pollen catchment, for example when a disturbed, actively utilised landscape, where sparse, secondary forest assemblages and cultivated land predominated, transitions to a landscape that was utilised less intensively, where forest has been able to rejuvenate and/or where open, shallow water bodies have been colonised by encroaching vegetation and transitioned into swamp assemblages.

Taxa were then displayed on separate pollen diagrams, this time grouped in these vegetation assemblages (i.e. 'pre-disturbance', 'anthropogenic' and 'post-disturbance'). In the instances where taxa had been assigned to more than one vegetation assemblage (for e.g. Combretaceae/Melastomaceae), these were displayed more than once.

5.8 Disentangling anthropogenic signals from climate impacts in the palaeoecological record

The various components of the sedimentary record described above are useful proxies for identifying human activity in the landscape, but are also reactive to changes in climate (Daniau et al. 2012, Li et al. 2014). Periods of warmer temperatures, particularly in highly seasonal climate zones, when coupled with increases in precipitation can result in high biomass productivity, thus generating altered forest structures and higher fuel loads for burning (Krawchuk et al. 2009), as well as increased incidences of storms and lightning strikes (Price 2009). Alternatively, during cold, dry periods the dehydration of fuel loads can result in increases in fuel efficiency and thus greater levels of biomass burning (Harrison et al. 2010) and consequent changes in vegetation community structure. However, cold periods can also reduce biomass burning through declines in vegetative productivity and hence fuel availability (Harrison et al. 2010), also leading to changes in vegetation landscapes (Pickett et al. 2004). As such, understanding the climate signal in palaeoenvironmental archives from anthropogenic landscapes has been an ongoing challenge (e.g. Kershaw 1994, Seppa and Bennett 2003, Birks and Seppa 2004, D'Angou et al. 2012).

The confounding influences of both humans and climate on environmental change are complicated further by the fact that the relative influence of each varies considerably across both space and time (Li et al. 2014), as well as by the two-way interactive nature of these variables (see Haberle and Ledru 2001, Sémah and Détroit 2006, Bird et al. 2013). Human migration and the intensity of anthropogenic land use and modification are regularly influenced by climatic conditions (Weiss and Bradley 2001, Haug et al. 2003, Lieberman and Buckley 2012, Wohlfarth et al. 2016), and human activity affects the climate via practices such as landscape fragmentation and deforestation (Lavorel et al. 2007). Anthropogenic burning (for land clearance, for example) have also been shown to be climate-dependent (on an interannual scale), in that managed burns will predominantly be restricted to times of optimal weather conditions (van der Werf et al. 2008). Accordingly, some authors have suggested that it may be prudent to treat climate and human activity as mutually dependent variables (Haberle and Ledru 2001). However, several studies have concluded that seasonally dry tropical forests are in fact fairly resilient and well-adapted to regional fluctuations in climate (Mayle and Power 2008, Hamilton 2016), and therefore these ecosystem types may have a greater potential sensitivity to human influence, thus allowing the human signal to emerge over the background influence of a changing climate.

One method used to unravel the complexity of human-climate-landscape interactions is the comparison of the palaeoecological record to known climate records, where they exist (Marlon et al. 2008, Power et al. 2013). Fortunately, two long-term climate reconstructions (for which data was available) exist for this region impacted by the range of Asian and South Asian monsoon systems, specifically one from the Vietnamese Highlands, and a second from tropical India (Figure 5.9). Buckley et al. (2010) provide a 759-year record Palmer Drought Severity Index (PDSI) from an analysis of tree rings retrieved from a rare conifer in Vietnam's Bidoup Nui Ba National Park, to the east of Cambodia. A complimentary record from the west is provided by Berkelhammer et al. (2010) and covers a greater temporal extent. Berkelhammer and his colleagues have reconstructed a 900-year (600-1550 AD) sub-annually resolved record of the Indian Summer Monsoon from speleothem oxygen isotope records (δ^{18}O) retrieved from east-central India. More recently, Yamoah et al. (2017) have reconstructed a hydroclimate proxy record from a radiocarbon-dated leaf wax (δD_{wax}) record collected from Lake Pa Kho in Thailand, and Hua et al. (Hua et al. in review) have, using a radiocarbon dated speleothem, reconstructed a continuous, high-resolution climate record from southern Cambodia (Phnom Chngauk). Correlating the palaeoenvironmental record presented here with these three pan-regional proxy climate records will help decouple the influences of humans and climate on the fire and pollen record.

However, direct comparison with these climate records is difficult in this region, due to the significant variation in precipitation patterns between the Indian subcontinent and across mainland Southeast Asia (Yang and Lau 2006) (see also section 4.4). Microcharcoal records, however, can provide an additional, more geographically relevant, supplementary climate proxy. Several studies have indicated that fluctuations in charcoal found in sediment deposits consistently mirror reconstructed climate records, especially over longer (centennial to millennial) timescales of analysis (Haberle and Ledru 2001, Marlon et al. 2008, Archibald et al. 2009, Daniau et al. 2010, Mooney et al. 2011, Daniau et al. 2012, Power et al. 2013, Hamilton 2016). The relationship between climate and biomass burning is, undeniably, modulated by local-scale, short- and long-term fluxes in fuel load and anthropogenic activity, as well as the inherent characteristics of the vegetation assemblage (Mooney et al. 2011). However both regional and global-scale analyses have shown that, in situations where both the degree of human and climate influences have changed concurrently and in opposing directions, it is the influence of climate that preferentially drives changes in regional-scale biomass burning (see Haberle and Ledru 2001, Marlon et al. 2008, Turner et al. 2008, Mooney et al. 2011, Daniau et al. 2012, Power et al. 2013). Therefore, the microcharcoal record, which presents the regional-scale burning regime (Clark 1988, see also section 5.6 above), should provide a fairly robust proxy for the overarching influence of regional climate in the midst of human impact on the local landscape. While both the macroscopic and microscopic charcoal records have been shown to reflect broader fire histories (Tinner et al. 2006, Conedera et al. 2009), any discrepancies between the two records should signify deviations in the local burning regime, and in a sparsely-settled (in regards to broad spatial scales) historical landscape, are likely capturing human activity in the immediate landscape, if accompanied by complimentary changes in the archaeological, vegetation and sedimentary record.

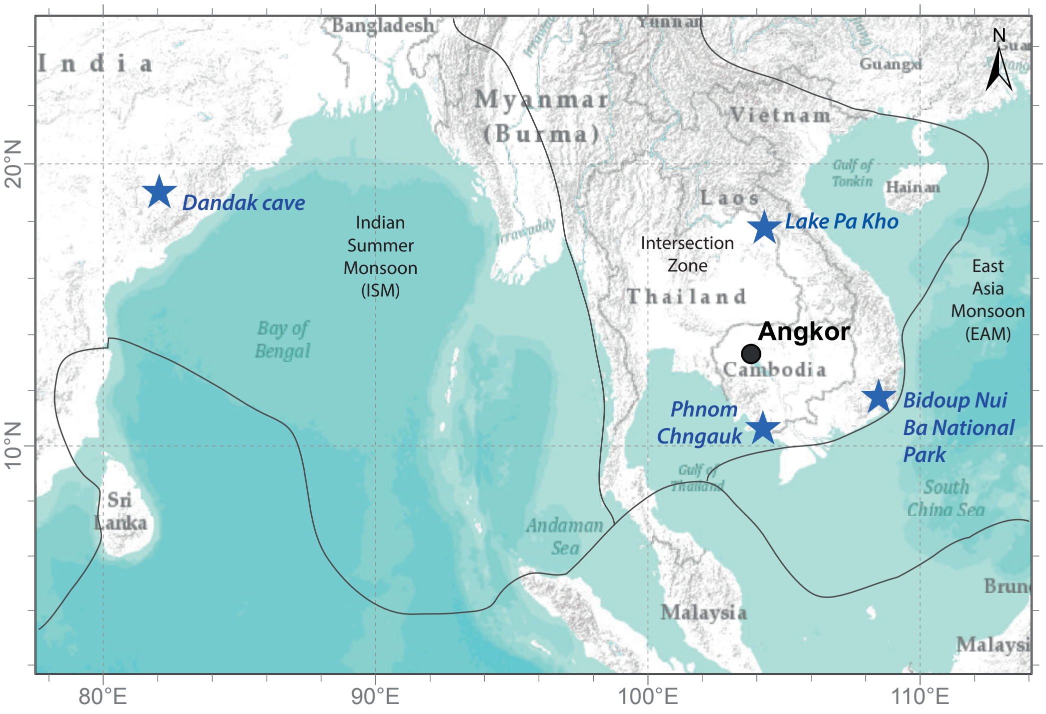

FIGURE 5.9: Geographic locations of the four climate proxy reconstructions referred to in this analysis and their relation to the region of study. Sources: Dandak Cave (Berkelhammer et al. 2010), Lake Pa Kho (Yamoah et al. 2017), Phnom Chngauk (Hua et al. 2017), and Bidoup Nui Ba National Park (Buckley et al. 2010).

6 Results: Palaeoecological records of the secondary cities

6.1 Introduction

The epigraphic, art-historical and – to date – limited archaeological records that exist for these peripheral cities provide a framework upon which to build absolute chronologies and robust occupational histories for the cities of the broader Khmer kingdom. This chapter will describe the results from the suite of palaeoecological analyses performed at each site. These results provide the first radiometric dates for many of the features constructed in or around these cities, allowing them be placed within the broader context of the city complex's archaeology and/or building programme. These results further provide the first landscape-scale environmental reconstructions from which to interpret human presence and activity during the Angkor and middle-period occupation of each city complex.

6.2 Banteay Chhmar

At all coring locations across Banteay Chhmar the percussion corer reached the clay substrate at relatively shallow depths. Consequently, only two cores were successfully retrieved from this city site – one from the NE corner of the moat at Banteay Chhmar and one from the Sa Rean reservoir (see Table 5.1 in the previous chapter). In all basins, even those that had been colonised by plants comprising an early swamp vegetation community, no overlying layer of organic-rich sediments, which is expected in an undisturbed swamp environment, was found. Overall, very little organic matter or sedimentation was present in either core recovered from Banteay Chhmar.

Unfortunately, due to the distinct lack of significant depositional sequences preserved throughout the Banteay Chhmar landscape, neither core recovered for this city site was appropriate for contribution to this study. As such, Banteay Chhmar was abandoned as a city site for the remainder of this research. Thus, only the palaeoecological analyses performed on the cores recovered from Preah Khan of Kompong Svay and Koh Ker will be presented moving forward.

6.3 Chronology

Table 6.1 outlines the radiocarbon results for the 22 organic samples taken from the three analysed cores. A number of temporal inversions with respect to stratigraphic order are evident in the uncalibrated dataset. Of the PKKS-C1 core samples, given that OZN549 is older than the three dates stratigraphically lower than it in the core, this sample (submitted as wood fragments) may potentially be displaying the 'old-wood' problem, where carbon exchange between the organism and the atmosphere ceased prior to death, as is often the case with wood

(Bowman 1990). There are also a number of anomalously young or 'modern' dates evident in the stratigraphy, including Beta-282655, Beta-282654 (from core PKKS-C1), and D-AMS 006502 (from Core PTC3). It is unlikely that these samples represent 'young' material that has intruded into lower depositional layers over time, as both PKKS-C1 and PTC3 show bedding in the sediment profile and show little evidence for the mechanisms for this downward movement to occur, such as burrows, root penetration, liquefaction, or turbidity flows (see section 6.5). Instead, it is possible that these samples have been contaminated by modern carbon during sample preparation. Modern or anomalously young radiocarbon ages were also present throughout the middle section of core KKPC2. Often, with highly organic bulk sediment samples such as these, modern or anomalously young ages can result from contamination from less stable and more mobile carbon sources such as humic acids (Hammond et al. 1991). However, as these samples were pretreated with potassium hydroxide (10% KOH w:v) specifically to avoid this phenomenon (see section 5.4 in the Methods and Materials chapter), this is unlikely to have occurred. Instead, it is most likely that this peat layer represents recent and rapid accumulation of organic material since the basin became colonised by floating swamp vegetation. Overall, however, a number of coherent radiocarbon ages were determined from each core from which it was possible to generate chronological models.

Calibrated age ranges are presented in Table 6.1, and displayed graphically in Figure 6.1. A number of the calibrated age ranges produced are very large, as a result of the probabilistic calibration method applied and the shape of the calibration curve to which these radiocarbon ages relate – specifically, the several 'plateaus' in this part of the calibration curve. This is particularly true for samples Beta-282654 from PKKS-C1, sample D-AMS 007111 from PTC3, and samples D-AMS 007109, D-AMS 008224 and D-AMS 018423 from KKPC2. Figure 6.1 shows how the Gaussian error distribution of each of these specific radiocarbon ages aligns with a broad range of dates along the particularly 'flat' section of the calibration curve between 300 and 0 years BP. In such cases, very broad calibrated age ranges are inevitably produced, and therefore often higher levels of uncertainty exist in the weighted mean ages generated. The Bacon modelling software, however, accounts for such wide probability distributions by applying a Student's t-distribution with wide tails (Christen and Perez 2009) (see section 5.4 in the Methods and Materials chapter) and therefore was often able to accommodate these broad calibration ranges in the final age-depth models (Blaauw and Christen 2011).

TABLE 6.1: Table of the conventional and calibrated ages (in calendar year before present), including errors, of radiocarbon dated samples submitted for all cores analysed.

City	**Core ID**	**Depth (cm)**	**Material description**	**Lab ID**	**^{14}C date BP $\pm 1\sigma$**	**Calibrated age range (2σ) (cal. yrs BP)**	**Calibrated age range (2σ) (AD)**	**Probability (%)**
Preah Khan of Kompong Svay	PKKS-C1	10-11	Macroplant material	Beta-282652	270 ± 40	151-215	1735-1799	18.7
						274-335	1615-1676	43
						358-447	1503-1592	33.2
		30-31	Macroplant material	Beta-282653	520 ± 40	492-559	1391-1458	95
		31-33		OZN549	703 ± 40	559-616	1334-1391	43.7
			Wood fragments			621-679	1271-1329	51.2
		31-35	Organic material	OZN553	593 ± 26	530-567	1383-1420	51.9
			Wood fragments			596-633	1317-1354	42.8
		35-36		OZN550	672 ± 69	533-687	1263-1417	92.8
						704-718	1232-1246	2.1
		85-86	Plant material	Beta-282654	100 ± 40	-2-148	1802-1952	75.7
						220-268	1682-1730	19.2
		86-88	Organic material	OZN552	740 ± 29	570-593	1357-1380	13.3
						636-690	1260-1314	73.1
						699-721	1229-1251	8.4
		130-135	Wood fragments	OZN551	867 ± 30	685-797	1153-1265	95
		140-141	Plant material	Beta-282655	450 ± 40	332-364	1586-1618	9.9
						444-539	1411-1506	85

Continued…

City	Core ID	Depth (cm)	Material description	Lab ID	^{14}C date BP $\pm 1\sigma$	Calibrated age range (2σ) (cal. yrs BP)	Calibrated age range (2σ) (AD)	Probability (%)
Koh Ker	KKPC2	10-11	Organic mud	D-AMS 007109	128 ± 14	-2-46	1904-1952	24.3
						54-125	1825-1896	41.3
						131-146	1804-1819	7.6
						222-261	1689-1728	21.7
		19-20	Sediment (humates)	D-AMS 018422	17 ± 22	-5-(-1)	1951-1955	88.5
						46-53	1897-1904	2.1
						123-132	1818-1827	4.2
		28-29	Organic mud	D-AMS 008223	Modern			
		46-47	Peat	D-AMS 008224	55 ± 28	-5-(-4)	1954-1955	0.4
						4-13	1937-1946	2.2
						17-72	1878-1933	49.5
						83-106	1844-1867	6.9
						112-141	1809-1838	28.1
						228-250	1700-1722	7.8
		51-52	Organic matter (twig fragments)	D-AMS 018423	170 ± 24	-3-26	1924-1953	8.7
						60-99	1851-1890	10.9
						101-114	1836-1849	4.4
						137-232	1718-1813	47
						238-283	1667-1712	23.9
		60-61	Peat	D-AMS 007110	528 ± 28	505-550	1400-1445	95
Koh Ker	PTC3	10-18	Leaf	D-AMS 006499	Modern			
		95-96	Peat	D-AMS 006500	345 ± 27	314-469	1481-1636	95
		111-112	Peat	D-AMS 006501	566 ± 22	518-560	1390-1432	89.4
						610-623	1327-1340	5.5
		125-126	Peat	D-AMS 007111	400 ± 25	328-376	1574-1622	27.3
						393-400	1550-1557	1.2
						439-502	1448-1511	66.4
		173-174	Organic mud	D-AMS 007112	758 ± 29	577-583	1367-1373	1.8
						649-727	1223-1301	93.1
		181-184	Leaf fragment	D-AMS 006502	Modern			
		213-214	Sapropel	D-AMS 006503	1234 ± 26	1060-1185	765-890	92.4
						1219-1232	718-731	1.5
						1250-1258	692-700	1

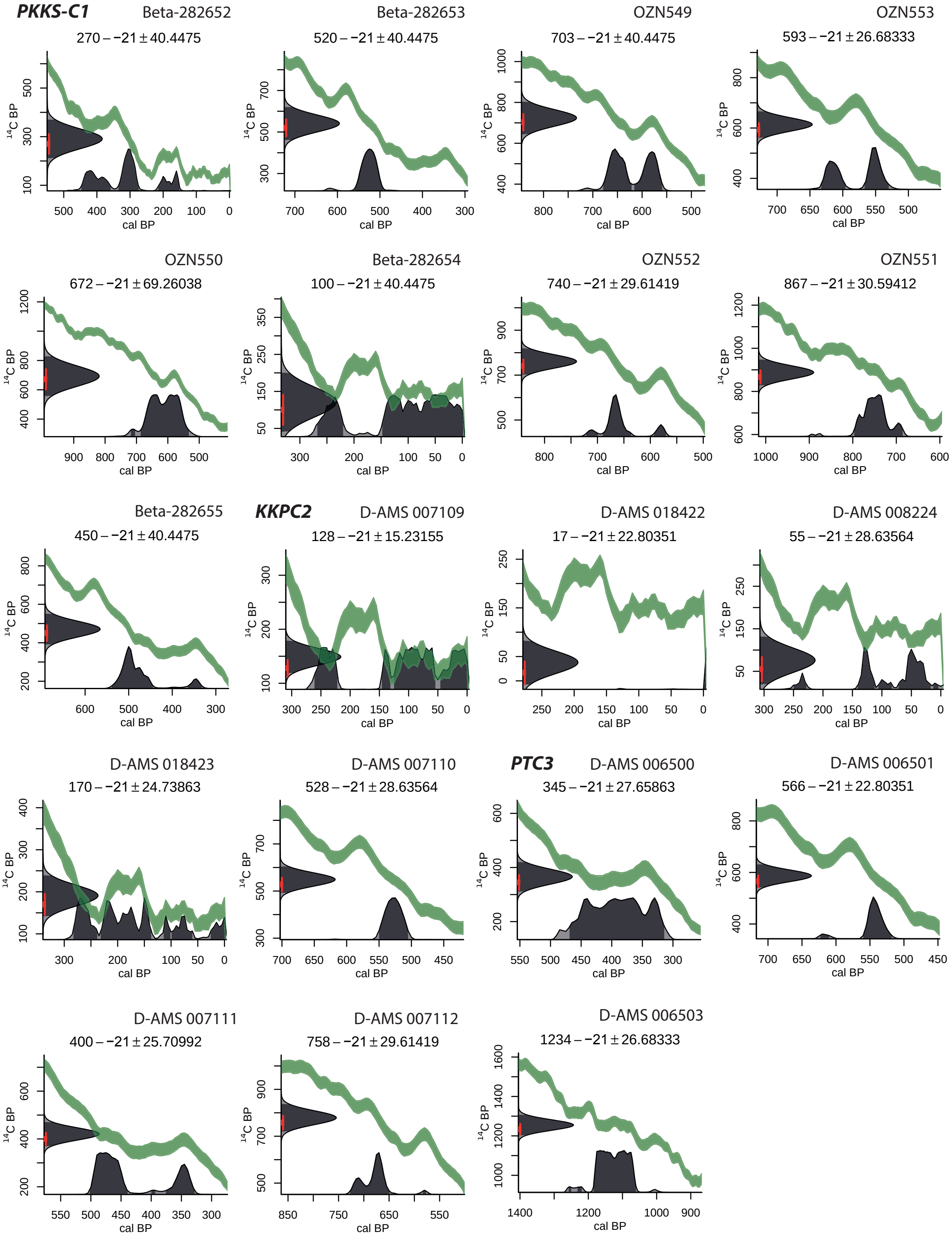

FIGURE 6.1: Individual plots showing radiocarbon ages against the SHCal13 calibration curve, and the resulting calibrated age ranges.

6.3.1 Core PKKS-C1 (Preah Khan of Kompong Svay)

Prior information set in Bacon included a mean accumulation rate of 2 years/cm, a minimum depth of 0 cm and maximum depth of 166.5 cm. No hiatuses were evident in the stratigraphy. The model identified both Beta-282654 and Beta-282655 as outlying dates incapable of being incorporated and excluded these from the final age-depth model, which is presented in Figure 6.2.

The calculated sediment accumulation rate is fairly constant, but declines marginally in the top 30 cm of the core. On average, the accumulation rate into the *baray* was calculated at 0.48 cm/year, which is very rapid compared to those observed in similar basins in other Angkor-period settlements. For example, rates of 0.04 and 0.18 cm/year were calculated for the reservoirs of the West Baray in Angkor and Bakong (Roluos) (Penny et al. 2006, Penny et al. 2007). Higher accumulation rates of 0.62 cm/year have been reported adjacent to the wall of the West Baray (Day et al. 2012), however these rates are likely usually high given the ample supply of sediment to the baray from the adjacent dykes.

6.3.2 Core PTC3 (Koh Ker)

A prior mean accumulation rate of 10 years/cm, a minimum depth of 108 cm and a maximum depth of 228 cm were set for the age-depth model of PTC3. All other parameters remained at default values. Because the top 107 cm was discarded from the analysis (due to mixing), only samples D-AMS 006501, D-AMS 007111, D-AMS 007112 and D-AMS 006503 were included in the age-depth model. Bacon identified a single outlying date, sample D-AMS 006501. The final age-depth model is presented in Figure 6.3.

The modelled accumulation rate of 0.13 cm/year is also fairly constant for PTC3, with a marginal decline ostensibly occurring from approximately 173 cm. This decline in accumulation rate may have begun earlier however, at around 189 cm (based on a change in the stratigraphy (see section 6.5).

6.3.3 Core KKPC2 (Koh Ker)

Generating an age-depth relationship for KKPC2 was problematic given the very broad calibrated age ranges calculated for a number of the radiocarbon-dated samples. A model was generated with the applied prior settings of 10 years/cm for the accumulation mean, a minimum depth of 0 cm and a maximum depth of 68 cm. In this case, the student-t values for the basal calibrated radiocarbon date (sample D-AMS 007110) were altered, as this calibrated age was considered more accurate (i.e. it generated a normal and relatively narrow distribution curve), compared to the above dates, and as such the *t.a* and *t.b* values were changed from 3 and 4 to 33 and 34 respectively. This was done to avoid the wide tails that are applied by default with the student's-t distribution, and therefore attempt to decrease the overall range of modelled age produced for the basal section of the core (see Christen and Blauuw 2011). The final age-depth model is presented in Figure 6.4.

The mean modelled bulk accumulation rate was calculated at 0.1 cm/year, very similar to core PTC3. The age-depth model presents a relatively sharp change in accumulation rate between 60 and 56 cm (from an initial rate of approximately 0.08 cm/year to 0.03 cm/year before declining to 0.15 cm/year for the remainder of the core). Given the overlapping calibrated age ranges produced for samples D-AMS 007109, D-AMS 018422, D-AMS 008224, and D-AMS 018423, it is probable that these sediments were likely deposited either instantaneously or within a similar

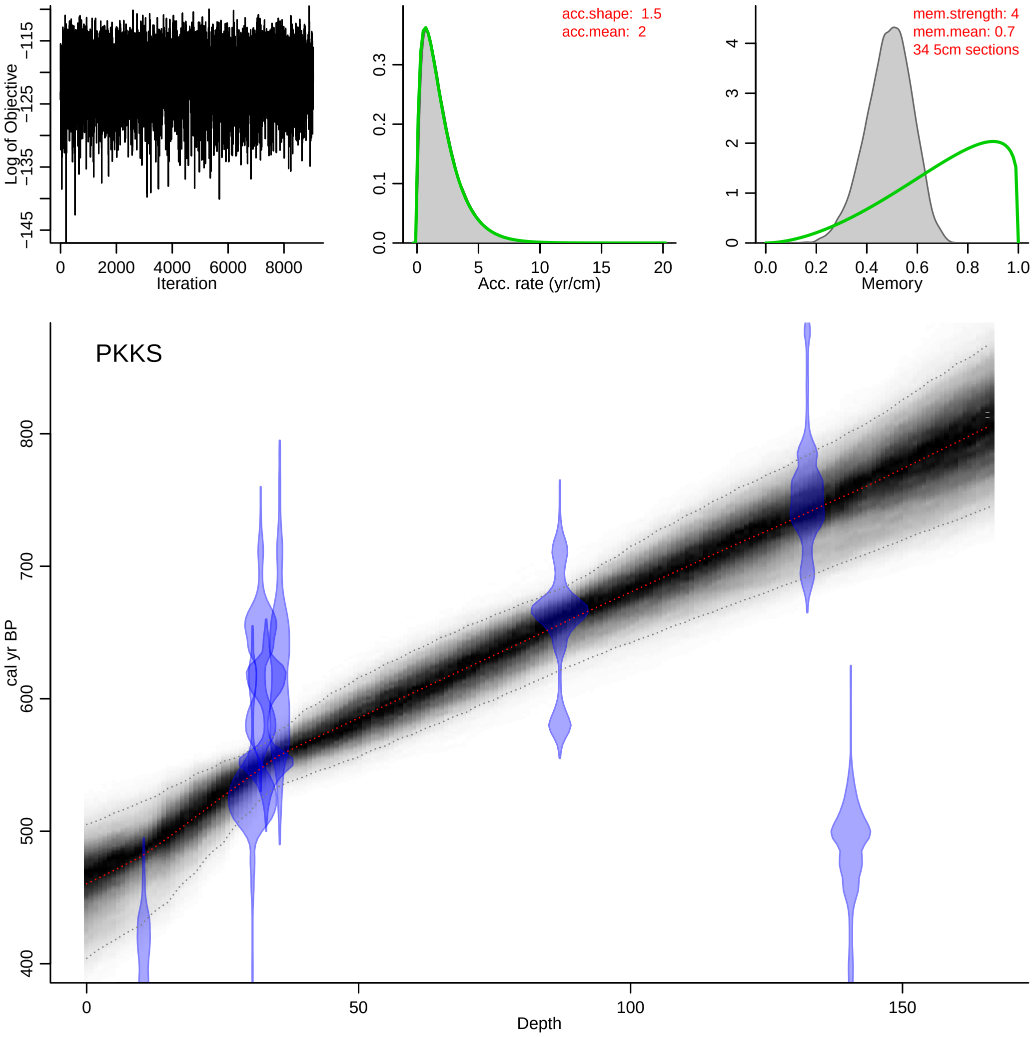

FIGURE 6.2: Age-depth model, plotted in Bacon, for core PKKS-C1. Top left panel depicts the MCMC iterations. Prior and posterior information is included at the top centre and right, including accumulation rate (centre) and the variability in the accumulation history (right). Calibrated radiocarbon ages are included individually in pale purple. Red curve indicates the weighted mean age for each modelled depth and grey stippled lines indicates the 95% confidence intervals for the final model.

period, and thus represent a change to rapid and recent bulk accumulation within the reservoir (perhaps associated with a removal of vegetation and cleaning of the reservoir (see section 7.5 in the next chapter)).

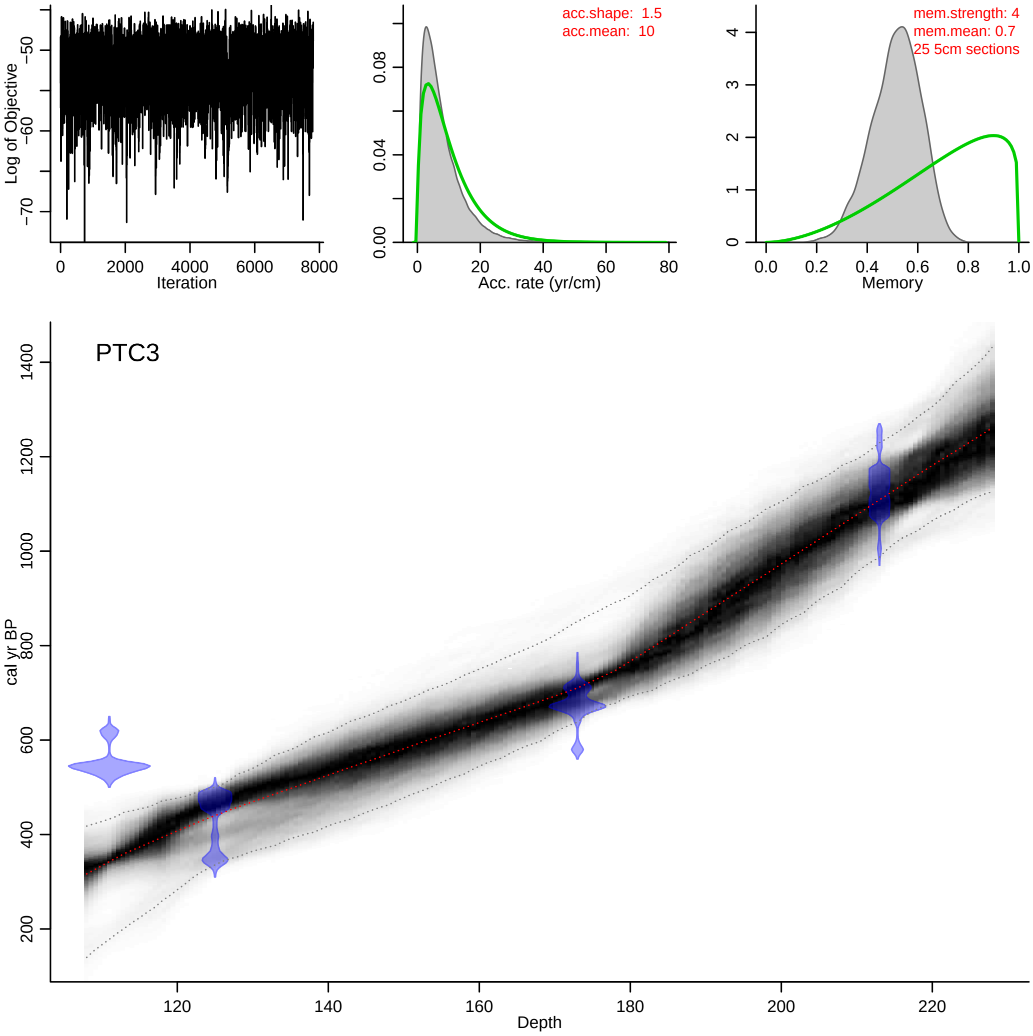

FIGURE 6.3: Age-depth model, plotted in Bacon, for core PTC3. Top left panel depicts the MCMC iterations. Prior and posterior information is included at the top centre and right, including accumulation rate (centre) and the variability in the accumulation history (right). Calibrated radiocarbon ages are included individually in pale purple. Red curve indicates the weighted mean age for each modelled depth and grey stippled lines indicates the 95% confidence intervals for the final model.

6.4 Sedimentary data

6.4.1 Core logging

Core PKKS-C1 (Preah Khan of Kompong Svay)

Core C1 is 166.5 cm in length comprising 12 stratigraphic units (see Fig. 6.5). The basal Unit I (166.5–155 cm depth) is a greenish grey [10GY/6/1], moist, massive, slightly gravelly sandy mud with distinct and irregular dark greenish grey mottles throughout the matrix and a clear, planar upper boundary. Unit II (155–144 cm depth) is a greenish grey [10Y/6/1], moist, massive, gleyed mud with an indistinct, wavy upper boundary. Unit III (144–139 cm depth) is a

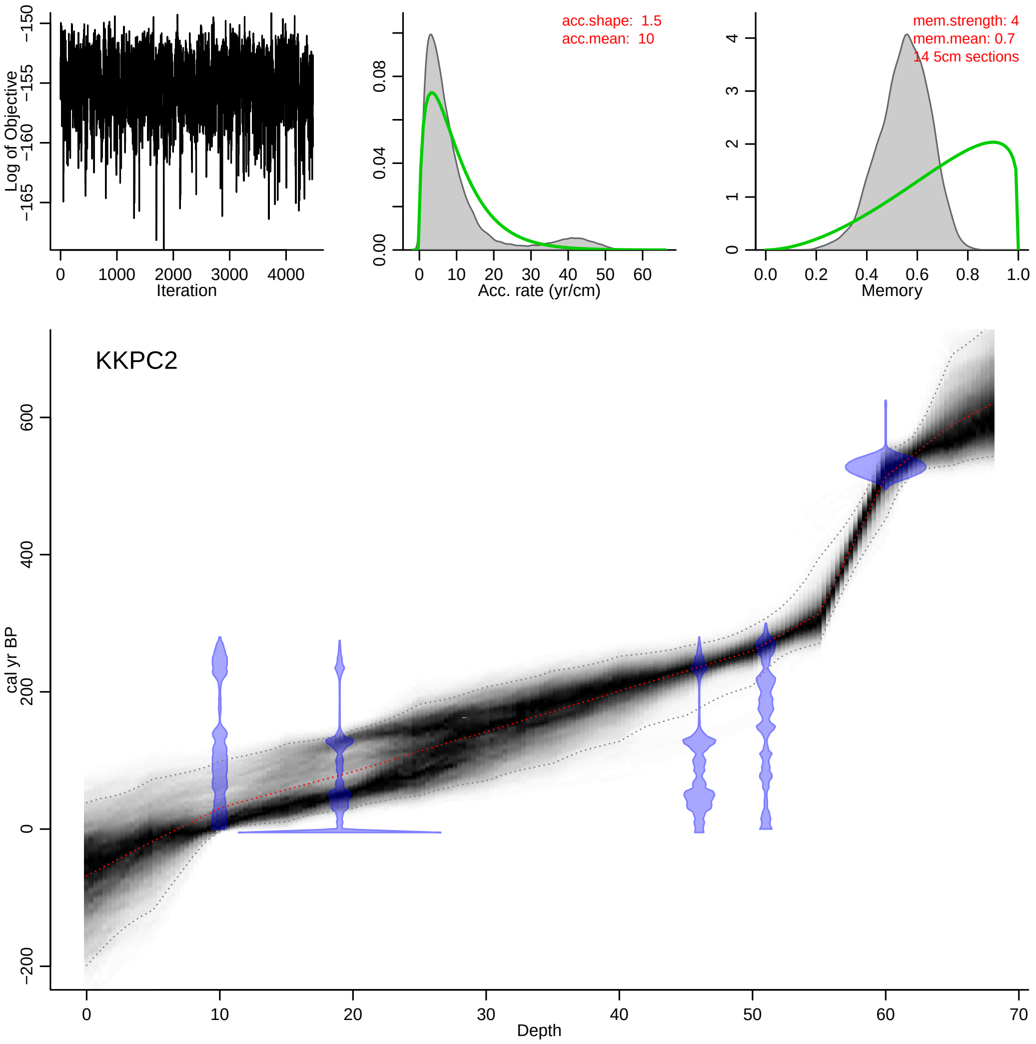

FIGURE 6.4: Age-depth model, plotted in Bacon, for core KKPC2. Top left panel depicts the MCMC iterations. Prior and posterior information is included at the top centre and right, including accumulation rate (centre) and the variability in the accumulation history (right). Calibrated radiocarbon ages are included individually in pale purple. Red curve indicates the weighted mean age for each modelled depth and grey stippled lines indicates the 95% confidence intervals for the final model.

greenish grey [5GY/6/1], moist, massive, sandy mud with an indistinct, wavy upper boundary. Unit IV (139–113 cm depth) is a grey [5Y/6/1], moist, massive, mud with a sharp, planar upper boundary. Unit V (112.5–110 depth) is a yellow [2.5Y/7/6], moist, massive, mud with a sharp, planar upper boundary. Unit VI (109.5–85 cm depth) is a light brownish grey [2.5Y/6/2], moist, massive mud with a diffuse, planar upper boundary and many very fine plant fragments. Unit VII (85–81 cm depth) is a dark grey [2.5Y/4/1], moist, massive mud grading to very poorly sorted, slightly gravelly sandy mud and contains an indistinct, gradational upper boundary. Unit VIII (80.5–77 cm) is a greyish brown [2.5Y/5/2], moist, massive, slightly gravelly mud with an indistinct, planar upper boundary. Unit IX (77–40 cm depth) is a light brownish grey [2.5Y/6/2], moist, massive mud to slightly gravelly sandy mud with many plant fragments and few fine roots throughout and an indistinct, planar upper boundary. Unit X (39.5–29 cm depth) is an olive brown [2.5Y/4/4], moist, massive, organic mud with many small-large plant fragments, contains few fine roots throughout and contains a diffuse, planar upper boundary. Unit XI (29–3.2 cm depth) is a very dark greyish brown [2.5Y/3/2], moist, massive, sandy to slightly gravelly sandy organic mud with few fine roots throughout and contains an indistinct, planar upper boundary. This is overlain by Unit XII (3.2–0 cm depth), which is a dark greyish brown [2.5Y/4/2], moist, massive slightly gravelly sandy organic mud containing few fine roots throughout. Original logs are provided in Appendix A.

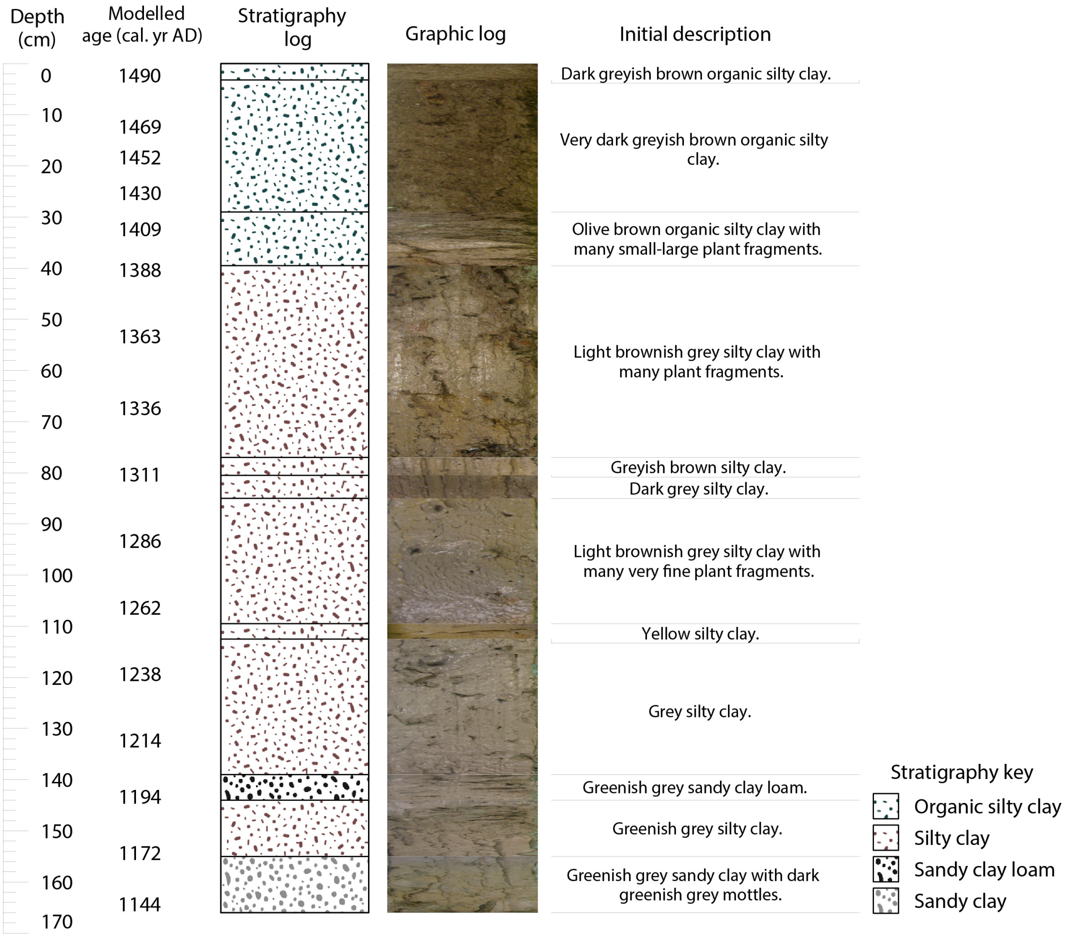

FIGURE 6.5: Photograph and stratigraphic descriptions for core PKKS-C1.

Core PTC3 (Koh Ker)

Core PTC3 is 229 cm in length comprising ten stratigraphic units (see Fig. 6.6). The basal Unit I (229-228 cm depth) is a very dark greyish brown [2.5Y/3/2] wet, massive, sapropelic mud with a sharp, wavy upper boundary. Unit II (228-211 cm depth) is a very dark greyish brown [2.5Y/3/2] wet, massive, sapropelic, slightly gravelly sandy mud to sandy mud with indistinct, planar upper boundary. Unit III (211-207 cm depth) is a very dark grey [2.5Y/3/1] wet, massive, sapropelic, sandy mud with a gradational, planar upper boundary. Unit IV (207-202 cm depth) is an olive black [2.5Y/2.5/1] wet, massive, sapropelic sandy mud with a gradational, planar upper boundary. Unit V (202-189 cm depth) is a very dark greyish brown [2.5Y/3/2] wet, massive, sapropelic, slightly gravelly sandy mud to sandy mud with an indistinct, planar upper boundary. Unit VI (189-158.5 cm depth) is a very dark grey [2.5Y/3/1] wet, massive, sapropelic, sandy mud containing a few large organic fragments and with an indistinct, planar upper boundary. Unit VII (158.5-140 cm depth) is a very dark greyish brown [2.5Y/3/2] wet, massive, sapropelic, sandy mud with an indistinct, planar upper boundary. Unit VIII (140-131.5 cm depth) is a very dark grey [2.5Y/3/1] wet, massive sapropelic sandy mud with a gradational, smooth upper boundary. Unit IX (131.5-108 cm depth) is a black [2.5Y/2.5/1] wet, massive, sapropelic mud with a sharp, planar upper boundary. This is overlain by Unit X (108-0 cm depth), which is a black [2.5Y/2.5/1], wet, massive, herbaceous peat containing many large organic fragments. This uppermost layer is highly unconsolidated and has likely mixed and was thus discarded from any further analysis. Original logs and smear slide descriptions are provided in Appendix A.

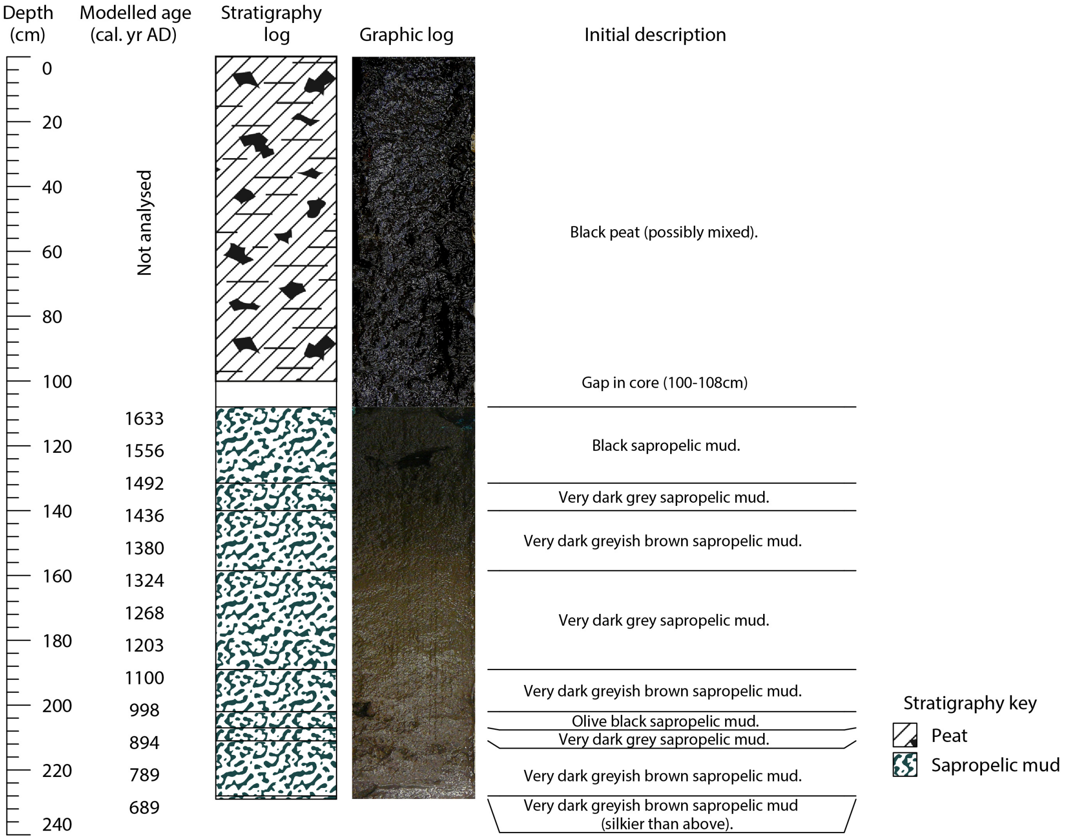

FIGURE 6.6: Photograph and stratigraphic descriptions for core PTC3.

Core KKPC2 (Koh Ker)

Core KKPC2 is 69 cm in length comprising three stratigraphic units (see Fig. 6.7). The basal Unit I (69-64.4 cm depth) is a very dark grey [2.5Y/3/1], moist, massive, sapropelic, sandy mud with an abrupt, wavy upper boundary. Unit II (64.4-24.5 cm depth) is a black [2.5Y/2.5/1], moist, massive peaty, sandy mud containing many large and very large woody and other organic fragments, and with a clear, smooth upper boundary. Organic/woody fragments are particularly concentrated between 41 and 44 cm depth. This is overlain by Unit III (24.5-0 cm depth), which is a very dark grey [2.5Y/3/1], moist, massive, peaty, sandy mud with black, distinct, irregular to platy mottles throughout. Original logs and smear slide descriptions are provided in Appendix A.

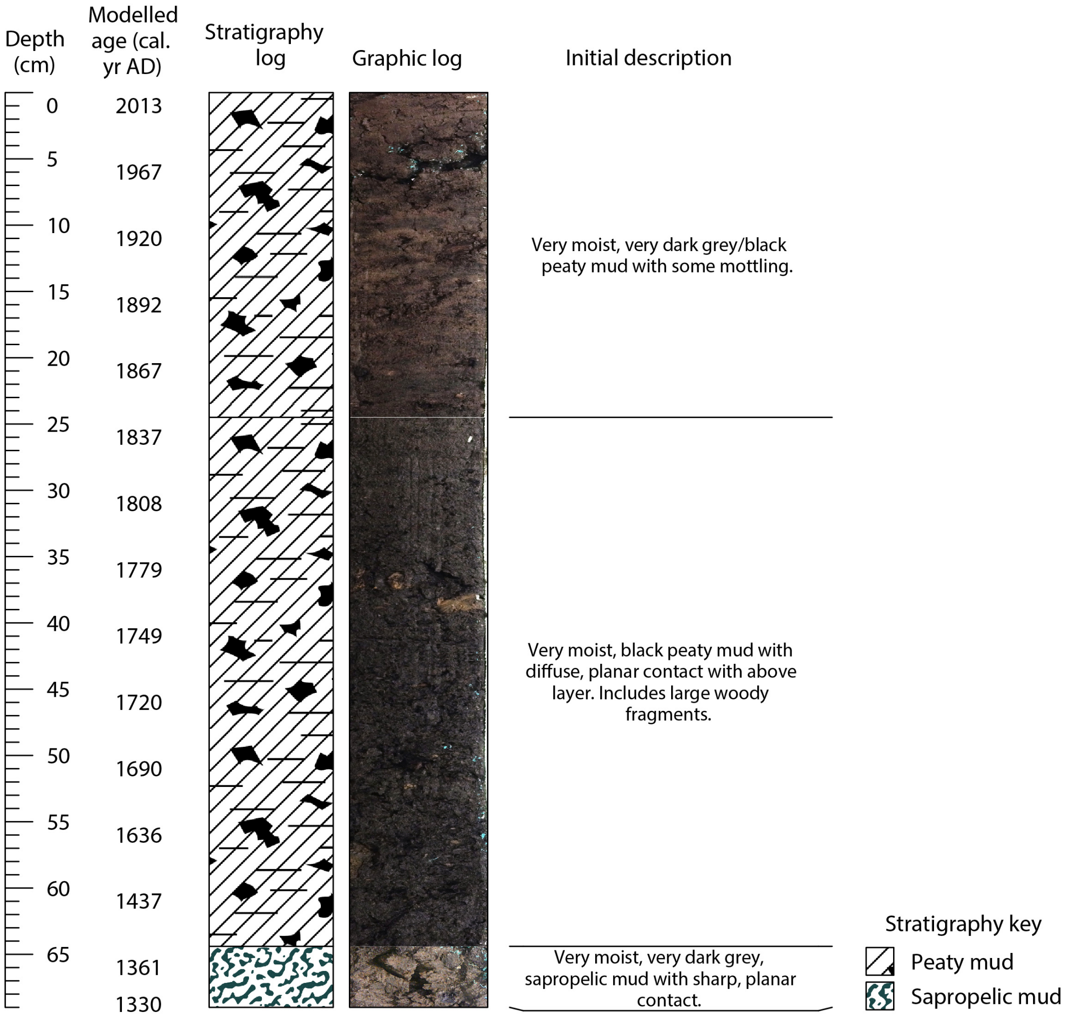

FIGURE 6.7: Photograph and stratigraphic descriptions for core KKPC2.

6.4.2 Accumulation rates, magnetic susceptibility, organic and moisture content

Core PKKS-C1 (Preah Khan of Kompong Svay)

Figure 6.8 presents the calculated accumulation rates (bulk sediment and mineral sediment only), the magnetic susceptibility data, and the summary metrics from mineral particle size analysis, plotted against depth in core and the modelled ages. Figure 6.9 further presents the initial magnetic susceptibility readings taken in the field (see section 5.2 in the Methods and Materials chapter). A double peak in magnetic susceptibility recurred in multiple cores and potentially indicates an erosion event in the catchment that was captured similarly across the basin, suggesting that deposition is relatively uniform.

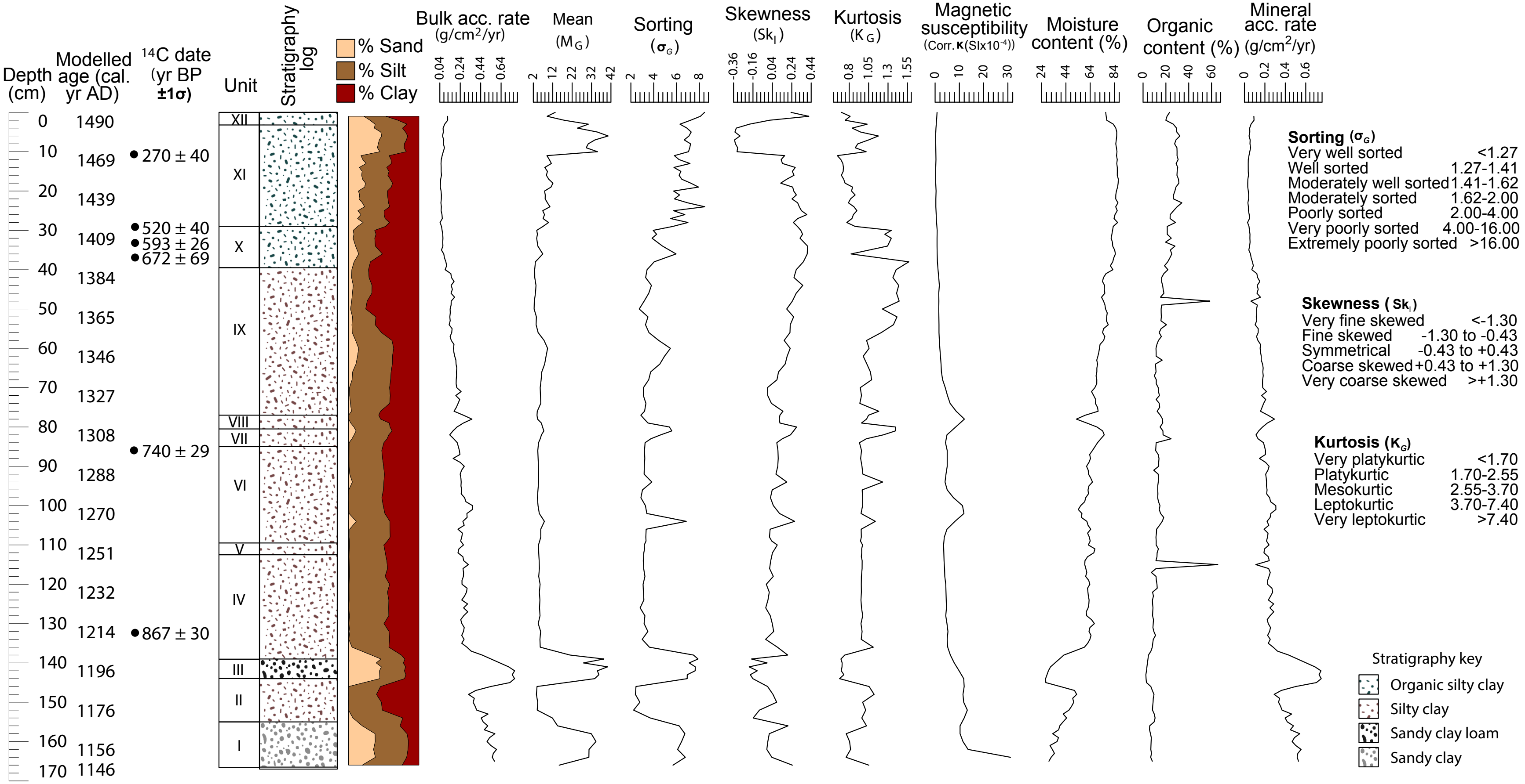

FIGURE 6.8: Log core and sedimentary data for core PKKS-C1.

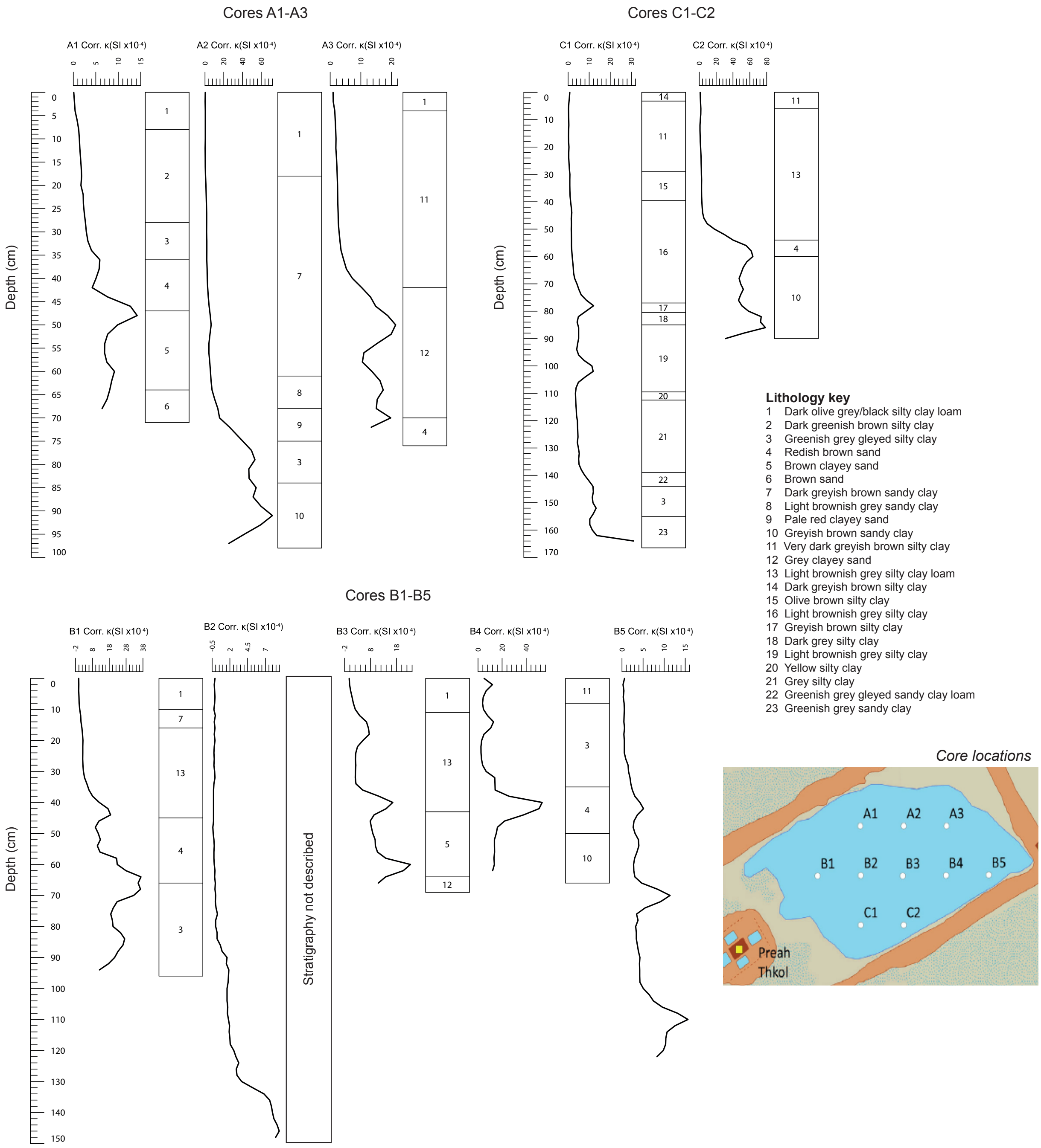

FIGURE 6.9: Core correlation for cores retrieved at PKKS. Stratigraphy and magnetic susceptibility readings are shown.

Bulk accumulation rates and mineral accumulation rates are variable (mean = 0.24 0.16 g cm^{-2} yr^{-1} and 0.21 ± 0.156 g cm^{-2} yr^{-1} (1σ), respectively) throughout the core, and following initial high rates in Units I (mean = 0.54 ± 0.04 g cm^{-2} yr^{-1} and 0.50 ± 0.04 g cm^{-2} yr^{-1} respectively) and III (mean = 0.75 ± 0.02 g cm^{-2} yr^{-1} and 0.72 ± 0.02 g cm^{-2} yr^{-1} respectively), rates decline fairly steadily throughout the remainder of the core. Accumulation rates stabilize at their lowest levels for the top 36 cm of the record (mean = 0.06 ± 0.017 g cm^{-2} yr^{-1} and 0.05 ± 0.014 g cm^{-2} yr^{-1} respectively). Bulk and mineral accumulation rates show a strong positive relationship (r = 0.994) throughout the entire core.

The magnetic susceptibility record follows a similar trend to the bulk and mineral accumulation rates, declining in general from the base of the core upwards. Levels are high and variable in the bottom 24 cm of the core (mean = 13.25 ± 5.48 x 10^{-4} SI), compared to the whole core (mean = 4.85 ± 4.83 x 10^{-4} SI). Other small peaks in magnetic susceptibility occur at 104-98 cm (mean = 9.74 ± 1.87 x 10^{-4} SI) and 80-76 cm (mean = 9.75 ± 1.65 x 10^{-4} SI), in conjunction with the input of terrigenous material derived from the surrounding catchment – shown by concurrent peaks in bulk and mineral accumulation rates. Otherwise, over the whole core, magnetic susceptibility is moderately correlated with mineral accumulation rates (r = 0.777).

While overall organic and moisture content generally increase throughout the core, they are otherwise only moderately correlated in this record (r = 0.692). Over the whole core, organic and moisture content levels are on average 16 ± 9.1% and 66.3 ± 15.5% respectively, and are highest in Units XI and XII (mean = 28.1 ± 3.2% and 84.9 ± 2.8% respectively). Sharp peaks in organic content are evident in Units IV and IX, at 115 cm (65.5%) and 48 cm (58.5%).

Core PTC3 (Koh Ker)

Figure 6.10 presents the physico-chemical parameters analysed for core PTC3. Bulk and mineral accumulation rates are strongly correlated throughout this record (r = 0.993). Highest bulk accumulation rates occur at 228-210 cm (mean = 0.04 ± 0.016 g cm^{-2} yr^{-1}) and rates remain relatively high between 198-190 cm (mean = 0.03 ± 0.004 g cm^{-2} yr^{-1}) and between 174-134 cm (0.039 ± 0.009 g cm^{-2} yr^{-1}), compared to the overall mean of 0.029 ± 0.015 g cm^{-2} yr^{-1} for the record. Lowest and least variable rates are evident through the top 18 cm of the core (mean = 0.011 ± 0.001 g cm^{-2} yr^{-1}).

Magnetic susceptibility shows the greatest variation between 228-188 cm (σ = 0.374 SI x 10^{-4} compared to 0.111 SI x 10^{-4} for the remainder of the core) and overall appears to be weakly correlated with mineral accumulation rates (r = 0.447). Two strong peaks occur towards the base of the core, at 226 cm (1.226 SI x 10^{-4}) and 222 cm (2.474 SI x 10^{-4}), compared to the overall mean of 0.358 ± 0.258 SI x 10^{-4}. Separate magnetic susceptibility readings including errors (1σ) are provided in Appendix C.

Average organic and moisture content for the whole core is 38.6 ± 13.8% and 86.4 ± 4.8% respectively. These two parameters are strongly positively correlated throughout the core (r = 0.870), with highest and least variable levels of both organic (mean = 62.3 ± 1.9%) and moisture content (mean = 91.8 ± 0.9%) occurring in the top 18 cm (concurrent with lowest bulk and mineral accumulation rates). Peaks in organic and moisture content also occur at 206-200 cm (mean = 46.9 ± 4.6% and 89.8 ± 0.8% respectively) and 184-182 cm (mean = 53.2 ± 0.4% and 92.3 ± 0.1% respectively). Overall, there is a strong inverse relationship between organic content and bulk accumulation rates (r = -0.828).

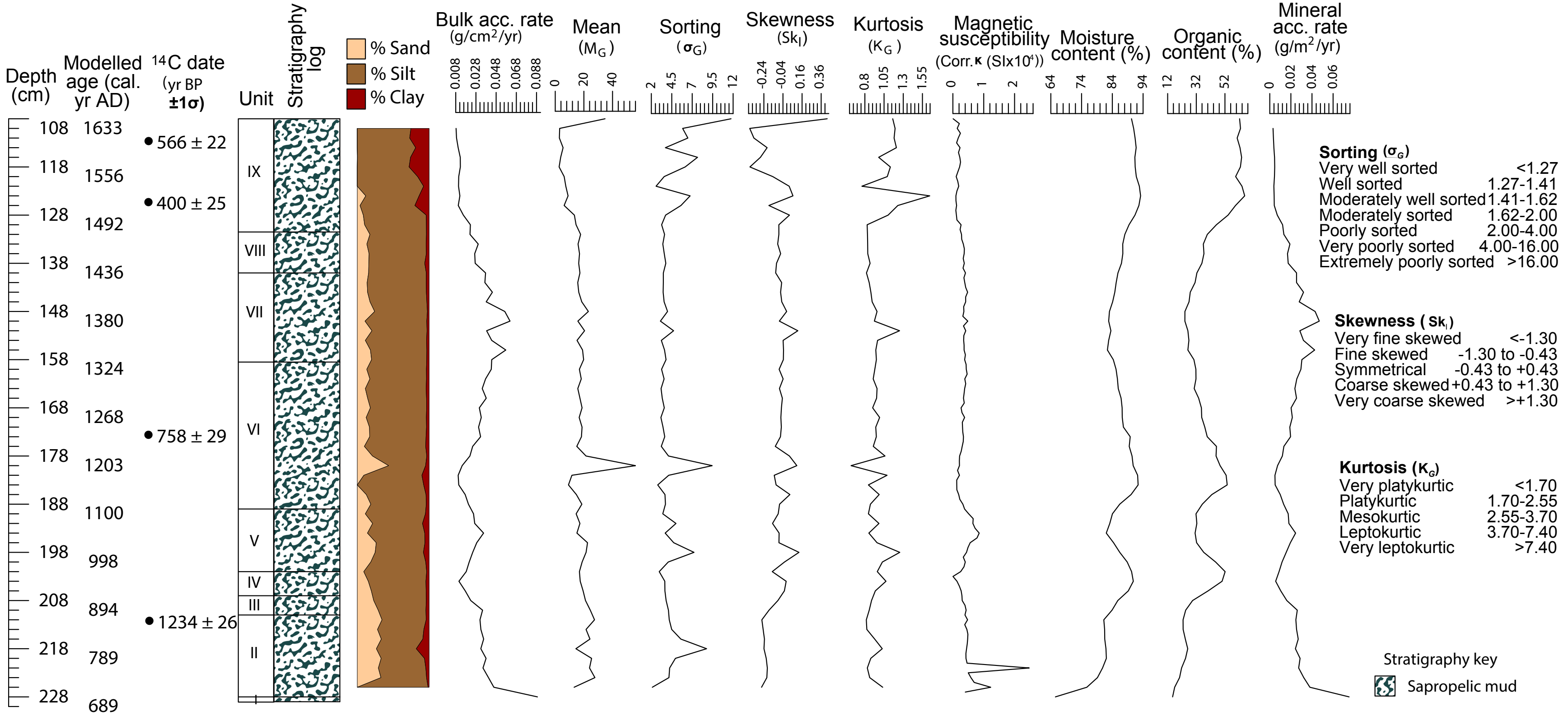

FIGURE 6.10: Log core and sedimentary data for core PTC3.

Core KKPC2 (Koh Ker)

Bulk accumulation rates (mean = 0.038 ± 0.016 g cm^{-2} yr^{-1}), while decreasing initially across the boundary of Units I and II, generally increase throughout Units II and into III, before a decrease and relative stabilization occurs during the top 10cm of the core (σ = 0.005 g cm^{-2} yr^{-1}) (Fig. 6.11). Lowest bulk accumulation rates occur at 60-56 cm (mean = 0.005 ± 0.001 g cm^{-2} yr^{-1}) and highest rates occur at 16-12 cm (mean = 0.066 ± 0.001 g cm^{-2} yr^{-1}). Mineral and bulk accumulation rates appear moderately positively related in core KKPC2 (r = 0.839).

Magnetic susceptibility readings are low and variable throughout the core (mean = 0.000017 ± 0.000024 SI x 10^{-4}), however variability declines for the top 20 cm of core (σ = 0.000017 SI x 10^{-4}). Magnetic susceptibility shows no clear trend or relationship with any other variable. Separate magnetic susceptibility readings including errors (1σ) are provided in Appendix C.

KKPC2 is a highly organic core. On average for the whole core, organic and moisture content is 48.9 ± 14.6% and 76.3 ± 6.1% respectively. There appears to be a clear inverse relationship between organic and moisture content in this core (r = -0.864), which is unusual and may reflect differential drying between the very organic layers containing greater pore-water space, and the higher siliciclastic layers containing tighter pore-water spaces. After initial high (highest in the record) organic (75.9%) and low (lowest in the record) moisture (62.9%) content in Unit I, organic content steadily increases throughout Units II and III, while moisture content decreases, before the highest organic levels (for Units II and III) and lowest moisture levels (for Units II and III) are reached at the top of the core, and remain fairly constant between 8-0 cm (organic content mean = 63.8 ± 1.6%, moisture content mean = 67.2 ± 0.8%). Organic content also appears to be moderately positively related to bulk accumulation rates (r = 0.740).

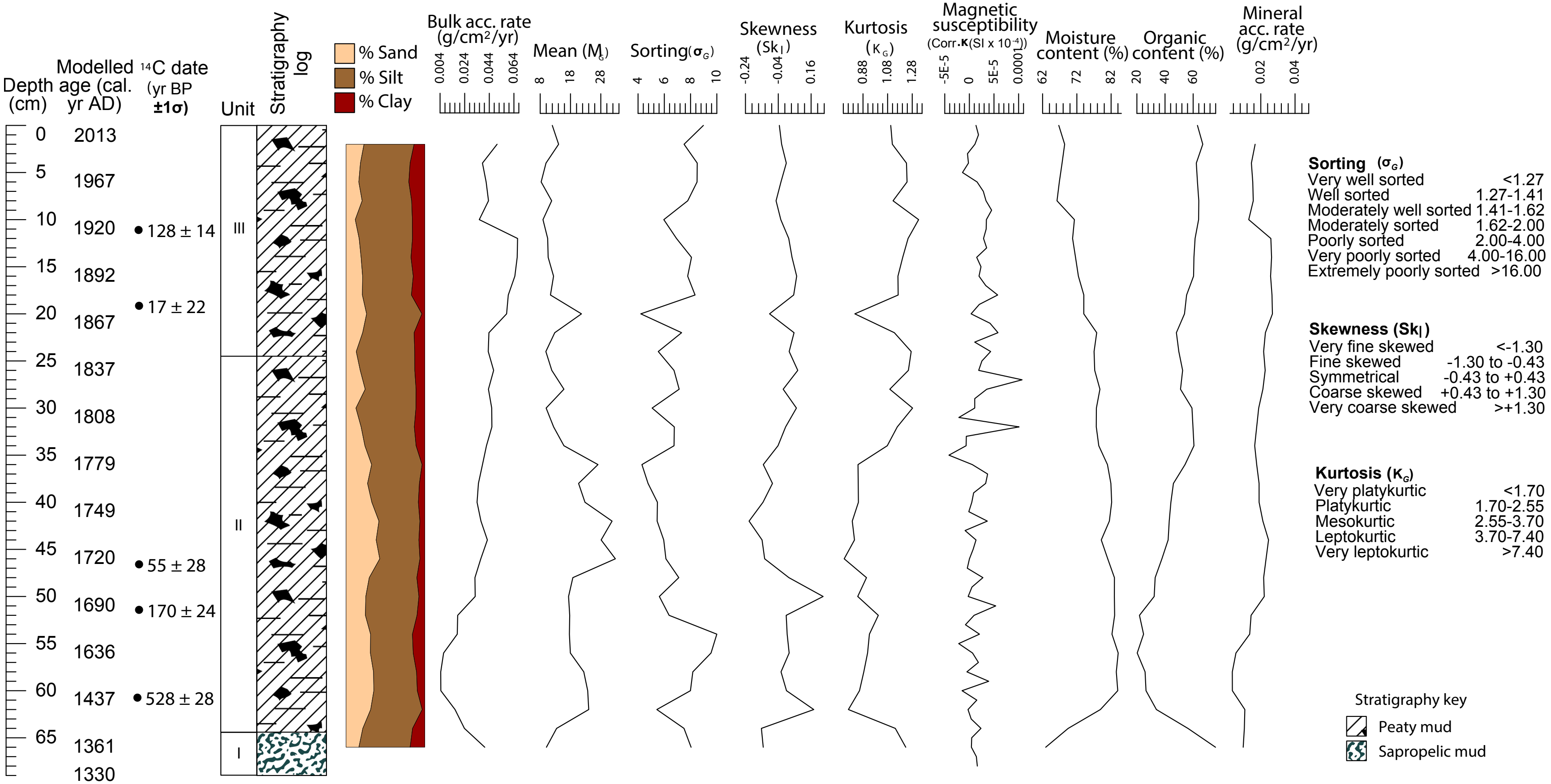

FIGURE 6.11: Log core and sedimentary data for core KKPC2.

6.4.3 Particle size analysis

Core PKKS-C1 (Koh Ker)

Mean particle size is variable throughout the core (mean = 23.15 ± 12.94 μm), however this large variation is effected by three distinct peaks in Unit I between 164-158 cm (mean = 31.87 ± 1.47 μm), Unit III between 144-138 cm (mean = 33.12 ± 6.16 μm) and at the top of Unit XI between 10-3 cm (mean = 32.39 ± 4.45 μm), reflecting the proportionately greater input of sand at these layers (ranging between 32-47%) (Fig. 6.8). Mean particle size remains relatively constant throughout Units IV-X (mean = 5.08 ± 1.43 μm), where the percentage of sand-sized particles is low (mean = 4.2 ± 3.95%). Mean particle size begins to increase from 68 cm prior to the peak towards the top of the core.

The relative proportions of clay, silt and sand appear to influence the degree of sorting, skewness and kurtosis in the particle size data. There appears to be a strong positive relationship between higher proportions of sand and the degree of sorting (r = 0.884). Skewness shows a weak to moderate negative relationship (r = -0.428) with sand proportions, while kurtosis shows a moderate positive correlation (r = 0.592) with clay proportions. Overall, deposits containing greater proportions of fine silt and clays are very poorly sorted, and display coarsely skewed and leptokurtic to platykurtic distributions. In sections where coarse silt and sand proportions are relatively high, particle size distributions tend to be more finely skewed and platykurtic to mesokurtic.

Core PTC3 (Koh Ker)

Core PTC3 (Fig. 6.10) is dominated by silt-sized particles (on average, 76.8 ± 9.1% silt). Mean particle size, as a result remains generally within the clay and coarse silt-sized size fractions (mean = 17.2 ± 8.1 μm). A distinct peak in mean particle size occurs at 180 cm (56 μm), in conjunction with a peak in the relative proportion of sand (43.6%) being deposited in the basin. On average, sand proportions are low and variable (15.9 ± 9.9%) and generally decrease upward throughout the core, with sand being almost absent from the top 14 cm of the core (excepting the very top sample at 108 cm) (mean = 0.04 ± 0.1%). In general, sand proportions appear to be weakly positively related to magnetic susceptibility (r = 0.269) and maintain an inverse relationship with organic (r = -0.593) and moisture (r = -0.510) content.

In general, mean particle size appears to influence the degree of sorting, skewness and kurtosis. Throughout the whole core, there is a weak positive relationship between mean particle size and sorting (r = 0.297), a weak to moderate positive correlation between mean particle size and skewness (r = 0.457), and a weak to moderate inverse correlation between mean particle size and kurtosis (r = -0.435). Overall, these silt-rich deposits tend to be poorly to very poorly sorted, with fine skewed to symmetrical and mesokurtic to platykurtic distribution curves. Distribution curves become more leptokurtic as the relative proportion of clay increases.

Core KKPC2 (Koh Ker)

Figure 6.11 illustrates how mean particle size is dominated by silt-size particles and is moderately variable throughout the core (mean = 16.7 ± 6.6 μm). Highest mean particle sizes are evident in sections where the relative proportion of sand increases, particularly at 46-36 cm (mean = 27.2 ± 4.4 μm, mean sand proportion = 35.9 ± 5.5%). In general, relative proportions of sand (mean = 24.8 ± 8%), silt (mean = 63.1 ± 6.1%) and clay (mean = 12.1 ± 4.6%) remain fairly consistent, with the proportion of sand decreasing slightly upwards through the core.

Few strong correlations exit between the grain size parameters in this core. The relationship between mean particle size and kurtosis, however, is strongly inversely correlated (r = -0.927). Overall, the deposits in Units II and II are generally very poorly sorted, and display symmetrical and platykurtic to leptokurtic distribution curves. Unit I is similarly very poorly sorted, however displays more skewed and leptokurtic particle size distribution curves.

6.5 Charcoal

In this analysis, the long-term mean value is considered a sufficient representation of the background fire regime (see section 5.6 in the Methods and Materials chapter). All ages are weighted-mean ages derived from the age-depth model. For all three size classes, charcoal counts and their errors are displayed against calculated influx values and deviations from long-term mean values.

6.5.1 Core PKKS-C1 (Preah Khan of Kompong Svay)

Stratigraphically constrained cluster analysis (see Appendix B) identified four distinct zones in the charcoal data for core C1 (Fig. 6.12). Zone 1 extends from 166-133 cm and contains minimal charcoal (consistently below average) levels across all three size classes. Zone 2 extends from 133-93 cm and contains small peaks in both macrocharcoal size fractions, particularly from 132-125 cm and 106-103 cm. These small peaks generally remain below the average for the record, and likely represent only low intensity fire activity. Microcharcoal levels increase marginally, but generally remain below average through this zone. Zone 3 extends from 93-37 cm and contains marked peaks (consistently above average levels) in both marcocharcoal size fractions, in particular between 53-37 cm, showing sustained fire activity in the local catchment at this time. Microcharcoal levels fluctuate throughout this zone, however are also generally above average, particularly in the earlier stages of this zone prior to the pronounced increase in macrocharcoal levels. Finally, Zone 4 extends from 37-0 cm and includes only below average levels of the 106-250 μm macrocharcoal size fraction and generally above average microcharcoal levels. Trends in macrocharcoal and microcharcoal influx appear weakly positively correlated (r = 0.236), and where simultaneous peaks in all size fractions occur, this suggests that both local and regional fire activity may be a response to broader-scale climate forcing.

6.5.2 Core PTC3 (Koh Ker)

Stratigraphically constrained cluster analysis (see Appendix B) identified three distinct zones in the charcoal data for core PTC3 (Fig. 6.13). Zone 1 extends from 228-178 cm and contains the lowest macrocharcoal levels in the record (consistently below average), with the exception of a small peak in both size fractions at 228-222 cm. Microcharcoal levels are similarly below average throughout this zone. Zone 2 extends from 178-130 cm and shows an increase in local fire activity, evidenced by several sustained peaks of above average macrocharcoal levels, in particular at 172 cm and between 142-134 cm. Microcharcoal levels are consistently above average throughout this zone, with marked increases occurring in conjunction with peaks in the macrocharcoal record. Zone 3 extends from 130-108 cm and contains the highest levels of both macrocharcoal fractions, indicating high and sustained levels of local fire activity during

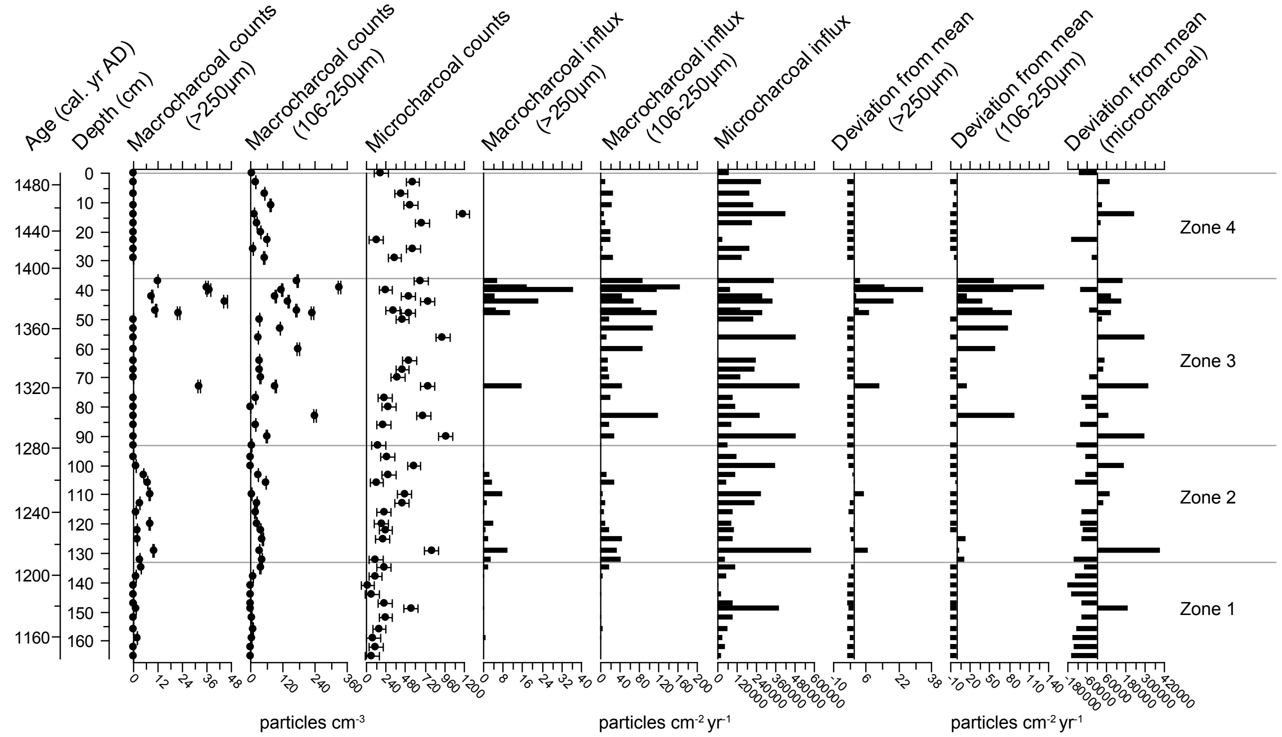

FIGURE 6.12: Charcoal data for core PKKS-C1, divided into stratigraphically constrained cluster zones. Includes raw counts, calculated influx values and deviations from the long-term mean.

this period. Inversely, microcharcoal levels are the lowest in the record through this zone, consistently falling well below average.

6.5.3 Core KKPC2 (Koh Ker)

Overall, very limited amounts of charcoal were found in core KKPC2. Stratigraphically constrained cluster analysis (see Appendix B) identified three distinct zones in this limited charcoal data (Fig. 6.14). Zone 1 extends from 67-33 cm and contains very minimal evidence for fire activity. Charcoal levels are consistently below average for all size fractions, with the exception of 67 cm in the micrcocharcoal size class, and 35 cm in both macrocharcoal size classes, where isolated peaks occur. Zone 2 extends from 33-21 cm and contains a slight increase in the < 250 μm macrocharcoal size fraction, which is not, however, reflected in the 106-250 μm size fraction. Microcharcoal levels in this zone also show a slight, but sustained increase. Zone 3 extends from 21-0 cm. Highest levels of microcharcoal occur in this final zone, however macrocharcoal levels are consistently below average.

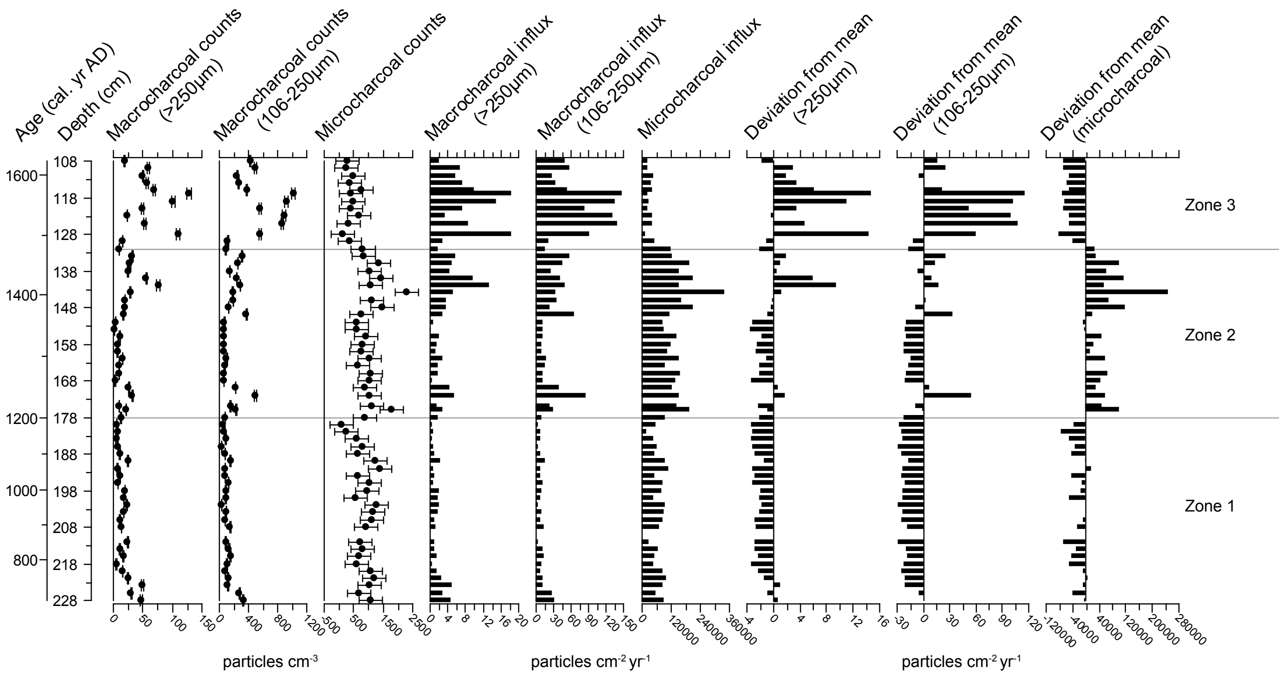

FIGURE 6.13: Charcoal data for core PTC3, divided into stratigraphically constrained cluster zones. Includes raw counts, calculated influx values and deviations from the long-term mean.

6.6 Plant microfossil

6.6.1 Core PKKS-C1 (Preah Khan of Kompong Svay)

Ninety pollen and spore types were identified from 21 samples between 0 and 156 cm of core PKKS-C1. Highest concentrations of plant microfossils were encountered where estimated bulk accumulation levels were lowest. However, in general, microfossil abundances were very low and variable throughout the core, and often up to 5 pollen slides had to be counted in order to reach sufficient counts. Total plant microfossils counted per depth ranged from 288 to 731, with an average of 375. Stratigraphically constrained cluster analysis (see Appendix B) of pollen and pore assemblages identified three major zones, indicating three successive vegetation phases. Zone 1 extends from 156-86 cm, Zone 2 from 86-37 cm and Zone 3 from 37-0 cm. Very limited plant microfossils were found between 152 and 132 cm, coincident with a peak in bulk accumulation rates (at 146-138 cm). High proportions of sand (33-46% compared to an average of 13.8% for the whole core) occur at these depths. Note: 'cf.' and 'sf.' refer to 'comparable form' and 'similar form' pollen morphology to the genus/species identified (see section **??** for more details).

Zone 1 is dominated by *Elaeocarpus/Tetremeles*, *Macaranga/Mallotus*, *Ficus*, *Pinus* and *Celtis* cf. in the arboreal pollen sum (Fig. 6.15) and Poaceae and Cyperaceae in the herbaceous pollen sum (Fig. 6.16). The relative abundances of Cyperaceae and Chenopodiaceae/Amarantheacae reach their highest levels in the record, while Poaceae is at its lowest. *Aglaia*, Anacardiaceae, *Cephalanthus* cf., *Dipterocarpus*, *Hopea/Shorea*, *Ficus*, *Lithocarpus/Castanopsis*, and *Trema* are at their most well-represented. *Schleichera oleosa* is almost absent from the arboreal assemblage. Fern spores

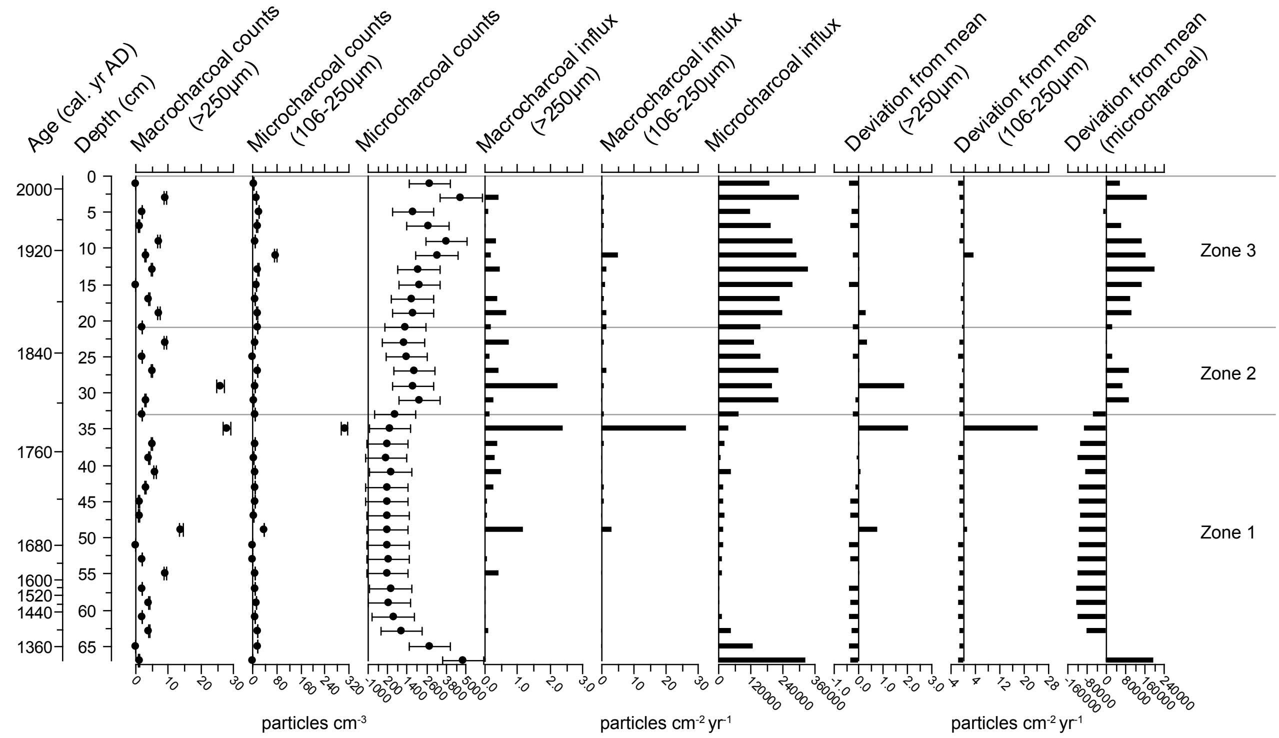

FIGURE 6.14: Charcoal data for core KKPC2, divided into stratigraphically constrained cluster zones. Includes raw counts, calculated influx values and deviations from the long-term mean.

are frequently represented, while the herbs Asteraceae (with fenestrate/lophate pollen morphology), *Brassica* cf., *Colocasia* sf. and *Justica* occur solely in this zone.

Combretaceae/Melastomaceae, *Betula* cf., *Macaranga/Mallotus*, and *Myrica* increasingly dominate the arboreal assemblage in Zone 2. *Pinus* remains well represented. Peaks in *Adina/Nauclea* cf., *Altingia*, *Engelhardtia* and declines in *Trema*, *Celtis* cf., *Elaeocarpus/Tetremeles*, *Ficus*, and *Hopea/Shorea* occur. *Pandanus* and Rhizophoraceae are frequently represented in this zone, while the relative abundance of *Schleichera oleosa* increases substantially (from 0-16.5% of the arboreal pollen sum). Poaceae increasingly dominates the herbaceous pollen assemblage and Cyperaceae begins to decrease. Ferns are poorly represented, except for a small peak in *Pteridium* spores at the beginning of this zone, however other aquatic taxa occur frequently, such as *Nymphoides* and *Persicaria*. In particular, a distinct peak in *Nelumbo nucifera* occurs toward the end of this zone (from 47-37 cm).

A marked shift in the arboreal assemblage occurs in Zone 3. Taxa that had been poorly represented in previous zones, such as *Eugenia* and *Schleichera oleosa*, now dominate the pollen sum. *Uncaria/Wendlandia* cf., Myrtaceae, and *Elaeocarpus/Tetremeles* are also well represented. Decreases in the relative abundance of Urticaceae/Moraceae (both types), *Quercus* cf., *Trema*, *Lagerstroemia*, *Lithocarpus/Castanopsis*, *Hopea/Shorea*, *Altingia* and Euphorbiaceae occur, and *Pandanus*, Rhizophoraceae, *Podocarpus/Dacrydium*, *Ficus*, *Celtis* cf. and *Aglaia* are absent, or almost absent. Of the herbaceous taxa, while Poaceae remains prevalent, Cyperaceae declines to its lowest levels in the record. Ferns increase, however most dryland and wetland herbs are very poorly represented, excepting for isolated peaks in Asteraceae (echinate) and *Rotala* at 7cm, and Labiatae at 17cm. After substantial declines in the previous zone, Chenopodiaceae/Amaranthaceae is absent for much of Zone 3.

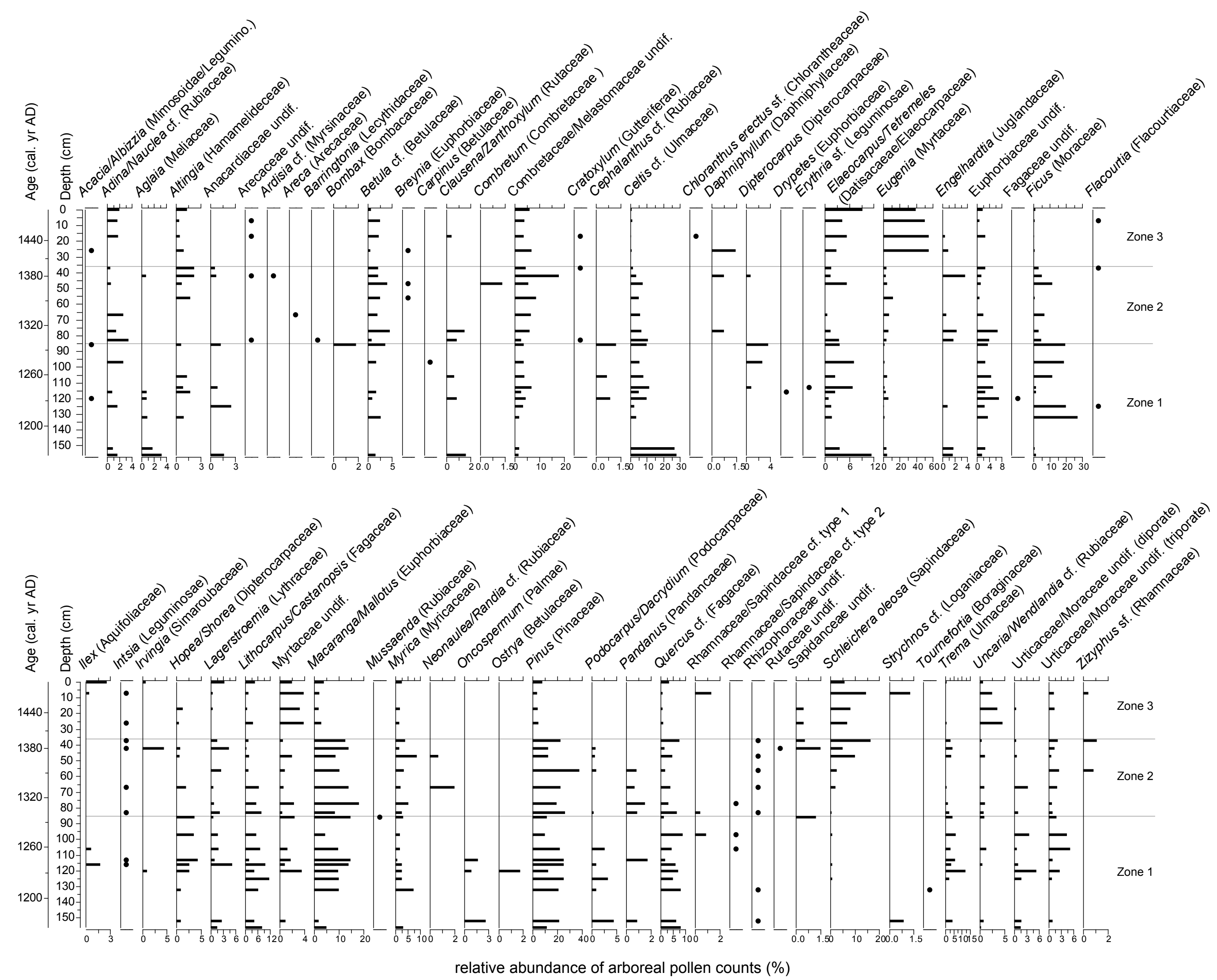

FIGURE 6.15: Relative abundances of pollen taxa observed in PKKS-C1. Includes only trees and woody shrubs.

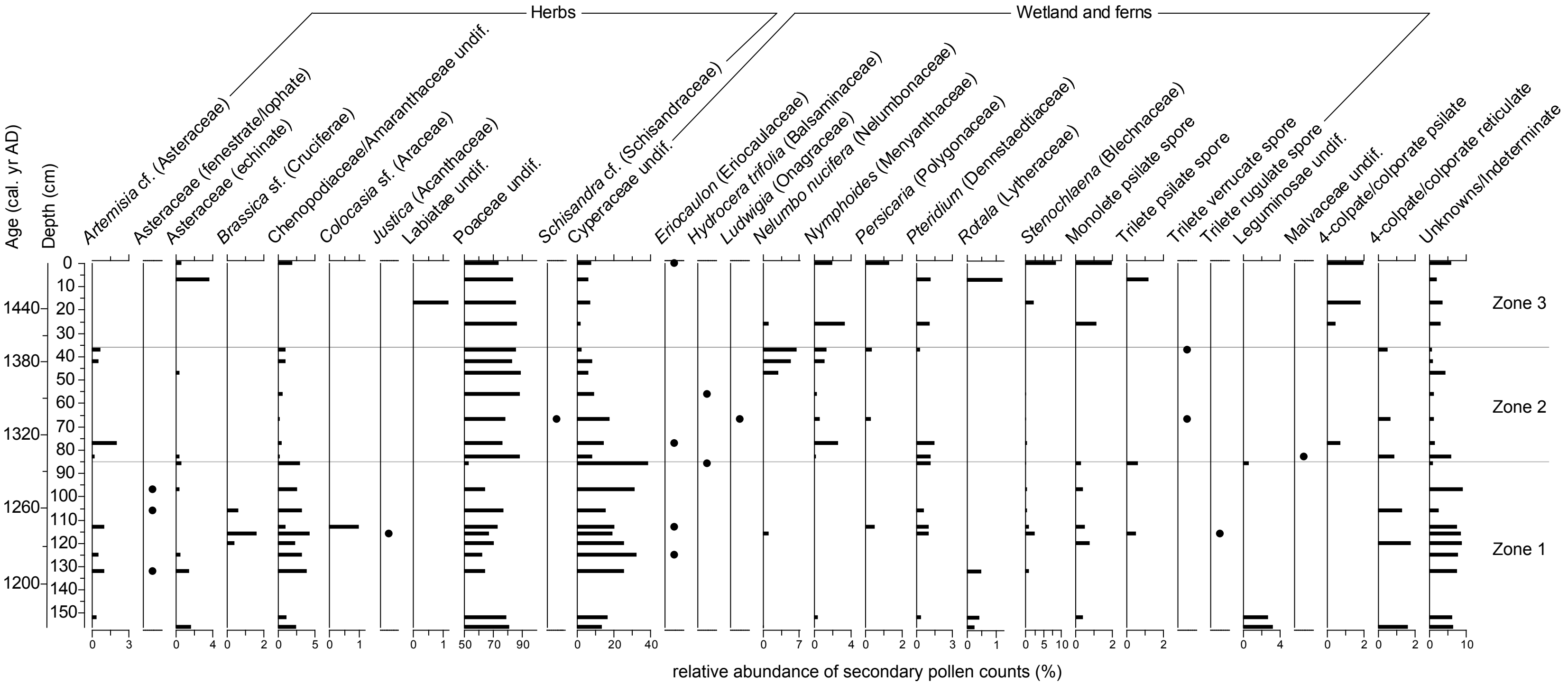

FIGURE 6.16: Relative abundances of pollen taxa observed in PKKS-C1. Includes only herbaceous plant types, as well as those unclassified into plant type groups.

6.6.2 Core PTC3 (Koh Ker)

Eighty pollen and spore types were identified from 17 samples between 108 and 228 cm of core PTC3. Total plant microfossil counts per depth ranged between 299 and 361, with an average of 322. Microfossil concentrations were, in general, very low, and often up to 4 pollen slides had to be counted in order to reach sufficient counts. Stratigraphically constrained cluster analysis defined three successive vegetation zones (see Appenidx B). Zone 1 extends from 689 to 998 AD (228-198 cm), Zone 2 from 998 to 1380 AD (198-148 cm), and Zone 3 from 1380 to 1633 AD (148-108 cm).

Adina/Nauclea cf. and Urticaceae/Moraceae (diporate) dominate the arboreal assemblage of Zone 1 (Fig. 6.17). *Trema*, *Pinus*, *Quercus* cf., *Myrica*, *Hopea/Shorea*, *Lagestroemia*, *Lithocarpus/ Castanopsis*, *Ficus*, *Celtis* cf. and *Betula* cf. are also abundant, while Rhamnaceae/Sapindaceae (types 1 and 2), *Pandanus*, *Eugenia*, *Diospyros* and *Acacia/Albizzia* occur infrequently or not at all. Poaceae and Cyperaceae are prevalent herbaceous taxa, however Asteraceae (both types), Chenopodiaceae/Amarantheaceae and *Costus speciosus* are also relatively abundant in Zone 1 (Fig. 6.18). Ferns and aquatic taxa are very infrequent.

Zone 2 includes high relative abundances of Euphorbiaceae (in particular *Macaranga/Mallotus*) and *Uncaria/Wendlandia* cf. *Lithocarpus/Castanopsis*, Arecaceae, *Pinus*, *Elaeocarpus/Tetremeles*, *Trema* and *Lagerstroemia* remain frequent. Declines in *Adina/Nauclea* cf., *Celtis* cf., *Betula* cf., *Quercus* cf. and *Clausena/Zanthoxylum* are evident, while *Acacia/Albizzia*, *Aglaia*, *Diospyros* and Rhamnaceae/Sapindaceae (both types) occur for the first time in the record. Dryland herb taxa, except for Caryophyllaceae and Chenopodiaceae/Amaranthaceae, decline in relative abundance. Poaceae also remains dominant. *Vitis* cf. appears in the record for the first time, and steadily increases throughout Zone 2. Slight declines in Cyperaceae occur, and *Costus speciosus* disappears from the record. Ferns and aquatic species remain very infrequent.

The flora assemblage changes substantially in Zone 3. *Eugenia* and *Schleichera oleosa* overwhelm the arboreal pollen assemblage and wetland taxa, in particular, Cyperaceae and ferns, dominate the herbaceous pollen sum. Of the arboreal taxa, declines are evident across the assemblage, excepting for Combretaceae/Melastomaceae, *Elaeocarpus/Tetremeles*, *Zizyphus* sf. and *Ficus*, which all remain relatively frequent. *Adina/Nauclea* cf. and *Uncaria/Wendlandia* cf. decline substantially or disappear entirely from the record. Of the dryland herbs/vines, only Chenopodiaceae/Amarantheaceae, *Vitis* cf., *Schisandra*, and Poaceae remain frequent, however a decline in the relative abundance of Poaceae does occur from 134 cm.

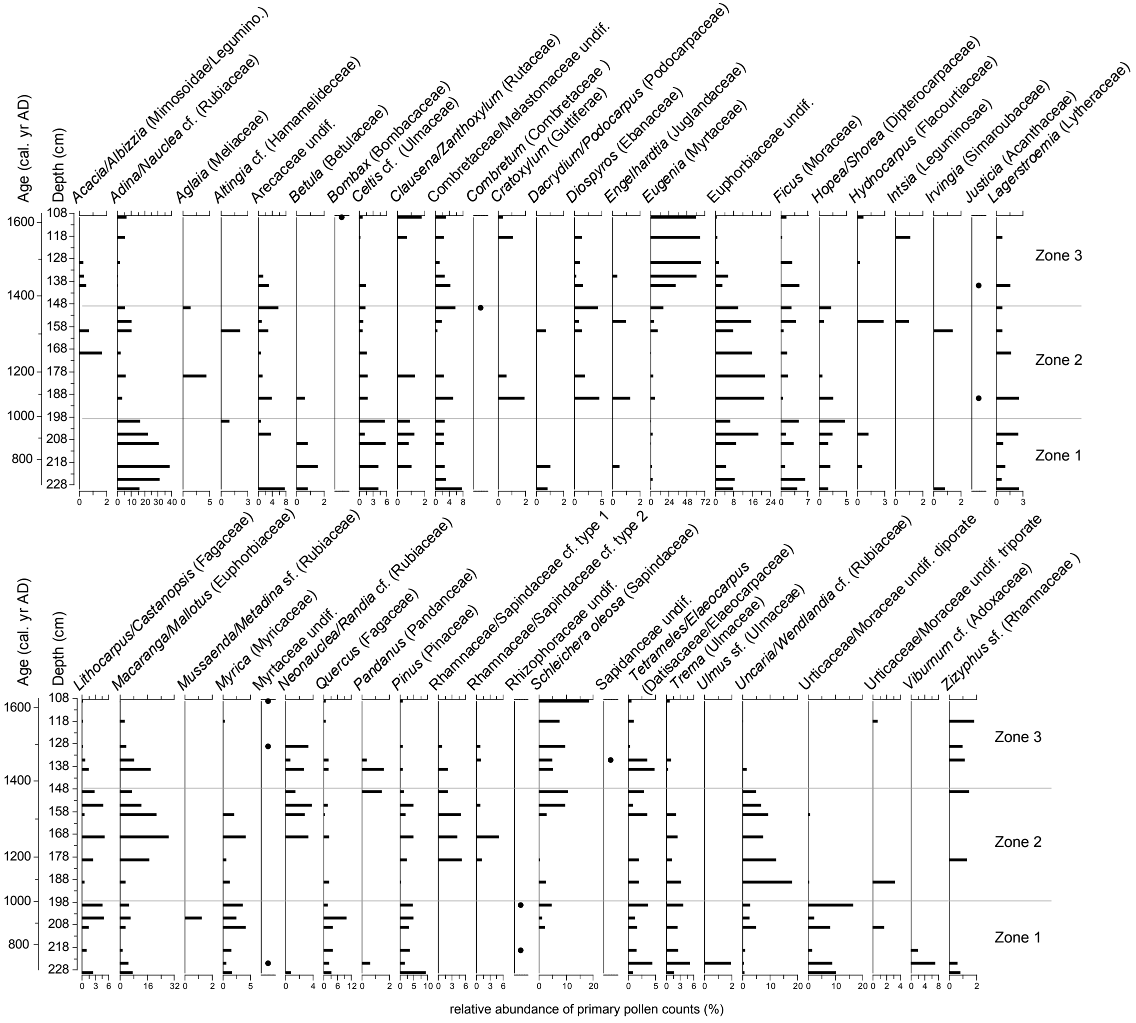

FIGURE 6.17: Relative abundances of pollen taxa observed in PTC3. Includes only trees and woody shrubs.

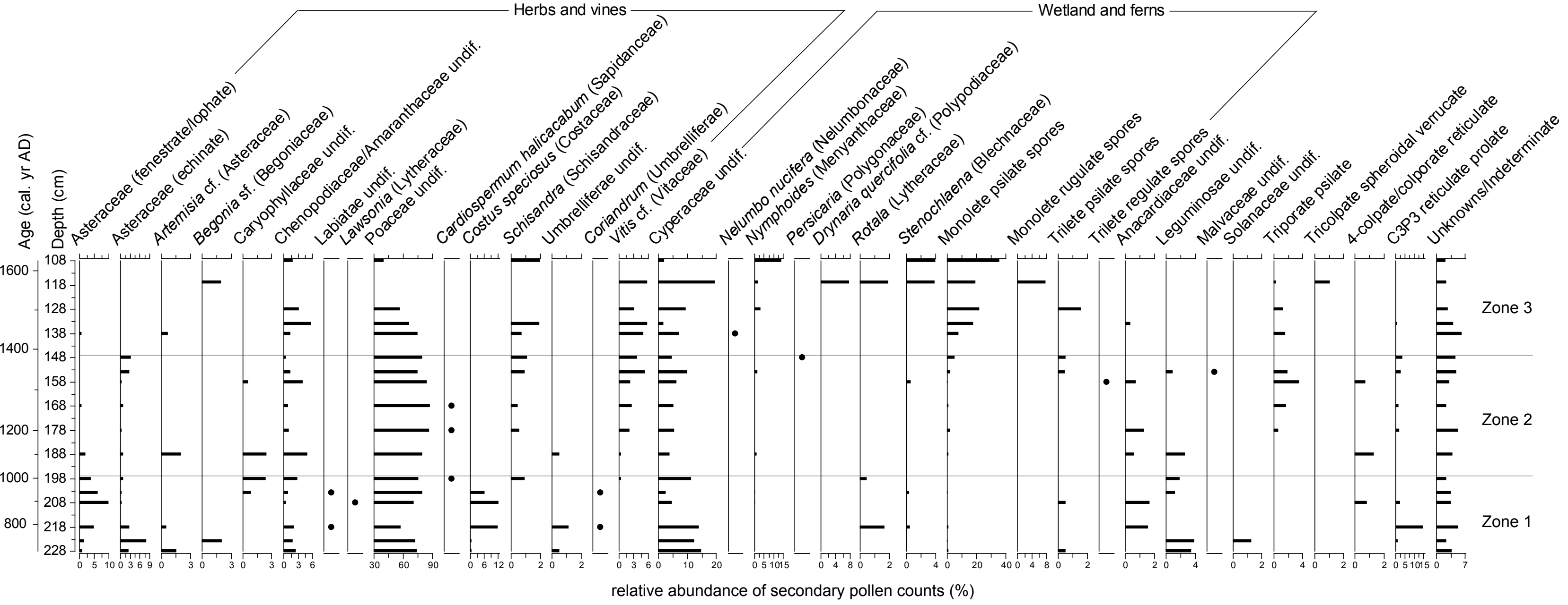

FIGURE 6.18: Relative abundances of pollen taxa observed in PTC3. Includes only herbaceous plant types, as well as those unclassified into plant type groups.

6.6.3 Core KKPC2 (Koh Ker)

Sixty-five pollen and spore types were identified from 12 samples between 1 and 67 cm of core KKPC2. Total plant microfossils counted per depth ranged from 306 to 687, with an average of 417. Stratigraphically constrained cluster analysis delineated three zones representing successive ecological shifts in the record. Zone 1 is relatively narrow and extends from 1576 to 1587 AD (67-65 cm), Zone 2 from 1587 to 1738 AD (65-41 cm), and Zone 3 from 1738 to 1930 AD (41-1 cm).

Zone 1 is relatively diverse, with *Adina/Nauclea* cf., Arecaceae, *Celtis* cf., Euphorbiaceae, Combretaceae/Melastomaceae, *Hopea/Shorea*, *Irvingia*, *Macaranga/Mallotus*, *Myrica*, *Pinus*, *Quercus* cf., *Elaeocarpus/Tetremeles*, *Uncaria/Wendlandia* cf. and Urticaceae/Moraceae (diporate) all being well represented in the arboreal pollen sum, with Chenopodiaceae/Amarantheaceae, *Stenochlaena* and *Nephrolepis* cf. ferns, and particularly Poaceae, comprising the bulk of the herbaceous pollen assemblage.

A significant shift in vegetation occurs in Zone 2. *Ficus* is very strongly represented, and *Schleichera oleosa* and *Zizyphus* sf. are also a relatively abundant component of the arboreal pollen sum. Sharp declines occur in all other taxa, except for *Areca*, *Bombax*, *Cratoxylum*, *Delonix* cf. and *Pandanus*, which increase or appear in the record for the first time. Ferns remain strongly represented at the beginning of Zone 2, however declines are evident from 57 cm. A peak in *Rotala* occurs at 51 cm. *Nymphoides* is strongly represented, and Cyperaceae and Poaceae remain frequent throughout this zone.

The arboreal assemblage of Zone 3 is heavily dominated by *Eugenia* and *Ficus*, and *Pandanus*, *Adina/Naulcea* cf., *Schleichera oleosa* and Combretaceae/Melastomaceae are also abundant. *Elaeocarpus/Tetremeles* and *Lagerstroemia* also increase toward the end of this zone. All other arboreal taxa are poorly represented. Of the herbaceous taxa, Cyperaceae, Poaceae and the ferns dominate, and dryland herbs are generally poorly represented. A strong spike in Cyperaceae also occurs at the top of the core.

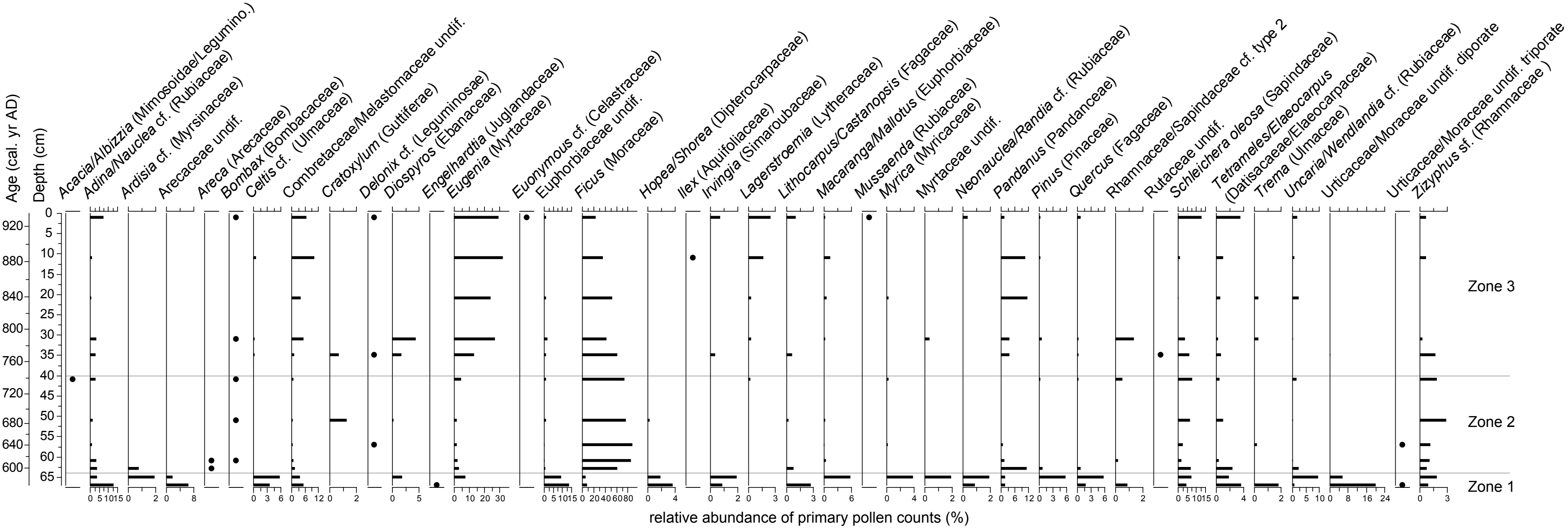

FIGURE 6.19: Relative abundances of pollen taxa observed in KKPC2. Includes only trees and woody shrubs.

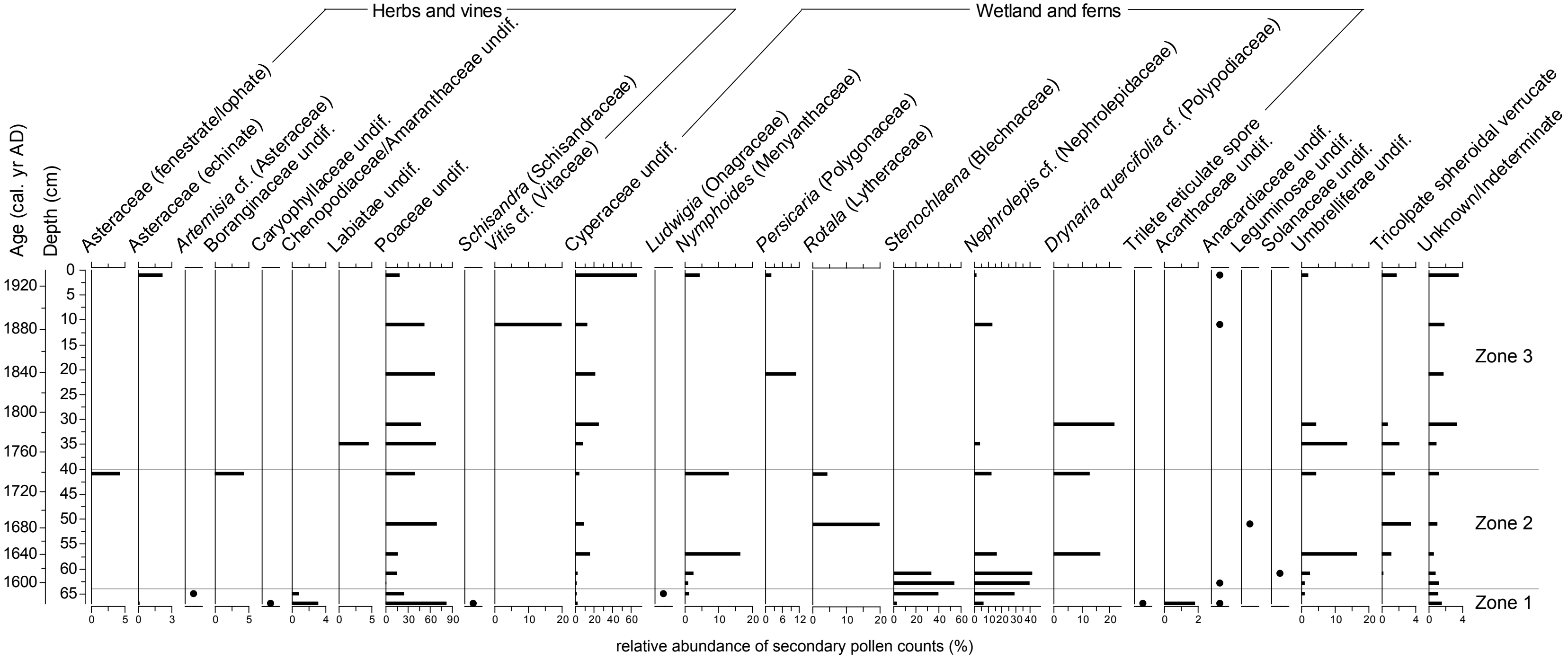

FIGURE 6.20: Relative abundances of pollen taxa observed in KKPC2. Includes only herbaceous plant types, as well as those unclassified into plant type groups.

7 Discussion: Occupation histories of two major secondary Angkor-period cities

7.1 Introduction

This chapter synthesizes and interprets the results described in Chapter 6 to reconstruct the occupation histories of Preah Khan of Kompong Svay (PKKS) and Koh Ker. This will be done in an effort to achieve the first main objective of this research; namely determining the response of secondary cities within the Khmer city network to disruption in the primate city, with a particular focus on the timing of these responses relative to the capital of Angkor.

The chapter will begin with a comparison of the charcoal record with relevant, extra-regional hydroclimate records, as well as archaeological records (where the data exists), in order to identify those episodes of fire activity captured in the sediment archives that are more likely associated with human presence in the landscape. Next, the pollen results (section 6.6) will be discussed through an analysis of changing vegetation assemblages – this time by grouping the pollen and spore specimens according to their associated vegetation groups (see section 5.7), looking in particular for evidence of declines in primary (or undisturbed) vegetation assemblages, the presence of or increase in secondary vegetation assemblages or vegetation commonly associated with anthropogenic/agricultural landscapes, and finally increases in vegetation assemblages that indicate land abandonment or declines in the intensity of anthropogenic land uses. Following this, changing levels of landscape disturbance will be further deciphered from each of the collated multi-proxy palaeoenvironmental records to determine the history of occupation and further evidence of significant transitions in land cover and use at each city site. Finally, focusing on specific elements of the pollen and spore record, namely those plant types and species that indicate the shift to post-disturbance or swamp forest in the sampling basin or surrounding catchment, the timing of city abandonment or near-abandonment will be identified and discussed.

Extra-regional climate, in this chapter, refers to the reconstructed hydroclimate records from localities influenced by similar climate systems to Cambodia, in particular the Indian Summer Monsoon (ISM) and East Asian Monsoon (EAM) (see section 4.4). Regional climate, however, specifically refers to the climate acting on the landscape in the within the broad region of the city site (i.e. central and north-central Cambodia), coinciding with the pollen and microcharcoal (particles < 106 m) catchment.

7.2 Disentangling the human and climate signals in the charcoal record

7.2.1 The correlation between microcharcoal and hydroclimate records

The microcharcoal record from PKKS indicates that the regional burning regime is relatively well correlated with extra-regional climate at this site (Fig. 7.1). While individual peaks in microcharcoal often do not correspond with distinct drought episodes, differences in chronological resolutions, as well as geographic disparity between these records, makes them difficult to correlate precisely. Microcharcoal influx between the mid-12th and late 14th century AD is highly variable, however, an overall trend from below to above average microcharcoal influx, during which time the δ^{18}O record from central-eastern India (Berkelhammer et al. 2010) indicates extra-regional climate was trending from wet to dry, in general, and suggests that an increasingly dry climate is driving fire activity in the regional landscape during this period. While the tree-ring record does not extend beyond the late 13th century, a leaf wax (δD_{wax}) hydroclimate record from northeast Thailand (Yamoah et al. 2017) confirms that the Southeast Asian mainland was experiencing a similar trend of high but decreasing rainfall extending from the 9th to the 13th century AD. Individual peaks in the microcharcoal record throughout the 15th century correlate well with drought episodes in the tree-ring (PDSI) hydroclimate record from the Vietnamese highlands (Buckley et al. 2010), further suggesting that a strong relationship exists between microcharcoal and extra-regional climate.

In the PTC3 record, the highest microcharcoal influx levels occur during the late 14th to mid-15th century, during a series of intense drought periods recorded in all extra-regional hydroclimate records (Berkelhammer et al. 2010, Buckley et al. 2010, Yamoah et al. 2017, Hua et al. in review). Otherwise, consistently below average microcharcoal influx coincides with relatively wetter periods in the extra-regional landscape. This microcharcoal record therefore further suggests that, in general, the microcharcoal and extra-regional hydroclimate records are relatively well coupled.

In the KKPC2 record, microcharcoal influx remains below average from the mid-14th century to the late 18th century, when the tree-ring (PDSI) hydroclimate record from the Vietnamese highlands (Buckley et al. 2010) indicates that the climate of the Southeast Asian mainland was relatively wet. While a series of incipient to moderate droughts occurred in the region, particularly throughout the early 18th century, this dryness is not apparent in the microcharcoal record. However, consistently above average levels of microcharcoal in KKPC2 occur from the beginning of the 19th century to the early 20th century, consistent with a wetter period in the PDSI record and a trend towards increasing summer monsoon intensity in the leaf wax (δD_{wax}) record from northeast Thailand (Yamoah et al. 2017), suggesting a more complex relationship between climate and microcharcoal exists at this site.

Overall, the microcharcoal record appears to correlate well with extra-regional climate records, and therefore is likely a good proxy for local climate against which to compare the remaining palaeoecological record, in particular the macrocharcoal and pollen record. Where microcharcoal influx deviates from the hydroclimate records, particularly at Koh Ker in the 19th and 20th centuries, this may reflect an increase in vegetative biomass availability in the regional landscape, aided by a relatively wet climate. The relative abundance of several arboreal dry forest taxa begin to increase from the early 20th century as well, and perhaps suggests a period of long-term reforestation. However, the increase in regional fire activity may also possibly represent an increase in anthropogenic activity in the broader region during this period, or a combination of both anthropogenic and ecological succession factors.

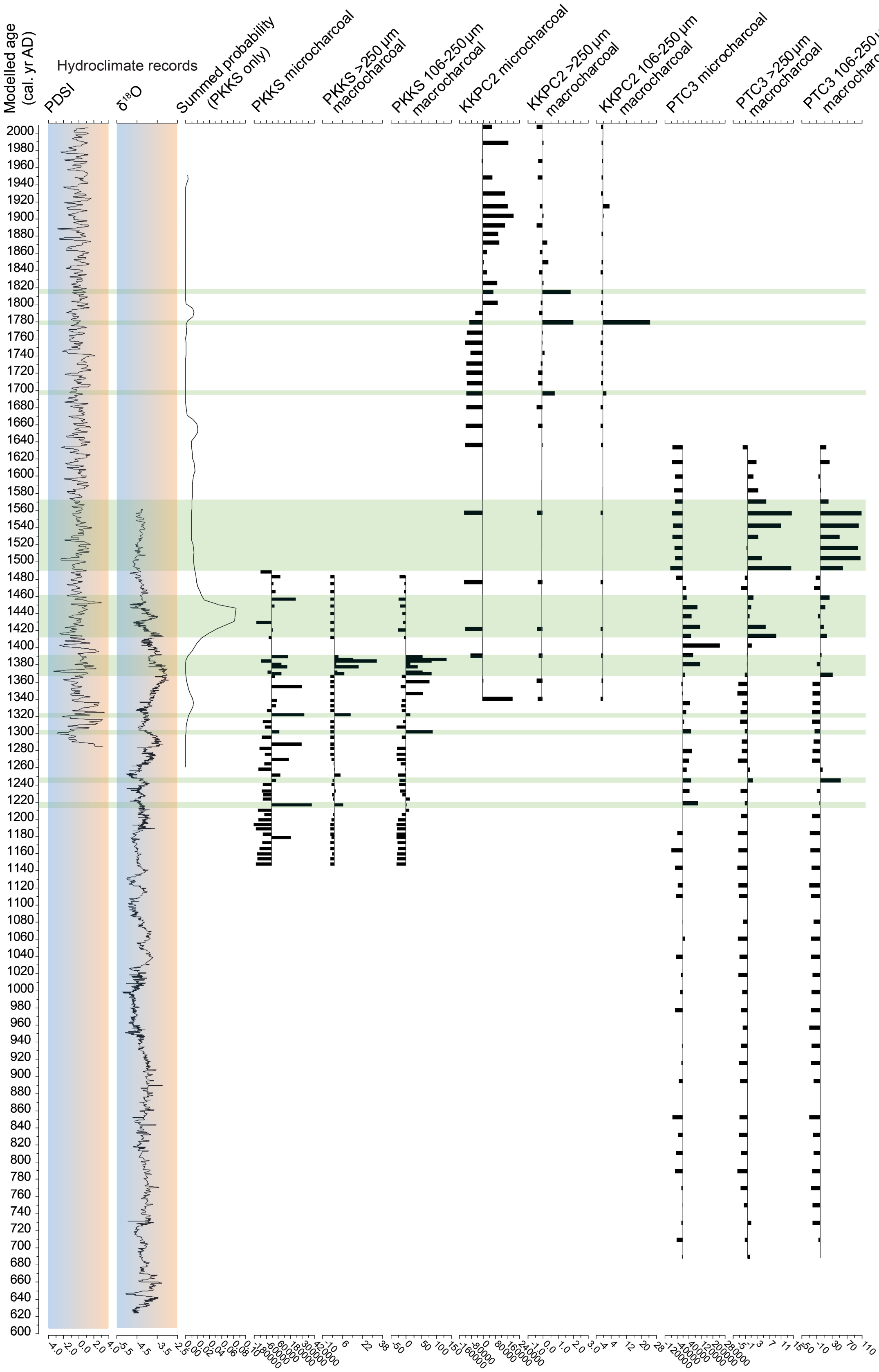

FIGURE 7.1: Published hydroclimate records representing extra-regional climate (blue to orange represents wet to dry) plotted against macro- and micro-charcoal records for each core analysed. Charcoal influx is presented as the deviation from the long-term (whole-of-record) mean. Hydroclimate records are from Berkelhammer et al. (2010) (δ^{18}O) and Buckley et al. (2010) (PDSI). Green bars represent distinct events or periods of heightened fire activity.

7.2.2 Fire activity in the local catchment

Preah Khan of Kompong Svay (PKKS)

Figure 7.1 shows no strong relationship between macrocharcoal and climate. Between the mid-12th and mid-14th century AD peaks in macrocharcoal coincide with relatively wet (but highly variable) periods in the tree-ring extra-regional hydroclimate record. However, these macrocharcoal peaks also coincide with isolated peaks in microcharcoal influx, suggesting several potential causes. Firstly, these local fires may reflect isolated wildfires initiated by lightning strikes that would have been more common during these periods of more active summer monsoon activity (see Price 2009). Alternatively, these peaks may reflect brief and limited anthropogenic burns. In either scenario, but particularly in the latter, concomitant peaks in microcharcoal may be the result of taphonomic processes working on the macrochacoal either during transport or in situ following deposition. Small peaks in accumulation rates, higher proportions of sand in sediment deposits, variations in magnetic susceptibility (see Fig 7.11) and anthropogenic or disturbance forest taxa, particularly *Macaranga/Mallotus*, other Euphorbiaceae, open canopy herbs such as Asteraceae, and the presence of the commonly cultivated *Areca* (see Fig. 6.15 and 6.16), suggest that anthropogenic land disturbance was occurring in conjunction with these peaks in macrocharcoal influx during the early 14th century AD. Together this evidence suggests that this particular local fire activity was potentially human-induced, or alternatively represents isolated wildfires in an otherwise managed landscape.

Strong and sustained peaks in macrocharcoal influx between the mid- to late-14th century AD presents a similarly complex case. While this period coincides with a very dry (but with increasing summer monsoon intensity) period in the δ^{18}O record, and Yamoah et al. (2017) similarly report reduced summer monsoon rainfall during the 14th century, the tree-ring record indicates that, following an isolated, but intense period of drought between approximately 1370 and 1380 AD, the extra-regional and regional climate was relatively wet. This pattern of intense droughts interspersed with periods of relatively high rainfall could potentially drive heightened wildfires, considering the dehydration of fuel loads that occurs during drought periods and increased chance of lightning during subsequent wetter years (see Harrison et al. 2010). Furthermore, changes in the forest structure instigated by these intense droughts (including the preceding drought in the mid-14th century) may have further encouraged increased levels of wildfire. Indeed, the pollen record indicates a temporary increase in secondary dry forest taxa and a high relative abundance of Poaceae occurs during and following the late 14th century drought period (see Figs. 6.15, 6.16 and 7.11 below).

Alternatively, this period of heightened fire activity may be human-induced, and support for this exists in the archaeological record. Hendrickson et al. (2013) have revealed a period of increased industrial activity, occurring inside the enclosure walls, between the 11th and 17th centuries (but was most pronounced between the late 13th and late 15th centuries AD). This industrial activity coincides broadly with the period of heightened fire activity in the mid-14th century to early 15th century AD, suggesting that this peak in fire activity in the local catchment represents increased anthropogenic burning within the catchment of the baray at PKKS. The fact that the peak probability of industrial activity is offset from the sustained peak in charcoal production (see Fig. 7.1) may be the product of the baray's location relative to the various and shifting loci of iron smelting throughout and outside of the temple enclosure (Hendrickson et al. 2013). It is therefore possible that the macrocharcoal record is reflecting these shifting patterns of iron production across space, or domestic activity associated with production.

Furthermore, the microcharcoal record, while consistently above average between the late 14th and early 15th century AD, is more subdued than would be expected if these peaks in macrocharcoal were predominantly due to climate forcing. Also, if these peaks in macrocharcoal were the result of local climate, similar peaks in micro- and macrocharcoal would be evident (but are generally not) in the sediment archives retrieved from the Koh Ker cores (see Fig. 7.1). Together, this preliminary (albeit equivocal) evidence suggests that peaks in macrocharcoal, particularly between the late 14th and early 15th century AD, may be predominantly the result of increased human-induced burning.

Koh Ker

In the older core (PTC3), a single peak in both macrocharcoal size classes during the mid-13th century AD correlates with a wet period in extra-regional climate, but a potentially dry period in the regional climate (evidenced by a peak in microcharcoal influx). A phase of sustained above average macrocharcoal influx occurs between the early and mid-15th century AD coincides with wet or dry but increasingly wet periods in the extra-regional climate records, and a potentially dry period in the regional climate record. Yamoah et al. (2017) records a highly variable climate during this period in the lead-up to and during the period of the 'Angkor droughts' (Buckley et al. 2010). Alternatively, the coincident peaks in microcharchoal here may instead represent the breakdown of macrocharcoal fragments during transportation, and if so this fire activity could potentially be human-induced. A second sustained phase in macrocharcoal influx occurs between the late 15th and late 16th century AD is more clearly the result of anthropogenic activity, given that it coincides with wet periods across all three extra-regional and regional (microcharcoal) climate records.

In the second core, KKPC2, very minimal macrocharcoal captured throughout the sediment archive suggests that fire activity in the catchment was limited. Three isolated peaks in macrocharcoal influx occur in the late 17th century, late 18th century and early 19th century, all in conjunction with a relatively wet extra-regional climate. Overall this suggests that these data likely represent small-scale anthropogenic burning within the local catchment, in conjunction with an increasingly inhabited regional landscape (see section 7.3). Overall, both records from Koh Ker show that the macrocharcoal record is highly variable and strongly decoupled from the hydroclimate records, suggesting a prevalent anthropogenic influence.

Summary

Overall, microcharcoal records are relatively well correlated with climate throughout all three sediment records, suggesting that, for the most part, these data reflect climate-induced burning in the regional and extra-regional catchment or, in isolated cases, fragmentation and other taphonomic processes working on deposited macrocharcoal, in conjunction with a changing climate.

A preliminary comparison of charcoal records against regional and extra-regional climate records suggests that the macrocharcoal record presented here potentially provides a signature of human-induced fire activity. Of particular interest is the fact that in the series of decades-long, severe droughts that befell the region in the 14th and early 15th centuries AD (Buckley et al. 2010, Berkelhammer et al. 2010, Yamoah et al. 2017, Hua et al. in review), and have been attributed to the political abandonment of Angkor (Buckley et al. 2010, Yamoah et al. 2017), are not generally accompanied by concomitant peaks in the macrocharcoal record, particularly in the cores from Koh Ker, further suggesting that the anthropogenic signal is the dominant signal in these charcoal records.

7.3 Vegetation assemblage change inferred from pollen results

For the following discussion, 'pre-disturbance' vegetation assemblages refer to those assemblages commonly associated with the Deciduous Dipterocarp Forest (DDF), Mixed Deciduous Forest (MDF) and Semi-Evergreen Dry Forest (SEDF) (see section 4.4). 'Anthropogenic' assemblages refer to those assemblages associated with secondary forest or cleared/disturbed landscapes that may have been altered by anthropogenic forces (e.g. agricultural land uses, etc.). Finally, 'post-disturbance' assemblages refer to vegetation that, in Khmer temple cities, is associated with either the development of swamp communities and, in particular, the floating vegetation mats that commonly colonise water bodies in these city complexes following the retreat or reduction in land use by local communities. Lists of the species/genus that are commonly found in each assemblage are included in Table 4.1, and a more specific list of the common (top 99%) pollen and spore types identified – and the vegetation assemblage/s they have been assigned to – is provided in Table 5.3. Obviously, many taxa have been assigned to multiple vegetation assemblages. References and further readings regarding these vegetation assemblages are also provided in these tables. A more thorough discussion of the background to this analysis can be found in section 5.7.

Summary plots showing the relative changes in the proportions of summed 'pre-disturbance', 'anthropogenic', and 'post-disturbance' classified taxa (with arboreal (woody shrubs and trees) and herbaceous plant types summed and plotted separately) have been included on Figures 7.2 to 7.10. These proportions have been calculated using only taxa that have been classified into at least one of the three vegetation assemblages, in order to remove the influence of extra-regional forest taxa (where *Celtis* cf. or *Pinus*, for example, can overwhelm proportional fluctuations in arboreal pollen data) or unclassified taxa.

7.3.1 PKKS-C1

The summary plots for PKKS-C1 reveal that the arboreal component of the 'pre-disturbance' vegetation assemblage declines gradually up-core, and is largely replaced by mature swamp taxa, or 'post-disturbance' vegetation assemblages, by Zone 3. The proportion of herbaceous taxa associated with anthropogenic vegetation assemblages, which is dominated by Poaceae here, remains relatively steady throughout the core, while the proportion of 'anthropogenic' arboreal taxa is highest in Zone 2 and lowest in Zone 3. The proportion of 'post-disturbance' herbaceous taxa decreases at the boundary of Zone 1 and 2, and remains low for the remainder of the core, however this is largely the result of a decline in Cyperaceae pollen, which strongly contributes to the herbaceous pollen sum in the post-disturbance vegetation assemblage (note: plotting absolute abundances are not appropriate for this data set, given the high variability in pollen deposition throughout the core). Relative abundances of other herbaceous 'post-disturbance' taxa increase in Zone 3 however, in particular *Stenochlaena* ferns.

Figures 7.2 to 7.4 show the relative abundances of taxa grouped into vegetation assemblages, with each plot zoned according to the stratigraphically constrained cluster analyses used in the pollen results (section 6.6, also see Appendix B). Very limited plant microfossils were found between 152 and 132 cm, coincident with a peak in bulk accumulation rates (at 146-138 cm). High proportions of sand (33-46% compared to an average of 13.8% for the whole core) occur at these depths, indicating this increase in pollen deposition may be the result of slumping and inwash of excavation spoils into the baray. Having been exposed to the air prior to re-deposition into the baray would have eliminated or damaged much of the preserved plant microfossils, and high levels of bulk accumulation would have diluted the concentration of any microfossils that remained intact.

Zone 1 comprises similar proportions of all three vegetation assemblages in the arboreal pollen sum, except at 1210 AD (132 cm), where a spike in *Ficus* and *Myrica* temporarily inflates the proportion of 'post-disturbance' taxa. Highest relative abundances of various 'pre-disturbance' taxa, such as *Dipterocarpus*, *Hopea/Shorea*, *Lithocarpus/Castanopsis*, *Oncospermum*, both di- and triporate Urticaceae/Moraceae, and Euphorbiaceae taxa, occur in this zone (see Fig. 7.2). Relative abundances of *Trema*, a common pioneer component of secondary (disturbed) forest (Maxwell 1999), are highest in the latter portion of Zone 1. Several herbaceous taxa from families that commonly flourish in disturbed or anthropogenic landscapes, such as Cyperaceae, Chenopodiaceae/Amarantheaceae, and Asteraceae are more regularly present, or are at their most relatively abundant, particularly from 1210 AD (132 cm) onwards up-core (see Fig. 7.3). A number of possibly cultivated taxa, in particular *Colocasia* sf., *Brassica* sf., and *Flacourtia* (see Dy Phon 2000), also appear at this depth (132 cm). In general, emergent wetland aquatic taxa (indicative of early-stage floating vegetation mats) are at their lowest relative abundance, as are a number of swamp forest indicator species, such as *Eugenia* and *Schleichera oleosa* (Theilade et al. 2011) (see Fig. 7.4). *Ficus* is, counterintuitively, at its highest relative abundance in Zone 1, in association with predominantly dry deciduous and mixed deciduous forest type species ('pre-disturbance' vegetation assemblages). While *Ficus* has been classified broadly here as a common component of wet, dense or swamp forests (and hence 'post-disturbance' forests) (assuming that they represent species such as *Ficus palmatiloba*, *F. heterophylla* (Maxwell 1999), *F. fistulosa*, *F. rumphii*, *F. pumila* (Theilade et al. 2011), the diversity of this genera found in Cambodia means that the species represented in this pollen record may instead reflect those species found in secondary forests, riparian or gallery forest on the riverside edges of more dry forest types, or in the understory of semi-evergreen forests (Maxwell 1999), such as *F. altissima*, *F. curtipes*, *F. hirta*, *F, hispida* (Dy Phon 2000). Relative abundances of *Ficus* pollen are also complicated by large differences in pollen production and dispersal between species (see Wang et al. 2014), and as such a shift in the proportion of *Ficus* may reflect a shift in the dominant species, rather than absolute abundances, found in the catchment.

A marked increase in the relative abundance of Poaceae pollen occurs in Zone 2, at the expense of Cyperaceae (see Fig. **??** and 7.3). Of the 'pre-disturbance' forest taxa, relatively low abundances of *Elaeocarpus/Tetremeles*, and taxa that were more relatively abundant in Zone 1 (such as *Lithocarpus/Castanopsis*, *Oncospermum*, Euphorbiaceae, *Dipterocarpus*, *Hopea/Shorea*, and Urticaceae/Moraceae) begin to decline. A number of genus common in dry dipterocarp forests disappear from the pollen record, including *Drypetes*, *Justicia*, and *Cephalanthus*, while Arecaceae species (aside from *Oncospermum*) appear for the first time in Zone 2. Several disturbance ('anthropogenic') genera, in particular *Macaranga/Mallotus*, *Zizyphus*, *Breynia*, *Cratoxylum*, appear or increase in relative abundance. *Macaranga/Mallotus* are particularly dominant genera in Zone 2, where relative abundances fluctuate between 10 and 18% of the arboreal pollen record. Emergent wetland/aquatic taxa also appear more frequently and in higher relative abundances, with marked and consistent increases in *Nelumbo nucifera* and *Nymphoides* occurring late in Zone 2 and into Zone 3, between 1371 and 1420 AD (47-26 cm). Some swamp ('post-disturbance') and riparian forest taxa, notably *Pandanus* and *Myrica*, are frequently present or more dominant in this zone.

The transition to Zone 3 is marked by distinct increases in many taxa associated with 'post-disturbance' vegetation assemblages, in particular *Eugenia*, *Schleichera oleosa*, and *Elaeocarpus/Tetremeles* in the arboreal pollen sum (see Fig. 7.4). *Eugenia* is very strongly represented in Zone 3, comprising 40-55% of the arboreal pollen record. Pteridophytes and other herbaceous 'post-disturbance' taxa appear frequently and relatively consistently throughout the core, except for *Stenochlaena*, which distinctly increases in relative abundance in Zone 3. *Ilex* also shows a spike in relative abundance toward the end (top) of Zone 3. High relative abundances of extra-regional forest taxa persist throughout the record, in particular *Pinus*, *Celtis* cf., and *Quercus* cf., reflecting consistent input of highly dispersed, wind-borne pollen rain to the catchment. While a sharp decrease in the contribution of these taxa to the arboreal pollen record occurs in Zone 3, much of this relative decrease is likely the result of the overwhelming increase in locally sourced *Eugenia* pollen in this zone.

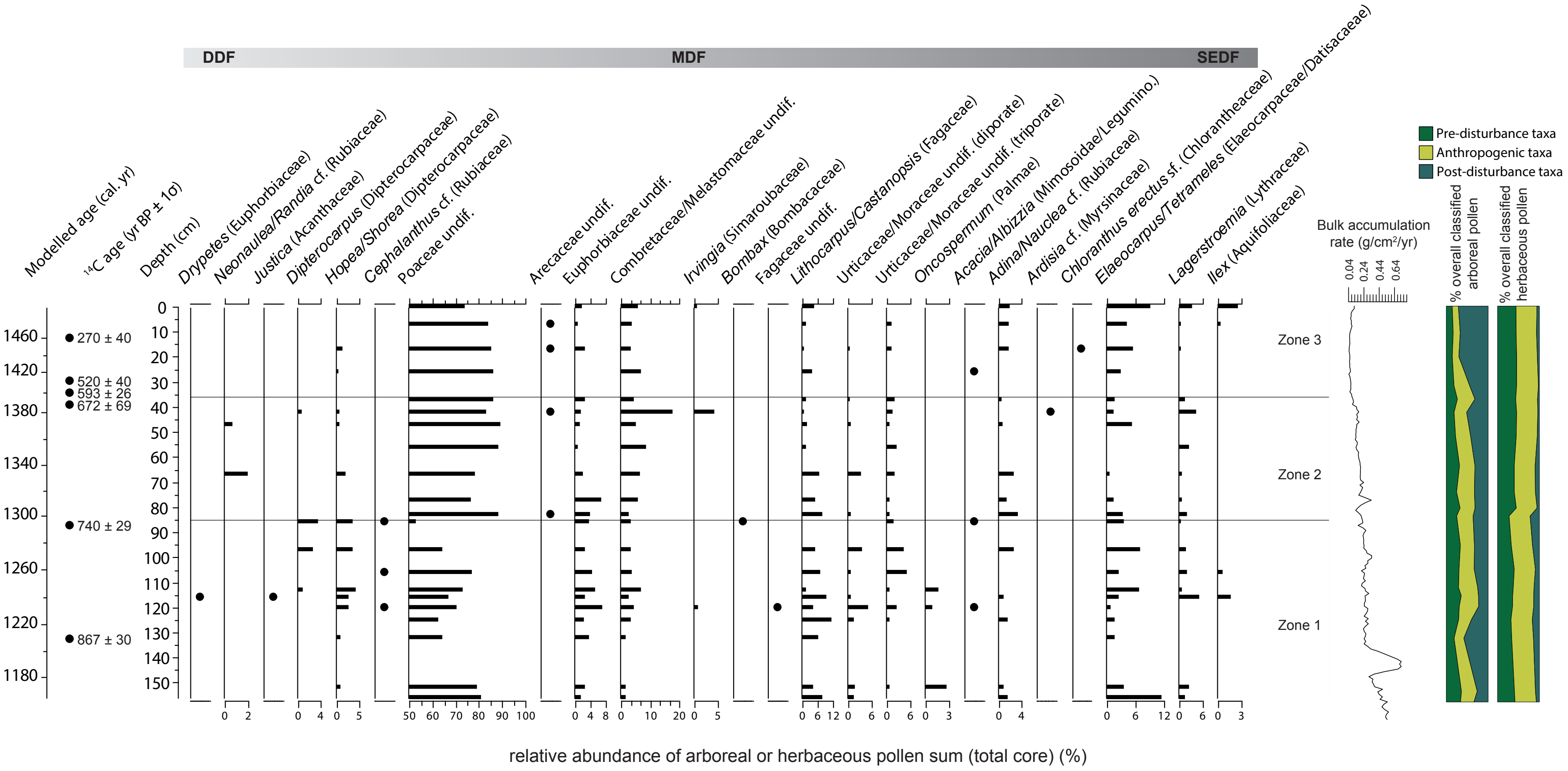

FIGURE 7.2: Pollen diagram for core PKKS-C1 showing pollen and spore relative abundances classified under the pre-disturbance vegetation assemblage. Specimens are ordered along a rough spectrum from Deciduous Dipterocarp Forest species to those more commonly found in Semi-Evergreen Dry Forest. Plot is divided into stratigraphically defined cluster zones. Bulk accumulation rate has been included on the right to contextualize changes in pollen abundance. Overall relative abundances of each classified vegetation assemblage has also been included on the far right.

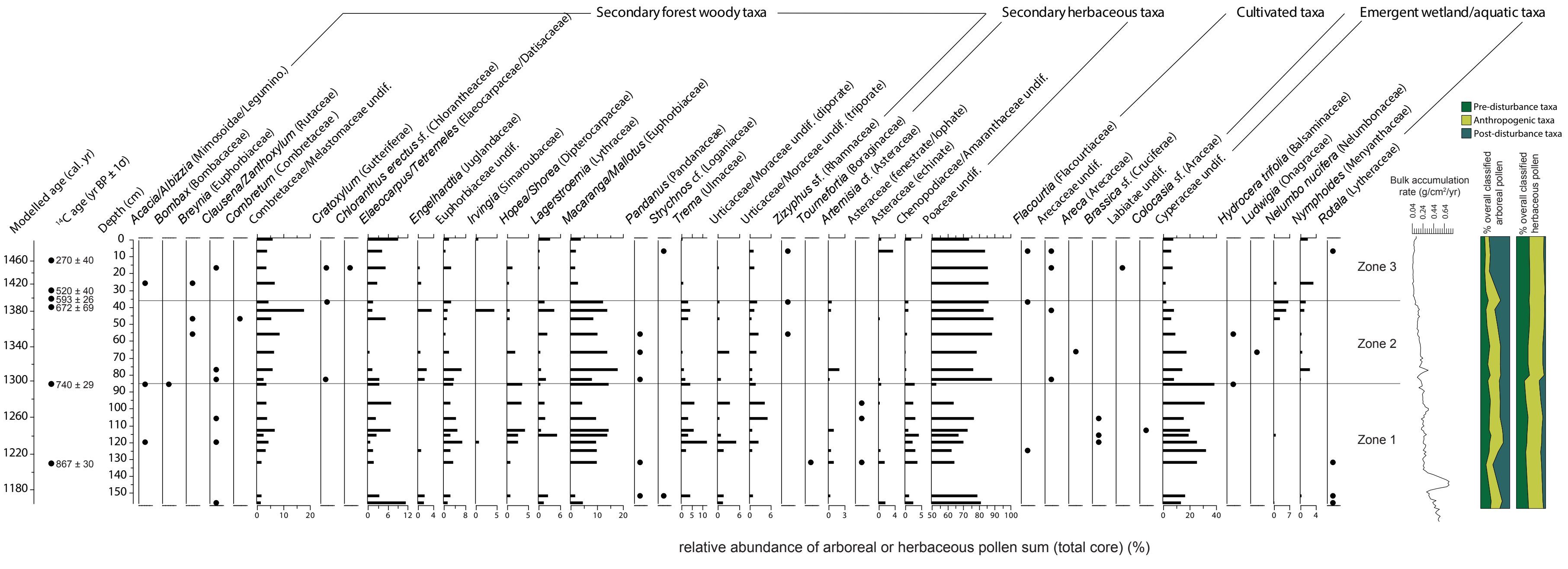

FIGURE 7.3: Pollen diagram for core PKKS-C1 showing pollen and spore relative abundances classified under the anthropogenic vegetation assemblage. Specimens are grouped according to habit (woody, herbaceous, or aquatic), with those species likely to be cultivated as food crops grouped separately. Plot is divided into stratigraphically defined cluster zones. Bulk accumulation rate has been included on the right to contextualize changes in pollen abundance. Overall relative abundances of each classified vegetation assemblage has also been included on the far right.

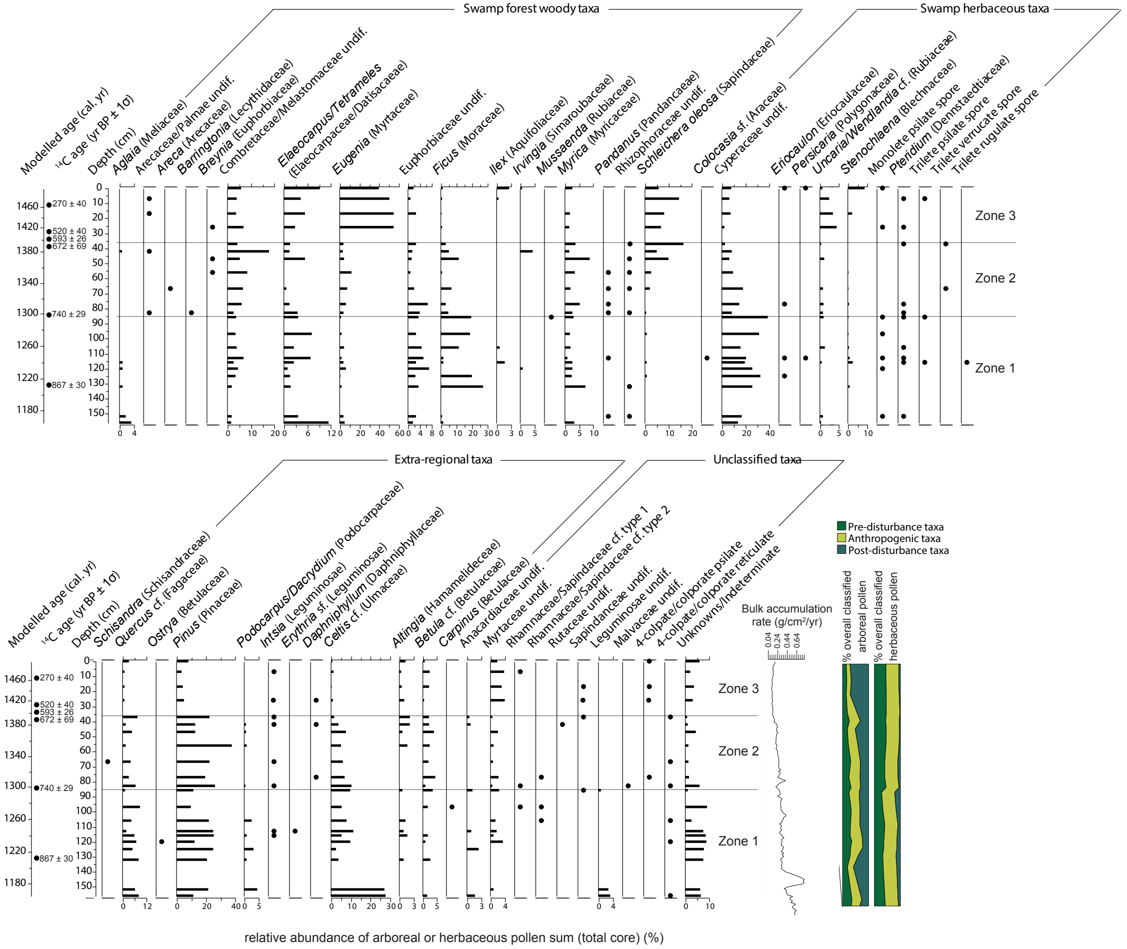

FIGURE 7.4: Pollen diagram for core PKKS-C1 showing pollen and spore relative abundances classified under the post-disturbance and extra-regional vegetation assemblages. Unclassified families and unknowns are also included. Post-disturbance forest type specimens are grouped by habit (woody and herbaceous). Plot is divided into stratigraphically defined cluster zones. Bulk accumulation rate has been included on the right to contextualize changes in pollen abundance. Overall relative abundances of each classified vegetation assemblage has also been included on the far right.

7.3.2 PTC3

Summary plots showing the relative changes in the proportions of 'pre-disturbance', 'anthropogenic' and 'post-disturbance' vegetation assemblages throughout the record indicate that 'post-disturbance' arboreal taxa increase up-core, at the expense of 'pre-disturbance' and 'anthropogenic' arboreal taxa (see Fig. 7.5 to 7.7). Highest relative proportions (72-80%) of 'post-disturbance' arboreal taxa are found in the topmost 141 years of the record (128-108 cm). The relative decrease in 'pre-disturbance' arboreal taxa is the most pronounced, declining from a maximum of 60.5% at 789 AD (218 cm) to 12.8% at the top of the core. The relative proportion of 'post-disturbance' herbaceous taxa remains very low for the majority of the record, until 1492 AD (128 cm) when relative abundances begin to increase, concurrent with the increase in the overall relative abundance of arboreal components of 'post-disturbance' swamp forest.

Zone 1 is characterized by the predominance of both 'pre-disturbance' and 'anthropogenic' arboreal and herbaceous taxa (Fig. 7.5 and 7.6), namely *Hopea/Shorea*, *Costus speciosus*, Urticaceae/Moraceae (diporate), Asteraceae (fenestrate/lophate), and particularly *Adina/Nauclea* cf. Potentially cultivated taxa are also most frequently present in Zone 1. 'Post-disturbance' taxa (both arboreal and herbaceous) (Fig. 7.7), in particular *Eugenia* and pteridophytes, are very poorly represented, excepting *Uncaria/Wendlandia* cf. Relative abundances or presence of extra-regional forest species, such as *Pinus*, *Quercus* cf., *Celtis* cf. and *Betula* cf. are highest in this zone.

Zone 2 comprises relatively high abundances of Euphorbiaceae species, in particular *Macaranga/Mallotus*. Some 'anthropogenic' arobreal taxa, such as *Diospyros*, *Cratoxylum* and *Acacia/Albizzia*, appear for the first time in this zone. Some 'post-disturbance' arboreal taxa begin to increase in the 56 years (158-148 cm) prior to the boundary of Zones 2 and 3, notably *Eugenia* and *Schleichera oleosa*. Sustained increases in both types of Rhamnaceae/Sapindaceae cf. pollen also occur in this zone.

Zone 3 is characterized by the dominance of 'post-disturbance' taxa, with *Eugenia* and *Schleichera oleosa* strongly represented in the arboreal pollen record, and Monolete psilate fern spores in particular becoming increasingly represented in the herbaceous component. Of the other arboreal 'post-disturbance' taxa, *Pandanus* occurs more frequently in this zone, however *Myrica* and *Ficus* species decline to their lowest relative abundances. Of the 'anthropogenic' taxa, both morphological types of Asteraceae, which were relatively prevalent throughout the preceding zones, are almost absent from Zone 3. Occurrences of emergent wetland/aquatic taxa, of which *Nymphoides* is the most prevalent, increase in this zone, particularly toward the topmost layers of the core. *Trema*, which occurs consistently throughout Zones 1 and 2, is largely absent from this topmost zone. Relative abundances of Poaceae decline slightly, after remaining high (fluctuating between 57 and 87%) throughout the first two zones, as the proportions of pteridophytes and Cyperaceae increase. Much of the 'pre-disturbance' arboreal taxa, especially *Hopea/Shorea*, *Costus speciosus*, *Adina/Nauclea* cf., *Lithocarpus/Castanopsis*, and Urticaceae/Moraceae have declined substantially or disappeared altogether from the pollen record. Extra-regional forest types that frequently occurred throughout Zones 1 and 2 have also declined substantially here.

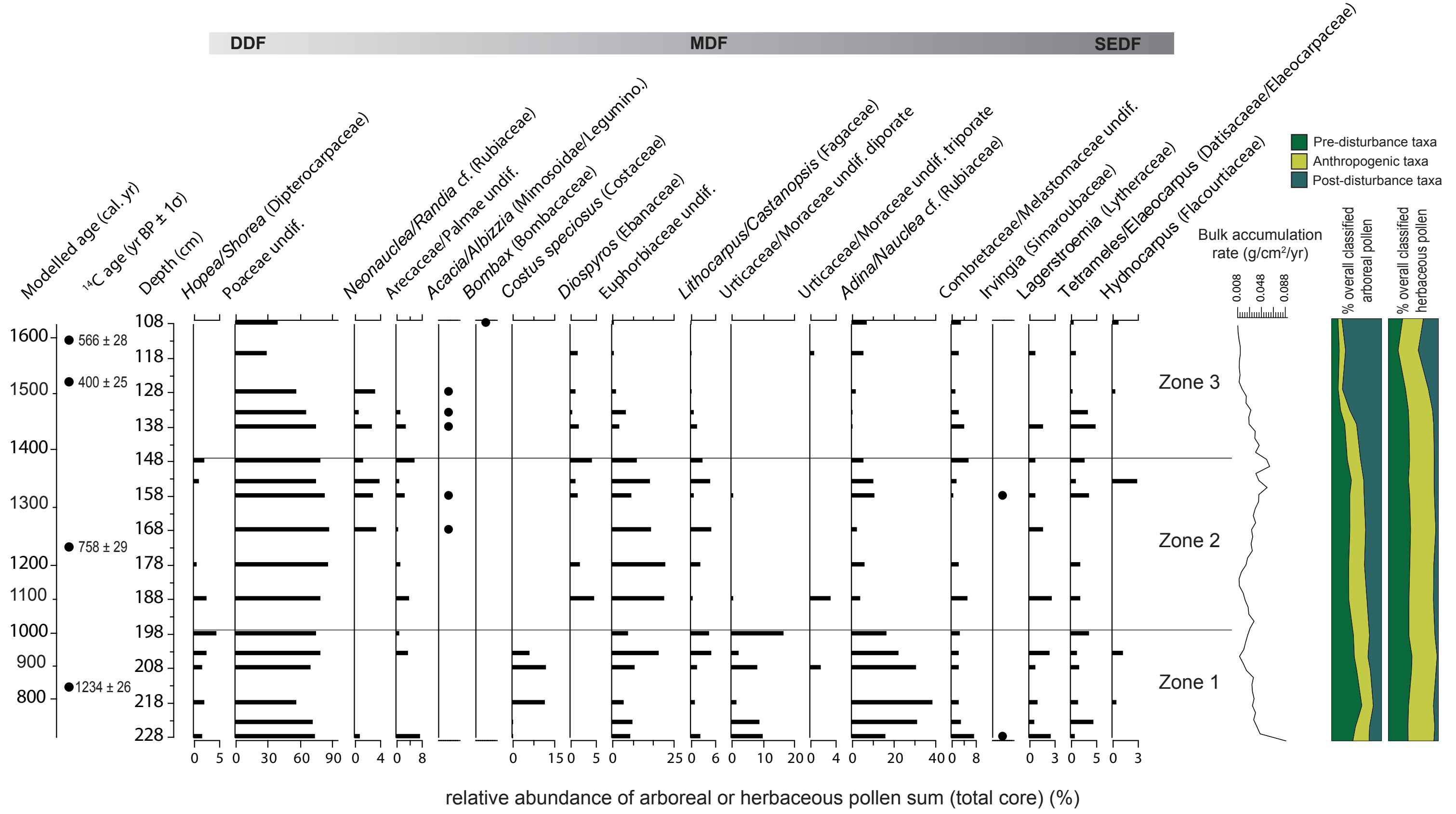

FIGURE 7.5: Pollen diagram for core PTC3 showing pollen and spore relative abundances classified under the pre-disturbance forest type. Specimens are ordered along a rough spectrum from Deciduous Dipterocarp Forest species to those more commonly found in Semi-Evergreen Dry Forest. Plot is divided into stratigraphically defined cluster zones. Bulk accumulation rate has been included on the right to contextualize changes in pollen abundance. Overall relative abundances of each classified forest type has also been included on the far right.

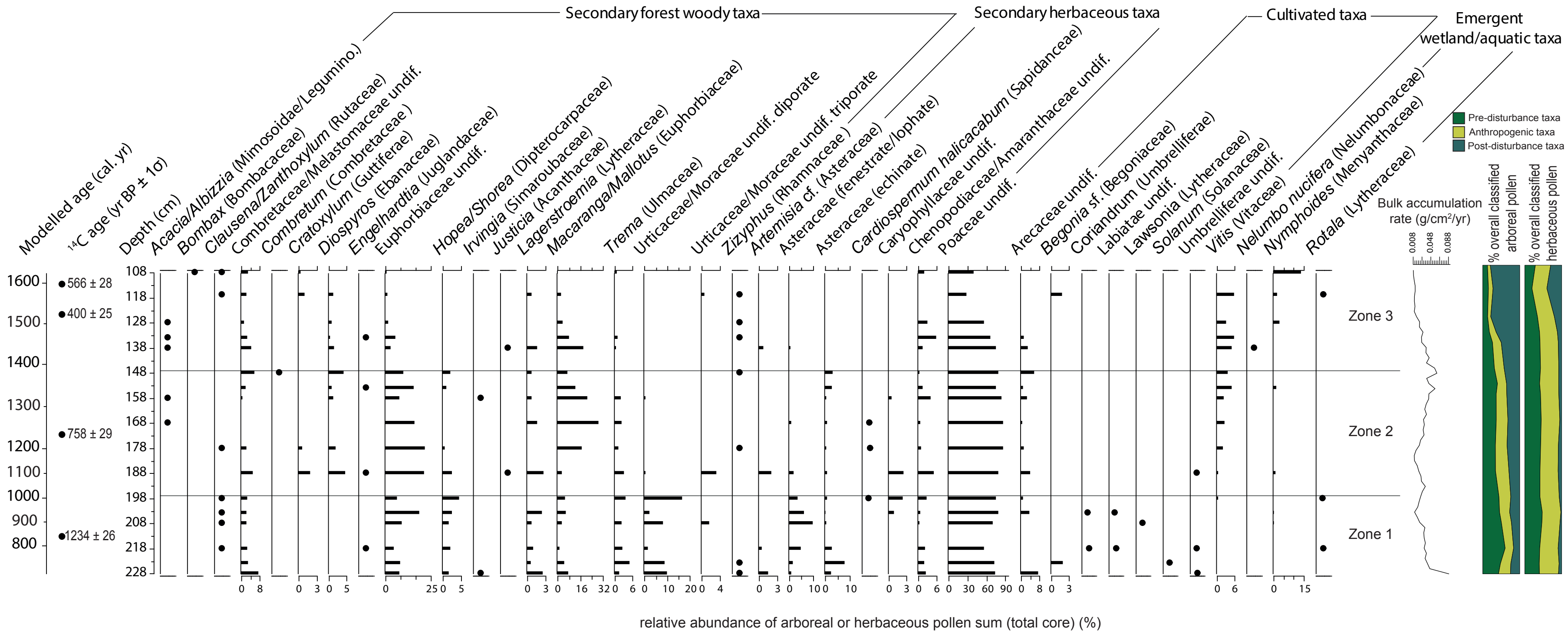

FIGURE 7.6: Pollen diagram for core PTC3 showing pollen and spore relative abundances classified under the anthropogenic forest type. Specimens are grouped according to habit (woody, herbaceous, or aquatic), with those species likely to be cultivated as food crops grouped separately. Plot is divided into stratigraphically defined cluster zones. Bulk accumulation rate has been included on the right to contextualize changes in pollen abundance. Overall relative abundances of each classified forest type has also been included on the far right.

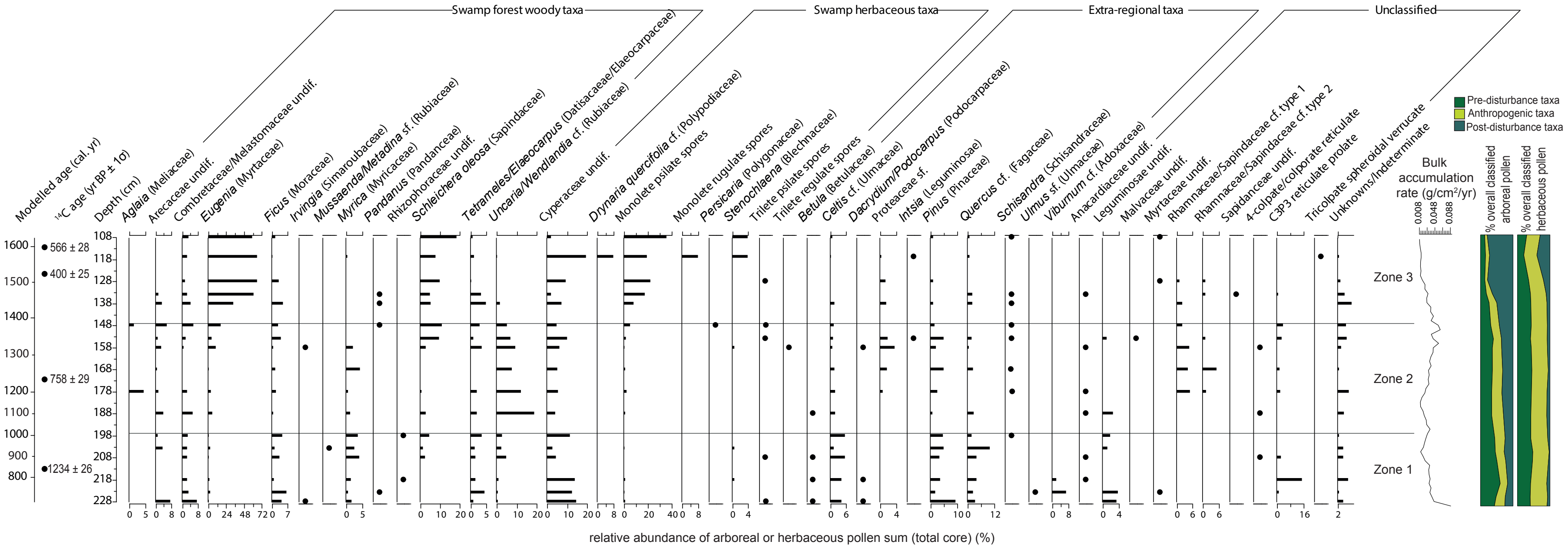

FIGURE 7.7: Pollen diagram for core PTC3 showing pollen and spore relative abundances classified under the post-disturbance and extra-regional forest types. Unclassified families and unknowns are also included. Post-disturbance forest type specimens are grouped by habit (woody and herbaceous). Plot is divided into stratigraphically defined cluster zones. Bulk accumulation rate has been included on the right to contextualize changes in pollen abundance. Overall relative abundances of each classified forest type has also been included on the far right.

7.3.3 KKPC2

Summary plots of the changing relative proportion of each vegetation assemblage throughout the core (see Fig. 7.8 to 7.10) show that, in the arboreal component, 'post-disturbance' taxa overwhelming dominate the majority of the core. Given the disproportionate influence of Poaceae pollen on the 'pre-disturbance' and 'anthropogenic' herbaceous pollen sum, the relative proportions of 'pre-disturbance', 'anthropogenic' and 'post-disturbance' herbaceous taxa are less dominated by one vegetation assemblage over another. The relative proportion of 'post-disturbance' herbaceous taxa does, however, peak substantially (comprising 94% of the herbaceous pollen sum) at 1598 AD (63 cm), as a result of a large spike in the relative abundance of pteridophytes (see below for more detail) (Fig. 7.10).

Zone 1 is characterized by short-lived peaks in a number of species found in both 'pre-disturbance' and 'anthropogenic' vegetation assemblages, such as *Hopea/Shorea*, Arecaceae, Euphorbiaceae, *Adina/Nauclea* cf., Urticaceae/Moraceae (diporate), *Tetrameles/Elaeocarpus*, and Combretaceae/ Melastomaceae. Peaks in extra-regional forest species (*Pinus*, *Celtis* cf. and *Quercus* cf.) also occur. Very substantial peaks in herbaceous 'post-disturbance' taxa, in particular *Nephrolepis* cf. and *Stenochlaena*, increase in Zone 1 and remain very high across the transition in Zone 2. An isolated peak in *Myrica*, a common component of mature wetland/riparian forests (Maxwell 1999), also occurs.

Relative abundances of these herbaceous 'post-disturbance' taxa remain high for the first section of Zone 2, but have declined by 1686 AD (51 cm). Under the influence of such abundant herbaceous 'post-disturbance' assemblages, Poaceae abundances are at their lowest in the record. Relative abundances of *Ficus* overwhelmingly dominate the arboreal taxa of Zone 2, fluctuating between 62 and 89% of the primary pollen record. Both 'pre-disturbance' and 'anthropogenic' arboreal taxa, in particular Euphorbiaceae, *Lithocarpus/Castanopsis*, Urticaceae/Moraceae (diporate), and *Hopea/Shorea*, decline and remain low for the remainder of the record. *Macaranga/ Mallotus* remain relatively low or absent from the record. A common component of secondary (disturbed) forests or 'anthropogenic' assemblages, *Zizyphus* sf. (Maxwell 1999), occurs throughout this zone, and several potentially cultivated taxa, including Umbrelliferae, *Areca*, and Solanaceae also occur. Emergent wetland/aquatic taxa, namely *Rotala* and *Nymphoides*, are most prevalent during Zone 2.

As *Ficus* begin to decrease in relative abundance in Zone 3, the proportion of other 'post-disturbance' arboreal taxa, such as *Eugenia*, *Pandanus* and Combretaceae/Melastomaceae, increases. As a result, this upper zone is largely characterized by the dominance of *Ficus* and *Eugenia*. *Schleichera oleosa*, which has appeared in close association with *Eugenia* in cores PKKS-C1 and PTC3, is in this case fairly consistent throughout this core, with a temporary decline in Zone 3 between 1838 and 1884 (21-11 cm). Instead, trends in the relative abundance of *Eugenia* correspond to those of Combretaceae/Melastomaceae, suggesting that the species within these families represented in these sediments are those found in wet, dense/swamp forests. Of the 'pre-disturbance' arboreal taxa, *Adina/Nauclea* cf. and *Tetrameles/Elaeocarpus* increase again after declining in Zone 2. *Lagerstroemia* occurs for the first time just prior to the Zone 2/3 boundary and continues throughout Zone 3. The relative abundance of Cyperaceae reaches its highest levels in Zone 3, however other 'post-disturbance' herbaceous taxa, such as *Stenochlaena*, *Nephroplepis* cf., and *Drynaria quercifolia*, generally decline. Proportions of extra-regional forest taxa remain low throughout the core.

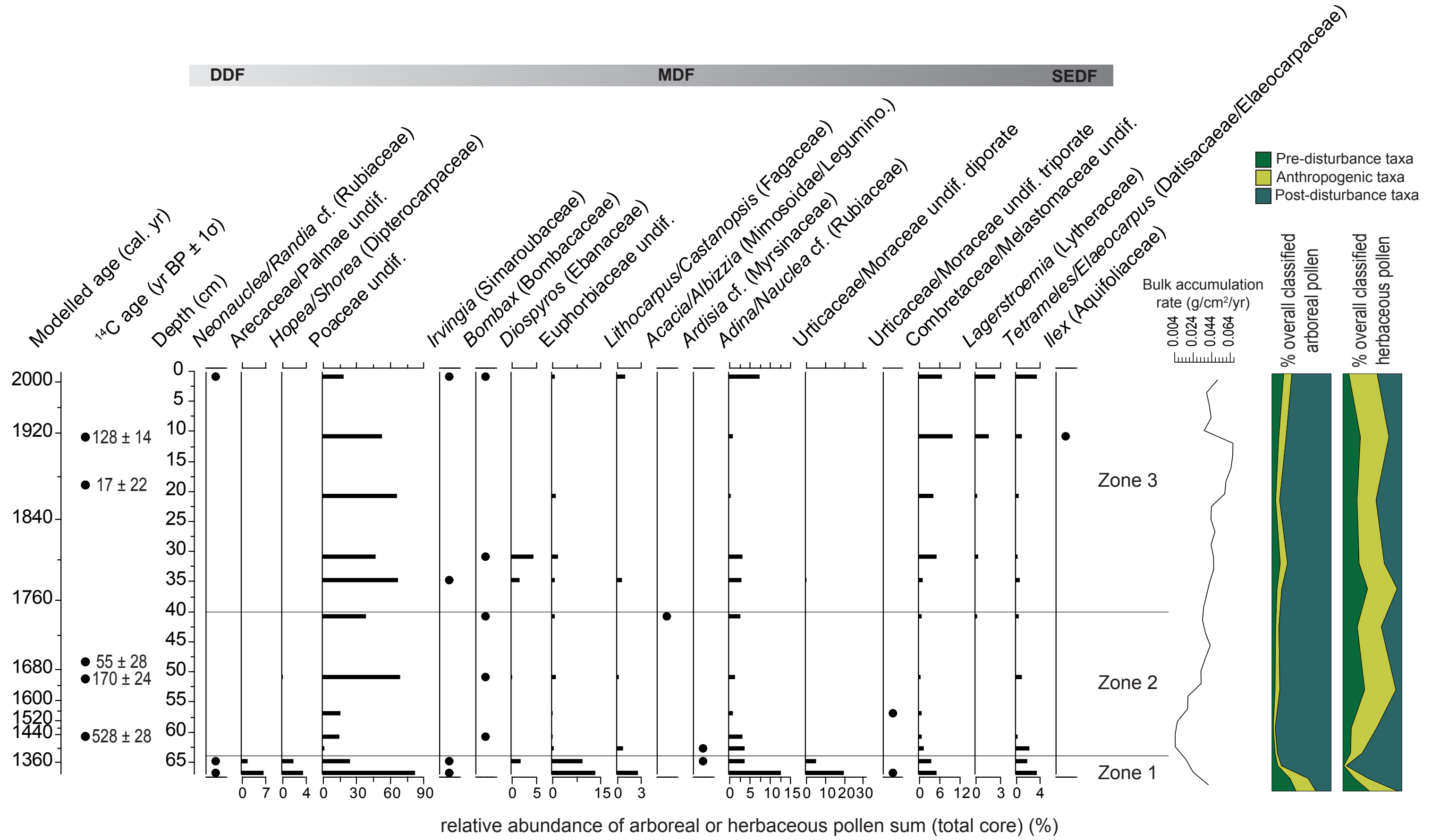

FIGURE 7.8: Pollen diagram for core KKPC2 showing pollen and spore relative abundances classified under the pre-disturbance forest type. Specimens are ordered along a rough spectrum from Deciduous Dipterocarp Forest species to those more commonly found in Semi-Evergreen Dry Forest. Plot is divided into stratigraphically defined cluster zones. Bulk accumulation rate has been included on the right to contextualize changes in pollen abundance. Overall relative abundances of each classified forest type has also been included on the far right.

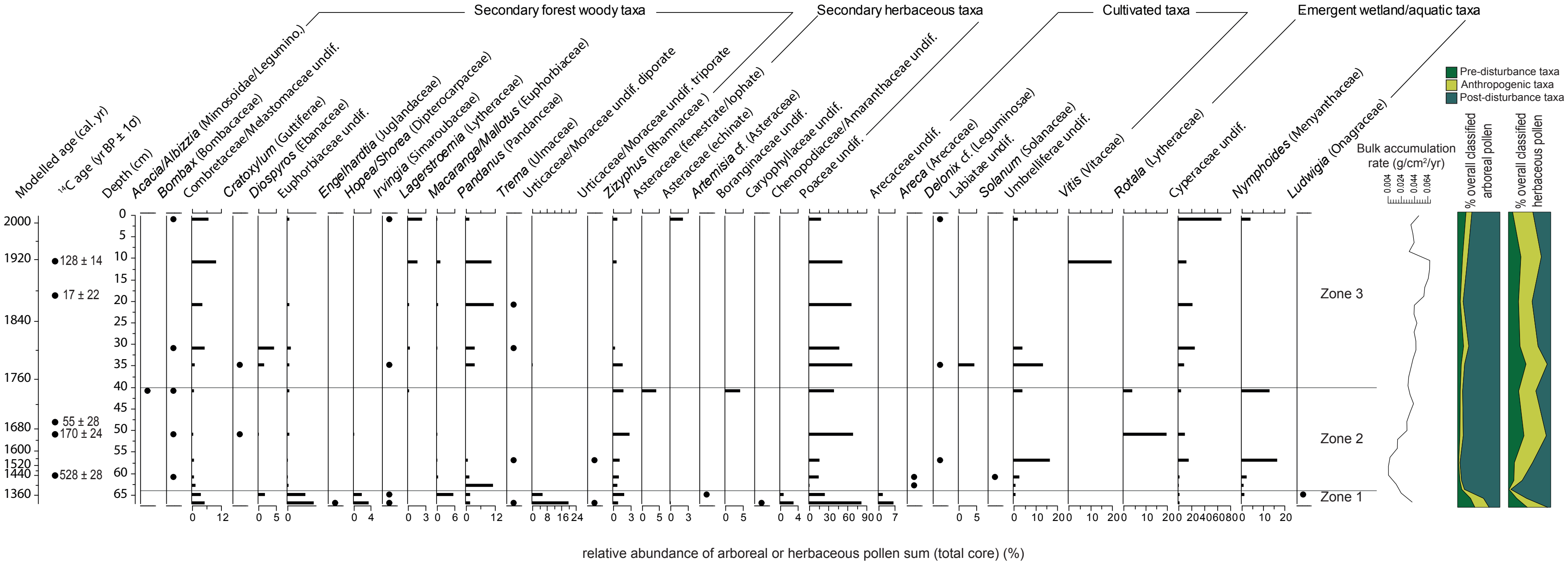

FIGURE 7.9: Pollen diagram for core KKPC2 showing pollen and spore relative abundances classified under the anthropogenic forest type. Specimens are grouped according to habit (woody, herbaceous, or aquatic), with those species likely to be cultivated as food crops grouped separately. Plot is divided into stratigraphically defined cluster zones. Bulk accumulation rate has been included on the right to contextualize changes in pollen abundance. Overall relative abundances of each classified forest type has also been included on the far right.

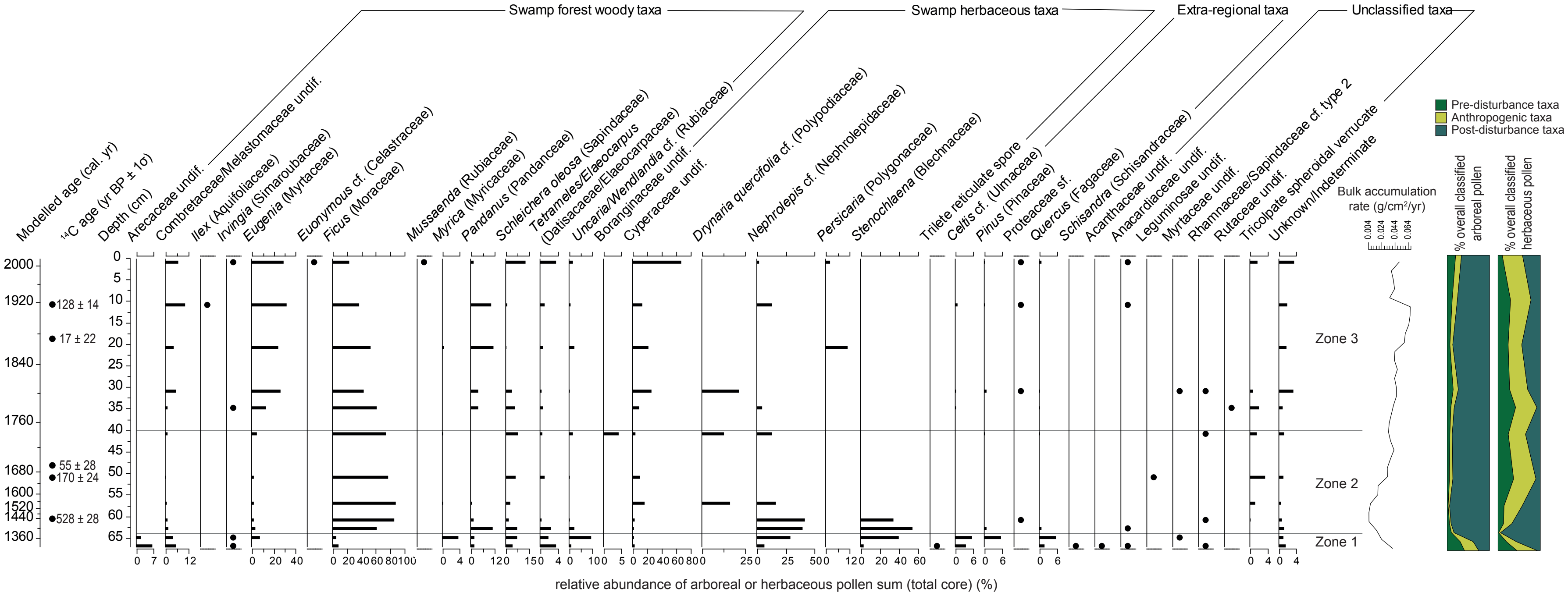

FIGURE 7.10: Pollen diagram for core KKPC2 showing pollen and spore relative abundances classified under the post-disturbance and extra-regional forest types. Unclassified families and unknowns are also included. Post-disturbance forest type specimens are grouped by habit (woody and herbaceous). Plot is divided into stratigraphically defined cluster zones. Bulk accumulation rate has been included on the right to contextualize changes in pollen abundance. Overall relative abundances of each classified forest type has also been included on the far right.

7.4 Occupation history of Preah Khan of Kompong Svay

7.4.1 PKKS-C1

The chronology modelled for PKKS suggests that the *baray* was constructed in the mid-12th century AD, almost a century earlier than Mauger's (1939) original assessment. Stylistic dating of the monuments constructed along the banks of the reservoir, performed by Mauger (1939), can be used to constrain the possible time period of the *baray's* construction and hence corroborate this finding. Firstly, a strong resemblance exists between the monuments of Preah Damrei, built on the eastern edge of the baray, and Kong Plok situated to the east of PKKS at Beng Mealea – a temple city potentially affiliated with king Suryavarman II, who reigned between 1113 and 1150 AD. Secondly, two monuments built after or contemporaneously with the baray are in the style of Jayavarman VII who reigned between 1182 and 1218 AD. These include Prasat Stung, a monument built across the western edge of the baray dyke, and the Preah Thkol temple, constructed on an island in the middle of the reservoir. This evidence combined indicates that excavation of this reservoir was initiated in the mid-12th century, with construction being completed toward the second half of the century. However, the single inscription found at the site dates to the early 11th century, and some limited evidence exists for occupation of the site from the late 10th century AD (Mauger 1939, Jacques and Lafond 2004). Therefore, the excavation of the baray occurred relatively late in the occupational history of PKKS. It also likely postdates the construction of the central Preah Khan temple, which was built in the Ta Keo style of Jayavarman V, probably in the late 11th century (Jacques and Lafond 2004). As such, the palaeoecological record presented here comprises the latter period of occupation at this city complex.

The palaeoecological record reveals an occupation history that progressed in three general phases (Fig. 7.11). The first extends from the *baray's* construction in in the early 12th century to the early 14th century AD. The second lasts for approximately a century, continuing until the early 15th century AD, while the third continues until the late 15th century. Intriguingly, the record does not extend to the present day in this reservoir, which may be the result of recent excavation or a significant decline in sedimentation rates within the basin. This decrease in sedimentation may possibly be associated with colonisation of aquatic vegetation along the margins of the basin that would have captured much of the incoming sediment, in conjunction with a potentially more sediment-starved and vegetated landscape following the city's active tenure.

In general, from the early 12th to early 14th century AD, relatively high accumulation rates and magnetic susceptibility values suggest erosion in the surrounding catchment was relatively high, and could be reflecting heightened anthropogenic disturbance, possibly associated with ongoing building works in the city complex. As mentioned above, two monuments in close proximity to the basin (Prasat Stung and Preah Thkol) were likely built in the decades following *baray* construction. Two sandy layers, deposited in the mid- and late 12th century AD, are probably the result of infill from either excavation spoils, or disturbance created by the construction of the central island temple. Minimal fire activity evident in the catchment during the mid to late 12th century, however, ostensibly suggests that these building works were accompanied by limited domestic occupation, industrial activity within the city complex, or significant forest clearance for agriculture in the surrounding landscape.

However, as discussed in section 7.2, the PKKS macrocharcoal record is decoupled from the climate record, suggesting human intervention in the natural fire regime. Therefore, an alternative interpretation of this relative lack of fire history between the early 12th to early 14th century AD of the record is also possible. Several lines of evidence exist for the presence of human populations from the 13th century onwards to the early 14th century, despite fire activity in the local catchment remaining limited. Firstly, during this period a marked change occurs in local forest structure despite the persistence of limited fire activity. Secondary or disturbance forest becomes more prominent, after low levels following initial *baray* construction, as the relative abundance of *Macaranga/Mallotus*, *Trema*, Urticaceae/Moraceae, *Hopea/Shorea*, and *Lagerstroemia* increase (see Fig. 7.3). Some of these taxa, however, particularly *Hopea/Shorea* and Urticaceae/Moraceae can also be indicative of 'pre-disturbance' forest. Poaceae, after an initial decline in relative abundance in the early 13th century, begin to increase, perhaps representing an increase in the intensity of rice cultivation, and the presence of several cultivated taxa also appears (e.g. *Brassica* sf., *Flacourtia*, *Colocasia* sf.). Secondly, Jacques (2004) claims that several additions to Preah Khan's infrastructure, the construction of the three Prasats Choeutel just to the north of the city, as well as improvements to the highway linking PKKS to Angkor were all likely made during the 13th century. This suggests that use of the site continued and potentially increased beyond the proposed 12th century height of the city when the majority of the building works were being carried out.

Thirdly, relatively low organic content early in the record suggests that the *baray* was kept relatively clear of encroaching vegetation in the century following its construction. Alternatively, higher turbidity levels in the *baray*, evidenced by higher mineral influx that was sustained by continued erosion in the catchment, may have discouraged macrophyte growth. Throughout the mid-late 13th century, slight increases in organic content and herbaceous 'post-disturbance' taxa, particular Cyperaceae and ferns (*Pteridium* and monolete/trilete spores), suggests some growth of semi-aquatic vegetation on the margins of the basin at this time. These changes are only minimal, however, and clearance and ongoing maintenance of the *baray* likely continued through this period, and slight increases in organic content may instead be a response to natural hydroseral vegetation succession occurring within the reservoir.

Together this evidence suggests that domestic occupation of the city persisted at PKKS at least throughout the 13th century to the early 14th century AD. During this time, however, human populations appear to have suppressed, rather than amplified, the local fire regime. Similar results have been found in the Maya landscape, where the relationship between charcoal production and anthropogenic activity is also unclear and variable through time. In the case of the dry tropical forest landscape of the Maya cities, while the initial appearance of agricultural pollen indicators (e.g. *Zea* pollen) are accompanied by substantial increases in charcoal production, subsequent periods show that, despite the continuation of agricultural activity, charcoal levels decline, before entering a period of considerable variability where charcoal is regularly absent (Pohl et al. 1996, Rue et al. 2003). Similarly, other studies in the region have shown a counter-intuitive correlation between charcoal levels and forest type or land use, where low charcoal levels and more muted variability occur during periods of agricultural productivity and heightened building and industrial activity (Anderson and Wahl 2016). These authors attribute the reduction in local burning to a change in land management and use, in particular the intensification of agricultural strategies and, potentially, increases in the efficiency of fuel combustion associated with high-temperature industrial practices (Anderson and Wahl 2016). Penny (1999) similarly observes a decline in charcoal particles preserved in a sedimentary record in north-east Thailand during the late Holocene, when agricultural practices intensified and rice growing began occurring within permanent, bunded fields. Penny (1999) attributes this shift in the charcoal record to the change in land-use strategies, in particular from the wide-spread burning of arboreal forest to lower-intensity, controlled burning of herbaceous vegetation associated with agriculture.

A similar explanation may be relevant for the charcoal record at PKKS. Fire is a constant component of both primary (or 'pre-disturbance') and secondary ('or anthropogenic') seasonally dry tropical forests in Southeast Asia (Bunyavejchewin et al. 2011, Wikramanayake et al. 2017a, b) and thus a reduction, absence or muting of variability in the fire regime may be indicative of increased landscape stability through anthropogenic intervention. Considering that the construction of the *baray* occurred relatively late in the construction sequence of the city complex, peaks in charcoal generated from the broad-scale forest clearance during the early construction phase of the city likely occurred prior to the beginning of this sediment archive. By the time the *baray* was built, relatively high abundances of 'anthropogenic' herbaceous taxa, particularly Asteraceae and Chenopodiaceae/Amarantheaceae (see Fig. 7.3) reflect a landscape that is already relatively open and disturbed. Employing intensive agricultural strategies in such a landscape would have required only small, deliberate burning within rice fields to burn off annual crops, which would have been actively managed and contained. Furthermore, the maintenance of a landscape low in remnant biomass and dominated instead by irrigated rice agriculture would have likely discouraged the natural burning regime. During the Angkor period, and to the present day, the Khmer employed a variety of rice cultivation techniques, including broad-cast flooding, flood-retreat, swidden, transplanted and hydroagriculture (Higham 1989). The former two techniques were more suited to lakefront regions adjacent to the Tonle Sap, in PKKS region, and therefore potentially only swidden, transplanted and hydroagriculture techniques dominated. For transplanted rice, low bunds were built into the soil that could retain rainwater in the rice-field, into which rice plants were transplanted following the onset of monsoon rains (Higham 1989). Hydroagriculture rice is fed predominantly by small water tanks built, where possible, into the water table (Acker 1998), and hence both techniques would likely have been suitable for the majority of the PKKS landscape. Upland regions would only have been amenable to rainfall-dependent swidden agriculture techniques (Nesbitt 1997). However PKKS sits within a broad and very flat catchment with little variation in altitude (see Fig. 4.6). Further evidence produced from remote sensing work (see Evans 2016), which has identified the presence of an urban layout containing a relatively dense and gridded array of small tanks and rice fields in the area, supports this hypothesis.

A marked increased in macrocharcoal influx into the *baray* occurs during the 14th century AD, where fire activity remains consistently well above background levels for at least twenty years, and ostensibly suggests a decrease in landscape maintenance and a significant change in use and function of the city. This increase in fire activity could potentially be the product of an increase in industrial activity (see Hendrickson et al. 2013) and/or domestic wood fuel use in the city complex, or a change in climate that has driven a return to natural burning regimes during a period of reduced human intervention. The climate during the 14th century had become increasingly variable, where a series of intense droughts interspersed with strong monsoon events, and a multi-decadal drought is evident in the hydroclimate records in the mid-14th century AD (Fig. 7.1). As such, this increased fire activity between the mid- and late-14th century AD may have been initiated by this period of intense and sustained drought, particularly if land management practices had reduced in intensity or scale. Hydroclimate records also indicate that a similar period of drought in the early 15th century occurred, however this event is not reflected by a peak in the charcoal record. Potentially, a change in forest structure – in particular towards more sparse forests with open canopies – may have occurred as a result of the increased burning throughout the second half of the 14th century, given the increased relative abundance of Poaceae and general decreases in 'pre-disturbance' arboreal taxa such as *Lithocarpus/Castanopsis*, *Hopea/Shorea*, Urticaceae/Moraceae and *Adina/Nauclea* cf. evident in the pollen record (Fig. 7.2). This shift may have affected the landscape response to drought periods, by favouring small, low intensity fires that would have less of an effect on the charcoal record.

However, despite this shift towards increased fire frequency and a potential reduction in land management, it is likely that populations remained at PKKS during this time. Hendrickson et al. (2013) report that industrial activity continued within and outside the city throughout this period. Evidence from the pollen record (see Fig. 7.3) provides further support for continued human activity, in that high relative abundances of arboreal and herbaceous 'anthropogenic' taxa persist through this period, in particular *Macaranga/Mallotus*, *Breynia*, *Trema* and Arecaceae. The agricultural landscape, however, may also have begun to change, and potentially rice paddies and water reservoirs were gradually being abandoned. Increases in emergent wetland and other aquatic taxa, in particular *Nelumbo nucifera* and *Nymphoides* increase from the mid- to late-14th century AD, and while these species are often present in reservoirs that are actively maintained in Angkor-period cities (see Penny et al. 2006, Day et al. 2012), they could be expected to proliferate in the initial years following a reduction in Khmer land and water management practices. Furthermore, gradual increases in the proportion of sand accumulating in the baray (see Fig. 7.11) may also be indicative of the slow drying out of the southeastern end of the *baray*, which would have produced a large new source of sand-sized material for entrainment and deposition in the northeastern end during a period of more variable climate.

The fact that this shift in land use at PKKS occurs after environmental, economic and political pressures began to escalate in Angkor during the 14th century but prior to Angkor's supposed 'urban diaspora', suggests this shift is indicative of either a repurposing of the city by late-Angkor-period Khmer, or the opportunistic use of the site by surrounding ethnic minorities (specifically the Kouy) following the departure of the Khmer and the contraction of territorial control. The latter scenario seems most plausible, particularly when considering the history of industrial activity in the region. Iron smelting activity here, for the majority of the Angkor-period, remains restricted to the surrounding landscape – particularly surrounding Phnom Dek – and only occurs inside the city complex from the 13th century onwards (Hendrickson et al. 2013, Hendrickson and Evans 2015). However, despite this infiltration of iron production, it remains small in scale and sporadic relative to the scale of production and distribution outside the temple walls (Hendrickson et al. 2013, Hendrickson and Evans 2015). Furthermore, Khmer maintenance of the religious architecture and water infrastructure of the city appears to have ceased at this time, given the encroaching vegetation into and surrounding the *baray*. Together this evidence suggests the opportunistic reuse of the city by surrounding minority groups, rather than the strategic repurpose by the Khmer, and potentially represents the dilution or removal of centralised control operating at PKKS.

Nonetheless, by the early 15th century AD human activity appears to have ceased, or at least migrated outside of the pollen/charcoal/sediment catchment. Industrial activity, however, according to Hendrickson et al. (2013) likely continued within the city complex until the 17th century AD. Despite continued iron production activity at the site, increases in biomass suggest that clearance and maintenance of the *baray* appears to have ceased, which at other Angkor-period cities has been used to indicate a reduction in use or the abandonment of the temple site (Penny et al. 2006, Penny et al. 2007). The *baray* and its margins have become dominated by *Eugenia*, *Schleichera oleosa* and *Elaeocarpus/Tetrameles*, which are all indicators of mature swamp forest (Theilade et al. 2011). Potentially, high levels of organic content deposited in the *baray* are also the result of greater moisture availability and hence primary productivity, however hydroclimate records indicate that only from the mid-15th century did the region return to a wetter climate following the recurrent droughts of the late 14th and early 15th century AD. Encroaching vegetation through the littoral zone of the baray, as well as potentially reduced anthropogenic disturbance in the catchment, have likely reduced mineral influx in the basin. Macrocharcoal influx is also low during this period, most likely in response to reduced industrial burning in the catchment in conjunction with an increasingly wet climate and a reduction in fire-encouraging dry forest taxa.

Overall, the intensity of occupation of PKKS fluctuates throughout the record. The palaeoecological data suggest that, throughout the second half of the 12th and early 13th century, the city maintained politico-religious and administration functions in respect to the capital, consistent with the suggestions of Groslier (1973) and Hendrickson et al. (2013), however the city potentially sustained larger populations during this period than previously assumed (see Evans 2010, Hendrickson and Evans 2015, Evans 2016). Here, the dominance of anthropogenic control of the environment has been inferred from the persistence of an open, disturbed forest landscape, a decoupling of the charcoal and climate records, and a strong reduction and muted variability in the fire regime (see also Anderson and Wahl 2016, Penny 1999). From the mid-13th century, towards the end of Angkor's height of power (11th-13th centuries AD), it is possible that populations began to increase. From here, a substantial shift in land use and function of the city appears to have occurred in the 14th century AD, under the influence of a highly variable climate. At this time an increase in fire activity likely represents the combined result of climate change and a shift in land use practices associated with possible demographic change in the city. By the early 15th century AD, the site, or at least maintenance of the *baray* and activity within its catchment, appears to have been abandoned.

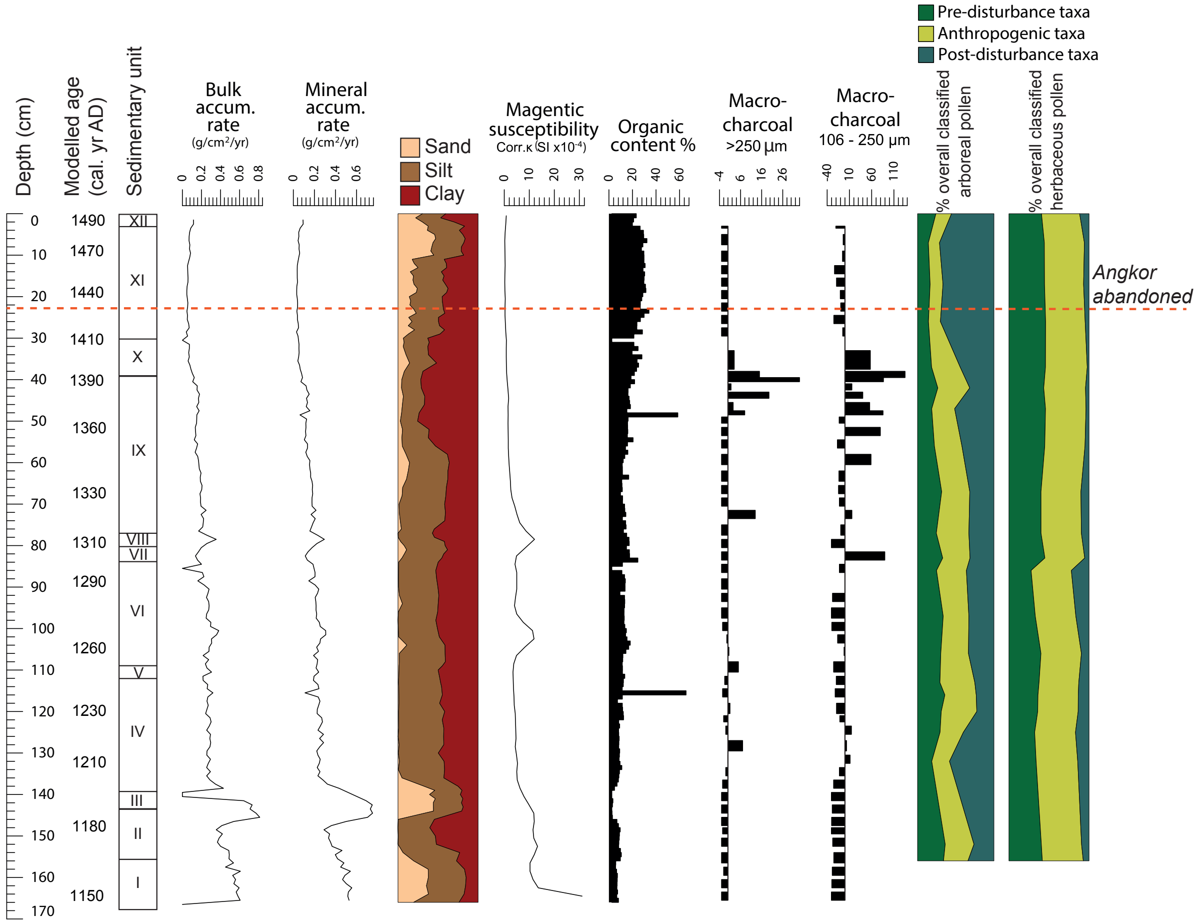

FIGURE 7.11: The combined multi-proxy record for core PKKS-C1.

7.5 Occupation history of Koh Ker

7.5.1 PTC3

While conventional historiography suggests that the city of Koh Ker was established in 921 AD (Vickery 1986), the chronology presented here suggests that the excavation of the moat (core PTC3, see Fig. 7.12) surrounding the central temple of Prasat Thom began much earlier, in the late 7th century AD. This result potentially supports Jacques (2004) suggestion that construction of Prasat Thom was likely earlier than the conventional date, and that Jayavarman IV's 921 AD association with the temple city, and Prasat Thom's establishment as the central temple of the royal capital, involved modifications and enhancements by that king to existing temple infrastructure. It should be noted, however, that this basal date is modelled, and the closest calibrated radiocarbon date was taken from 14 cm above the base of the core. The calibrated age range for this date (D-AMS 006503) is broad, but well defined (i.e. relatively normal) and has a 92.4% probability of falling between 765 and 890 AD. While one radiocarbon date above this basal date returned as 'modern' (in addition to the 'modern' date returned for the topmost sample) – the leaf fragment retrieved from 29 cm above the basal date – the chronology is otherwise robust and the sedimentation sequence supports this basal date.

The multi-proxy palaeocological record presented here (Fig. 7.12) suggests that landscape disturbance in the catchment of the temple moat (PTC3) was relatively high, evidenced by relatively high mineral accumulation rates, higher relative proportions of sand in sediment deposits and several peaks in magnetic susceptibility – all suggestive of soil disturbance and mobilisation – between the late 7th and early 12th centuries AD. A gradual decline in the relative abundance of 'pre-disturbance' arboreal taxa, the presence of multiple cultivated taxa and relatively high abundances of 'anthropogenic' herb taxa (for e.g. Asteraceae, Chenopodiaceae/Amarantheaceae) during this period may also be indicative of land clearance and agriculture proximal to the temple. High proportions of long-distance transport pollen, such as *Pinus*, *Celtis* cf., and *Quercus* cf. throughout this period indicates that local pollen production was low (Solomon 1976), suggesting a sparsely forested or open-canopied landscape (although this may also reflect a dominance of plants that do not disperse pollen on the wind). Macrocharcoal levels were also regularly below the long-term average and showed little variability in the areas surrounding the site, likely indicative of a managed landscape with a stable fuel load and fire regime, indicative of agricultural land uses (see Anderson and Wahl 2016). Genera commonly found in the less-fire tolerant semi-evergreen and mixed dry forest, such as *Adina/Nauclea* cf., *Lagerstoemia*, *Tetrameles/Elaeocarpus* and Urticaceae/Moraceae, are particularly abundant in the early centuries of the record (Fig. 7.5), and considering Koh Ker today is heavily dominated by the more fire-tolerant dry deciduous forest (see Fig. 4.7), also implies that fire was being actively managed in the landscape through this period (see Ruangpanit 1995, MacKinnon 1997). There is some possible evidence to support Jacques and Lafond's (2004, p.113) proposition that the moat had been widened sometime after 928 AD, as accumulation rates, magnetic susceptibility and the proportion of sand-sized sediments peak slightly in the early to mid-11th century AD, in conjunction with a decline in the organic content being deposited within the moat, potentially indicating localised landscape disturbance and the clearance of littoral or floating vegetation.

There appears to be potential evidence in the PTC3 record to support the mid-10th century abandonment of Koh Ker recorded in the epigraphic corpus (see Aymonier 1900, Parmentier 1939, Jacques and Lafond 2004). Evidence for landscape disturbance, including accumulation rates, sand deposition and magnetic susceptibility all decline and organic content within the moat increases. These changes however, are temporary, and by the late 10th century erosional disturbance in the catchment has resumed. In spite of this apparent lull in human activity in the catchment, there is only minimal evidence of forest recovery (only *Hopea/Shorea*, *Lithocarpus/Castanopsis* and *Lagerstroemia* marginally increase in relative abundance during that period). Furthermore, several indicator species of 'post-disturbance' vegetation assemblages, such as *Eugenia*, *Schleichera oleosa*, and *Pandanus* are at some of their lowest levels in the record, and almost no ferns, sedges (Cyperaceae) or other herbaceous swamp taxa have colonised the moat, suggesting that it was periodically cleared of the ceaselessly encroaching herbaceous swamp and maintained as an open water body throughout this time. Therefore, it is possible that the mid-10th century political abandonment of Koh Ker, said to represent the permanent abandonment of the city and a return to the traditional seat of power at Angkor, amounted to little more than a brief hiatus before agricultural land use and the management of water features continued, unabated.

The period between the early 15th century and the turn of the 16th century appears to mark a gradual transition in land use and occupation in the catchment of the Prasat Thom moat. From the early 15th century AD, bulk and mineral accumulation rates begin to decline, organic content begins to increase and macrocharcoal influx increases in variability. By the 16th century however, a marked shift in the palaeoecological record has occurred. Organic content stabilises at approximately 62%, the proportion of sand being deposited in the moat declines, macrocharcoal influx peaks and both size classes maintain levels consistently above average, and, importantly, substantial increases in the relative abundance of both arboreal and herbaceous 'post-disturbance' taxa are clearly evident. As bulk accumulation rates are very low during this period, much of this shift in the pollen record is likely representative of an ecological transition within and directly adjacent to the moat itself. That is, the contribution of herbaceous swamp taxa pollen and spores, such as those from ferns and aquatics, as well as the input of *Eugenia* and *Schleichera oleosa* growing on the margins of the moat, is likely overwhelming the vegetation signal from the broader catchment. This localised shift, therefore, is strongly suggestive of a decline in the management of the temple's water infrastructure (i.e. ongoing vegetation clearance within and surrounding these water features).

7.5.2 KKPC2

Aymonier (1900) originally proposed that the *trapeang* Andong Preng, from which core KKPC2 was retrieved, may have been associated with the Royal Palace, which, being made predominantly of wood, has now perished in the tropical climate. While excavations conducted near the basin unearthed little evidence to confirm this hypothesis (Parmentier 1939), the existence of a series of laterite foundations close to the eastern margin of the pond that probably supported a series of the galleries for wooden walls (Shimoda et al. 2011), remnants of a laterite foundation for a possible enclosure wall , and plentiful stoneware roof tiles scattered inside the enclosure space suggest the previous existence of a grand wooden edifice at this site (Evans 2013). Given that it stood separate from any particular temple, it was thus very likely the Royal Palace (Evans 2013).

The palaeoecological record here (Fig. 7.13) indicates that the basin had been constructed by at least the early 14th century AD. KKPC2 did not reach the basal sediments of the basin, however, and as such this date is likely conservative. If Andong Preng was in fact associated with the Royal Palace, and considering the timing of royal tenure at Koh Ker during the early to mid-10th century, the basin was likely constructed centuries earlier than this date suggests. Ongoing excavation and maintenance of this reservoir, which is probable if it was utilised regularly by royal personnel, may have eradicated the earlier sediment record. Considering that Unit I of

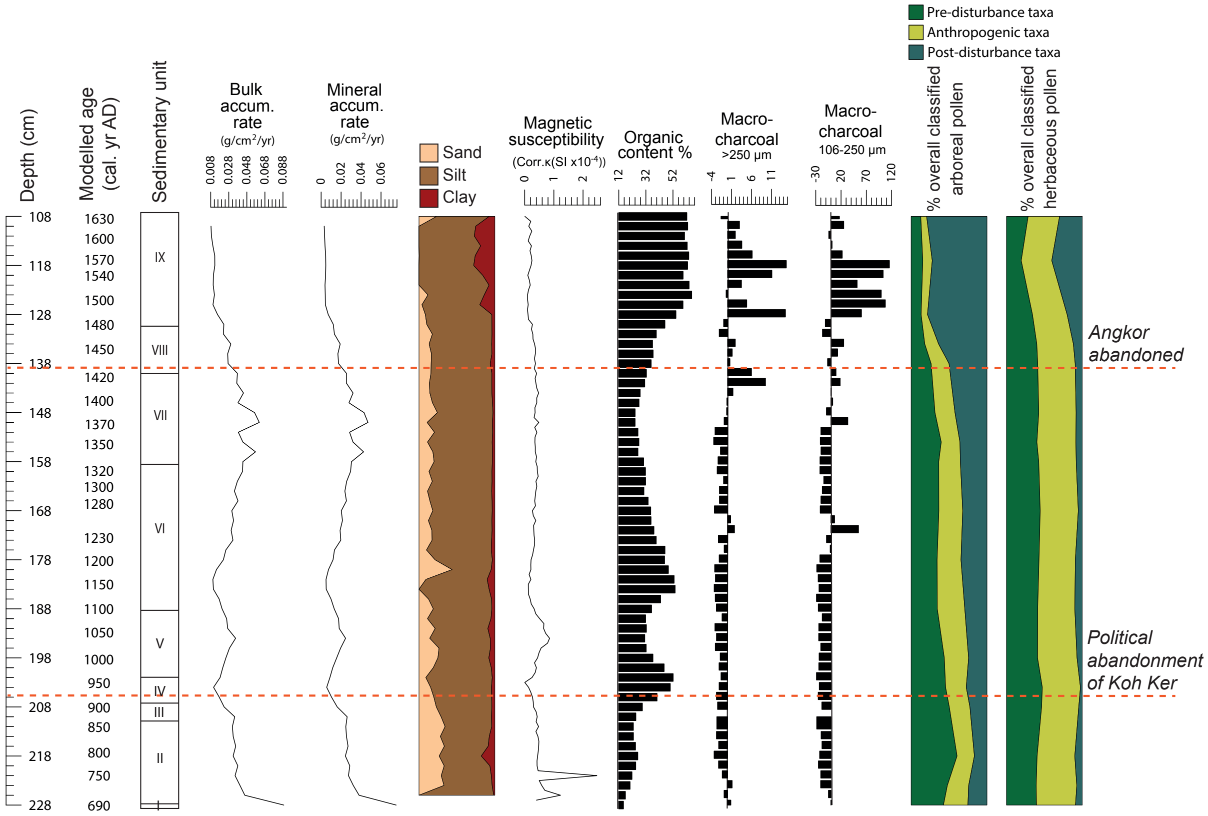

FIGURE 7.12: The combined multi-proxy record for core PTC3.

this core – the shallow basal unit – contains the highest organic content in the record (up to 75.8%), this possibly suggests that the majority of this record occurs after a period of cessation of maintenance and abandonment, when local populations ceased the continual clearance of encroaching vegetation from the basin, and therefore after the period in which the basin was actively utilised. Moreover, while the stratigraphy does not necessarily suggest that a hiatus occurs at the transition between Units I and II (i.e. there is no clear evidence of an unconformity, such as an erosional surface or the truncation of a bedding plane, etc.), drastic changes in the pollen assemblage (largely dominated by 'pre-disturbance' and 'anthropogenic' vegetation assemblages, see Figs. 7.8 to 7.9) and organic content between these two units (i.e. at 1361 AD (65 cm)) suggest that a hiatus may indeed occur here. This further supports the suggestion that prior to the early 15th century the basin was being regularly cleared of encroaching vegetation, and its accumulating sediment excavated. Several families and genera that appear in the pollen record prior to the late 14th century decline dramatically or disappear entirely from the record at that time, including Arecaceae, *Hopea/Shorea*, Euphorbiaceae, Urticaceae/Moraceae, *Macaranga/Mallotus*, and Chenopodiaceae/Amarantheaceae. Moreover, if a hiatus does exist between Units I and II, then the age of the basal sediments is likely older than the modelled date of 1330 AD.

Evidence for human occupation in this palaeoecological record is difficult to interpret. During the late 14th century, the basin appears to have been temporarily overtaken by herbaceous swamp taxa, in particular the ferns *Nephrolepis* cf. and *Stenochlaena* (Fig. 7.11), suggesting that maintenance of the basin briefly ceased. This growth appears to have been cleared by the mid-15th century AD, when a marked shift in the floral assemblage occurs. Here, the relative abundance of arboreal swamp taxa increases and remains very high for the remainder of the record. This dominance is heavily influenced by the overwhelming presence of *Ficus* pollen, which in parts contributes up to 88% of the arboreal pollen component, which is unusually high and thus likely represents the influx of pollen from a tree (or trees) immediately adjacent to the reservoir. The dominant taxa within this swamp or 'post-disturbance' vegetation assemblage varies substantially through time, shifting from *Ficus* to *Eugenia* in the late 18th century AD, and this succession has implications for the timing of abandonment of this city (see section 7.6 below).

Macrocharcoal records show very little variation, largely because charcoal was so scarce in this record. One notable peak in both size classes occurs in the late 18th century and coincides with a temporary decrease in herbaceous swamp taxa, potentially suggesting the occurrence of either a local wildfire or anthropogenic burn in the swamp undergrowth surrounding the basin at this time. This general lack of fire activity ostensibly suggests relatively intensive management in the landscape and the dominance of irrigated agriculture or otherwise heavily managed land uses. However, the lack of local fire activity may have also been influenced by the increasing domination of wet, dense forest or swamp taxa, which would have altered the natural fire regime of the catchment, and therefore fire suppression in the landscape may be the result of ecological, rather than anthropological forcing. Several important taxa that often occur in close association with villages and cultivated land, including *Areca* and other Arecaceae, have disappeared from the record by the early 16th century AD (Fig. 7.9). The 19th century potentially sees the return of regional populations at least, when the microcharcoal record shifts to consistently above average levels, despite a moderately wet regional climate. It is common practice today for local populations to systematically burn the undergrowth of the open dry deciduous forest that currently dominates the region (Evans 2013). While there appears to be very limited evidence of a growing human presence in the pollen record, the overwhelming local swamp vegetation signal may have dampened any resurgence in disturbance or cultivated taxa signalling a return of the landscape to agricultural land uses. However, in spite of the potential growth of populations in the broader, regional landscape, local populations (within or immediately surrounding the Koh Ker temple complex) appear to have remained low to absent, given that macrocharcoal influx remains low (showing no evidence of land clearance to instigate a return to agricultural land uses) and swamp taxa remain relatively abundant, potentially reflecting the continued disuse of the reservoir and its immediate catchment. Finally, organic content, after an initial decrease in the mid-15th century AD, steadily increases throughout the remainder of the record, suggesting the basin was no longer being maintained. The fact that stratigraphic changes are also minimal after the possible unconformity in the mid-late 14th century AD, suggests that excavation of the pond had also ceased, and provides further potential indication that the city was abandoned from this time forward (see Penny et al. 2007).

7.5.3 The combined Koh Ker record

Together these two palaeoecological records strongly support the suggestion that the conventional occupational history of Koh Ker needs to be re-evaluated, in keeping with Evans (2013) in particular. Evidence from the pollen and charcoal records indicate that occupation extends well beyond the reign of Jayavarman IV in the early 10th century AD and very possibly began centuries prior to his declaration of Koh Ker as the royal capital. The PTC3 record suggests that at least one of the major monuments in Koh Ker's temple precinct was undergoing construction as early as the late 7th century AD, towards the end of the pre-Angkorian period. This proposal is potentially supported elsewhere in the city complex; for example, evidence for occupation, in particular earthenware fragments and roof tiles found within the city suggest that occupation of the area may have begun as early as 500 AD (Ly et al. 2010). Stylistic similarities have also been ascertained between earthenwares found at Prasat Boh Lohong in the far southwest

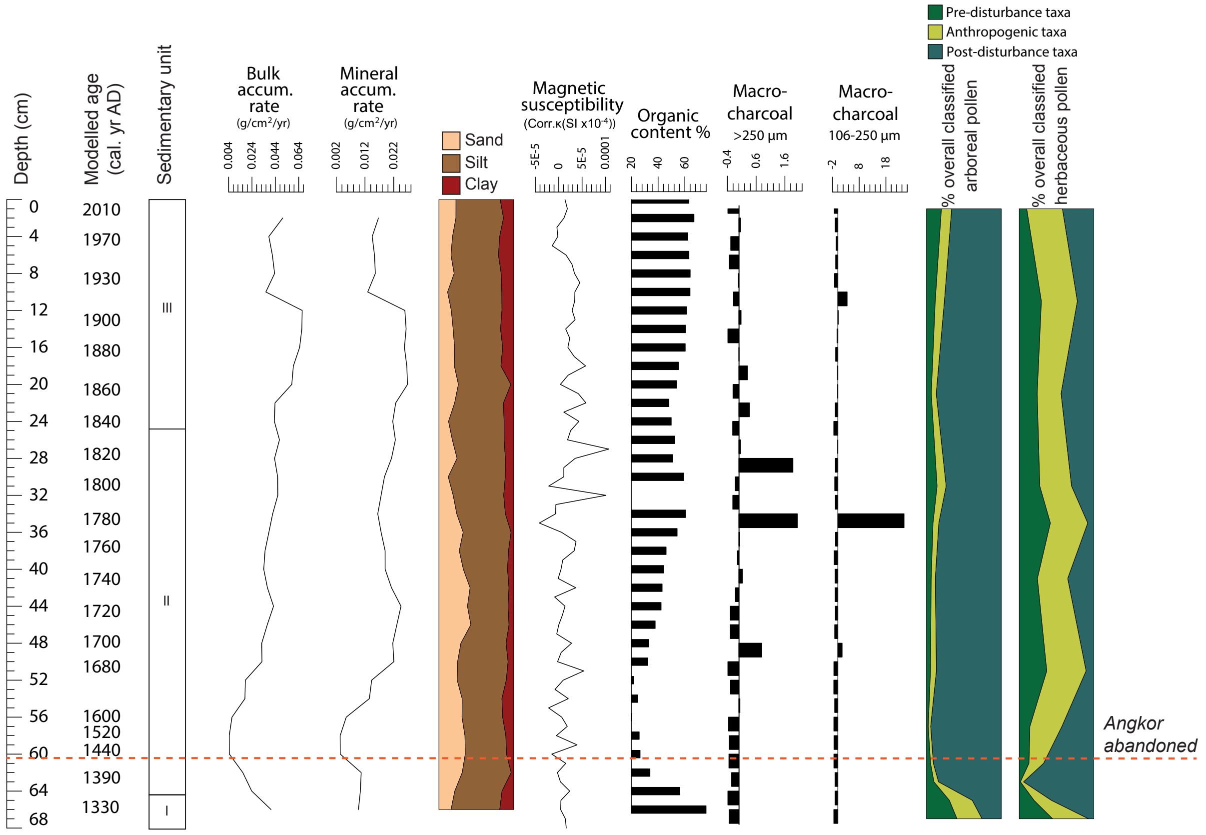

FIGURE 7.13: The combined multi-proxy record for core KKPC2.

corner of the city region, and the pre-Angkorian temple of Prei Khmeng at Angkor, which are commonly found in contexts dating from the 1st to 8th centuries AD (Llopis 2009). However, it is not uncommon for Angkor-period temples to be built within or overlying proto-historic or pre-Angkorian occupation sites (e.g. Prei Khmeng (Pottier 2004)), and thus archaeological context in this case may be poor support for an earlier age of construction for Prasat Thom. It is however, also possible that the moat had been excavated in association with a previous (and subsequently destroyed) structure or temple and had begun to accumulate sediment and autochthonous organic material decades or even centuries prior to the final completion and dedication of the replacement structure, Prasat Thom (much like the 8th century excavation of the moat at Bakong, at Haraiharalaya in Angkor, surrounding the 9th century temple and its 12th century central tower, see Penny et al. 2007).

It is worth nothing that Evans (2013) has tentatively proposed that the ascendancy of Koh Ker in the 10th century AD may be related to a period of anomalously favourable environmental conditions (more rainfall and higher water tables), in this case during the wet period associated with the Medieval Climate Anomaly. Evans (2013) mentions that these circumstances may partially explain the choice of Koh Ker, with its apparently inhospitable landscape, as the location for an important agrarian city in the Khmer city network. A similar pretext could potentially be applied to this earlier date for the city's establishment, as the δ^{18}O hydroclimate record (Berkelhammer et al. 2010) suggests that the region may have been experiencing a particularly wet period between the mid to late 7th century and the early 8th century AD (see Fig. 7.1).

Despite these variations in climate, occupation and use of the city appears to have been maintained throughout the next seven centuries. This is supported by several lines of archaeological evidence, including the late 12th century construction of Prasat Andon Kuk – a hospital to the northeast of the main *baray*, Rahal (Jacques and Lafond 2004), several stages of renovation being undertaken on Rahal (Ly et al. 2010), an abundance of ceramics found within the city that date, using thermoluminescence techniques, to between the 10th and 13th centuries (Sipos et al. 2011), as well as two inscriptions found at Prasat Dan and Prasat Thom that date to 966 AD (K. 674) and 1001 AD (K. 682) respectively (Coedes 1937-1966, Higham 2001, Lustig 2009) – all well beyond the supposed 940-941 AD abandonment of the city. Furthermore, the traditional belief that Koh Ker is a single-period city is based on the stylistic dating of only a small minority of central monuments, when in fact the vast majority of building remains at Koh Ker cannot be dated stylistically beyond identification as 'Angkorian', as they comprise little more than generic, unadorned stonework (Evans 2013). In fact, the results presented here suggest that occupation instead persisted throughout the entire Angkor period, up until at least the late 14th century or early 15th century AD.

Overall, Koh Ker was not an ephemeral city established on pristine land and abandoned two decades later as has been previously insinuated (Aymonier 1900). While the establishment of Koh Ker as the capital city in 921 AD and the relocation from Koh Ker to Angkor in 940-941 AD were undoubtedly significant politically, little may have changed for the communities living and working around the city. While the political influx and the migration of royal officials from Angkor that occurred during the changing seats of power (Coedes and Dupont 1943) would have likely resulted in population and demographic changes in the city, the 10th century royal exodus had less apparent effect and it is clear that local populations remained and the city continued to function. It has been a recurring assumption in the traditional scholarship of the Khmer kingdom that a shift in the locus of power results in the wholesale migration of populations and the abandonment of urban centres (see Lucero et al. 2015), with the 15th century abandonment of Angkor being the classic example. These results from Koh Ker can now complement the research from Angkor and other Khmer centres that have re-evaluated these assumptions and shown that residual populations often remain for decades or centuries after political abandonment (see Bishop et al. 2003, Penny et al. 2006, Penny et al. 2007).

7.6 Temporal dynamics of city network abandonment

The previous section has identified that the occupation history of subordinate cities within Angkor's settlement network was complex and more prolonged than the historical evidence has suggested. In the case of Koh Ker, human activity in the city continued for several centuries beyond the return of the seat of power to the Angkor region before being eventually abandoned, and for Preah Khan of Kompong Svay, the evidence suggests that small, sporadic occupation, potentially by ethnic minority groups, occurred from the mid-14th century following the retraction of Khmer control over the site. The timing of withdrawal by the Khmer across the network, however, is critical to determine if the timing and patterns of the supposed 'urban diaspora' in the Khmer kingdom was consistent regionally. For example, did Khmer withdrawal from secondary centres pre-date, post-date or occur simultaneously with the political abandonment of Angkor?

Evidence for abandonment in the palaeoecological record, particularly in the case of Angkor-period cities, can be most effectively identified through significant changes in the ecology of actively managed water-bodies and their adjacent littoral zones. Firstly, an increase in emergent aquatic plants signals the initial stages of a stabilisation of water levels within a reservoir (Penny et al. 2007). While an abundance of pteridophytes can be indicative of a shift to more humid climate conditions in lowland environments (Bunleng and Lutat 2011), they are also commonly pioneer components of the understorey of forest communities that grow on the alluvial sandy soils adjacent to lakes and watercourses (Theilade et al. 2011) and often dominate the fringes of pond and lagoon systems (Li et al. 2012). Once regular maintenance of an open-water reservoir ceases, these fringing ferns and emergent aquatics are often the first to encroach towards the centre of the water body, and over time these plants can form a dense mat of floating vegetation (Penny et al. 2007). While this occurs, woody swamp forest species begin to colonise the basin margins, and the floating vegetation mat can also eventually establish a relatively stable substrate upon which woody hydrophytic plants can also colonise. If the surface area of the reservoir is large enough to preclude the complete coverage of a floating vegetation mat, sedimentation levels can sometimes be significant enough to reduce water levels to the point where arboreal hydrophytic species can inhabit the central regions of the basin as well.

These developing swamp communities were observed at numerous sites in the field, and example photos of these successional stages are shown in Figure 7.14. In the observed cases across the study sites of north-eastern Cambodia, species such as *Nymphoides*, *Nelumbo nucifera* (sacred lotus), *Nymphaea pubescens* (pink water-lily), and *Pistia stratiotes* (water lettuce) often represent the initial colonising emergent aquatics (Fig. 7.14i), ferns such as *Drynaria quercifolia*, *Nephrolepis*, and *Pteridium* (braken) often comprise the swamp understorey and fern-dominated littoral zone that help develop the floating vegetation mat (Fig. 7.14ii). An exception to this, which is regularly found in the pollen record presented here, may be the epiphytic fern, *Stenochlaena palustris*, which tends to become most prolific only after the establishment of woody shrubs and small trees within a swamp community. The climax stage of swamp forest succession generally includes several arboreal genus/species such as *Eugenia*, *Schleichera oleosa*, *Myrica*, and *Pandanus* (Maloney 1991, Maxwell 1999, Theilade et al. 2011), however at the Koh Ker and PKKS sites, *Schleichera oleosa* and *Eugenia* (Fig. 7.14iv) were particularly dominant in their pollen contributions.

This sequence clearly manifests in the pollen assemblages of all three cores analysed. Figure 7.15 shows the dominant pollen at each stage of the succession, beginning with the emergent aquatics, followed by ferns, *Schleichera oleosa* and *Eugenia*. The year 1431 AD – taken as a provisional, convenient date to represent the political abandonment of the capital Angkor – is also highlighted to compare the timing of abandonment of these secondary centres to the capital. In this case, it should be noted that the near total abandonment of secondary cities is being compared to the potential political-only abandonment of Angkor. Firstly, while this is not an ideal comparison, until a more comprehensive spatial analysis of the palaeoecological record is available for Angkor, such a comparison is impossible. A palaeoecological study conducted at the Bakong temple in the Rolous group, on the periphery of the Angkor region, has indicated that no evidence exists for the wholesale abandonment of the region during the 15th century political migration to port cities in the south of the kingdom (Penny et al. 2007), suggesting that similar residual populations may have remained in the central regions of the capital also. This study revealed instead that while the temple was abandoned and the focus of settlement shifted when the king relocated in the 9th century AD, the site was never completely abandoned and near abandonment of agricultural land uses was only evident from the mid-17th century AD (Penny et al. 2007). Secondly, as discussed in section 3.5, the year 1431 AD has been the conventional date considered for the political abandonment of Angkor, however is based on chronicular evidence that has been labelled “internally inconsistent” (Coe 2003, p. 196). As such, the political abandonment of Angkor might have occurred earlier, and possibly by a century or more (D. Penny, pers. comm.). Thus 1431 AD should be considered the latest possible date of political abandonment of the 15th century capital city. However, until more evidence exists for an alternative date, 1431 AD will be used.

Figure 7.15 indicates that the initial stages of abandonment occur almost simultaneously across

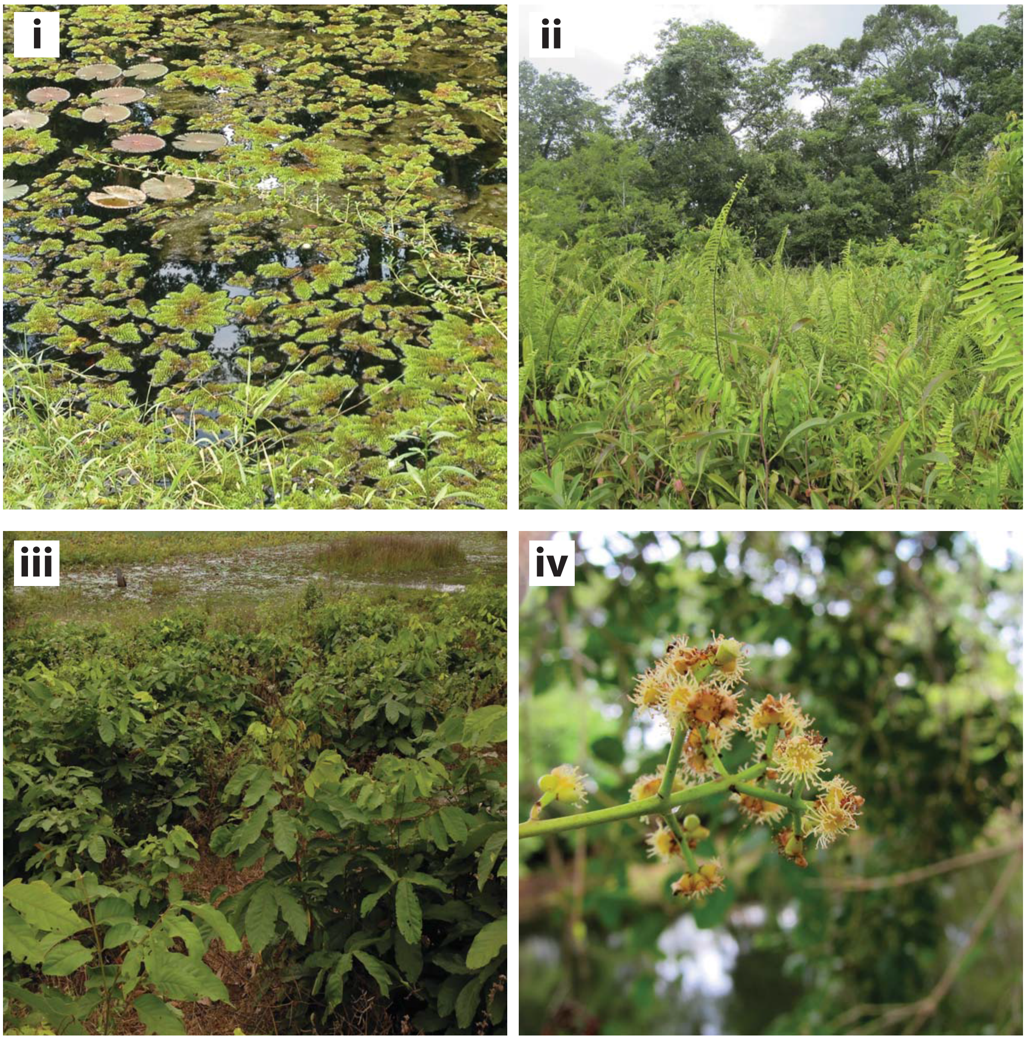

FIGURE 7.14: Example photos of the various stages in swamp succession in and surrounding the water bodies cored: (i) Initial colonisation of emergent, herbaceous aquatics; (ii) dominance of pteridophytes; (iii) early development of woody swamp and riparian forest species, such as *Schleichera oleosa*; (iv) eventual maturing of woody swamp species, such as *Eugenia* spp.

the secondary cities. Sharp increases in emergent aquatics and ferns in each basin coincide in the late 14th and early 15th century AD, suggesting that active management of water resources in the secondary cities had subsided toward the end of Angkor's final political tenure, but prior to the exodus of the king and his court. The development of the mature forest stage of the 'post-disturbance' succession however is more variable across the kingdom. At PKKS, the colonisation of *Schleichera oleosa* peaks a century or more prior to the peak influxes of ferns and aquatics, while *Eugenia* forest develops slowly over the entire record and culminates in a distinct peak in the 15th century AD. In this instance, the size of the basin likely had a strong influence on the succession of the 'post-disturbance' community. Given the large size of the *baray*, colonisation of the floating mat would have only likely occurred along the peripheral margins, and may have been considerably reduced due to fluctuating water levels induced by the extremely varied climate that characterised the 14th and 15th centuries AD. Nonetheless, successional 'post-disturbance' swamp appears to develop unabated from the mid-14th century through to the end of the record in the end of the 15th century.

At Koh Ker, the development of mature 'post-disturbance' forest varies across the city region. While the influx of emergent aquatics and ferns are generally coincident in the palace reservoir and the moat of Prasat Thom, the timing of the growth of swamp forest canopy species differs substantially between the two sites. There is some overlap in the *Schleichera oleosa*, however the influx of *Eugenia* pollen, which begins to peak in the mid-15th century in the moat, is delayed by approximately two and a half centuries in the palace reservoir. There are two potential explanations for this discrepancy. Firstly, these pollen records likely represent spatially disparate episodes of mature swamp vegetation colonisation that, due to site-specific differences (i.e. soil conditions, depth of water table etc), occurred at different points in time. More specifically, the 'post-disturbance' vegetation assemblage indicators captured in the palace reservoir may have been sourced less from the immediate margins of the reservoir and more from the nearby Rahal, where it may have taken decades or centuries for water levels to reduce to the point where mature forest could become established. Furthermore, as Andong Preng was stone-lined, mature swamp forest indicators would have limited opportunity to find purchase within and on the immediate margins of the pond. However, it should also be noted that the calibrated age ranges sampled closest to the peaks in ferns and emergent aquatics in both Koh Ker cores potentially overlap, suggesting that these peaks may, in fact, be simultaneous. The peak in ferns in PTC3 occurs between 138 and 108 cm, which aligns closest with radiocarbon ages sampled at 111-112cm (D-AMS 006501), returning an age of 566 ± 22 and 125-126cm (D-AMS 007111), returning an age of 400 ± 25. The overall calibrated age range of these two samples combined is 1327 AD to 1622 AD. In the KKPC2 core, the peak in ferns occurs between 67 and 61 cm (D-AMS 007110), which falls after the basal radiocarbon dating sample taken at 60-61 cm that returned a calibrated age range between 1400 and 1445 AD (see Table 6.1). The significant temporal disparity occurred in the final results (see Fig 7.15) because the Bacon model identified sample D-AMS 006501 as an outlier, and therefore the peak in ferns occurred in PTC3 in the (modelled) mid-14th century, almost a century prior to KKPC2. If, however, sample D-AMS 007111 was alternatively identified as the outlier (they present an age inversion at the top of the core and could conceivably both be considered as the outlier, however presumably to maintain a relatively constant sedimentation rate, Bacon identified the older date as the preferable outlier), then the modelled age would have fallen between the mid-14th and the beginning of the 15th century AD. Nevertheless, whether or not the colonisation of mature 'post-disturbance' forest developed synchronously across space at Koh Ker, the initial signs of abandonment (i.e. colonisation of herbaceous swamp forest and aquatic taxa within the water reservoirs) began at Koh Ker in the late 14th century AD, and the development of significant patches of mature, 'post-disturbance' forest surrounding important temple infrastructure continued throughout subsequent centuries.

It is also worth noting that at both PKKS and Koh Ker the dramatic increases in 'post-disturbance' taxa (herbaceous and arboreal) occur concurrently with equally drastic decreases in extra-regional forest taxa, indicating an important spatial shift in the dominant pollen source occurred at this time. *Eugenia*, in general, is insect-pollinated and so often travels only limited distances from its source. Extra-regional forest taxa, in this case represented predominantly by *Pinus*, *Celtis* cf. and *Quercus* cf., are wind-pollinated and are generally transported over long distances. A high proportion of such extra-regional and regional pollen in the pollen record reflects poor local pollen production, and is therefore potentially a good proxy for a sparsely forested landscape (Solomon 1976). As such, the shift from high relative abundances of extra-regional forest taxa to locally-sourced forest taxa marks the point where the local catchment has transitioned from a sparsely forested, anthropogenic landscape to one that is heavily forested and less impacted by anthropogenic land uses.

Overall, the evidence suggests that the attenuation of land use and eventual near or total abandonment of the Khmer at both Preah Khan of Kompong Svay and Koh Ker began sometime in the mid to late 14th century AD, prior to the political abandonment of Angkor in the mid-15th century AD. These spatial dynamics of city abandonment has important implications for the operation of the Khmer city network and the relationships that were maintained between the primate city and its secondary centres, which will be discussed in the final chapter.

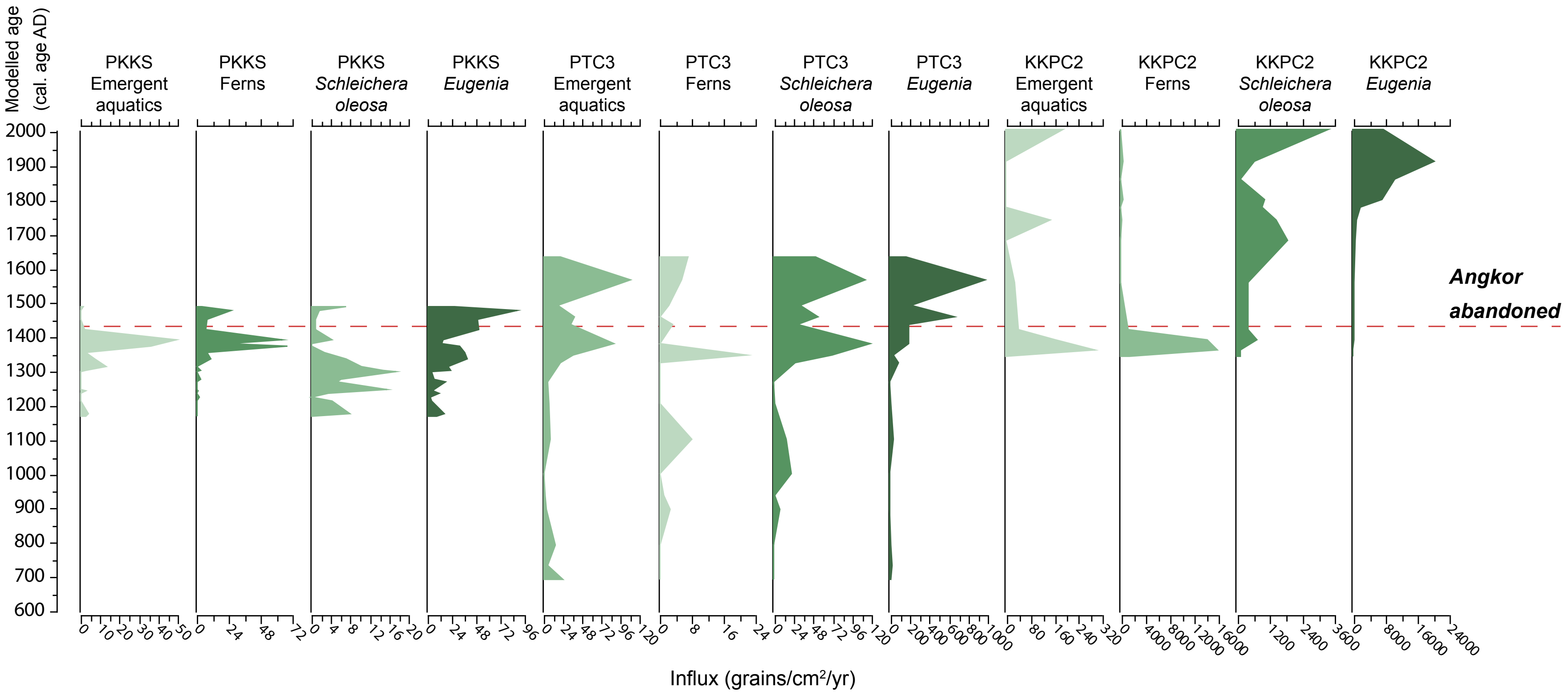

FIGURE 7.15: Swamp forest succession indicator specimens plotted in reference to the 1431 AD – the year assumed to represent the political abandonment of Angkor.

7.7 Chapter conclusion

This chapter has synthesised the palaeoecological proxy analyses presented in Chapter 6 and has interpreted this synthesis to present an occupation history of two important secondary Angkor-period cities and the population dynamics operating at the scale of the Khmer city network. The most pertinent results discussed here include the charcoal and post-disturbance pollen records. While higher charcoal influx values are generally associated with increases in anthropogenic activity (e.g. Maloney et al. 1989, Maloney 1991, Stanley and Bernhardt 2010) in the context of intensively managed agricultural land uses of Angkor-period Khmer cities, human presence is instead represented here as a reduction in fire activity due to fire suppression. Secondly, the influx of both herbaceous and arboreal swamp forest species in and surrounding the water bodies at these sites has been interpreted as indicative of a reduction in Angkorian land and water management practices and the near abandonment of the Khmer from these cities. This analysis has revealed that both secondary cities were abandoned roughly synchronously and prior to the political abandonment of the Angkorian capital (Fig. 7.16). Overall, this discussion has revealed evidence that has proven significant for several fundamental aspects of the settlement history for secondary Angkor-period centres, including the date of construction for several key temple sites, as well as the longevity of these cities beyond the assumed timeframes that conventional historiography suggests.

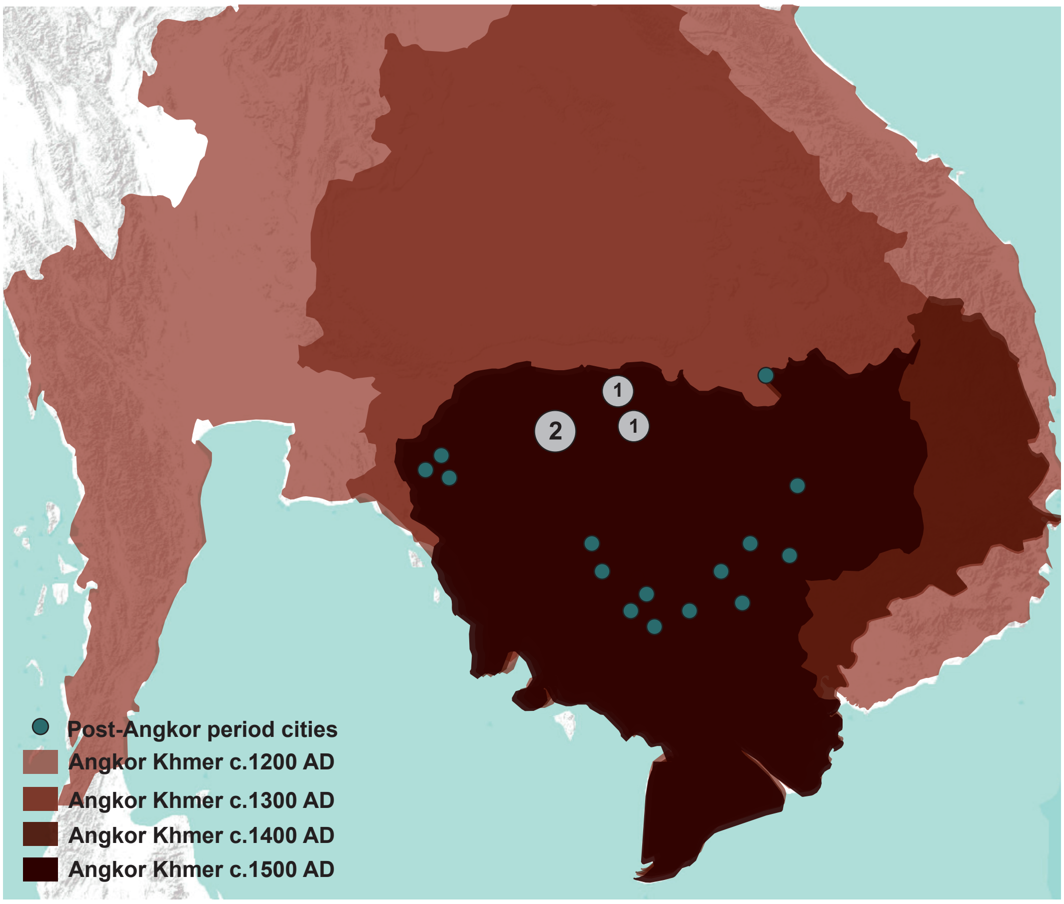

FIGURE 7.16: Map showing sequence of 'urban diaspora' from Angkor period settlements (light grey) and migration to post-Angkor period cities (blue-green) on the periphery of the kingdom. Map modelled on that provided by D. Brotherson in Lucero et al. (2015).

8 Conclusion: The relationships and interdependencies operating within the Khmer city network

8.1 Introduction

This thesis set out to decipher the spatial response of a complex, networked civilisation following the abandonment of its social, political and economic centre. It had the following overarching aims:

- to determine the spatial dynamics of transformation in the broader city network of a complex society, following significant disruption in the network, for example the removal of an administrative or economic capital
- to explore what these dynamics reveal about how these city and settlement networks operated mechanistically, and what makes a complex, networked society vulnerable to collapse or transformation

This chapter will answer the second research objective, by determining what the population dynamics of secondary cities in the Khmer city network reveal about the relationships and interdependencies that existed between the primate city and its broader city network prior to transformation in the Khmer kingdom in the 15th century AD. This discussion will also explore how these relationships affected the stability of the settlement system and its response to network disruption. The chapter will conclude with an overall summation of this thesis and identify opportunities for further research.

8.2 The relationships and interdependencies operating between Angkor and its city network

The previous chapter has determined that the Khmer eventually abandoned both Preah Khan Kompong Svay and Koh Ker, with abandonment at these regional centres occurring prior to the accepted, but provisional date for the political exodus at Angkor. This implies that the 15th century transformation that occurred in the Khmer kingdom did, in fact, involve an 'urban diaspora' (see Lucero et al. 2015) from a number of major population centres on the northern and central plains north of the Tonle Sap, rather than fragmentation into a series of smaller regional and semi-autonomous Khmer settlements. However, the timing of the abandonment across the kingdom clearly differed, and on the scale of the city network it appears that the course of transformation occurred from the 'outside in'. This outcome suggests that the processes and dynamics of the proposed 'urban diaspora' varied between the capital and its secondary centres. However, the timing of abandonment at both the secondary centres analysed here was remarkably simultaneous, implying that the type of relationship and degree of interdependency that these two secondary centres maintained with the capital Angkor may have been similar.

The abandonment of both Koh Ker and Preah Khan of Kompong Svay occurred prior to the disruption of the communication, political and economic networks that had sustained the extensive kingdom for several centuries, if the political abandonment of Angkor is taken as the point in time when this disruption occurred. However, this pattern of abandonment suggests the occurrence of two possible scenarios throughout this period, with each providing alternative explanations for the kingdom's vulnerability to transformation at this time. Firstly, the spatial sequence of 'urban diaspora' suggests that perhaps the disruption to kingdom-wide networks had been instigated earlier than assumed, sometime in the 14th century, as political, economic and environmental pressures were mounting in the capital. If this was the case it appears that, as the power of the Angkor elite was weakening or being directed elsewhere (possibly outside of the network), the retraction of overarching control structures began to occur, which swept any vital physical nodes in those networks along in its wake. In other words, as territorial control retracted, populations began to migrate (*Scenario 1*). Khmer territory had begun contracting as early as the 13th century in the northern and western outskirts of the kingdom (Lieberman and Buckley 2012), so it seems plausible that retraction closer to the capital would be delayed until subsequent centuries. However, while loss of territory on the outskirts of the kingdom in the 13th century appears to have been the result of outside force (Lieberman 2003), the abandonment of secondary centres on the northern central plains, according to the evidence presented here, appears to be more likely the result of forces internal to the Khmer kingdom (i.e. structural and economic vulnerability exposed by climate instability). As such these centres remained depopulated or were opportunistically utilised only temporarily following Khmer exodus (as was likely the case with Preah Khan of Kompong Svay).

Alternatively, it may instead have been the mid- to late-14th century decline of secondary centres throughout the kingdom that provided the impetus for decline and abandonment in the capital and the subsequent disruption of political and economic networks (*Scenario 2*). It has been noted by many that both Preah Khan of Kompong Svay and Koh Ker were established in landscapes that were less favourable for large and productive agrarian populations than the fertile floodplains of Angkor. As such, the intense climate instability that beset the Southeast Asian mainland from the mid-14th century (Buckley et al. 2010) would likely have impacted these cities severely, and perhaps more severely than Angkor itself, where, initially at least, the effects of this climate change may have been mitigated by the large-scale water infrastructure networks in operation there. Evidence suggesting an anthropogenic response to increasing aridity (damming of a lake) at the beginning of the 14th century AD has been found at another peripheral secondary Angkor-period settlement, in northeast Thailand (Yamoah et al. 2017), suggesting that the effects of climate-induced water shortages were manifesting across the kingdom at this time.

This second scenario, the fact that the peripheral cities were abandoned prior to Angkor, may also be testament to the importance of place and, in particular, the environmental setting and materiality of a settlement – in this case the proximity to freshwater resources and the efficacy of the large-scale water infrastructure network at Angkor for ameliorating extremes in climate. The centuries during which abandonment transpired, as discussed, were characterized by a series of prolonged droughts interspersed with intense pluvial episodes, and would have presented severe challenges for an agrarian society in an already dry, destabilised landscape. The proximity to the Tonle Sap, the relative shallowness of the water tables, and the maintenance of the large-scale water infrastructure network may have enabled the persistence of the capital even after other interconnected cities in less favourable landscapes underwent a net outward migration of people. A similar outcome may have eventuated in the Mayan collapses between 750 and 950 AD – where spatial differences in environmental setting (i.e. access to groundwater) likely influenced the persistence of select cities in the face of intense droughts (Peterson and Haug 2005, Dunning et al. 2012).

Either scenario, however, illustrates that a strong interdependency must have existed between the major cities in the Khmer settlement network. Relating this city network-wide 'urban diaspora' to Kolata's (2006) framework that describes the operating control ideologies that precede particular collapse and transformation scenarios (see section 2.6), it would appear that the Khmer kingdom was operating under a highly centralised and interdependent style of authority at its height, with the capital maintaining 'hegemony and sovereignty' relationships with its peripheral populations. Under such rulership, two potential outcomes could arise following disruption, either the re-emergence of a faithful rendering of the original polity, or near total abandonment and collapse, leaving behind an almost unrecognisable landscape. In the case of the Khmers, it could be argued that a hybridised scenario eventuated, in that near abandonment of many of the Angkor-period cities occurred, to be followed by relocation and the reestablishment of cities on the southern periphery of the kingdom, which maintained similar political, ideological and economic institutions, albeit largely reduced in scale.

If a style of hegemony and sovereignty was operating in the Khmer kingdom, then the level of control emanating from the capital must have been very high, especially during the 14th century AD. This, potentially, may have been in response to increasing levels of scarcity or hardship in the capital under growing economic and environmental pressures and potential difficulties with infrastructure. The era of territorialisation and expansion appears to be in decline by the end of the 13th century, and the breakdown of the water management network had become apparent in the capital. Modifications and additions to the network had ceased by the 13th century AD (Fletcher et al. 2008), and significant alterations to the natural hydrology of the landscape, and the excavation of unnaturally linear channels that went against the topographic slope produced issues of erosion and sedimentation and ultimately functionality losses and debilitating inertia towards the end of Angkor's tenure (Groslier 1979, Fletcher et al. 2008, Kummu 2009). Under such a scenario, the elite may have attempted to turn outward and extract greater resources from its peripheral centres to maintain the needs of the capital. This level of interdependency would likely have seen diversity and flexibility losses in the peripheral settlements and ultimately rendered a large and fundamental node like Angkor become dependent on its smaller interconnected nodes in the network (see also Buldyrev et al. 2010, Barthelemy 2011). How long this interdependency had been operating though, and whether or not it had only reached its height just prior to the political abandonment of Angkor, remains unknown.

This narrative illustrates how the Khmer kingdom was indeed operating as an interdependent spatial system, where the capital and its interlinked secondary centres maintained a co-dependency between themselves, the material, economic and political networks that sustained these relationships, as well as the broader environmental context. System stability persists when the needs of both the core city and its peripheral centres are being met (Eisenstadt 1963), and thus in the event of climate-induced stress and scarcity, in all or either of the city centres, the settlement networks disintegrated and the system transformed. High levels of integration, between the material and socio-political world (see also Fletcher 1995) as well as between the interlinked city network, seemed to have encouraged prosperity throughout much of the kingdom's height, as this interplay was likely able to buffer the kingdom against less severe disturbances. However, this same integration saw the effects of more severe environmental or economic stress, when it occurred, to propagate throughout the entire network. Now that Angkor could no longer reliably secure resources from its secondary centres, the king and his elite may have decided to desert the city and its infrastructure, as well as restructure the administrative institutions that previously connected the settlement network and aided the kingdom's dominance of the mainland (see also Yoffee 2005, Nichols and Weber 2006).

8.3 Preconditions to transformation in the Khmer kingdom

As discussed in Chapter 3, by the 11th and 12th centuries AD the kings of Angkor reigned over an increasingly extensive, and increasingly integrated kingdom, and governed largely from political bases of increasing infrastructural complexity and settlement uniformity. By the 13th century, the king was administering over 90 provincial capitals, according to the visiting Chinese diplomat Zhou Daguan (Zhou 2001). The idea of kingship had become more entrenched, a progression reflected in the inscriptions; where only a third during the pre-Angkorian period make mention of a king, during the Angkorian period it was notable for a king not to be referenced (Jacques and Lafond 2004). These references additionally acknowledge the growing magnitude of the king's power, with the ruler becoming more commonly described as the universal monarch (*chakravartin*) or god-king (*devaraja*) (Coedes 1968). As the Khmer civilization approached statehood, it became progressively isolationist, focusing less on (but not excluding) external trade and more on an internally-generated agrarian economy (Hall 1975, Stark 2006) that was supported, in part, by increasingly interconnected hydraulic infrastructure networks and newly developed formal road networks (Hendrickson 2010). Hindu and Buddhist belief systems propagated at a new intensity, aided by more rampant construction of monumental architecture and other artistic works. These ideological networks became more systematized, bureaucratic and hierarchical, allowing the segmentation of the king's power further afield and the diminishing of local autonomies (although local economic autonomy likely remained (see Lustig 2009)). The installation of such systematic ideological and labour networks, funnelling agricultural surpluses through a system of central temple systems, would very likely made significant reductions to the autonomy, diversity and flexibility of subordinate village communities.

However, whether or not the Khmer kingdom had reached a point where, in Wittfogel's (1953) terms, "the cumulative strength of superior power. . . result[ed] in a single autocratic centre of organisation and decision-making" (p. 104) cannot easily be determined. The previous section, however, illustrated that the kings of Angkor likely formed relationships with their city network through a leadership style that Kolata (2006) refers to as 'hegemony and sovereignty', which would imply that a very high degree of centralised control had been achieved.

Such highly centralised control, applied across such a highly interdependent city network (i.e. high vertical and horizontal network integration), meant that any change that occurred in the power dynamics operating in the system would have had system-wide ramifications. This logic presents an alternative way of viewing *Scenario 1* above. The fact that the Khmer abandoned the secondary centres first also may suggest that centralised political control in the capital had begun to weaken substantially by the 14th century AD, and the effects of which initially manifested as the waning of power in peripheral territory. That is, as power in the primate city weakened, so were its control relationships with the broader kingdom, which had ramifications on the linked, dependent components, i.e. the secondary city centres, at a regional (system) scale. Therefore, it was likely the combination of a highly centralised control system managing a highly integrated city network that created the internal preconditions for drastic system-wide transformation to occur when it did (see Adams 1978, Van Buren 2000).

If, however, the secondary centres were abandoned first due to differential environmental and material/technological settings, as discussed in *Scenario 2* above, this may also be partly the result of this high degree of control centralisation. As discussed in Chapter 2, Butzer (1980) and Tainter (1988) both attest to the problematic nature of highly centralised society, with Butzer maintaining that in such cases, dominating, but non-productive, control structures have the ability to strain the productive capacities of supporting subsystems (secondary cities in the case of the Khmer kingdom) in order to meet centrally determined needs, and in doing so, render the society susceptible to collapse. Such a system may operate productively, particularly where technological and administrative capabilities enhance the ability for resource exchange, however such productivity can mask an underlying vulnerability that, in the case of the Khmer kingdom, was uncovered during the climate stress of the 14th and 15th centuries AD. Climate variability was then able to destabilise the weakened system and lead to an 'urban diaspora', beginning first in the outer settlements and followed by the primate centre. Similarly, applying the views of Tainter (1988), the ever-increasing levels of centralisation that occurred in the Khmer kingdom from the 9th to 13th centuries would have been a very effective problem-solving strategy during the administration and maintenance of a kingdom during increasing territorialisation. However, eventually a point was reached where territory began shrinking, rainfall became more variable and thus water management infrastructure became more problematic, agricultural productivity may have begun to decline kingdom-wide, and therefore a highly centralised kingdom had become less effectual and more costly to maintain. Eventually, the king and his administration may have seen city abandonment, migration and down-scaling and restructure of the settlement network as the most effective strategy moving forward.

Overall, this condition of highly centralised control, combined with an ambitious focus on territorialisation supported by highly interdependent physical, ideological and political networks, likely fostered a growing vulnerability in the Khmer kingdom between the 9th and 13th centuries AD. Therefore, the severe climate stress that befell the region during the 14th and 15th centuries exposed a society in a weakened state, and possibly revealed the inherent vulnerability of creating an agrarian economy which, at the city network scale, depended on resource productivity in an unfavourable landscape. Eventually, this climate stress culminated in the restructuring of administration and settlement networks in the 15th century AD, and a kingdom-wide transformation in which the Khmer kingdom behaved as an interactive spatial system (see Tainter 1988, Chase-Dunn and Grimes 1995).

8.4 Summary and future research

This research has applied a palaeoecological approach to analysing the spatial occupation dynamics of two regional Khmer cities during an important transition period in Cambodian history. This research aimed to test a key assumption that has prevailed in Khmer scholarship, namely that the 15th century political abandonment of Angkor coincided with the wholesale migration out of urban centres across the kingdom. By testing these assumptions regarding the occurrence and timing of this 'urban diaspora' (Lucero et al. 2015), this research has been able to unpack the spatial dynamics of occupation for a complex, networked society in response to a period of destabilisation and transformation.

This study is of significance because it illustrates the degree to which the palaeoecological approach can be a highly informative tool for reconstructing occupation and land use dynamics in historical settings or time periods where the traditional archaeological and written records have been insufficient. Specifically, this study has uncovered the settlement histories of two key secondary cities within the Khmer city network, namely Preah Khan of Kompong Svay and Koh Ker, from their period of active construction through to either the post-Angkor period or the present day. Overall, the occupation histories presented here show that these cities experienced complex, enduring histories and maintained relatively intensive populations, long after the historical records claim they were abandoned. The history and use of Koh Ker, in particular, needs to be re-evaluated in regards to its conventional assessment as a single, 20-year period tenured city. In this case, it appears that the mobility of the Khmer king and his administration did not invariably represent similar mobility in local, urban-agrarian populations. The evidence suggests, however, that both cities did eventually undergo near or total abandonment, almost concurrently, during the century prior to the political abandonment of Angkor. In the case of Preah Khan of Kompong Svay, the possible opportunistic reuse of the city by surrounding minority populations following Khmer evacuation has also been captured in this analysis.

These spatial dynamics of transformation in the city network suggests that a high degree of integration and interdependency had either been established or had developed between Angkor and its secondary centres by at least the 14th century AD. As such, in the event of severe and destabilising climate change in the 14th and 15th centuries, this interdependent city network unravelled – in this instance from the outside in – as the overarching economic and political networks that had sustained the kingdom dissolved or relocated, and territory retracted. Overall, this research supports the idea that a high degree of socio-political complexity, excessive territorialisation, the highly integrated organisation of physical space, and highly centralised, potentially autocratic power mechanisms, can be a precursor to political and economic disruption that leads to regional-scale transformation in a settlement system.

This investigation of transformation following disturbance at the city-network scale has important implications for the management of contemporary urban and social networks. It is clearly important that as urban, economic and institutional networks are becoming increasingly global in scale, increasingly integrated, and are becoming controlled by increasingly centralised bureaucracies – where the distinction between economic and political control is often blurred, it is vital that efforts are undertaken to maintain a degree of independence, flexibility and diversity in subordinate, interconnected subsystems and cities. This research has supported the research elsewhere (Flannery 1972, Rappaport 1977, Dunning et al. 2012) that insists that too high a degree of interdependency and uniformity within a settlement network evidently leads to a lack of resiliency in the event of disturbance and destabilisation.

Moving forward, there are several opportunities for further research that could augment these findings. Firstly, and most obviously, the palaeoecological record needs to be reconstructed for additional Angkor-period cities within the city network, in order to test the narrative of kingdom-scale transformation presented here. Secondly, the palaeoecological record of these secondary centres should be compared to a more spatially comprehensive palaeoecological analysis of the cities within Angkor, to gain a better understanding of whether or not the 15th century political abandonment of Angkor coincided with a true 'urban diaspora' as assumed. Such an analysis from the city of Rolous, in the southeast corner of the greater Angkor region, provided no evidence for such an exodus. Finally, a similar reconstruction of the occupation dynamics for the post-Angkor or 'middle period' cities, on the periphery of the kingdom, is also needed to better understand the spatial dynamics of Khmer migration and settlement, at the kingdom scale, beyond the Angkor period and its transition towards modernity.

Finally, the timing of the migration of the Khmer administration out of Angkor, and any agricultural populations that may have followed, needs to be refined. If the evidence shows that the transition away from Angkor as a major settlement and political hub occurred prior to 1431 AD, then the arguments presented here may need adjustment. The framework presented in this thesis, which argues for a broader spatial scale of analysis for civilisations undergoing transformation, will, however, remain highly constructive for understanding the power dynamics and interdependencies operating within a networked settlement system. Moreover, if the evidence uncovered suggests Angkor underwent significant depopulation up to (but not exceeding) a century prior to 1431 AD (i.e. up to the mid-14th century AD), then the arguments presented in this thesis still hold. Even if near abandonment of Angkor and its secondary centres occurred simultaneously, applying the model presented in this thesis, this spatial dynamic also implies that a high degree of interdependency and centralised power had developed in the kingdom prior to transformation.

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A Core logging supplementary data

A.1 Glossary for stratigraphic descriptions

TABLE A.1: Glossary for stratigraphic descriptions used in core logging protocols: comparable terminology between the SSDS (2017) and the Schnurrenberger et al. (2003) protocols. PKKS-C1 core logs were translated into the Schnurrenberger et al. (2003) terminology for consistency (see 5.3 and 6.5)

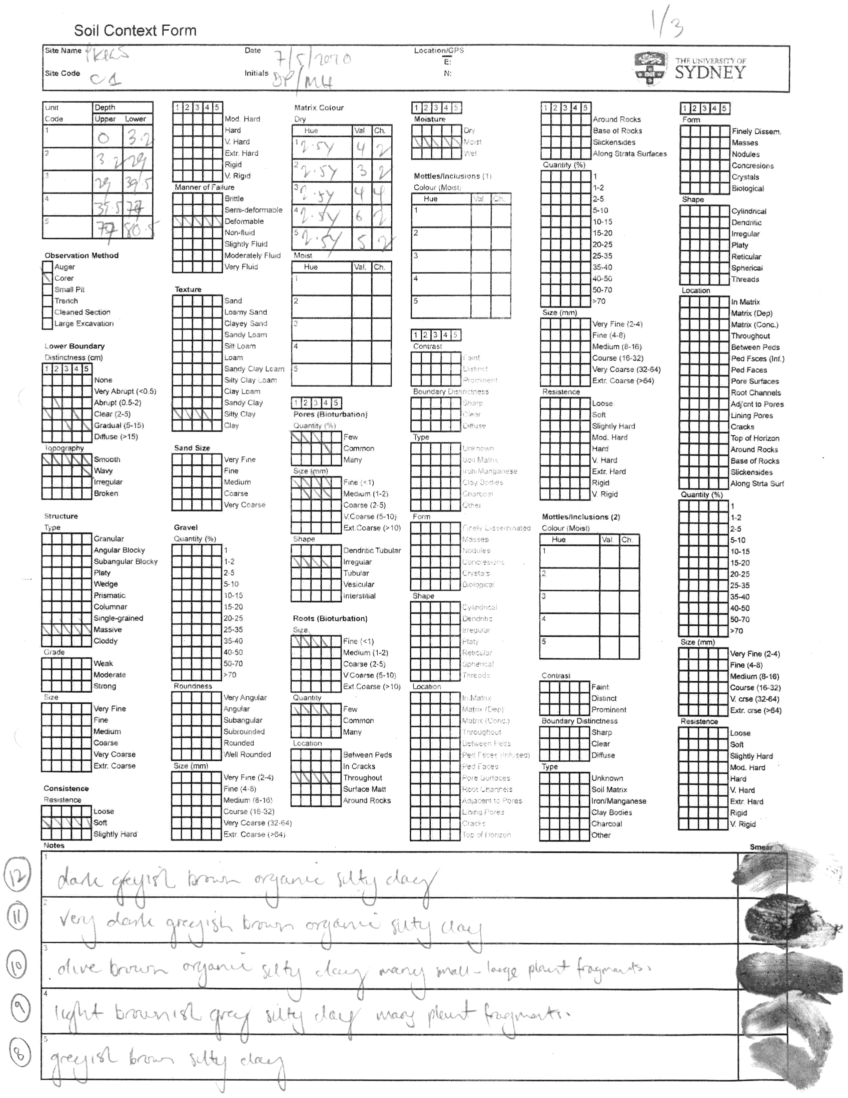
Category	**SSDS (2017) terminology**	**Comparative Schnurrenberger et al. (2003) terminology**
Boundary distinctness	Very abrupt (< 5 mm)	Sharp (< 1 mm)
	Abrupt (5-20 mm)	Diffuse (1-10 mm)
	Clear (20-50 mm)	
	Gradual (50-150 mm)	Indistinct (> 10 mm)
	Diffuse (> 150 mm)	
Boundary topography	Smooth	Planar/Gradational
	Wavy	Wavy/Undulose
	Irregular	Wavy/Undulose
	Broken	*No comparison*

A.2 Smear slide descriptions

TABLE A.2: Smear slide descriptions for Koh Ker cores

Core	**Depth (cm)**	**Sediment description**
PTC3	0.10	Unconsolidated herbaceous peat with abundant humic, thin, small fragments of amorphous organic matter. Contains frequent rootlets.
	0.50	Unconsolidated herbaceous peat with abundant humic, thin, small fragments of amorphous organic matter. Common very humic, amorphous clumps of organic matter about 70m across. Contains possible rootlets.
	0.99	Unconsolidated herbaceous peat with abundant humic, thin, small fragments of amorphous organic matter. Common very humic amorphous clumps of organic matter about 70um across. Contains possible rootlets.
	1.10	Unconsolidated herbaceous peat with abundant humic, thin, small fragments of amorphous organic matter. Common very humic amorphous clumps of organic matter about 70um across. Contains possible rootlets.
	1.30	Herbaceous peat with abundant partly humic thin and small clumps of organic matter, frequent single-celled organic matter. Contains possible rootlets.
	1.50	Sapropelic, sandy mud with small clumps of partly humic organic matter.
	1.70	Sapropelic, sandy mud with abundant humic, thin, small fragments of amorphous organic matter. Common very humic round clumps of organic matter.
	1.90	Sapropelic, sandy mud with frequent partly humic thin and small clumps of amorphous organic matter. Infrequent small clumps of very humic organic matter.
	2.03	Sapropelic, sandy mud with frequent humic thin and small clumps of amorphous organic matter. Infrequent small clumps of very humic organic matter.
	2.10	Sapropelic, sandy mud with abundant humic small clumps of organic matter and clastic material.
	2.18	Sapropelic, sandy mud with abundant humic small clumps of organic matter and clastic material.
	2.28	Sapropelic, sandy mud with humic small clumps of organic matter abundant and silty clays.
KKPC2	0.024	Herbaceous peat and sandy mud with abundant humic, fragmented organic matter.
	0.300	Herbaceous and woody peat and sandy mud with abundant, humic amorphous organic matter. Includes some rootlets.
	0.500	Herbaceous and woody peat and sandy mud with abundant, humic amorphous organic matter.
	0.670	Sapropelic, sandy mud with abundant humic fragmented organic matter and silt-clays.

A.3 Original sediment core logs



Soil Context Form 1/3

Site Name PKKS
Site Code C1
Date 7/5/2020
Initials DP/MH
Location/GPS
E:
N:

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Unit Code	Depth Upper	Depth Lower
1	0	3.2
2	3.2	29
3	29	39.5
4	35.5	77
5	77	80.5

Matrix Colour
Dry

Hue	Val.	Ch.
1 2.5Y	4	2
2 2.5Y	3	2
3 2.5Y	4	4
4 2.5Y	6	2
5 2.5Y	5	2

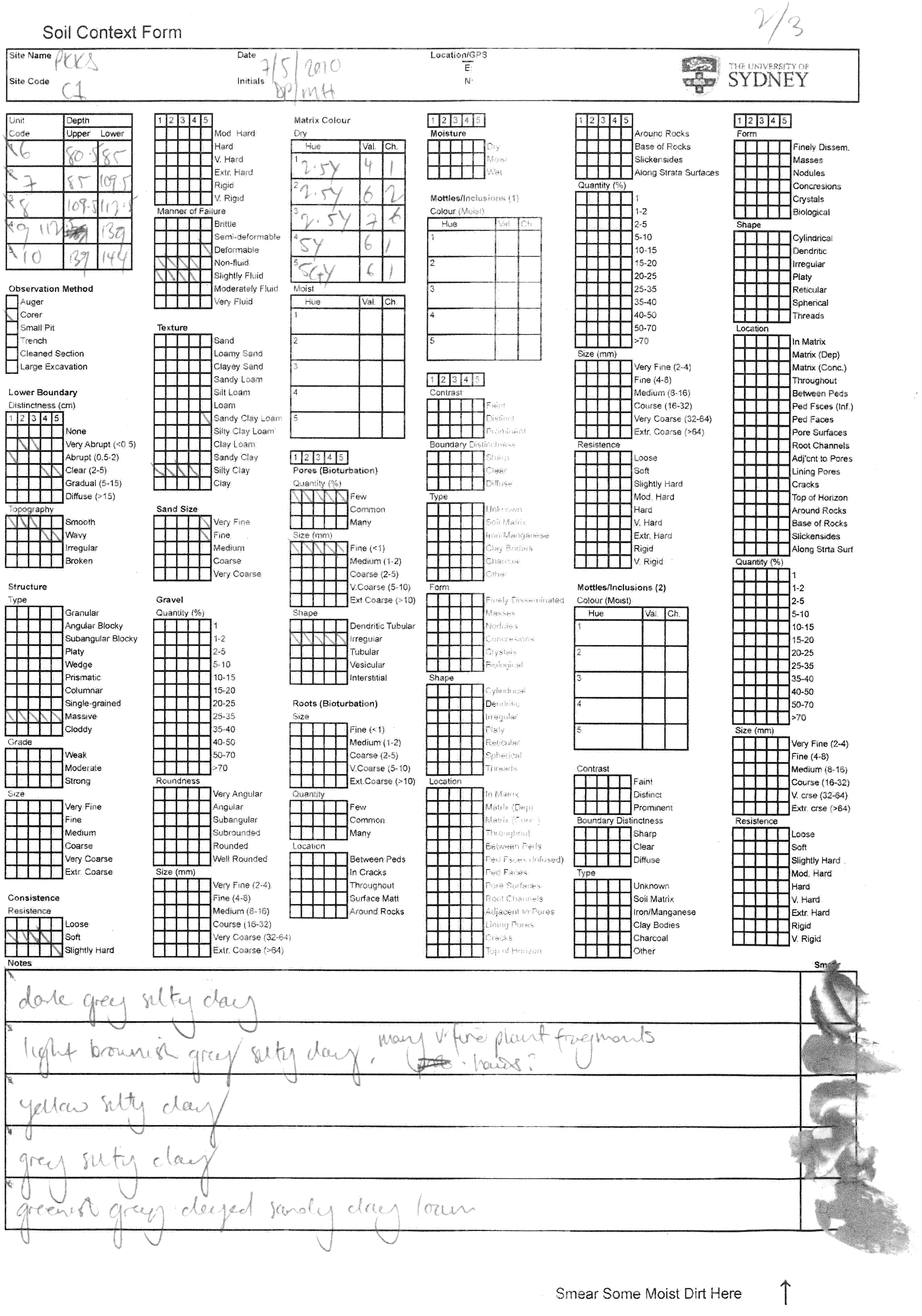
Observation Method
☐ Auger
☑ Corer
☐ Small Pit
☐ Trench
☐ Cleaned Section
☐ Large Excavation

Notes

		Smear
⑫	1 dark greyish brown organic silty clay	
⑪	2 very dark greyish brown organic silty clay	
⑩	3 olive brown organic silty clay many small - large plant fragments.	
⑨	4 light brownish grey silty clay many plant fragments.	
⑧	5 greyish brown silty clay	

Smear Some Moist Dirt Here ↑

FIGURE A.1: Original sediment core log for PKKS-C1.



Soil Context Form

2/3

Site Name PKKS
Site Code C1
Date 7/5/2010
Initials DP/MH
Location/GPS
E:
N:

THE UNIVERSITY OF SYDNEY

Unit Code	Depth Upper	Depth Lower
1 6	80.5	85
2 7	85	109.5
3 8	109.5	117.5
4 9	[illegible]	139
5 10	139	144

Matrix Colour
Dry

	Hue	Val.	Ch.
1	2.5Y	4	1
2	2.5Y	6	2
3	2.5Y	7	6
4	5Y	6	1
5	5GY	6	1

Notes

⑦ 6 dark grey silty clay

⑥ 7 light brownish grey silty clay, many v. fine plant fragments (~~roo~~ hairs?

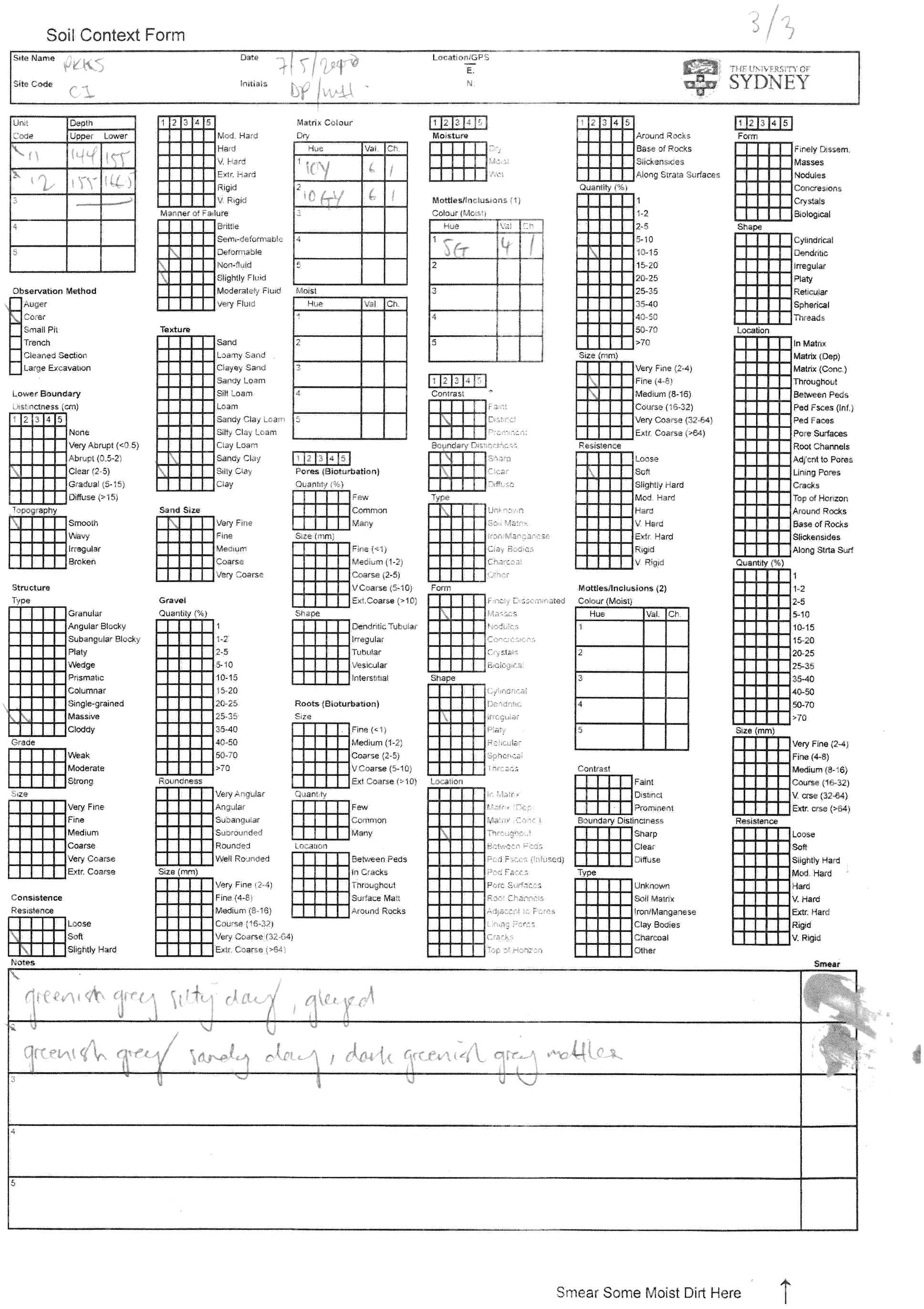
⑤ 8 yellow silty clay

④ 9 grey silty clay

③ 10 greenish grey gleyed sandy clay loam

Smear Some Moist Dirt Here ↑

FIGURE A.2: Original sediment core log for PKKS-C1 (cont.).



Soil Context Form

3/3

Site Name PKKS
Site Code C1
Date 7/5/2018
Initials DP/MH
Location/GPS E. N.

THE UNIVERSITY OF SYDNEY

Unit Code	Depth Upper	Depth Lower
1	144	155
2	155	166.5
3		
4		
5		

Matrix Colour

Dry

	Hue	Val.	Ch.
1	10Y	6	1
2	10GY	6	1
3			
4			
5			

Mottles/Inclusions (1)

Colour (Moist)

	Hue	Val.	Ch.
1	5G	4	1
2			
3			
4			
5			

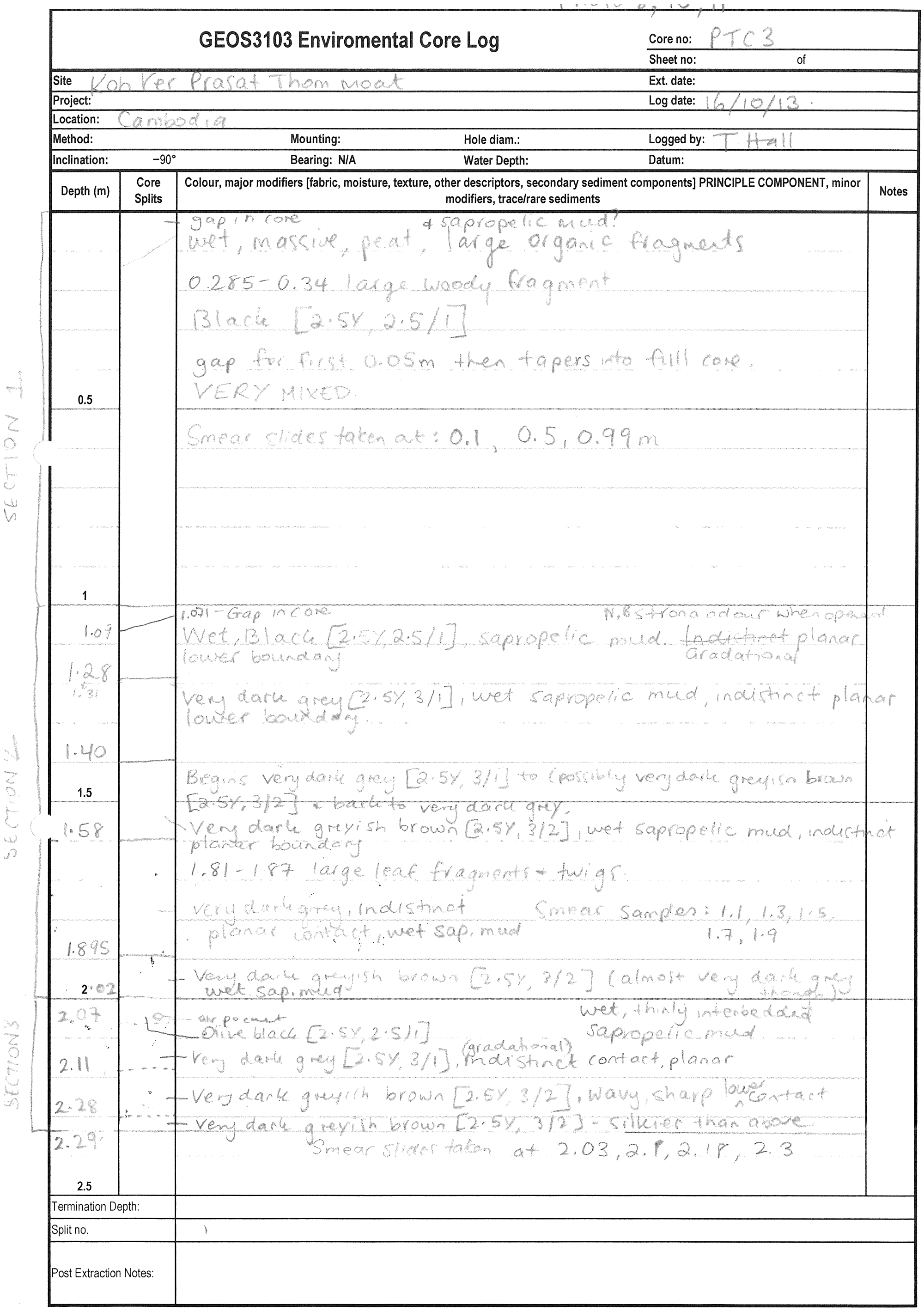
Observation Method
☐ Auger
☒ Corer
☐ Small Pit
☐ Trench
☐ Cleaned Section
☐ Large Excavation

Notes

		Smear
② 1	greenish grey silty clay, gleyed	
① 2	greenish grey/sandy clay, dark greenish grey mottles	
3		
4		
5		

Smear Some Moist Dirt Here ↑

FIGURE A.3: Original sediment core log for PKKS-C1 (cont.).



GEOS3103 Enviromental Core Log

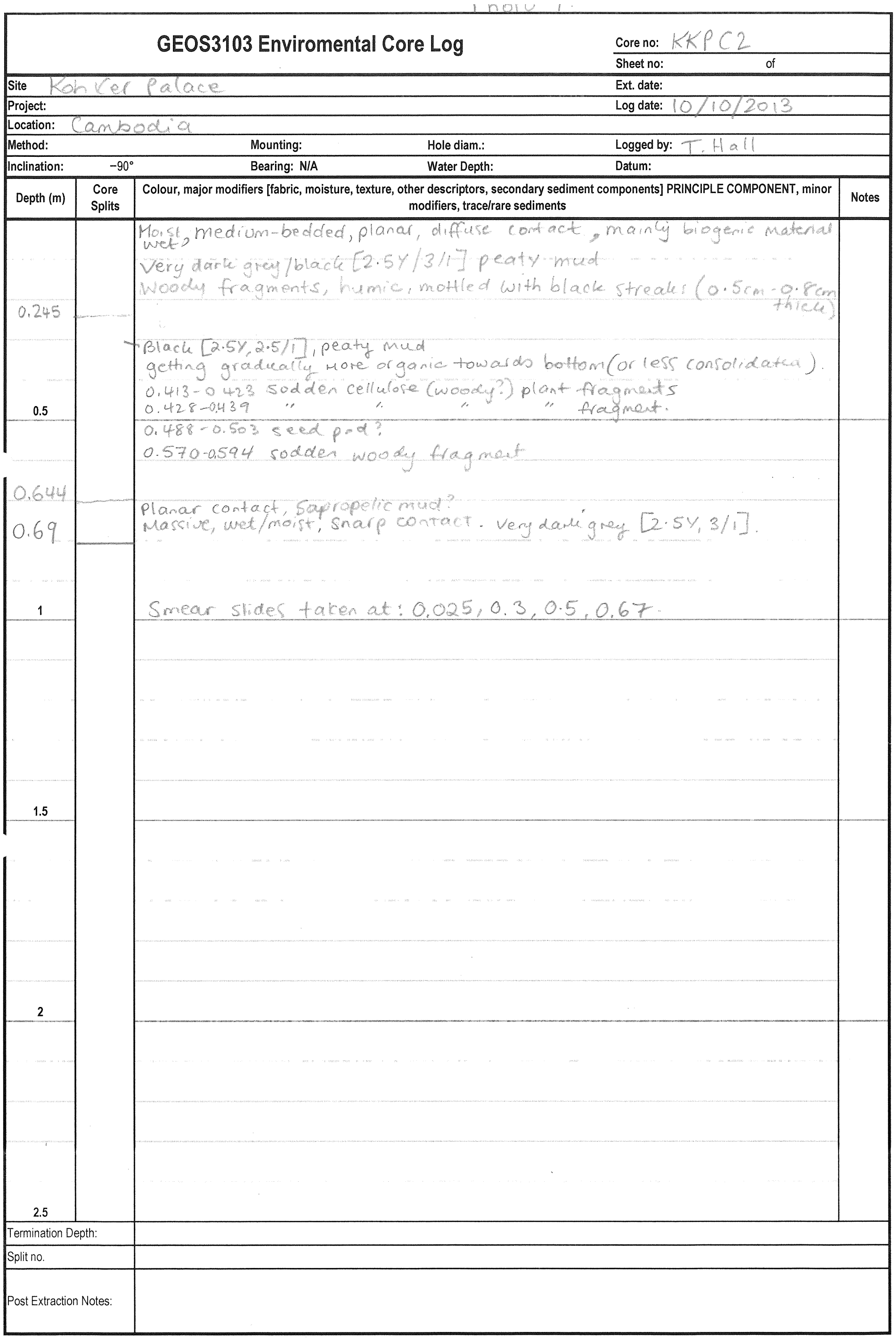
Core no: PTC3
Sheet no: of
Site Koh Ker Prasat Thom moat
Ext. date:
Project:
Log date: 16/10/13
Location: Cambodia
Method:
Mounting:
Hole diam.:
Logged by: T. Hall
Inclination: −90°
Bearing: N/A
Water Depth:
Datum:

Depth (m)	Core Splits	Colour, major modifiers [fabric, moisture, texture, other descriptors, secondary sediment components] PRINCIPLE COMPONENT, minor modifiers, trace/rare sediments	Notes
		gap in core	
		wet, massive, peat, large organic fragments + sapropelic mud?	
		0.285-0.34 large woody fragment	
		Black [2.5Y, 2.5/1]	
		gap for first 0.05m then tapers into full core.	
0.5		VERY MIXED	
		Smear slides taken at: 0.1, 0.5, 0.99m	
1			
		1.071 - Gap in core	N.B strong odour when opened
1.09		Wet, Black [2.5Y, 2.5/1], sapropelic mud. ~~Indistinct~~ Gradational planar lower boundary	
1.28 1.31		Very dark grey [2.5Y, 3/1], wet sapropelic mud, indistinct planar lower boundary.	
1.40		Begins very dark grey [2.5Y, 3/1] to (possibly very dark greyish brown [2.5Y, 3/2] + back to very dark grey.	
1.5			
1.58		Very dark greyish brown [2.5Y, 3/2], wet sapropelic mud, indistinct planar boundary	
		1.81 - 1.87 large leaf fragments + twigs.	
		very dark grey, indistinct planar contact, wet sap. mud	
		Smear Samples: 1.1, 1.3, 1.5, 1.7, 1.9	
1.895		Very dark greyish brown [2.5Y, 3/2] (almost very dark grey though) wet sap. mud	
2.02			
2.07		air pocket	
		Olive black [2.5Y, 2.5/1]	
		wet, thinly interbedded sapropelic mud	
2.11		Very dark grey [2.5Y, 3/1], (gradational) indistinct contact, planar	
2.28		Very dark greyish brown [2.5Y, 3/2], wavy, sharp lower contact	
2.29		Very dark greyish brown [2.5Y, 3/2] - siltier than above	
		Smear slides taken at 2.03, 2.1, 2.18, 2.3	
2.5			

SECTION 1
SECTION 2
SECTION 3

Termination Depth:
Split no. 1
Post Extraction Notes:

FIGURE A.4: Original sediment core log for PTC3.



GEOS3103 Enviromental Core Log

Core no: KKPC2
Sheet no: of
Site Koh Ker Palace
Ext. date:
Project:
Log date: 10/10/2013
Location: Cambodia
Method:
Mounting:
Hole diam.:
Logged by: T. Hall
Inclination: −90°
Bearing: N/A
Water Depth:
Datum:

Depth (m)	Core Splits	Colour, major modifiers [fabric, moisture, texture, other descriptors, secondary sediment components] PRINCIPLE COMPONENT, minor modifiers, trace/rare sediments	Notes
		Moist, medium-bedded, planar, diffuse contact, mainly biogenic material wet? Very dark grey/black [2.5Y/3/1] peaty mud Woody fragments, humic, mottled with black streaks (0.5cm-0.8cm thick)	
0.245			
		Black [2.5Y, 2.5/1], peaty mud getting gradually more organic towards bottom (or less consolidated). 0.413-0.423 sodden cellulose (woody?) plant fragments 0.428-0.439 " " " " fragment.	
0.5		0.488-0.503 seed pod? 0.570-0.594 sodden woody fragment	
0.644		Planar contact, Sapropelic mud? Massive, wet/moist, sharp contact. Very dark grey [2.5Y, 3/1].	
0.69			
1		Smear slides taken at: 0.025, 0.3, 0.5, 0.67.	
1.5			
2			
2.5			

Termination Depth:
Split no.
Post Extraction Notes:

FIGURE A.5: Original sediment core log for KKPC2.

B Cluster analysis: dendrograms

B.1 Cluster analyses: Sedimentary data

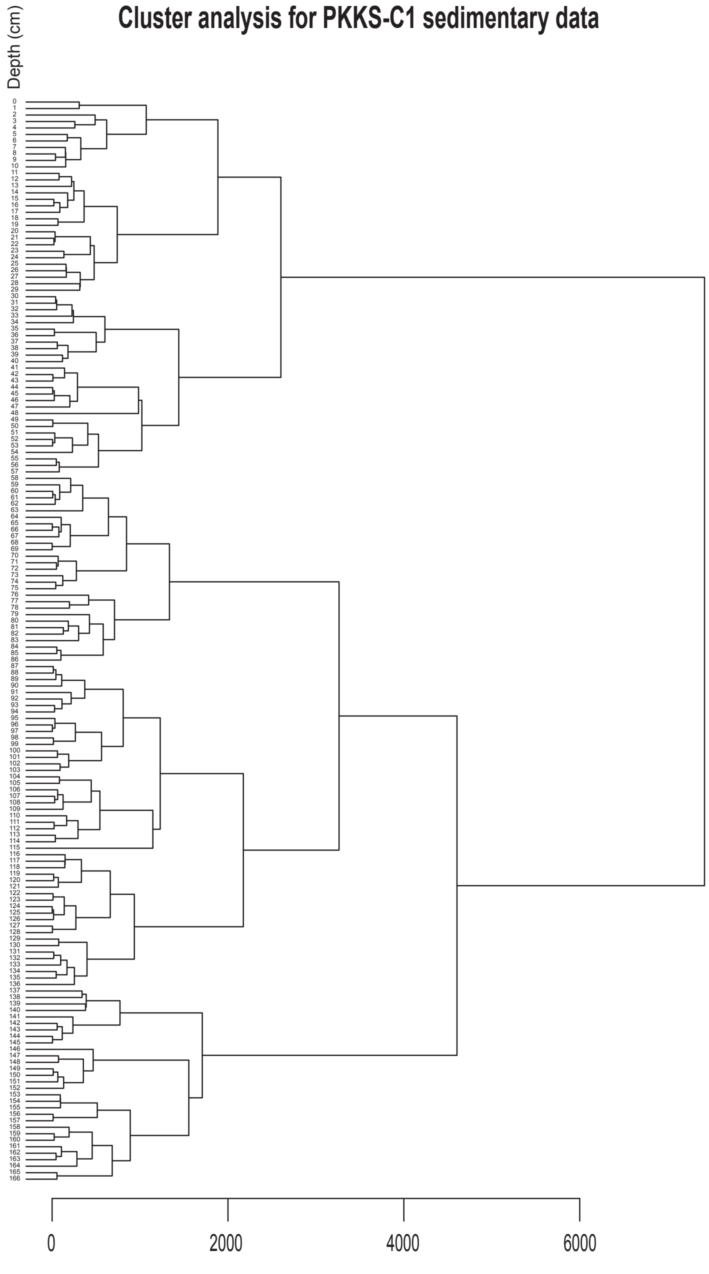


FIGURE B.1: Cluster analysis dendrogram for PKKS-C1 sedimentary data.

B.2 Cluster analyses: Charcoal data

B.3 Cluster analyses: Plant microfossil data

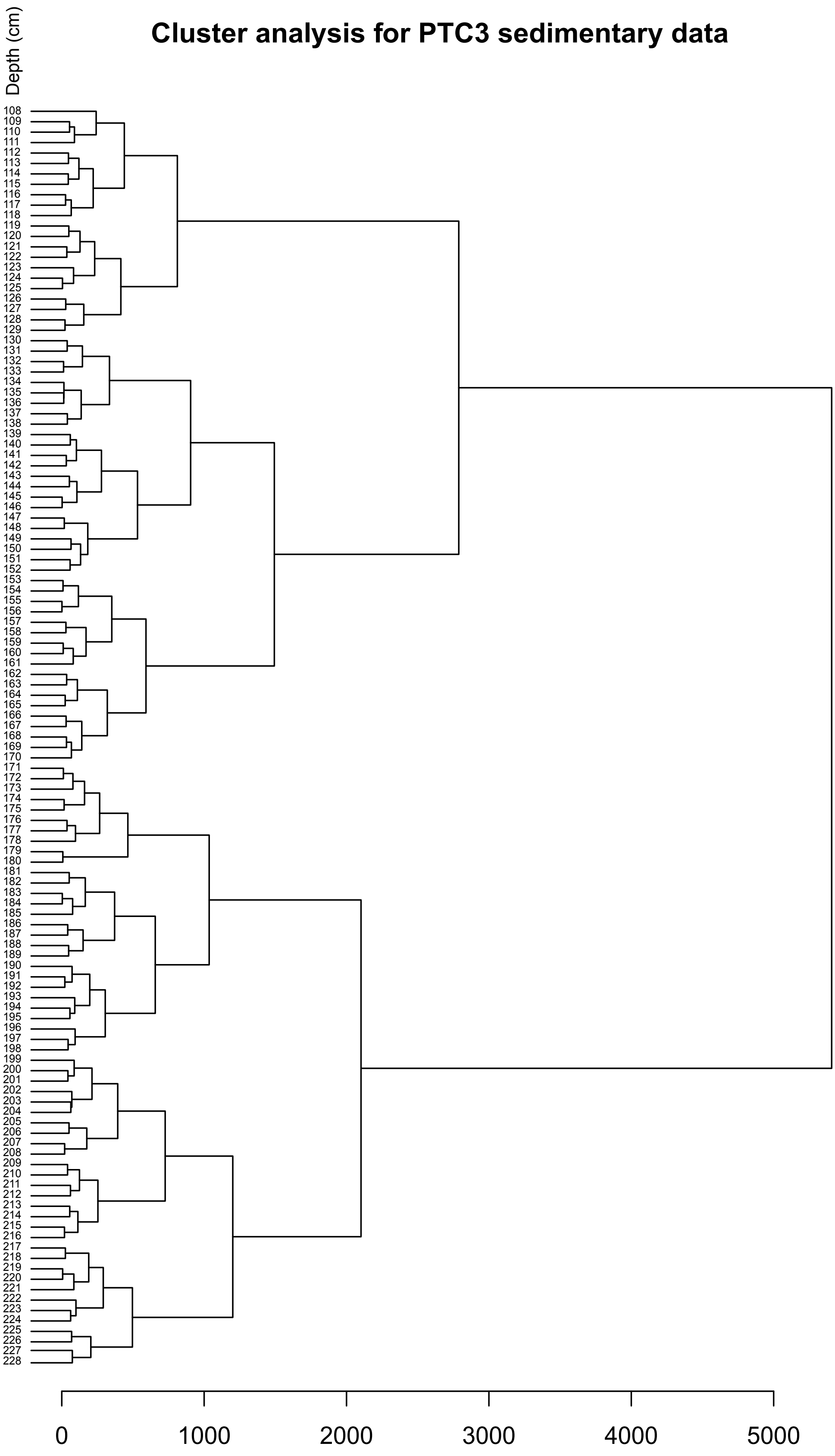


FIGURE B.2: Cluster analysis dendrogram for PTC3 sedimentary data.

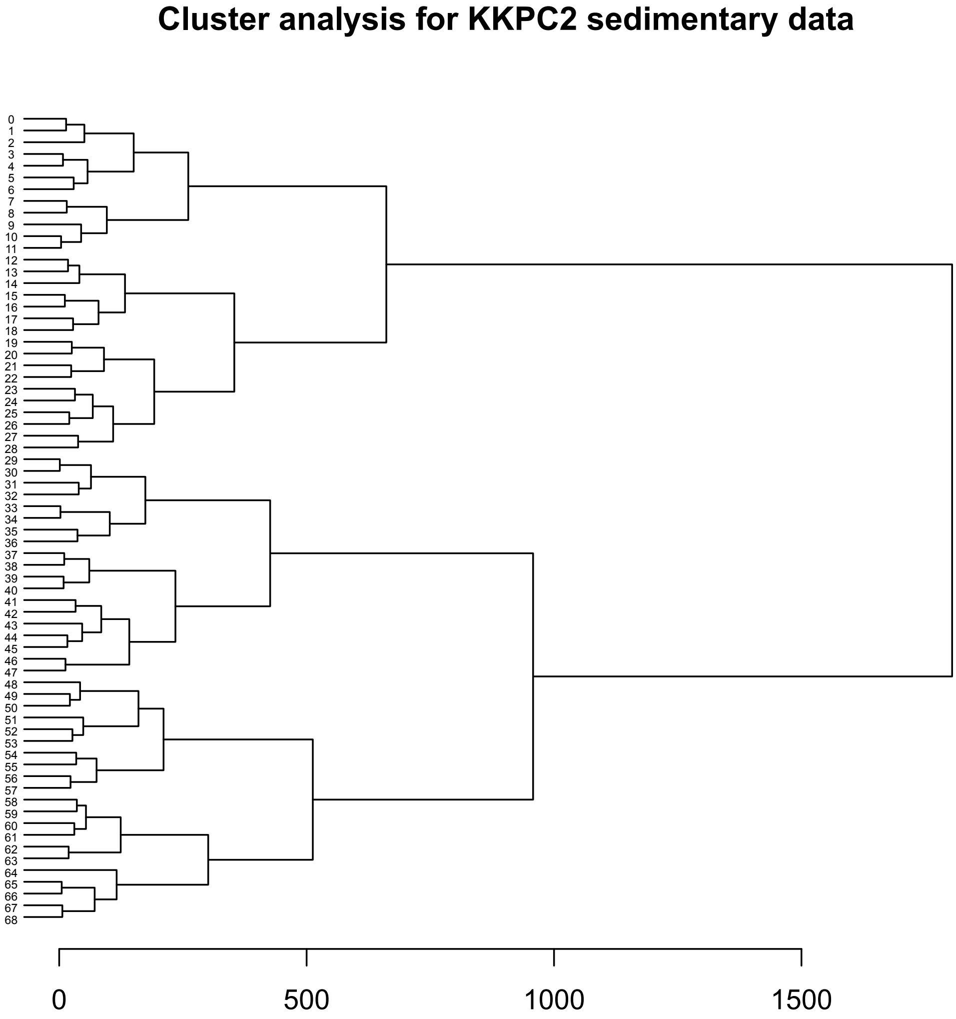


FIGURE B.3: Cluster analysis dendrogram for KKPC2 sedimentary data.

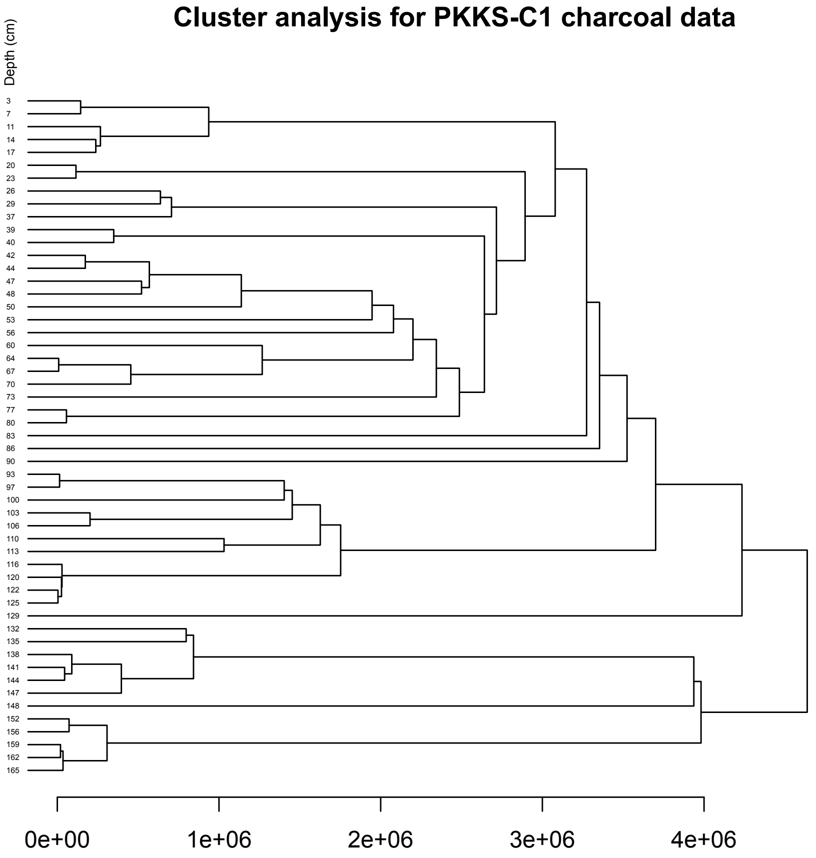


FIGURE B.4: Cluster analysis dendrogram for PKKS-C1 charcoal data.

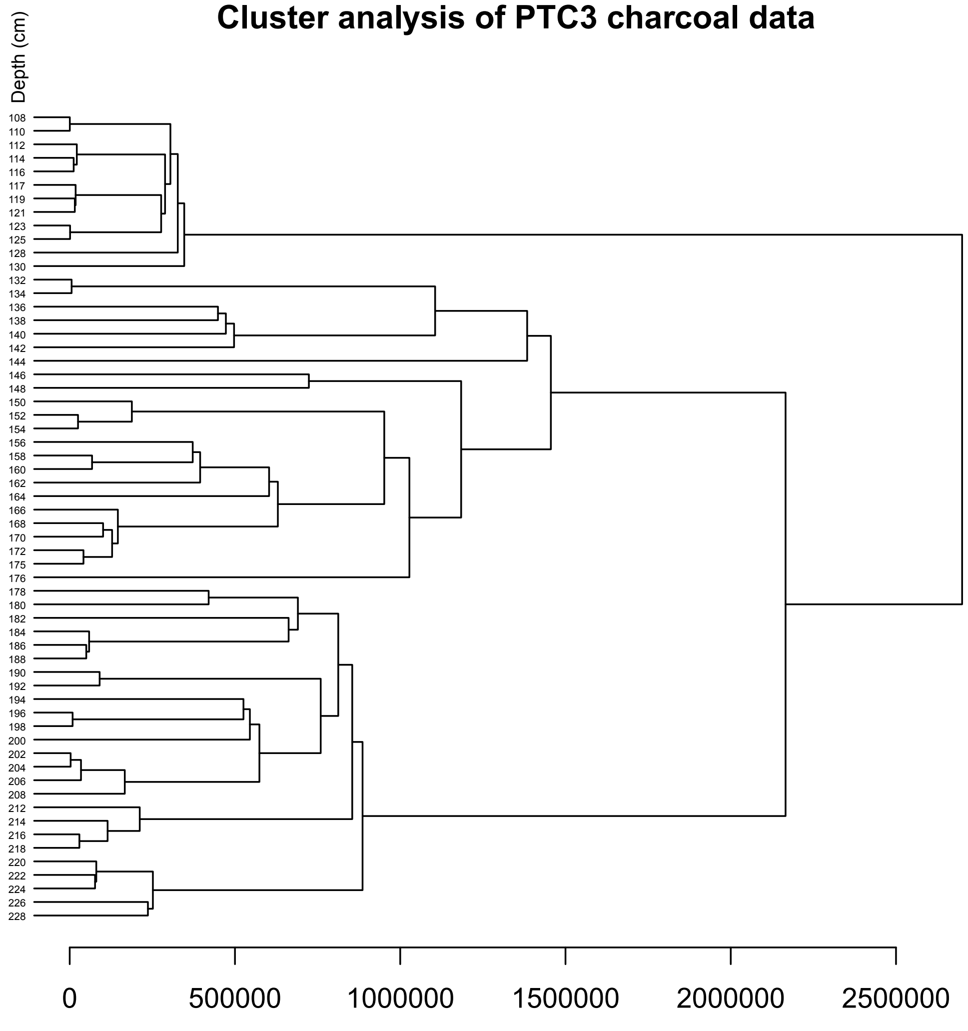


FIGURE B.5: Cluster analysis dendrogram for PTC3 charcoal data.

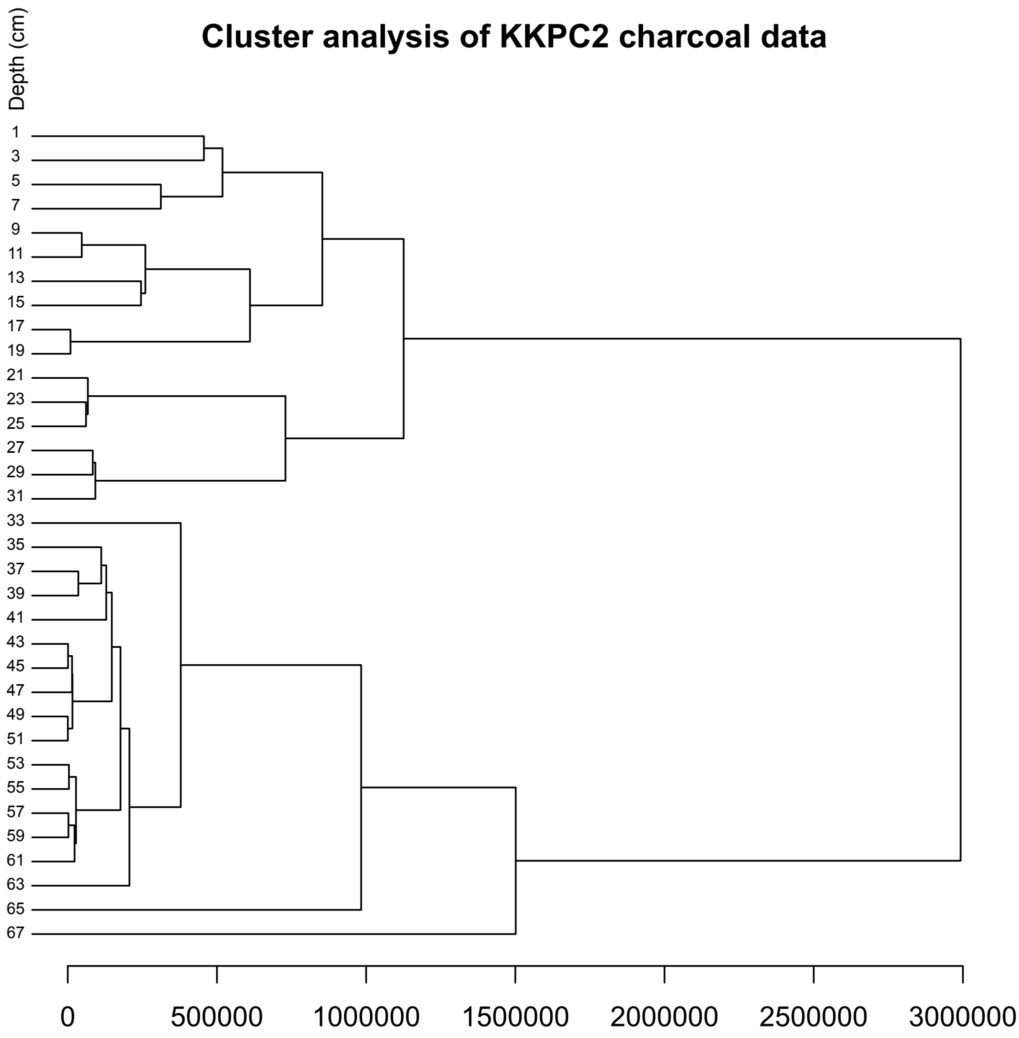


FIGURE B.6: Cluster analysis dendrogram for KKPC2 charcoal data.

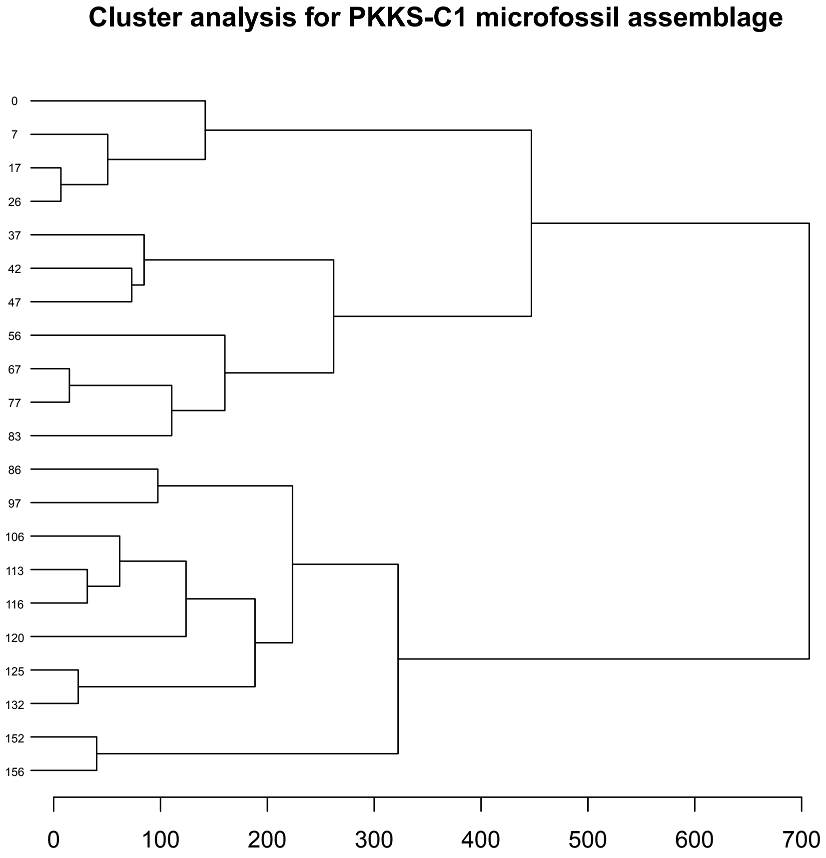


FIGURE B.7: Cluster analysis dendrogram for PKKS-C1 plant microfossil data.

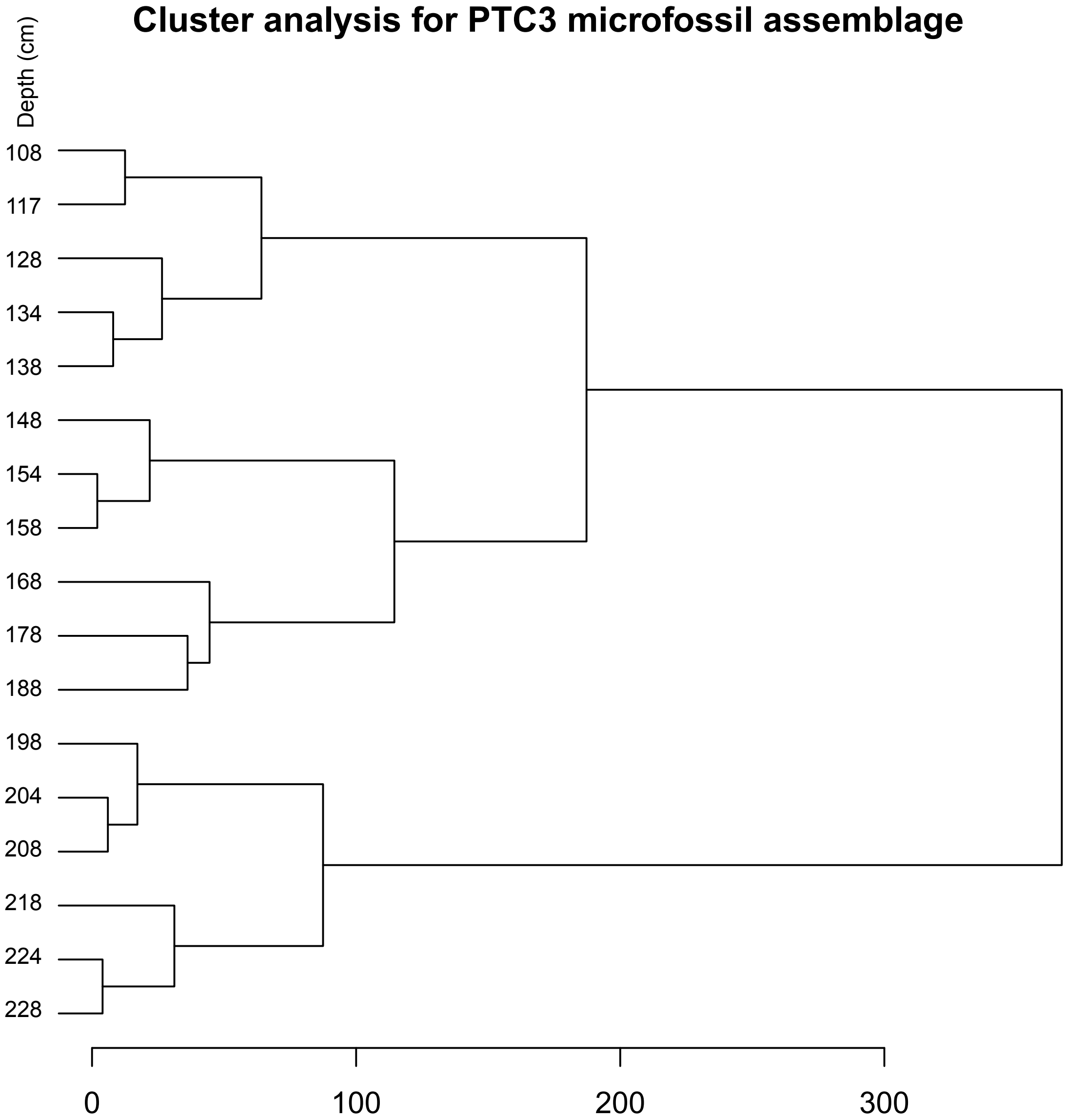


FIGURE B.8: Cluster analysis dendrogram for PTC3 plant microfossil data.

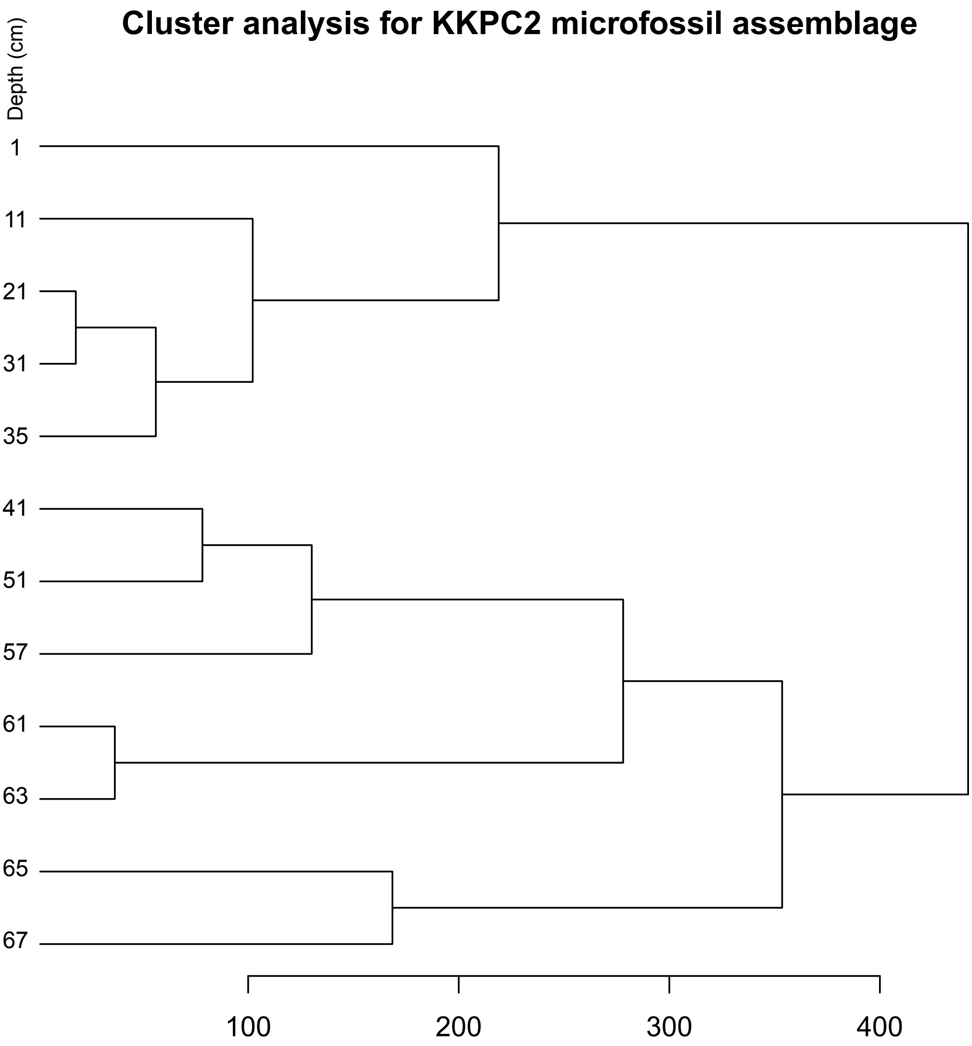


FIGURE B.9: Cluster analysis dendrogram for KKPC2 plant microfossil data.

C Magnetic susceptibility

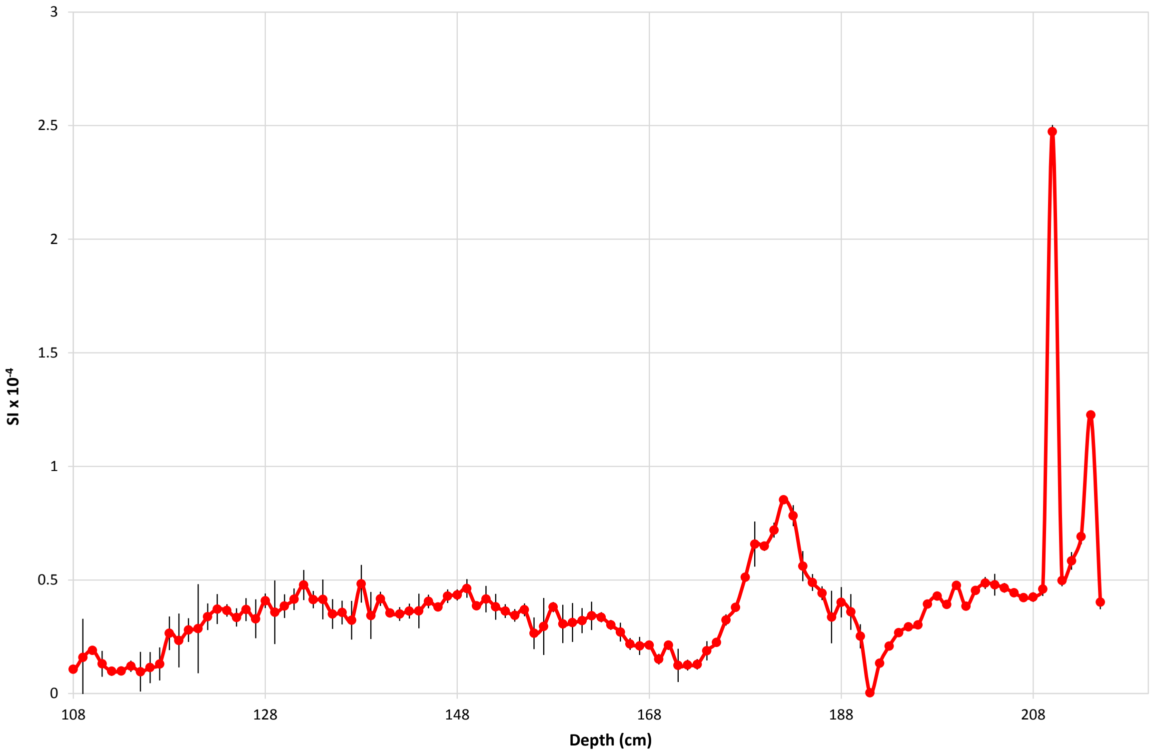


FIGURE C.1: Magnetic susceptibility measurements including errors (1σ) for core PTC3.

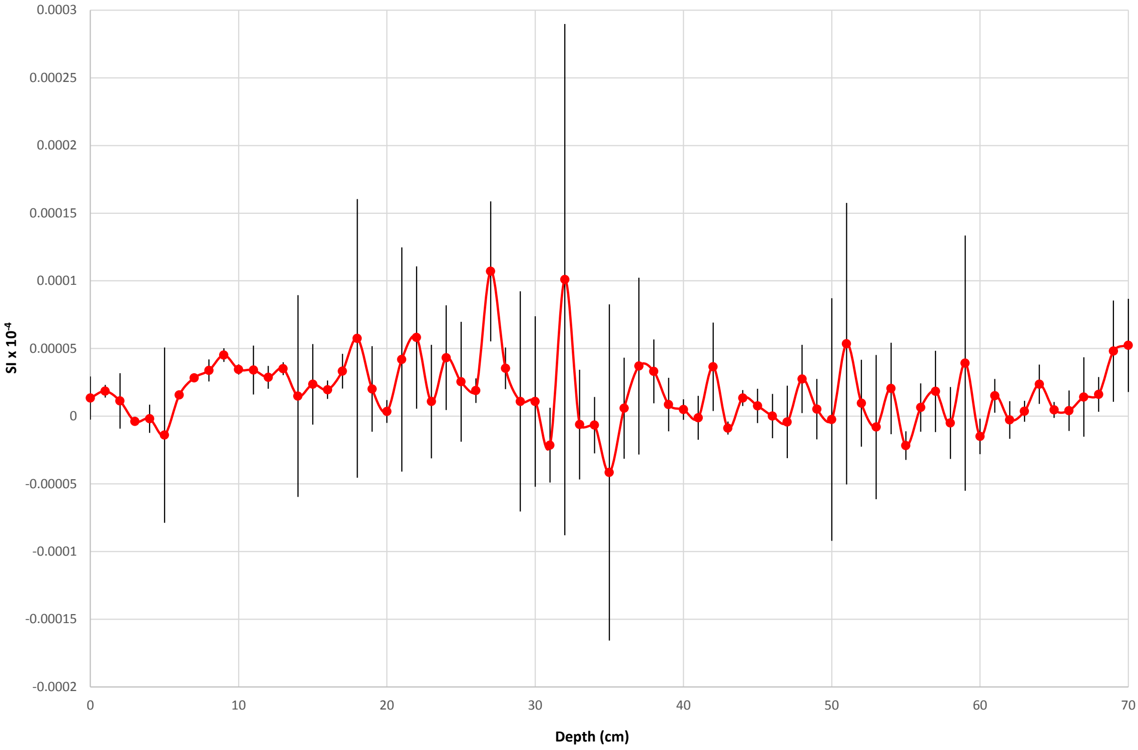


FIGURE C.2: Magnetic susceptibility measurements including errors (1σ) for core KKPC2.