

**Title**

Holocene development and human use of mangroves and limestone forest at an ancient  
hong lagoon in the Trảng An karst, Ninh Binh, Vietnam

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## Abstract

How past environments and communities responded to episodes of coastal inundation can inform preparations for future resilience to predicted rises in sea level. Southeast Asia's extensive coastlines and expanding coastal populations mean vast natural and human capital is at risk from future sea level rise. Regional mangroves provide many ecosystem services that can help mitigate such risks, but deforestation has left them threatened and compromised. The present study examines the Holocene development and human use of mangrove forest in northern Vietnam, where existing palaeo-records derive from sedimentary archives in tidal flat, estuarine and deltaic settings. Here, we expand that coverage by describing conditions at an enclosed doline within the Trảng An limestone karst in Ninh Binh Province that would have been sheltered from deltaic and marine processes. We present a multi-proxy assessment incorporating pollen analysis of the 8125-year-old discontinuous sediment core obtained from the doline floor, combined with inferences from erosional tidal notches in the enclosing limestone, and analyses of phytolith, vertebrate and mollusc assemblages from an adjacent archaeological cave site with deposits of comparable age. The results provide a detailed example of how enclosed coastal environments and communities responded to Middle Holocene marine inundation. High percentages of pollen from mangroves (17-57%) suggest their colonisation of the doline from ~8100 cal. BP and persistence until ~250 cal. BP, well after the intertidal zone regressed seaward beyond the massif. Archaeological assemblages dating to ~5500 cal. BP and containing palm and woody eudicot phytoliths and sponge spicules, neurocrania of the fish genus *Pomadasys* ('grunts', 'grunters' or 'javelins') and brackish-water molluscs *Sermyla riqueti* and *Neripteron violaceum* support the persistence of mangrove environments through the Middle Holocene high-stand, a period of hiatus within the core, and indicate human foraging and fishing activities took place in mangrove and lagoonal habitats alongside hunting in the surrounding limestone forest. Subsequent structural opening of this latter forest formation from ~1075 cal. BP (875 CE), evident in the pollen record, coincides with the Medieval Climate Anomaly and with the adjacent development of the ancient capital at Hoa Lu. We propose that given the long-term persistence of mangrove habitats and associated resources documented in this study, regional initiatives aimed at rehabilitating mangroves (with the positive consequences that this holds for biodiversity and socio-economic conditions) may wish to consider selective restorative measures within Trảng An and similar sheltered sub-coastal karst settings.

## Keywords

Holocene; Palaeoecology; Pollen; Phytoliths; Vegetation dynamics; Zooarchaeology; Sea Level changes; Southeast Asia

## 1. Introduction

Past eustatic changes in sea level throughout the Quaternary have cyclically drowned and exposed up to 2.5 million km<sup>2</sup> of Southeast Asia's Sunda Shelf (Sathiamurthy & Voris,

2006), repeatedly fragmenting and reconnecting landmasses and the ecosystems they support (Cannon et al., 2009). Rising sea levels in the Early-Middle Holocene drove the development of river deltas (e.g. Funabiki et al., 2007; Hori et al., 2004) and the expansion of mangroves across the region (Allen, 1996; Ellison, 2008; Li et al., 2012). Archaeological and palaeoecological evidence for human interaction with mangroves coincides with this expansion (Boulanger et al., 2019; Hunt & Rushworth, 2005; Nguyen, 2005; Rabett, 2005). Today, Southeast Asia's extensive coastlines and low-lying hinterland, combined with large and expanding human populations reliant upon rapidly developing coastal economies, infrastructure and cities, make this region especially vulnerable to predicted future sea level rise (Hijioka et al., 2014). Global rates of mangrove deforestation now stand at  $<0.4\% \text{ yr}^{-1}$  (Friess et al., 2019); however, the rate of loss in Southeast Asia remains considerably higher (e.g. 3.58-8.08% for the period 2000-2012) (Hamilton & Casey, 2016). Regional restoration of this habitat and the valuable ecosystem services and socio-economic resources it can provide to mitigate the impact of sea level rise depends on robust evidence-based programmes of replanting and restoration with careful site and species selection (Lee et al., 2019).

Quaternary scientists are increasingly highlighting the utility of palaeoenvironmental records to inform present and future biodiversity conservation and sustainable development decisions (e.g. Birks, 1996; Davies & Bunting, 2010; Froyd & Willis, 2008; Gillson, 2015; Grace et al., 2019; Nogue et al., 2017; Vegas-Vilarrubia et al., 2011; Willis et al., 2007; Wingard et al., 2017). In this context, we briefly review the Holocene history of mangrove forests in Southeast Asia and then employ palaeoenvironmental evidence obtained from the Trảng An limestone massif, northern Vietnam, to consider both the human use of mangroves in prehistory, and the current position of these habitats in preparations for human and ecological resilience to future sea level rise.

### *1.1. Mangroves of Southeast Asia and Vietnam*

Mangrove forests are distinctive coastal vegetation communities in intertidal zones within the tropics and subtropics where sediments are actively accumulating (van Steenis,

1958). Such conditions occur along low-gradient coastlines and tidally influenced low-lying hindshores, often near river mouths and deltas (Giesen et al., 2006/7; Woodroffe et al., 2016). Single-stratum architecture and physiological adaptations to periodic inundation by saline water, such as stilt roots, pneumatophores, salt excretion glands or capacity to sequester excess salts within tissues, vivipary and water-dispersed disseminules, are common mangrove characteristics (Tomlinson, 2016).

Across the Southeast Asian tropics, the world's most species-diverse and extensive mangroves underpin and sustain productive intertidal ecologies and the coastal economies that depend upon their resources (Giesen et al., 2006/7). Mangrove forests provide habitat and act as nurseries for a diverse range of fishes, molluscs, crustaceans, insects, reptiles, birds and mammals (MacNae, 1968). They yield timber, food and medicines to local communities, whilst indirectly sustaining nearshore fisheries through their ecological role as protection and breeding grounds for economically important species (Orchard et al., 2016). Mangroves also sequester ~1.5 metric tons of carbon per hectare per year in their organic soils and in their biomass (Ong, 1993); and they buffer coastlines against the erosive power of tropical storms and tsunamis (Alongi, 2008; 2015).

Mangroves are less diverse and more restricted in extent in the Song Hong (Red River) Delta region in the north of Vietnam than they are around the more tropical Mekong Delta in the south (Hong & San, 1993). Despite this, 31 species of 'true mangroves' – defined as those species that are found in mangrove habitat only (Giesen et al., 2006/7) – as well as a significant proportion of the 216 'mangrove associates' recorded regionally within mangrove and adjacent non-mangrove habitats, occur within northern Vietnamese mangrove vegetation. Rhizophoraceae (*Bruguiera*, *Ceriops*, *Kandelia* and *Rhizophora*) is the dominant plant family, while species of *Avicennia* (Acanthaceae), *Sonneratia* (Lythraceae), *Aegiceras* (Primulaceae), *Lumnitzera* (Combretaceae) and *Xylocarpus* (Meliaceae) are also abundant woody elements. The mangrove palm *Nypa fruticans* and mangrove fern *Acrostichum aureum* are conspicuous non-woody components. The remainder of taxa recorded in northern Vietnamese mangroves span all growth forms: trees and shrubs; palms, cycads and pandans; vines and climbers;



126 epiphytes; herbs; grasses and grass-like plants such as sedges and rushes; and ferns (Giesen  
127 et al., 2006/7).

128       Records of past mangrove presence, development and extent show how these habitats  
129 responded to periods of climatic and anthropogenic environmental change (Ellison, 2008).  
130 These data can also provide baselines for assessing the potential success of future restoration  
131 and conservation efforts. For example, Li et al.'s (2012) pollen record from the upper Mekong  
132 Delta shows the successional development through time of mangrove communities variably  
133 composed of taxa with adapted tolerances to the changing salinities, tidal regimes and  
134 sedimentary environments through a Holocene transgression-regression cycle. This implies  
135 that the benefits to local human communities and economies derived from a dynamic  
136 mangrove ecosystem extend well beyond the narrow and patchy band of habitat that currently  
137 exists in human-modified deltaic areas, if unimpeded hydrogeomorphic regimes can be re-  
138 established. At Yingluo Bay on the northern shore of the South China Sea, Meng et al.'s (2016)  
139 2000-year record of mangrove development shows the sensitivity of these ecosystems to  
140 changes in monsoon patterns, as well as their resilience to regional human activity when  
141 locally protected.

142       In Vietnam, as recently as the period prior to the Vietnam/American War (Veettil et al.,  
143 2019), the densely populated delta regions of the Song Hong in the north and the Mekong in  
144 the south had been covered by more than 400,000 ha of mangrove forests. Use of defoliants  
145 during that war, followed by a continuing trend in the post-war period of increasing demand  
146 for shrimp ponds and rice paddies (Hong & San, 1993), put these deltaic mangrove forests  
147 under threat and in some areas led to a 50-80% reduction in extent (Valiela et al., 2001).  
148 Mangrove restoration efforts in the Mekong Delta began in 1978, but with initially low survival  
149 rates attributed to inexperience with technical aspects such as planting density (Hong, 2001).  
150 In the Song Hong Delta, similar efforts were initiated in 1992 through funding from the Save  
151 the Children Fund Vietnam (Nguyen et al., 1998); in 1993 by a Japanese NGO called Action  
152 for Mangrove Restoration, and in 1994 by the Red Cross (Kogo & Kogo, 2000; Marchand,  
153 2008). Close cooperation with local communities by these projects resulted in a higher degree

of success. Both the impacts from shrimp aquaculture, the construction of flood control infrastructure and growing tourist numbers though leave the future of Vietnam's mangroves uncertain (Marchand, 2008).

## 1.2. *Mangroves and the Song Hong Delta throughout the Holocene*

The Holocene development of the Song Hong Delta and the palaeoenvironments it supported have been examined through sedimentological and microfossil analyses of at least 20 deep boreholes across the delta plain, largely following the path of the Song Hong and Red River Fault (Duong et al., 2020; Funabiki et al., 2007; Hori et al., 2004; Li et al., 2006a; Tanabe et al., 2006). Geomorphic processes, delta morphology and its palaeoenvironments have changed markedly across this time period, driven primarily by the effects of eustatic sea level changes tied to patterns of deglaciation. The Holocene portion of the regional sea level curve synthesised by Tanabe et al. (2003b) shows a steep rise from -60 m at the beginning of the Holocene to near present-day levels by ~7500 cal. BP. The rate of subsequent sea level rise slowed, reaching a high-stand of +3-5 m centred around 5500 cal. BP and remained relatively stable until ~4000 cal. BP before gradually returning to present-day levels after 2000 cal. BP.

Geomorphologic and palaeoenvironmental inferences drawn from sedimentological and microfossil analyses show that deglacial sea level rise drowned an ancient valley incised by the Song Hong during the preceding glacial low-stand (Duong et al., 2020; Funabiki et al., 2007; Hori et al., 2004; Li et al., 2006a; Tanabe et al., 2006). Early Holocene portions of cores from as far northwest as the vicinity of Hanoi (i.e. cores PD and DA from Funabiki et al., 2007; core HN from Duong et al., 2020) provide evidence for estuarine and tidal flat depositional environments inhabited by mangrove forests and brackish water ecosystems far inland from the present coast despite below-modern sea levels at the time. Delta progradation at the upstream end of the drowned Song Hong valley began ~8500 cal. BP (Hori et al., 2004) while sea level was still rising toward the Middle Holocene high-stand. Estuarine environments ahead of the delta front were infilled progressively seaward through the Middle and Late

Holocene, fringed by tidal flats supporting extensive mangrove forests (Duong et al., 2020; Li et al., 2006a).

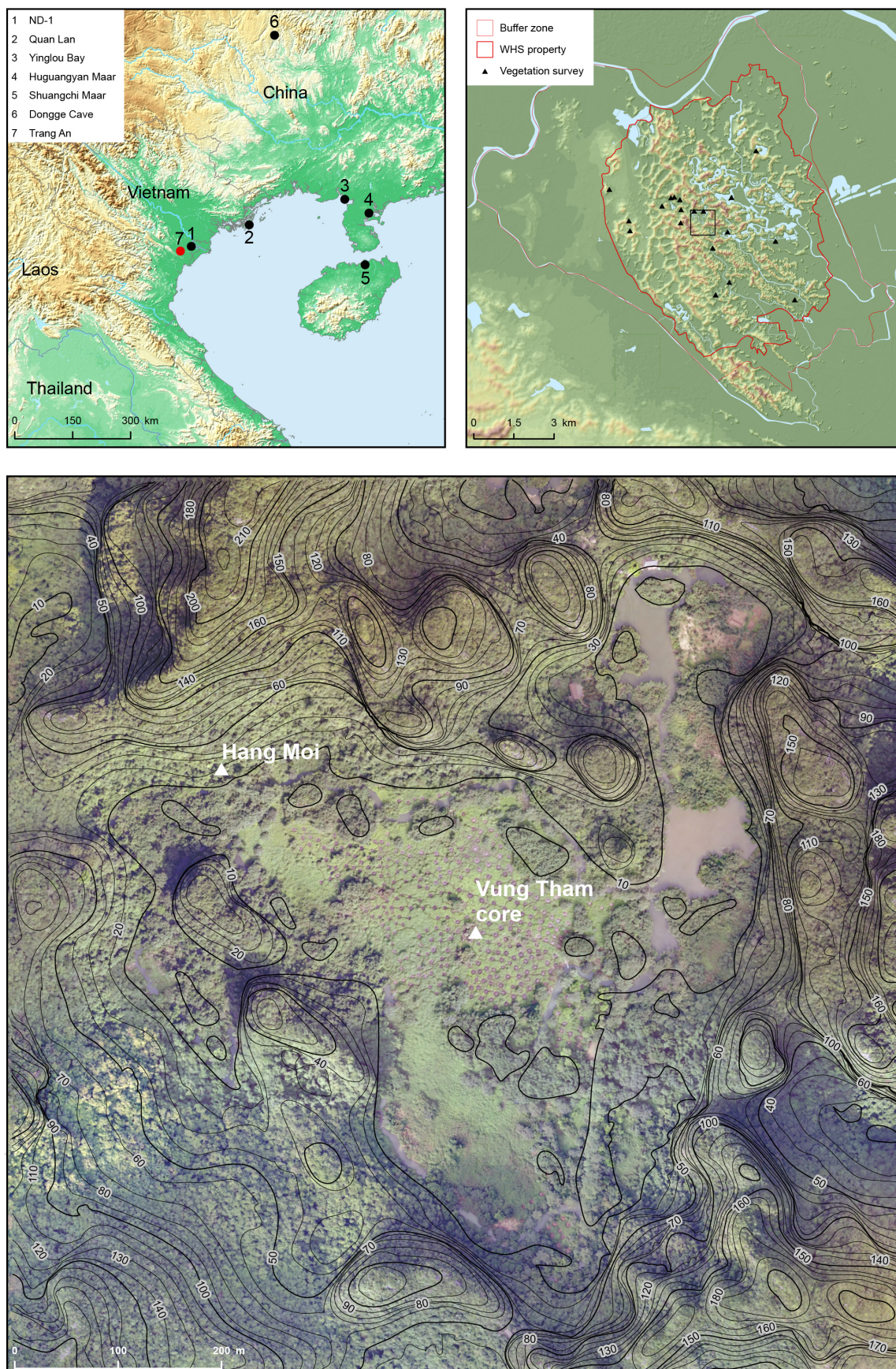
Existing palaeoenvironmental records of mangroves derive from deltaic, estuarine and tidal mudflat settings exposed to marine and fluvio-deltaic processes and surrounded by other wetland vegetation communities. In this paper we present palaeoenvironmental evidence of past mangrove habitats within an enclosed valley on the southern edge of the Song Hong Delta, sheltered by limestone karst from large-scale marine and fluvio-deltaic processes and surrounded by limestone forest. We examine how these mangrove ecosystems and past coastal communities have responded to episodes of sea level rise across the Holocene, and consider the future utility of sheltered sites to mangrove rehabilitation efforts.

## **2. Study area**

### *2.1. Geography and geology*

The Trảng An karst occupies most of the 6226-hectare core zone of the Trảng An Landscape Complex, a mixed-designation UNESCO World Heritage property in Ninh Binh province, northern Vietnam. The massif is situated on the southern margin of the Song Hong Delta, ~30 km inland from the present coast of the Gulf of Bac Bo (Tonkin) at its nearest point (Fig. 1). It is composed of Lower – Middle Triassic thinly bedded – massive limestone (VIGMR, 2012). This bedrock has subsequently undergone extensive uplift, deformation and weathering, especially associated with later-Mesozoic closure of the palaeo-Tethys Ocean and early Cenozoic extension and activation of the Red River Fault system after India's collision with Eurasia (Faure et al., 2014; Metcalfe, 2017). Tropical and subtropical climates acting throughout the Cenozoic (66 – 2.58 Ma), and Quaternary (2.58 Ma – present) climatic fluctuations and associated oscillations in sea level, have driven the geologically recent evolution of the massif. Today's karst landscape exhibits predominantly *fenglin* terrain composed of towers, sharp ridges and sheer limestone faces undercut laterally by alluvial planation and marine inundation, but with a small core of *fengcong*-doline topography where doline floors have remained well above the local water table (Waltham, 2009). Under present





**Fig. 1** Study area and sites mentioned in the text, at regional (top-left panel), Trảng An property (top-right panel) and local site scales (bottom panel). Red filled circle in top-left panel denotes Trảng An. Box in top-right panel denotes location of bottom panel. Figure credit: T. Kahlert.



hydrological conditions and management many of the deepest dolines within the *fenglin* terrain are flooded with fresh water and interconnected via both natural foot caves and man-made tunnels and waterways.

## 2.2. Climate

The Song Hong Delta region covers more than 15,000 km<sup>2</sup>, most of which sits at 2-6 m above present average sea level (a.s.l.; relative to sea level calibrated to the Vietnam National datum at Hon Dau). Today, lowland northern Vietnam experiences a tropical monsoonal climate with warm, wet summers and cool, dry winters (Averyanov et al., 2003), modified by maritime influence (Lawrimore et al., 2016; Li et al., 2006a) (See Supplementary Materials for more detail).

## 2.3. Vegetation

The vegetation of the Song Hong Delta region and surrounding outcrops and uplands of northern Vietnam is composed of a diverse mix of tropical and temperate components (Averyanov et al., 2003; Regalado et al., 2005). The complex and dynamic geological history of the region has created topographic, microclimatic and edaphic heterogeneity which supports seasonal evergreen broad-leaved and mixed forests, with compositional and structural variations according to soil type and along gradients in elevation and continentality (Ashton, 2014; Averyanov et al., 2003). Limestone outcrops and low-gradient coastal landscapes in northern Vietnam also support distinct limestone and mangrove floras (Clements et al., 2006; Giesen et al., 2006/7; Tomlinson, 2016).

Whilst the flora of Tr  ng An has not yet been comprehensively enumerated, a reasonable proxy can be assembled from the literature on the limestone floras of nearby Cuc Phuong and Ben En National Parks (Nguyen, 1997; Hoang, 2009). For the purposes of this study, these expectations were then ground-truthed as part of the SUNDASIA Project using pedestrian surveys and species lists of some of the limestone vegetation found near to focal sites of research interests in Tr  ng An (Fig. 1). The island-like nature of isolated limestone

massifs like Trảng An (*sensu* Kruckeberg, 1991), combined with the thin and usually nutrient-poor soils (Vermeulen & Whitten, 1999), and sharp karstic topographies forming a patchwork of exposed and shaded aspects, creates an array of microhabitats that support a diverse flora (Ashton, 2014; Crowther, 1982; Kruckeberg, 2002; Zhu et al., 2003). In valley bottoms and on shallow-gradient slopes, a tall and closed broad-leaved forest composed predominantly of tropical families occurs (Averyanov et al., 2003). These include Leguminosae (*Erythrophleum*; *Saraca*), Moraceae (*Ficus*; *Streblus*), Datisceae (*Tetrameles*), Anacardiaceae (*Cherospondias*; *Dracontomelon*), Meliaceae (*Aglaia*; *Chisocheton*; *Dysoxylum*), Sapindaceae (*Pometia*), Dipterocarpaceae (*Hopea*; *Shorea*; *Vatica*), Malvaceae (*Grewia*; *Pterospermum*; *Sterculia*), Ebenaceae (*Diospyros*) and Sapotaceae (*Madhuca*). In contrast, exposed ridges, vertical walls and steep slopes support a more open and shorter, often drought-adapted and semi-deciduous, mixed vegetation comprised of broad-leaved and gymnospermous elements such as cycads and podocarps, as well as epilithic herbs in Orchidaceae, *Impatiens* (Balsaminaceae), Urticaceae, Gesneriaceae, *Begonia* (Begoniaceae) and Araceae (Clements et al., 2006).

Today, alluviated valley floors within the *fenglin* terrain of Trảng An are dominated by development and cultivation of rice, maize, fruit trees and non-native *Acacia mangium* plantations and fringed by ruderal scrub composed largely of agricultural weeds, many of neotropical origin. Where not in cultivation, narrow floodplains and banks of waterways support wetland and riparian communities dominated by grasses (Poaceae), sedges (Cyperaceae), *Ficus* spp. and several species of trees and shrubs in the rubiaceous tribe Naucleaeae, as well as rapid colonisers of open ground in Phyllanthaceae (*Sauropus*, *Breynia*, *Glochidion* and *Cleistanthus*) and Euphorbiaceae (*Mallotus* and *Macaranga*).

## 2.4. Study sites

### 2.4.1. Vung Tham

Vung Tham is an alluviated doline occupying just over 20 ha near the centre of the massif (105.89745°E, 20.25281°N) (Figs. 1, 2). The modern floor of the doline is relatively flat



**Fig. 2** Aerial image of the Vung Tham doline, looking east. The white 'V' denotes the location of the coring site; the white 'H' denotes the location of Hang Moi cave. Image credit: T. Kahlert.

and sits at 2-3 m a.s.l. It is enclosed by the 160 m tall, nearly vertical limestone walls of the surrounding massif. Locally, peaks reach 225 m with intervening saddles as low as 70 m. Portions of the doline floor are flooded, with a dredged channel around the interior perimeter at the base of the enclosing limestone walls. The emergent portion of the valley floor has been cultivated continuously in recent decades despite a very shallow water table (<20 cm).

Notches near the base of the limestone walls have been surveyed as part of associated SUNDASIA Project work examining local sea level history. Palaeoenvironmental inferences that relate to the present study are also included here as a complementary line of evidence.

#### 2.4.2. Hang Moi

Of the 30 known archaeological cave sites within the Tràng An World Heritage Area, the only site that is located within Vung Tham is Hang Moi (105.894889°E, 20.254111°N) (Figs. 1, 2). The cave entrance is south-facing and opens out onto Vung Tham from the western portion of the northern wall, 11 m above the doline floor. Anthropogenic derived assemblages of phytoliths and faunal remains accumulated within Hang Moi during prehistory. As these neighbouring palaeoarchives accumulated under different immediate conditions (i.e. within a

cave setting), their incorporation into the current study provides a temporal sequence of comparative, if selected, palaeoenvironmental data that compliments that obtained from the Vung Tham core, and permits a more robust exploration of potential linkages between local habitat change and human agency.

Occupied intermittently from at least 15,000 cal. BP, Hang Moi was first excavated in 2011 by the Trảng An Archaeological Project (TAAP), followed in 2012 with excavation by a team from the Vietnamese Institute of Archaeology and, since 2016, by the SUNDASIA Project. Three trenches have so far been excavated; herein, we focus on Middle Holocene occupation layers from Trenches 1 and 2 excavated by TAAP and SUNDASIA (Figs. 3, 4). Trench 1 has revealed an in situ hearth sequence and a human burial (Field reports: Rabett et al., unpublished; Stimpson et al., a) & b), unpublished); the upper deposit of Trench 2 represents a 1 m-thick 'refuse dump' of ash, coarse-ware potsherds and faunal remains with abundant mollusc and crab. Contemporaneous radiocarbon dates have been recovered from Trenches 1 and 2 and place Middle Holocene occupation at ~5500 cal. BP (Table 1). Underlying the ash-rich material in Trench 2 are two as-yet undated deposits, (6504) and (6509), which also contain comparable coarse-ware ceramics.

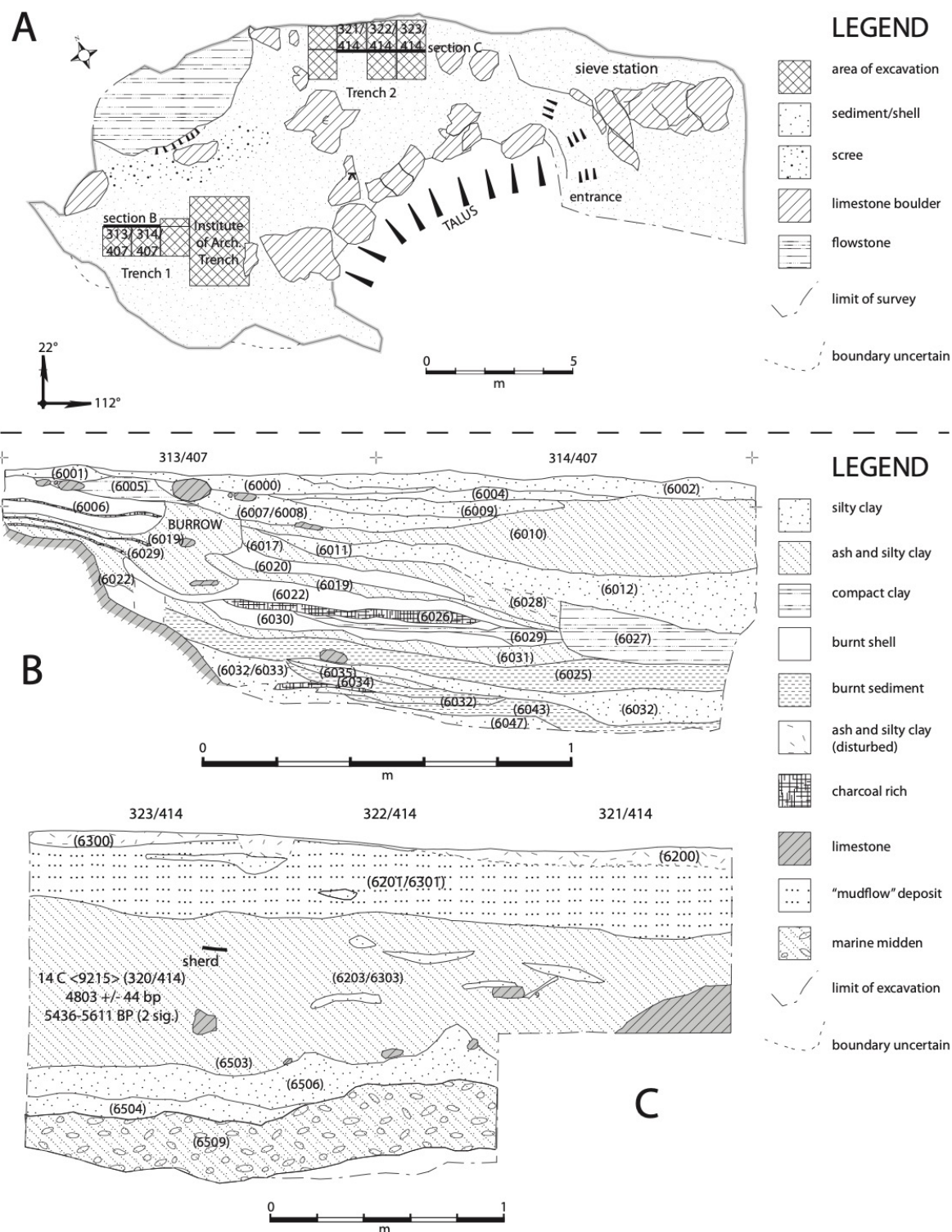




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**Fig. 3** Hang Moi, viewed from the cave entrance overlooking the chamber. The white '1' denotes Trench 1; the white '2' denotes Trench 2. Image credit: T. Kahlert.



**Fig. 4** Hang Moi site plan (A) and representative sections from Trench 1 (B) and Trench 2 (C). Bold trench boundaries in A denote specific sections illustrated in B and C. Drawing credit: C Stimpson.

**Table 1** Middle Holocene radiocarbon dates from Hang Moi.

Sample # / code	Trench	Context	<sup>14</sup> C	error	Cal BP <sup>a</sup>
9624 / UBA-40551	1	6608	4524	44	5041-5315
9059 / UBA-19757	1	6040	4773	34	5464-5591
9215 / UBA-19756	2	6203	4803	44	5436-5611

<sup>a</sup> 2 sigma ranges are shown

### 3. Materials and Methods

#### 3.1. Vung Tham sediment core

##### 3.1.1. Coring

The marshy deposit that fills the Vung Tham doline was cored to a depth of 382 cm in April 2018 using a modified Livingstone piston corer (*sensu* Wright, 1967). Core sections were photographed and described lithologically on site as they were extruded, and transported under permission to the Archaeology and Palaeoecology laboratories within the School of Natural and Built Environment at Queen's University Belfast (QUB) for further analyses.

##### 3.1.2. Chronology

Six samples of individual macroscopic plant fragments were submitted to the <sup>14</sup>CHRONO Centre at QUB for accelerator mass spectrometry (AMS) radiocarbon age estimation. All dates were calibrated using the IntCal13 calibration curve (Reimer et al., 2013). From the resulting dates (see Table 3), a Bayesian age-depth model was constructed with the 'rbacon' package (Blaauw & Christen, 2019) in R (R Core Team, 2019). Presence of mangrove and aquatic taxa within microfossil assemblages, as well as geomorphic features in the local landscape that are indicative of previous inundation (i.e. notches at the base of the limestone walls that enclose Vung Tham), guided the selection of priors for the Bayesian model. Based upon published estimates of vertical accretion rates within mangrove and deltaic systems (Ellison, 2008; Krauss et al., 2014; Woodroffe et al., 2016), and the expectation that these rates would have changed significantly through time with differing hydrogeomorphic settings as the intertidal zone transgressed and regressed across the coring site, the prior for the accumulation rate was set as a gamma distribution with shape 2 and mean 5.25 yr cm<sup>-1</sup> (i.e. 1.9 mm yr<sup>-1</sup>) and for the accumulation variability a beta distribution with strength of 20 and mean 0.1 (Blaauw & Christen, 2011). Chronological terminology follows Walker et al.'s (2018) subdivision of the Holocene.

##### 3.1.3. Physical analyses

Magnetic susceptibility was measured at 2 cm increments throughout the length of the core using a Bartington MS2C core scanning sensor (Bartington Instruments, 2019). A total of 38 paired subsamples were collected from the core at roughly 10 cm depth-intervals. One set of subsamples was used for loss-on-ignition (LOI) analysis, retaining the parallel set for pollen analysis. LOI analysis followed Cambridge Geography (2018).

#### 3.1.4. Pollen analysis

Each of the 38 subsamples collected for pollen analysis were measured to comprise one cc of sediment. One tablet containing a known quantity of exotic marker spores (*Lycopodium*) was then added to each subsample to enable estimation of microfossil concentrations (Stockmarr, 1971). Pollen extraction followed protocols based upon dense-media separation using a sodium polytungstate solution at specific gravity between 1.88 – 1.91 g cm<sup>-3</sup> (Nakagawa et al., 1998; Campbell et al., 2016). Acetolysis was omitted due to low total organic content and anticipated suboptimal pollen and spore preservation. Prior to the dense-media separation step, preliminary slides were made on which to quantify diatom abundances. Final residues were mounted in silicone oil for microfossil identification and counting which were carried out under light microscopy, primarily at 400x magnification. Pollen and spores were identified using keys and images for Southeast Asian taxa (Fujiki et al., 2005; Huang, 1972; Huang, 1981; Mao et al., 2012; Nguyen, unpublished; Semah, unpublished; Thanikaimoni, 1987) and the Australasian Pollen and Spore Atlas (APSA Members, 2007).

A target minimum of 300 microfossils per subsample guided the counting process. Relative abundances of taxa and summary groupings were calculated using a 'basic sum', 'total sum' or 'dryland sum' depending upon taxon (see Supplementary Materials for details). Stratigraphic diagrams were plotted using C2 version 1.7.7 (Juggins, 2010). Zonation of the stratigraphic diagrams was achieved through adjacency-constrained hierarchical agglomerative clustering analysis using the R packages adjclust (Ambroise et al., 2018) and vegan (Oksanen et al., 2018). Zones and subzones were defined by the branches of the dendrogram that were intersected by lines at arbitrarily selected threshold values of total

dispersion. Several principal components analysis (PCA) ordinations were performed on the entire dataset, as well as various subsets of it, in order to reveal possible patterns in the data that are difficult to detect visually in the stratigraphic diagrams.

### 3.2. *Vung Tham notches*

Marine or tidal notches form in the intertidal zone as horizontal bands along vertical or near-vertical limestone faces as a result of mechanical, biological and chemical erosion. Their formation requires prolonged phases of stable sea levels and their presence is used, alongside sedimentary cores, coral deposits and marine terraces, as past sea level indicators (Boyd & Lam, 2004; Lam & Boyd, 2003; Pirazzoli, 1986; Trenhaile, 2015). Limestone is particularly susceptible to erosion and elevated tidal notches are abundantly found in karst formations along modern and palaeo-coasts of the Thai-Malay Peninsula and in northern Vietnam (Gillieson, 2005; Tjia, 1996).

A detailed survey across Trảng An as part of the SUNDASIA Project documented the occurrence of notches at at least four different elevations that are indicative of relative stable sea levels higher than at present and that likely pertain to two marine transgressions of around 5.6 m and 3.2 m a.s.l. (Rabett et al., 2018). Previous studies and limited dating of notch sites at Trảng An have produced modelled relative sea levels that fall within established Middle Holocene sea level curves for Southeast Asia and the Song Hong Delta of 5 m (Boyd & Lam, 2004; Nguyen et al., 2012).

In Vung Tham, notches at the base of the enclosing limestone walls around the interior perimeter of the doline were surveyed using a total station and differential GPS. Geographical coordinates, elevation relative to the sea level datum at Hon Dau, and characteristics of notch morphology (vertical span, depth and shape in profile) were measured for each in situ notch.

### 3.3. *Hang Moi archaeology*

#### 3.3.1. *Phytolith Analysis*



An archived sediment column was taken from the north section of Trench 1 in Hang Moi, from which eleven subsamples were collected to target the series of hearth deposits that date from ~5500 cal. BP (see Table 1). Two grams of sediment from each subsample were processed for phytoliths following Rosen's protocol (1999) (full methodology in Supplementary Materials).

Phytoliths were identified and counted at 400x magnification under light microscopy through a polarising lens. Morphotypes were described using the International Code for Phytolith Nomenclature 1.0 (Madella et al., 2005) and identified using primarily regionally specific published images (e.g. Weisskopf, 2018; Piperno, 2006; Huang & Zhang, 2000; Bowdery, 1999; Kealhofer & Piperno, 1998). Due to poor preservation the aim of counting 300 phytoliths per slide was only achieved in one subsample, resulting in most slides being counted in their entirety. Total counts of silica aggregate and sponge spicules were also recorded as an indication of the presence of wood/bark and wet environments. Phytoliths g<sup>-1</sup> in each sample was calculated after Power et al. (2014).

### 3.3.2. Vertebrate faunal remains

The vertebrate remains recovered from the Middle Holocene hearth (Trench 1) and refuse dump (Trench 2) deposits were highly fragmentary and are parsimoniously the remnants of taxa exploited as food. The remains are principally comprised of broken fish spines and centra, mixed with copious numbers of broken crab chelae and mollusc shells. The bones of terrestrial vertebrate taxa are comparatively rare and are also highly fragmented. As such, only relatively small numbers of vertebrate remains were identifiable. The materials were exported under agreement with the Ninh Binh Peoples Committee and the Trảng An Management Board. Identifications were made using comparative osteological collections at the Oxford University Museum of Natural History.

Trench 1 yielded three identifiable teeth from contexts 6011 and 6014 and post-cranial remains from contexts 6032 and 6039. These specimens are associated with a date of 5464 – 5591 cal. BP (Table 1). Materials from Trench 2 incorporated two episodes of deposition

within the Middle Holocene. Firstly, materials from contexts 6203, 6303 and 6503 (Number of Identified Specimens, or NISP = 15) were of similar age to materials from Trench 1 and date to 5436 – 5611 cal. BP (Table 1). Secondly, materials from contexts 6506 and 6509 (NISP = 17) were directly underlying the Middle Holocene deposits but were stratigraphically distinct and represent earlier phases of deposition (Fig. 4C).

### 3.3.3. *Molluscs*

Mollusc assemblages from six contexts from Trench 2 were analysed under a low-powered binocular microscope and hand lens, and recorded using 'Minimum Number of Individuals' (MNI). Data were plotted stratigraphically using Tilia 2.1.1 (Grimm, 2019). Identifications were made using Vermeulen & Whitten (1998a; 1998b); Vermeulen & Maassen (2003); Phung et al. (2017); Raheem et al. (2017); Sutcharit et al. (2019); as well as modern comparative collections made by the SUNDASIA Project.

## 4. Results

### 4.1. *Vung Tham core*

#### 4.1.1. *Lithology*

The 382 cm sequence from the Vung Tham core consisted of fine-grained sediments throughout. Constituent units varied in oxidative state and colour as well as presence and composition of inclusions (Table 2). Boundaries between all constituent units below the 21 cm of modern soil were diffuse.

**Table 2** Lithology of the Vung Tham core sedimentary sequence.

Depth (cm)	Description	Colour
0-21	Organic silt & decaying plant fragments	Dark brown (no Munsell)
21-44	Silty clay	Dark greyish brown (2.5Y/4/2)
44-77	Silty clay, redoxed	Olive (5Y/4/3)
77-100	Silty clay, reduced	Dark greyish brown (10YR/4/2)
100-128	Clayey silt with decaying woody plant fragments	Dark greyish brown (10YR/4/2)

128-310	Clayey silt with occasional bark & shell fragments	Dark grey (5Y/4/1)
310-367	Clayey silt with limestone sand	Olive (5Y/4/3)
367-382	Silty clay with gravel-sized limestone inclusions	Olive (5Y/5/3)

#### 4.1.2. Chronology

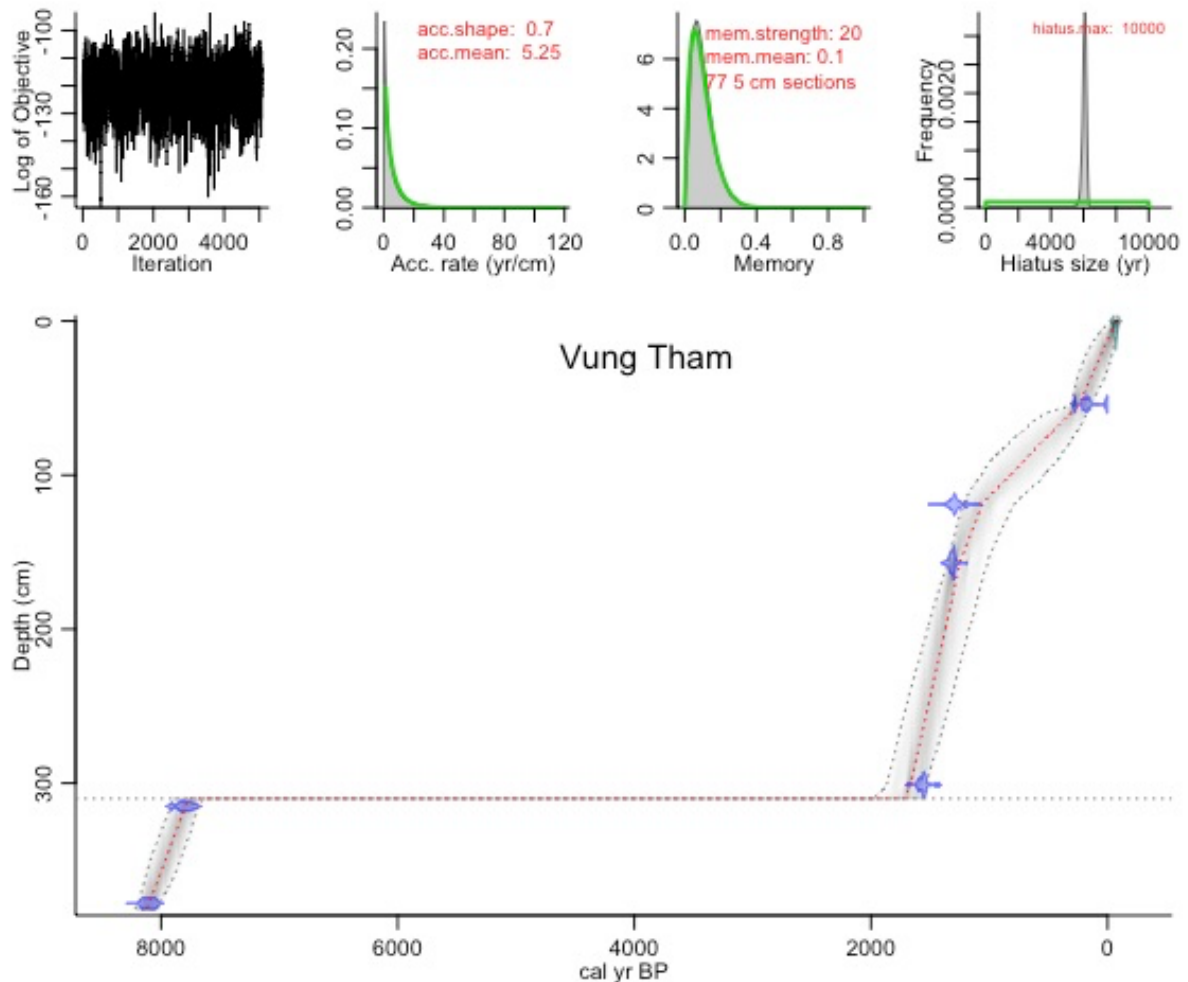
The six samples submitted for radiometric dating returned age estimates ranging from 8177 – 142 cal. BP (Table 3). The estimates from 315 and 301 cm depths provide evidence for either a long depositional hiatus lasting ~6000 years, a discontinuity representing erosion of a portion of the sequence followed by resumption of deposition, or younger material intruding older sedimentary layers from above. No signs of bioturbation were observed and so intrusion of younger material from higher levels is considered unlikely, though mangrove ecosystems support several potential agents of bioturbation (Tomlinson, 2016).

**Table 3** Radiocarbon age estimates from the Vung Tham core sedimentary sequence.

Depth (cm)	Material	Conventional $^{14}\text{C}$ age	Calibrated age ( $2\sigma$ )	Lab. Ref.
54	Leaf tissue	186 $\pm$ 22 BP	142 – 289 cal. BP	UBA-40840
119	Wood	1370 $\pm$ 46 BP	1183 – 1358 cal. BP	UBA-38672
157	Wood	1398 $\pm$ 31 BP	1280 – 1352 cal. BP	UBA-38673
301	Leaf tissue	1655 $\pm$ 25 BP	1521 – 1618 cal. BP	UBA-40841
315	Wood	6969 $\pm$ 44 BP	7693 – 7928 cal. BP	UBA-38674
378	Leaf tissue	7298 $\pm$ 34 BP	8026 – 8177 cal. BP	UBA-40842

The Bayesian age-depth model (Fig. 5) accounts for the non-Gaussian probability distributions of calibrated age estimates and provides for statistically robust age estimates for undated depths throughout the core. It is from this age-depth model that the age column in the pollen diagrams, as well as the age estimates of zone and subzone boundaries, are derived.





**Fig. 5** Bayesian age-depth model for the Vung Tham core sedimentary sequence.

#### 4.1.3. Physical analyses

The most striking feature of the magnetic susceptibility curve is the large peak near the base of the sequence, centred around depths 325 – 314 cm (corresponding to modelled mean ages of 7843 – 7789 cal. BP) (Fig. 6d). This peak is followed by an abrupt decline back to the low values that characterise the rest of the core. A minor additional peak occurs between depths 125 – 116 cm (corresponding to modelled mean ages of 1090 – 1025 cal. BP).

The LOI analyses revealed the largely minerogenic nature of the sediments throughout the sequence, excepting the uppermost ~20 cm (Fig. 6d). Total organic content remains between 5.3 – 8.3% for all but minor peaks at 298 cm (11.4%) and 122 cm (9.9%), as well as across the uppermost three subsamples. Pearson's product-moment correlation coefficients

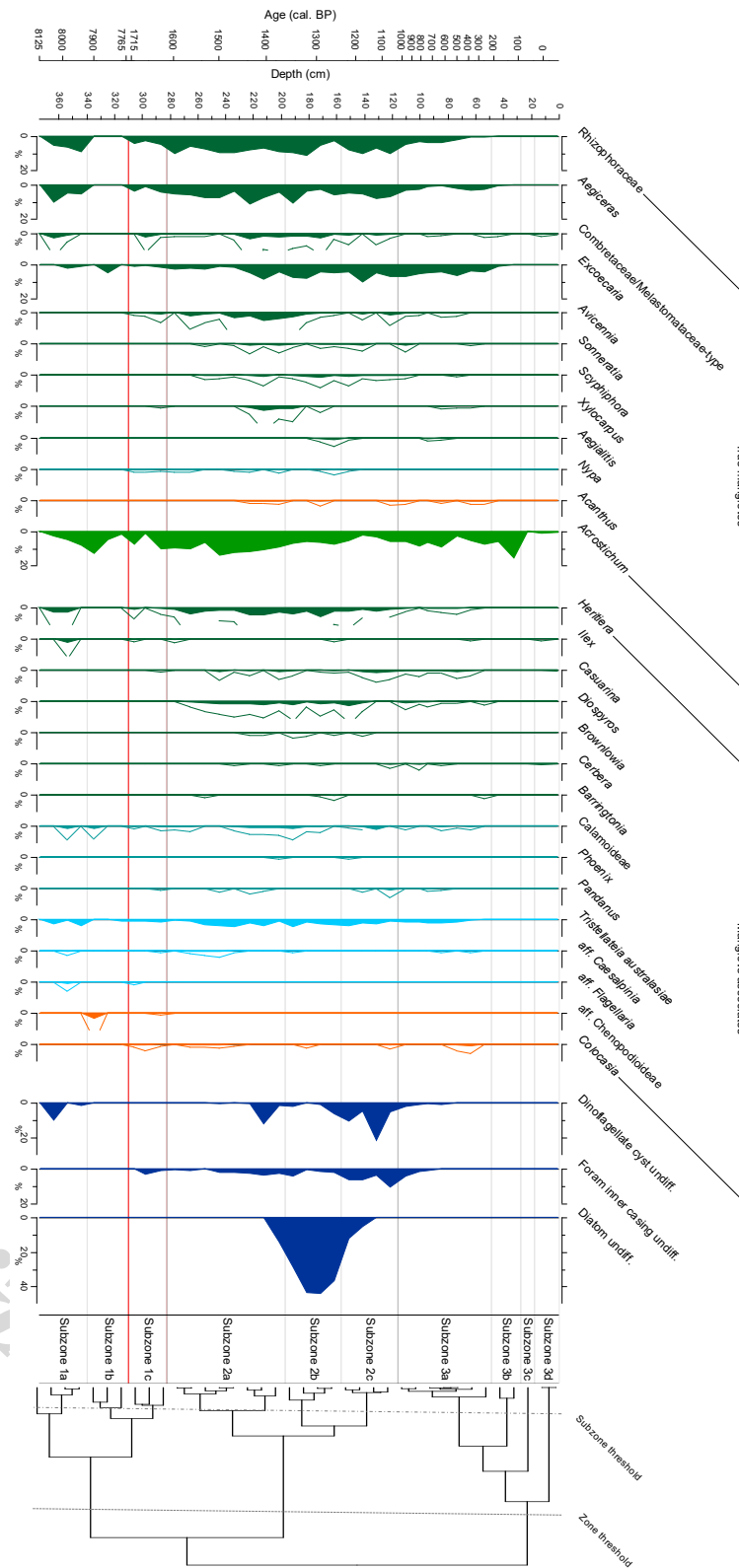
revealed strong positive linear correlations between total organic content and: carbohydrate content ( $r = 0.998$ ;  $p < 2.2e^{-16}$ ;  $df = 36$ ); and water content ( $r = 0.802$ ;  $p = 1.38e^{-9}$ ;  $df = 36$ ). Equally strong, though negative, correlations were revealed between mineral content and: total organic content ( $r = -0.999$ ;  $p < 2.2e^{-16}$ ;  $df = 36$ ); and water content ( $r = -0.804$ ;  $p = 1.16e^{-9}$ ;  $df = 36$ ).

#### 4.1.4. Microfossil assemblages

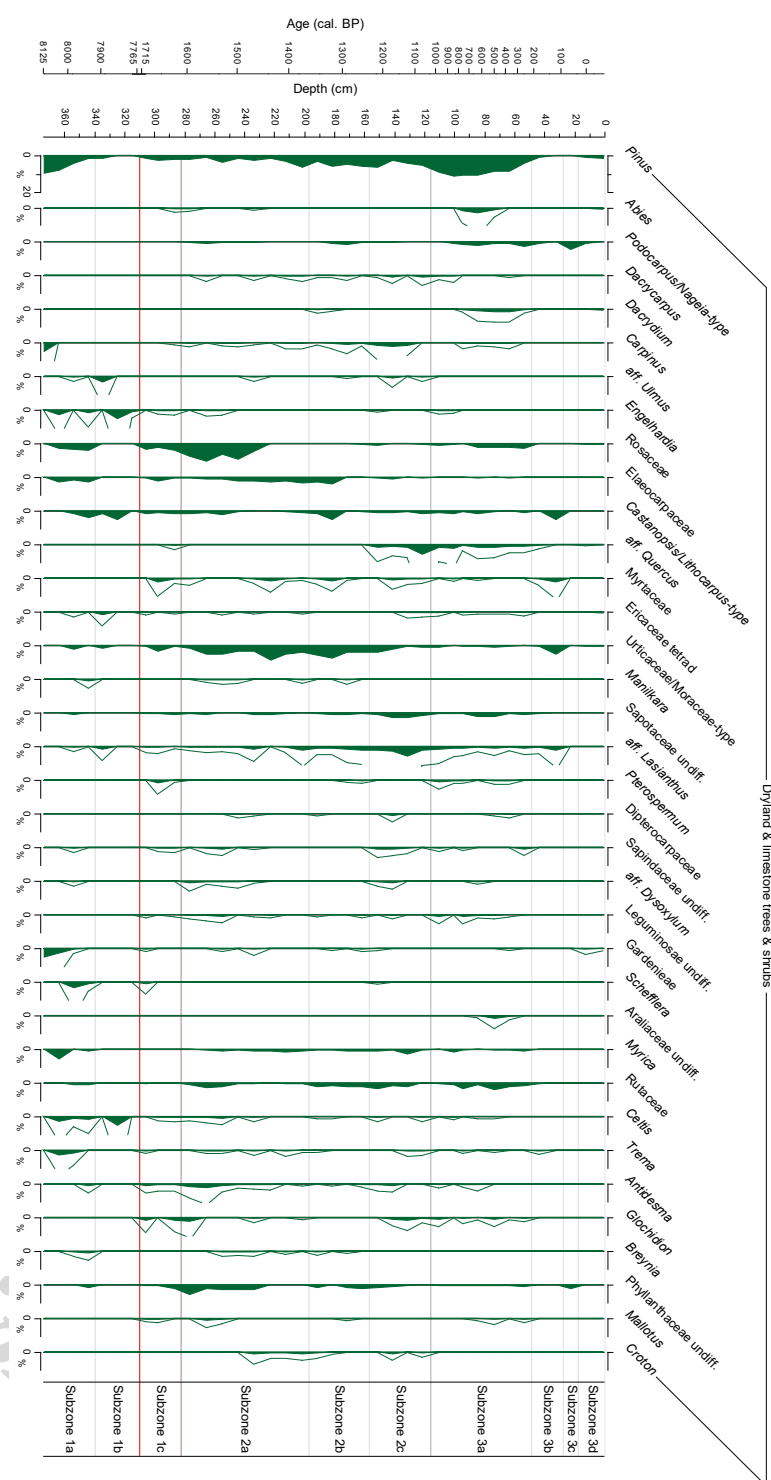
A total of 141 microfossil taxa were recorded across the 38 assemblages. These comprised pollen grains from seed plants; spores from ferns, fern allies and non-vascular plants; inner casings of foraminifera; diatom frustules; and dinoflagellate cysts. Only 24 of the 38 assemblages derive from microfossil counts that exceeded the target minimum of 300, and counts were highly variable ( $\mu = 556$ ;  $\sigma = 733$ ).

##### 4.1.4.1. Zonation

Three zones are defined by the branches of the dendrogram that are intersected by a line drawn at a threshold value of 60,000 total dispersion units (Fig. 6a). Each of these three zones are further divided into subzones by a secondary threshold placed at 15,000 total dispersion units, yielding three subzones each for Zones 1 and 2, whilst Zone 3 is split into four subzones.

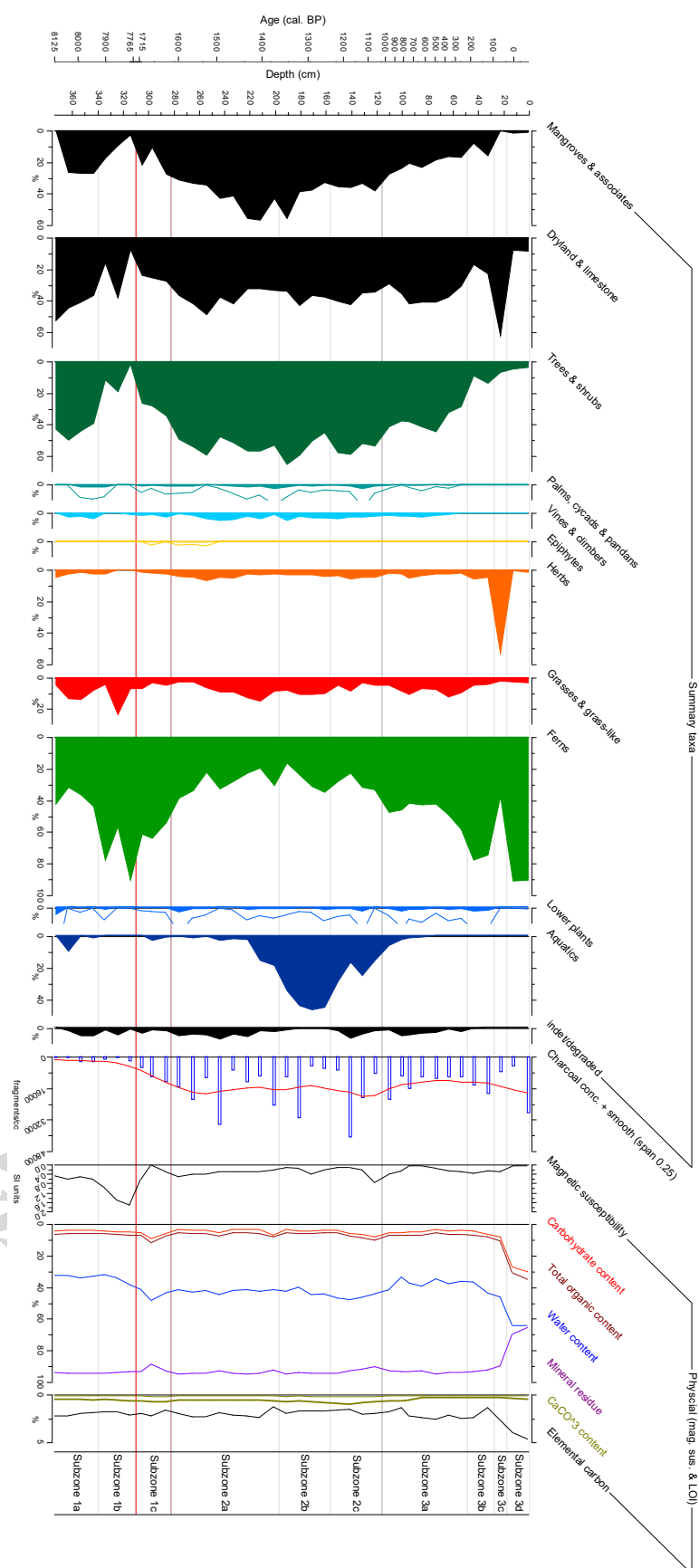


**Fig. 6a** Stratigraphic diagram of the Vung Tham core showing microfossil relative abundances of mangrove and aquatic taxa with depth, and dendrogram defining zonation. Colour-coding of curves correspond to life-form summary groupings in Fig. 6d. Outline curves represent 5x exaggeration. Horizontal red line represents the hiatus.



**Fig. 6b** Stratigraphic diagram of the Vung Tham core showing microfossil relative abundances of dryland and limestone forest tree and shrub taxa with depth. Dark green curves indicate constituent components of the 'Trees & shrubs' summary grouping in Fig. 6d. Outline curves represent 5x exaggeration. Horizontal red line represents the hiatus.





509

510 **Fig. 6d** Stratigraphic diagram of the Vung Tham core showing ecological and life-form summary  
 511 curves, microcharcoal concentration and physical measures with depth. Outline curves represent 5x  
 512 exaggeration;  $\text{CaCO}_3$  curve is 10x exaggeration. Horizontal red line represents the hiatus.

513

514 4.1.4.2. Assemblage descriptions by zonation

515 Subzone 1a: 8125 – 7915 cal. BP (382 – 340 cm)

516 The basal subzone of the sequence likely represents initial colonisation of the doline  
517 floor by mangroves as the transgressing inter-tidal zone moved over the coring site in the lead-  
518 up to the Middle Holocene high-stand in sea level.

519 Microfossil concentrations across these four assemblages are low ( $\mu = 2097$  grains  $\text{cc}^{-1}$ ,  
520  $\sigma = 1467$  grains  $\text{cc}^{-1}$ ). Ratios of pollen grains to fern spores, which can provide a rough  
521 indication of diagenetic bias via preferential preservation of the generally more robust fern  
522 spores (Havinga, 1964) are, however, acceptably high ( $\mu = 1.64$ ,  $\sigma = 0.51$ ). This may indicate  
523 a rapid sedimentation rate rather than poor preservation. In none of the four Zone 1  
524 assemblages was the target minimum count of 300 microfossils achieved; and in only the  
525 assemblage from 354 cm depth was a count of 200 grains surpassed. The count from the  
526 basal assemblage (374 cm) was extremely low (21 grains), containing a few grains of  
527 temperate and montane forest elements such as *Pinus*, *Tsuga*, Cupressaceae, Betulaceae,  
528 as well as *Artemisia*, Poaceae and a handful of fern spores (monolete psilate, as well as  
529 *Cibotium*). Microfossil concentrations increase through the subsequent three subsamples.  
530 The temperate components are maintained, with the addition of moderate representation of  
531 mangrove and associated taxa such as Rhizophoraceae, *Aegiceras*,  
532 Combretaceae/Melastomataceae-type, *Excoecaria*, *Heritiera*, the back-mangrove fern  
533 *Acrostichum* and undifferentiated dinocysts.

534

535 Subzone 1b: 7915 – 7765 cal. BP (340 – 310 cm)

536 Poor preservation and oxidised sediments, the absence of several mangrove and salt-  
537 tolerant taxa that were present in the previous subzone, small peaks in taxa that prefer less  
538 saline conditions and increases in temperate taxa suggest that Subzone 1b may represent  
539 back-mangrove and estuarine littoral vegetation above a fluctuating water table.

Microfossil concentrations are at their lowest in the core at 325 cm depth (403 grains cc<sup>-1</sup>), and low pollen to fern spore ratios throughout the subzone ( $\mu = 0.41$ ,  $\sigma = 0.38$ ) likely indicate a diagenetic biasing of assemblages. Fern spores are the dominant component of all three assemblages, ranging from 57.1 – 90.8%, which includes moderate representation of *Acrostichum*. *Excoecaria* is the only true mangrove seed plant taxon present. Several temperate or montane broad-leaved taxa, such as *Ulmus*, *Engelhardia*, *Castanopsis/Lithocarpus*-type, Ericaceae and *Celtis*, show small peaks, as do Poaceae, Cyperaceae, and the saltmarsh or dry-adapted Chenopodioideae.

*Subzone 1c: 1715 – 1610 cal. BP (310 – 282 cm)*

Despite the 6000-year gap between Subzones 1b and 1c, the three assemblages that comprise Subzone 1c are statistically more similar to those that predate the discontinuity than to those that overlie and follow continuously. This likely reflects the marginal to poor preservation that is common to these Zone 1 assemblages rather than likeness of parent vegetation. While microfossil concentrations are moderate across Subzone 1c ( $\mu = 9443$  grains cc<sup>-1</sup>;  $\sigma = 952$  grains cc<sup>-1</sup>), pollen to fern spore ratios remain low ( $\mu = 0.70$ ,  $\sigma = 0.15$ ). 'Ferns' remain the dominant summary taxon, ranging from 54.4 – 64.3%. Several mangrove and associated taxa that were present in Subzone 1a return, such as Rhizophoraceae, *Aegiceras*, Combretaceae/Melastomataceae-type, *Heritiera* and *Ilex*, while *Avicennia*, *Xylocarpus*, *Nypa*, *Casuarina*, *Pandanus*, *Colocasia* and inner casings of undifferentiated foraminifera make their respective first appearances.

*Zone 2: 1610 – 1025 cal. BP (282 – 116 cm)*

Assemblages across this zone collectively suggest persistence of diverse mangrove forest within the doline, as well as development of littoral elements and indicators of open water, particularly in the upper two subzones since 1365 cal. BP.

Indices for preservation across the 16 assemblages of Zone 2 are high though variable (ratio of pollen to fern spores:  $\mu = 2.80$ ,  $\sigma = 0.96$ ; microfossil concentration:  $\mu$



= 23,112 grains cc<sup>-1</sup>;  $\sigma$  = 20,302 grains cc<sup>-1</sup>). Average concentrations of microcharcoal fragments are higher across this zone than in other portions of the record, but values for individual subsamples vary widely ( $\mu$  = 16,979 fragments cc<sup>-1</sup>;  $\sigma$  = 11,179 fragments cc<sup>-1</sup>).

*Subzone 2a: 1610 – 1365 cal. BP (282 – 197 cm)*

Relative abundance of the 'Mangrove & associates' summary taxon is at its highest average value within this subzone ( $\mu$  = 42.49%;  $\sigma$  = 9.61%), rising steadily from 31.50% at 277 cm depth to 56.78% at 213 cm before tapering off slightly to 43.22% in the uppermost assemblage. In addition to the mangrove taxa that were already present from Zone 1, *Avicennia*, *Sonneratia*, *Scyphiphora*, *Xylocarpus*, *Casuarina*, *Diospyros*, *Brownlowia*, *Cerbera*, *Barringtonia* and *Pandanus* are all represented in these Subzone 2a assemblages. The 'Grass & grass-like' summary taxon shows a similar trend, rising from 2.56% to 14.83%, driven by Poaceae but with minor representation of Cyperaceae and *Typha*. Additional marked features of summary taxa are the consistently low values for 'Ferns' ( $\mu$  = 28.66%;  $\sigma$  = 6.69%), as well as the steep increase in 'Aquatics' in the two uppermost assemblages. *Acrostichum* is the dominant fern taxon, whilst the increase in aquatics is due to the first appearance of diatoms. A peak in the 'Dryland & limestone' summary taxon occurs at 255 cm (48.85%), whilst this taxon maintains values from 32.23 – 42.12% throughout the rest of the subzone. Within this summary grouping, prominent taxa are Rosaceae, Urticaceae/Moraceae-type, Phyllanthaceae and Lamiaceae/Verbenaceae-type, with minor representation of the conifers *Abies*, *Podocarpus/Nageia*-type and *Dacrydium*, as well as broad-leaved forest taxa such as *Carpinus*, Myrtaceae, *Lasianthus*, Sapotaceae and Rutaceae.

*Subzone 2b: 1365 – 1245 cal. BP (197 – 157 cm)*

The distinctive feature of this subzone is the very large peak in diatom abundance ( $\mu$  = 38.40%;  $\sigma$  = 7.40%). Diatoms dominate the signal of aquatic taxa in this subzone, though dinocysts and foraminifera maintain significant concentrations. Mangrove and terrestrial taxa remain abundant and diverse, though *Xylocarpus* decreases across the four assemblages.

Within the dryland and limestone taxa, *Pinus*, Urticaceae/Moraceae-type, *Lasianthus*, Rutaceae and Poaceae all occur at stable levels, whereas Elaeocarpaceae and *Castanopsis/Lithocarpus*-type show minor decreases.

#### Subzone 2c: 1245 – 1025 cal. BP (157 – 116 cm)

Diatom abundance declines sharply from the high values attained in the underlying subzone, and disappears altogether by the two uppermost assemblages, whilst dinocysts and foraminifera show marked increases. Within the mangrove taxa, Rhizophoraceae, *Aegiceras* and *Excoecaria* occur at high, stable relative abundances, whereas Combretaceae/Melastomataceae-type, *Scyphiphora*, *Acrostichum* and *Heritiera* decrease in abundance. The coastal strand and littoral taxa *Casuarina* and *Pandanus* show minor increases. Of the dryland and limestone components, the wind-dispersed pollen of temperate tree taxa *Carpinus*, *Ulmus* and *Quercus* are relatively abundant, alongside increases in the tropical forest and lowland taxa Sapotaceae, *Lasianthus*, Sapindaceae and *Glochidion*.

#### Zone 3: 1025 cal. BP – Present (116 – 0 cm)

The most significant vegetation change within the record occurs with the shift to Zone 3 assemblages, at a modelled mean age of 1025 cal. BP (925 CE). While this zone appears to represent a continued though diminished presence of mangroves, structural opening of the dryland and limestone vegetation is evident (beginning with the uppermost assemblage of Subzone 2c at 122 cm and a modelled mean age of 1075 cal. BP), with suggestions of both drought and increased disturbance to vegetation.

#### Subzone 3a: 1025 – 210 cal. BP (116 – 49 cm)

Amongst the summary taxa, decreases are marked in 'Trees & shrubs', as well as in 'Mangroves & associates', whilst the 'Ferns' and the 'Grasses & grass-like' taxa increase. Though individual mangrove taxa are still represented, relative abundances of all but the back-mangrove fern *Acrostichum* decrease, and many disappear from the record altogether by the

uppermost assemblage. Mangrove and associated taxa that do not occur above these Subzone 3a depths include Rhizophoraceae, *Avicennia*, *Sonneratia*, *Scyphiphora*, *Xylocarpus*, *Aegialitis*, *Acanthus*, *Heritiera*, *Pandanus* and *Tristellateia australasiae*. Additionally, foraminifera and dinocysts decrease across the lower three subsamples, and join diatoms in their absence from all assemblages above 85 cm depth. Concurrently, temperate trees, many of which are wind-pollinated and likely extra-local to the site, and drought-tolerant or disturbance-indicative taxa show corresponding increases. These taxa include conifers such as *Pinus*, *Abies*, *Podocarpus/Nageia*-type and *Dacrydium*, as well as the largely temperate taxa Rosaceae and Ericaceae, drought-adapted *Pterospermum*, and the often early-successional Rutaceae, *Glochidion*, *Mallotus* and Poaceae, as well as multiple fern taxa.

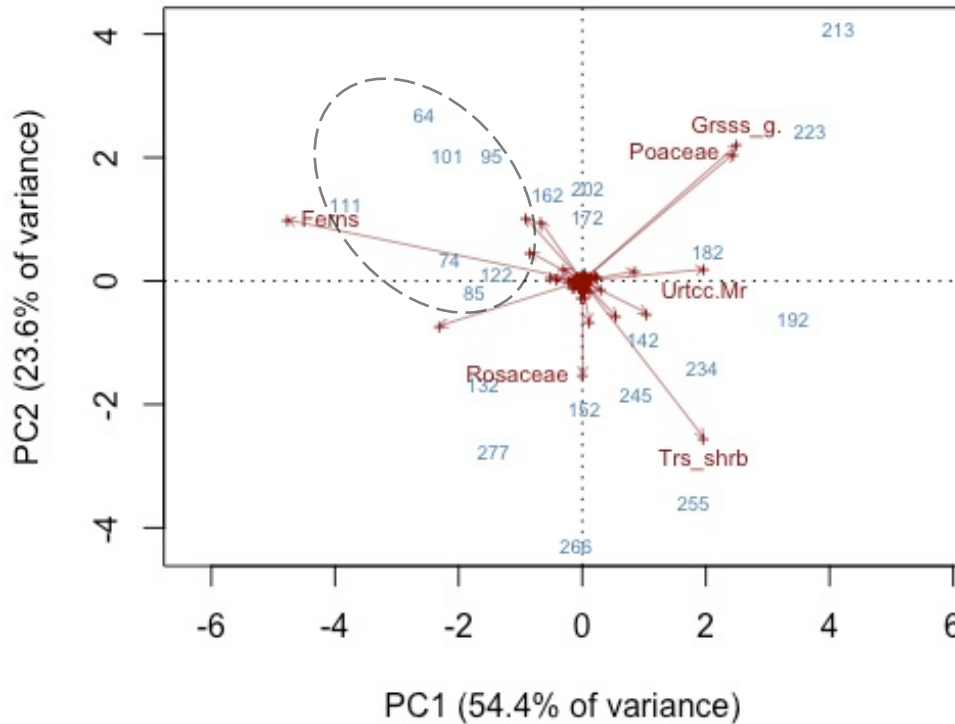
#### Subzones 3b-d: 210 cal. BP – Present (49 – 0 cm)

Poor preservation across the five uppermost assemblages, which comprise Subzones 3b – d prevents meaningful interpretation. ‘Ferns’ dominate the two Subzone 3b assemblages ( $\mu = 76.54\%$ ;  $\sigma = 2.18\%$ ), consisting largely of *Lygodium* and monolete psilate spores, but also with substantial representation of *Acrostichum*. Minor peaks in *Castanopsis/Lithocarpus*-type, Myrtaceae, Urticaceae/Moraceae-type, *Lasianthus*, Amaranthaceae and Cyperaceae occur, whilst Poaceae decreases. The single Subzone 3c assemblage at 23 cm is composed of little else apart from a large number of grains of Amaranthaceae pollen, a couple of grains of *Podocarpus/Nageia*-type, Phyllanthaceae and Cyperaceae, and a handful of fern spores. The two uppermost assemblages, comprising Subzone 3d, derive from what is presumably modern and recent humus and are dominated by monolete fern spores, though *Acrostichum* is also present in low relative abundance. Some elements of the modern disturbance-indicative flora are also present but not abundant, as are conifers and other likely extra-local wind-pollinated taxa.

#### 4.1.4.3. Ordination

Of the exploratory ordinations that were performed on various subsets of the palynological data, the most informative was the PCA run on a subset of the data that included only the well-preserved assemblages and non-mangrove terrestrial taxa. Analyses performed on data from all subsample levels were skewed by the diagenetically biased, poorly preserved assemblages at the base and top of the sequence. Similarly, whilst presence and relative abundances of mangrove taxa are informative for reconstructing the vegetation occupying the doline floor and for sea level inferences, these data reflect narrowly relevant tidal processes rather than more broadly important palaeoenvironmental parameters such as climatic factors. After the poorly preserved assemblages and the mangrove taxa were temporarily masked, patterns in the dryland and limestone vegetation were revealed.

In the PCA (Fig. 7), the summary taxa 'Trees & shrubs' (appearing as 'Trs\_shrb') and that of 'Ferns' plot in opposing directions with respect to the primary axis (PC1). This suggests that a structural gradient in the degree of openness of the limestone vegetation has considerable explanatory power in describing differences between assemblages. Like the 'Ferns' summary taxon, assemblages from 122 cm and above (the uppermost assemblage of Zone 2, plus Zone 3 assemblages) exhibit negative scores with respect to PC1, implying a structural opening of limestone vegetation from 122 cm and above. The Bayesian model suggests this change in vegetation occurred around 1075 cal. BP (875 CE).



**Fig. 7** PCA biplot of the non-mangrove taxa from well-preserved assemblages. Numbers correspond to core depths (cm) of assemblages; vectors correspond to constituent taxa of those assemblages and their loadings. Dashed oval encompasses depths 122 cm and above (uppermost assemblage of Zone 2 plus Zone 3 assemblages).

#### 4.2. Vung Tham notches

Notches were observed at the base of the vertical cliffs that enclose the doline and in isolated boulders. Their uniform U-shaped profile reaches a depth of 1.5 m with a horizontal roof and a slightly sloping floor which suggests low wave action and a relatively stable mean sea level over at least 1500 years based on an estimated annual planar erosion rate of 1 mm yr<sup>-1</sup> for tropical karst landscapes (Trenhaile, 2015). Measured notch heights indicate a mean tidal range of ~0.6 m, which is below the observed average of 1.2 m at sites that were exposed to the open sea. This indicates that water flow in and out of the doline during inundations was restricted and may have caused a delay in the tidal cycle and flattening of the tidal amplitude at Vung Tham. A similar effect was observed (by TK) at Cat Ba Island where the water table inside *hongs* was above the prevailing sea level and water was draining at high flow rates through small outlets in the rock.

#### 4.3. Hang Moi archaeology

##### 4.3.1. Phytoliths

Phytoliths were recovered from all contexts sampled, which date to within the Middle Holocene hiatus in the Vung Tham core sequence from the doline floor, though phytolith counts were consistently low. This is likely a result of degradation under alkaline conditions, evidenced by surface pitting on some phytoliths, and as a result of burning. Variation between contexts was still observed, however, with peaks (~2000 – 5000 phytoliths g<sup>-1</sup>) in the charcoal-rich contexts (6019) and (6026) contrasting with lows of ~500 phytoliths g<sup>-1</sup> in burnt shell layers.

The majority of morphotypes were only coarsely ascribed as being derived from the wood/bark of eudicotyledons (Table 4). These types make up 47% of the entire assemblage and indicate that wood was the main source of fuel used in the hearths. Globular echinate phytoliths from Arecaceae spp. (palms) were also common and relatively abundant in the samples at 17%. At much lower levels (<2%) phytoliths from taxa of Annonaceae, Asteraceae, *Celtis*, Marantaceae and Poaceae were recovered. Low numbers of sponge spicules were recovered throughout the samples but were more abundant in (6026) and (6019), suggesting that some of the foraged vegetation in the hearths came from wet environments.

**Table 4** Summary of Middle Holocene phytolith assemblages from Hang Moi.

Site Code	Trench	Context	Phytolith Assemblage
HMC11	1	6004	Low frequency of morphotypes from grasses, trees/shrubs and palms.
HMC11	1	6009	Low frequency of morphotypes from grasses, trees/shrubs, palms and sponge spicules.
HMC11	1	6007/6008	Relatively high numbers of morphotypes from trees/shrubs and low frequency from grasses and palms.
HMC11	1	6011	Increase in the presence of mesophyll and phytoliths from woody eudicots. Morphotypes from palms decline. First occurrence of <i>Celtis</i> sp. fruit/seed types.
HMC11	1	6020	Low phytolith count.
HMC11	1	6019	Most abundant context with high frequency of sponge spicules and phytoliths from <i>Celtis</i> sp., palms, and trees/shrubs.
HMC11	1	6022	Low phytolith count. Asteraceae sp. platelet recovered only from this context (n = 1). <i>Celtis</i> sp. present.
HMC11	1	6026	Increase in the phytoliths from leaves and hair cells. Only occurrence of Annonaceae sp. (n = 1). Sponge spicules, <i>Celtis</i> sp. and palms present.

HMC11	1	6031	High frequency of morphotypes from trees/shrubs but low frequency of phytoliths overall. Sponge spicules present.
HMC11	1	6033	High numbers of multi-cells indicative of the leaf/stem of monocots. Marantaceae sp. phytoliths recovered. Sponge spicules present.
HMC11	1	6037	Lowest phytolith abundance of all samples and the only context not to contain palm phytoliths.

#### 4.3.2. Vertebrate faunal remains

The three identifiable teeth from the Middle Holocene deposits of Trench 1 were attributable to two taxa: chevrotain (*Tragulus* sp.; NISP = 2) and serow (*Capricornis maritimus*; NISP = 1) (Table 5). The specimens are most likely attributable to the lesser Oriental chevrotain, *T. kanchil*. Two post-cranial specimens are attributable to small carnivores and are as-yet unidentified civets (Viverridae).

Post-cranial remains of serow were also recovered from the upper deposit from Trench 2, as were post-cranial elements of a large species of macaque (*Macaca* sp.), possibly *M. assamensis*. The presence of hog deer, *Hyelaphus* (*Axis*) *porcinus*, is indicated by an antler fragment. Carnivore remains include greater hog badger, *Arctonyx collaris*. Avian remains include fish owl (*Bubo* sp.) and Oriental pied hornbill, *Anthracoceros albirostris*. Finally, distinctive vertebrae of *Python* sp. indicate the exploitation of these snakes.

Specimens from the lower deposits of Trench 2 comprised several fragmented vertebrae from larger mammals including a large cervid (most likely sambar, *Rusa unicolor*), further post-cranial remains from a large species of macaque and a complete pig distal humerus (*Sus* sp.). Further vertebrae of *Python* sp. were also recovered from this lower deposit.

A particularly conspicuous component of the faunal remains from the lower deposit in Trench 2 (6509) was a relatively large discrete collection of distinctive neurocrania of the fish genus *Pomadasys*, variously known as 'grunts', 'grunters' or 'javelins' (MNI = 13). The size of complete specimens (greatest length:  $n = 3$ : 69.90 mm, 73.34 mm, 62.06 mm; greatest breadth:  $n = 4$ : 46.93 mm, 52.32 mm, 45.40 mm, 39.06 mm) within this collection indicate the presence of a relatively large species within the genus and fall within the range of *Pomadasys argenteus*, the silver 'grunt' or 'javelin' (cf. *Pomadasys "fuscus"* in Belcher, 1994).

730 **Table 5** Middle Holocene vertebrate faunal remains from Hang Moi.

Site code	Trench	Context	Element	Taxonomy
HMC11	1	6011	P3	<i>Capricornis maritimus</i>
HMC11	1	6014	M1	<i>Tragulus cf. kanchil</i>
HMC11	1	6014	P4	<i>Tragulus cf. kanchil</i>
HMC11	1	6039	McIII	cf. Viverridae
HMC11	1	6032	radius	cf. Viverridae
HMC11	2	6203-1	pelvis	<i>Capricornis maritimus</i>
HMC11	2	6203-1	mandible	<i>Capricornis maritimus</i>
HMC11	2	6203-1	ulna	<i>Anthracoceros albirostris</i>
HMC11	2	6203-1	scapula	<i>Capricornis maritimus</i>
HMC11	2	6203-1	radius	<i>Capricornis maritimus</i>
HMC11	2	6203-2	calcaneus	<i>Macaca</i> sp.
HMC11	2	6203-2	antler	<i>Hyelaphus porcinus</i>
HMC11	2	6203-2	tibiotarsus	<i>Bubo</i> sp.
HMC16	2	6303-1	tine	Cervidae
HMC16	2	6303-1	tibia	Viverridae
HMC16	2	6303-2	vertebra	<i>Python</i> sp.
HMC16	2	6303-2	tibia	Viverridae
HMC16	2	6303-2	vertebra	<i>Python</i> sp.
HMC16	2	6303-3	vertebra	<i>Python</i> sp.
HMC17	2	6503-1	humerus	<i>Arctonyx collaris</i>
HMC17	2	6506-A	humerus	<i>Sus</i> sp.
HMC17	2	6509-1	axis vertebra	Cervidae
HMC17	2	6509-1	neurocranium	<i>Pomadasys cf. argenteus</i>
HMC17	2	6509-2	neurocrania (x 12)	<i>Pomadasys cf. argenteus</i>
HMC17	2	6509-2	calcaneum	<i>Macaca</i> sp.
HMC17	2	6509-2	vertebra	<i>Python</i> sp.
HMC17	2	6509-2	femur	<i>Macaca</i> sp.

731

#### 732 4.3.3. Molluscs

733 Mollusc assemblages from six contexts within the shell midden of Trench 2 were  
734 grouped into four phases: HMC-1, 2, 3 and 4 (Fig. 8). HMC-1, HMC-3 and HMC-4 contain  
735 assemblages dominated by mangrove taxa *Sermyla riqueti* and *Neripteron violaceum* along  
736 with other common marine and terrestrial taxa associated with mangrove environments in  
737 Vietnam (Vermeulen & Maassen, 2003). HMC-2 is dominated by a large deposit of marine  
738 shells. The lack of a terrestrial component within these mollusc assemblages suggests that  
739 forest environments did not occur within the immediate vicinity of the cave when these  
740 contexts were deposited.





## 5. Discussion

### 5.1. Earliest Middle Holocene

The earliest Middle Holocene is represented in the Vung Tham sediment core by the basal 72 cm which, according to the Bayesian age-depth model, are estimated to date to 8125 – 7765 cal. BP. Seven pollen assemblages comprising Subzones 1a and 1b of the Vung Tham record derive from this portion of the sequence. These assemblages were interpreted to represent the initial colonisation of the doline floor by mangrove vegetation, succeeded by the development of back-mangrove and coastal strand communities over a fluctuating water table.

A possible explanation for the hydrological instability inferred from the Subzone 1b assemblages is that the vegetation response reflects the same marked though short-lived reduction in the intensity of the East Asian Monsoon (EAM) that is recorded in the oxygen isotope record from stalagmite D4 at Dongge Cave in Guizhou Province, southwestern China (Dykoski et al., 2005; Wang et al., 2005) (Fig. 1). The increasingly lighter  $\delta^{18}\text{O}$  values across the Early Holocene portion of the Dongge Cave record imply a general strengthening of the EAM which follows the trend of incoming summer solar radiation at 25°N, but with a 2 – 3 ka lag. During the Early Holocene, however, the D4 speleothem profile records four punctuated excursions to heavier  $\delta^{18}\text{O}$  values. Dykoski et al. (2005) interpret the last of these excursions, expressed as a 'double event' comprising two shifts centred around 8260 and 8080 cal. BP, as a correlate with the '8.2 ka event' of decreased temperature detected in the GISP2 and NGRIP ice core records from Greenland (Johnsen et al., 2001). The 8.2 ka event has also been detected in the Huguangyan Maar pollen record from the Leizhou Peninsula of tropical mainland South China, manifest as an increase in pollen from temperate taxa at the expense of tropical tree pollen (Sheng et al., 2017). In contrast, Dodson et al. (2019) found no corresponding change in the Shuangchi Maar pollen record from Hainan Island off the South China coast.

While no directly comparable pollen records yet exist from enclosed dolines near to Vung Tham for this time period, Subzone ND-1-Va of Li et al.'s (2006a) pollen record from the Nam Dinh-1 core (ND-1), located on the delta plain outside the Trảng An massif and ~30 km

ENE from Vung Tham (see Fig. 1), dates to 9000 – 7700 cal. BP (Tanabe et al., 2003a). Tanabe et al. (2003a; 2003b) interpret the lithology of this portion of the ND-1 core to represent a tidal flat depositional environment near the mouth of the Song Hong. Li et al. (2006a) describe the first peak in mangrove pollen within the ND-1 record to occur at about 9000 cal. BP, while pollen from tropical taxa increase across ND-1-Va at the expense of pollen from previously prevalent conifers and temperate broad-leaved trees. This palynological trend shows greater similarity to that of the insular Shuangchi Maar record than it does to the mainland Huguangyan Maar, likely reflecting the tempering effects of maritime influence shared by the Shuangchi Maar and ND-1 sites, whereas the 8.2 ka event is recorded in the more continental sites of Huguangyan Maar and Dongge Cave.

In this context, the hydrological instability inferred from the Subzone 1b assemblages of the Vung Tham pollen record more likely reflects the locally dynamic interplay between transgressive and regressive processes that Funabiki et al. (2007) describe for this portion of the delta infilling the flooded Song Hong valley than it does any large-scale climatic oscillation. It seems probable that the mangrove vegetation that colonised the Vung Tham doline prior to 8100 cal. BP was seeded from the more extensive mangroves that existed from 9000 cal. BP on the tidal flats outside the massif. Water-dispersed disseminules are life history traits common to mangrove plants (Tomlinson, 2016), implying that mangrove fruits, seeds and viviparous seedlings were likely brought into the Vung Tham doline on flooding tides via foot caves when Vung Tham was within the intertidal zone. Subsequently, sedimentation within the flooded Song Hong valley outside the massif to the east possibly outpaced relative sea level rise immediately after 8000 cal. BP, leading to a lower relative water table and the temporary development of back-mangrove vegetation within the Vung Tham doline.

## 5.2. Middle Holocene high-stand

A large gap in the Vung Tham record from the doline floor spans 7765 – 1715 cal. BP. Similar Middle-Late Holocene gaps exist in cores from the delta plain outside the Trảng An massif (e.g. cores HN, HT, HD, CD, DP, NP from Duong et al., 2020; cores PD, DA, TL from

Funabiki et al., 2007; core CC from Hori et al., 2004; core ND-1 from Tanabe et al., 2003a; core DT from Tanabe et al., 2003b; cores VN, HV, NB, GA from Tanabe et al., 2006). These sequences provide evidence for Middle Holocene delta progradation and infilling of the drowned Song Hong valley leading up to and during the high-stand centred ~5500 cal. BP. Microfossil analyses of Middle Holocene portions of these sequences suggest brackish estuarine environments within the drowned and infilling Song Hong valley, fringed by tidal flats supporting mangrove and other wetland vegetation (Duong et al., 2020). Immediately following the high-stand, sedimentation subsequently slowed and ceased at upstream sites such as PD, HN, DA and HT as sea level began to gradually regress toward that of the present-day; causing a drop in fluvial geomorphic base level and incision by the Song Hong of the sediments deposited during the preceding deglacial marine transgression.

While the gap in the Vung Tham sequence fits the pattern of sedimentation displayed by the borehole sequences from across the delta plain, the processes involved are less obvious. Vung Tham is enclosed by the surrounding limestone massif, and the fine-grained sediments throughout the deposit support the expectation that it had remained sheltered from the higher-energy marine and fluvio-deltaic processes acting outside the massif across the broader delta region. The likely prior colonisation of the doline floor by water-dispersed mangrove disseminules, as well as the existence of notches at the base of the enclosing limestone walls, imply that a direct hydrological connection existed with the transgressing sea and associated tidal cycles. Two plausible explanations for the gap in the Vung Tham record, which are not mutually exclusive, are proposed. The doline floor may have been starved of sediment during the Middle Holocene high-stand when Vung Tham appears to have been submerged from wall to wall; and that as the intertidal zone regressed back across the doline following the high-stand, portions of the deposit may have been eroded on ebbing tides. Observations made by SO, NTMH, TK and EH at an analogous modern flooded doline on Cat Ba Island, which is within the present intertidal zone and has hydrological connections to the surrounding sea, confirm that significant flow velocities and erosive potential are achieved on ebbing tides.

In the absence of high-stand sediments from the Vung Tham doline floor, palaeoenvironmental inferences for this time period have been drawn from the notches at the base of the enclosing limestone walls within Vung Tham, as well as from Middle Holocene archaeological assemblages from the adjacent cave site of Hang Moi. Data from the notches indicate that the entire doline was inundated to a level of ~3.3 m a.s.l. While there is presently no visible evidence of a connection to the surrounding delta plain, the current presence of water in Vung Tham is most likely facilitated by subterranean conduits that connect to the local aquifer. The microfossil evidence for the past presence of mangroves, discussed above, also implies a hydrological connection with the sea during times of higher sea level.

Phytolith analysis of the in situ hearth sequence from Trench 1 at Hang Moi confirmed the presence of Annonaceae, Arecaceae, Asteraceae, *Celtis*, Marantaceae and Poaceae, as well as unidentifiable woody eudicots (trees / shrubs) within the deposit at Hang Moi. The most abundant morphotypes present, that are attributable to trees / shrubs, are not diagnostic. However, previous analysis of charcoal recovered from the same contexts at Hang Moi (Ceron, 2012) attests to the presence of Dipterocarpaceae sp. (prob. *Dipterocarpus* sp.), Dilleniaceae sp. (prob. *Dillenia* sp.) and Sapotaceae sp. (prob. *Manilkara* sp. or *Palaquium* sp.), which are indicative of lowland and limestone forest and likely the source of fuel for the fires.

All the taxa recovered are common in Southeast Asian ethnographic examples and archaeobotanical assemblages. Palms are used as fuels, construction, in weaving, wrappings and as food (Haynes & McLaughlin, 2000; Tsuji et al., 2011). *Celtis* sp. fruit are edible; its bark/wood has medicinal properties; and it is suitable for cloth manufacture and for use as timber (Fu et al., 2003; Glover, 1986; Kealhofer & Piperno, 1998). Poaceae is an expansive family with many key economic species, with numerous additional uses which vary from construction to textiles. Whilst many of the families represented in the phytolith assemblages have species that produce edible fruits or nuts, the phytoliths identified mostly come from wood, bark, leaves and stems, and so do not in themselves provide immediate indication for use as foods.

Comparisons can be drawn between these assemblages from Hang Moi and existing contemporaneous evidence from subtropical South China. Phytoliths from Xincun attest to the importance of palms in the subsistence strategy of Middle Holocene gatherers (Yang et al., 2013). Similarly, Annonaceae, palms, cucurbits and grasses have been recovered in phytolith assemblages from Dingsishan sites (Chi & Hung, 2012). In this context, the abundance of globular echinates from the Hang Moi samples may indicate the importance of palms in the subsistence strategies of the people who used Hang Moi during the Middle Holocene, although it has been proposed that this morphotype of phytolith is more robust than others, so its high frequency may be a result of preferential preservation (Albert et al., 2008; Cabanes & Shahack-Gross, 2015). The results of the phytolith and charcoal analysis, together with the sponge spicules that were recovered, attest to the presence and exploitation of resources that can occur in a range of habitats, including forests and wetlands, by the people at Hang Moi during the Middle Holocene.

The animal bones recovered from Hang Moi overwhelmingly reflect subsistence behaviours of the prehistoric occupants of the cave rather than a comprehensive sampling of available local vertebrate taxa. As such, the zooarchaeological assemblages represent the product of the exploitation of different habitat types. With this caveat in mind, the current identifications of vertebrate taxa permit the following inferences.

The identified mammalian taxa from the Middle Holocene hearth and refuse dump deposits indicate the exploitation of serow (*Capricornis maritimus*). These large caprines most parsimoniously occupied the steep terrain of Tràng An (e.g. Castelló, 2016) reflecting the exploitation on the interior of the karst.

The ecology and behaviour of Indochinese chevrotains is understudied, but known habitat preferences of the species are a mosaic of riverine, seasonal swamp and drier undulating country. The main vegetation types associated with the lesser Oriental chevrotain (*T. kancil*) are legumes and dipterocarps (Timmins & Duckworth, 2015).

Post-cranial elements of primates indicate the exploitation of a large species of macaque (*Macaca* sp.), possibly *M. assamensis*. This is associated with lowland limestone karst forest

(Nadler & Brockman, 2014). The presence of hog deer, *Hyelaphus porcinus*, is indicated by an antler fragment. The hog deer is now extinct in Vietnam but is reported to strongly favour more open wet or moist tall grasslands, often associated with riverine habitats. The species is reported to occur in the highest densities in flood plain grasslands. Hog deer favour grazing on young grasses, especially *Imperata cylindrica* and *Saccharum* spp. In addition, herbs, flowers, fruits and some browse are also taken (Timmins et al., 2015).

Carnivore remains include as-yet unidentified civets (Viverridae) and greater hog badger (*Arctonyx collaris*). Many basic aspects of the natural history of the greater hog badger are poorly known and require study (e.g. Proulx et al., 2016) but the species is reported to be primarily associated with lowland and hill forests (Hunter & Barrett, 2011).

Avian remains include fish owl (*Bubo* sp.) and Oriental pied hornbill (*Anthracoceros albirostris*). The species of fish owl that are known from the region today show strong association with forested habitats near water (König & Weick, 2008). The Oriental pied hornbill is a widely distributed species (that remains a conspicuous and noisy resident of Trảng An today) and is predominantly associated with tropical and subtropical wet lowland forests (Kinnaird & O'Brian, 2007). Pythons are known from forested and grassland habitats but are strong swimmers and show a marked affinity for water.

Specimens of cervid, pig and macaque from the lower deposits of Trench 2 likely indicate the exploitation of interior habitats. Further vertebrae of *Python* sp. were also recovered from the lower deposit.

The assemblage of neurocrania from *Pomadasys* cf. *argenteus* is perhaps the strongest evidence of local high-stand conditions. On the basis of data currently available from Hang Moi this would seem to have occurred prior to 5500 cal. BP. While 'grunts' *per se.* are predominantly associated with marine and coastal habitats, species such as *P. argenteus* are also known to enter mangroves (Dahanukar, 2012).

Middle Holocene contexts from Trench 2 yielded mollusc assemblages containing a mix of taxa that inhabit mangrove, estuarine and terrestrial subtropical forest environments. Mangrove and estuarine gastropod taxa such as *Neripteron violaceum*, *Cerithidea obtusa*,

*Ellobium* cf. *aurisjudae*, *Sermyla riqueti*, *Brotia* spp. and *Cerithium* spp. predominate alongside shallow mud burrowing bivalves like *Meretrix* sp., various Tellinidae and Arcidae and a variety of small oysters, most likely *Crassostrea* sp., which are present in large numbers alongside several fragmentary *Unio* spp. The terrestrial component, which is significantly smaller than that from other cave assemblages in the area (Hill & Hunt, 2014), is dominated by *Cyclophorus* spp., a small number of which are identifiable to *C. cambodgensis*.

The composition of the assemblages within context 6203 reflects human foraging of mangrove and estuarine habitats. Comparative survey of modern intertidal environments on Cat Ba Island (by EH), treated here as an analogue to Middle Holocene Tràng An, demonstrate that many of these species are accessible within the intertidal zone and the edges of mangrove stands. The dominance of mangrove and estuarine taxa within the Trench 2 midden assemblages, which make up ~90% of the total across the sequence, suggests a heavy reliance on mangrove and estuarine environments as a foraging location for molluscs. *Sermyla riqueti* are still bought and sold in Vietnamese markets today as an edible species, and this taxon makes up 75% of all molluscs in the Trench 2 Middle Holocene midden layers at Hang Moi. The average size of the archaeological *S. riqueti* shells is 2.7 cm, which are slightly smaller than those sold today, while the largest are 4cm.

The reduced terrestrial components of these Middle Holocene mollusc assemblages from Hang Moi as compared to that of earlier Holocene assemblages from other cave deposits across Tràng An (cf. Rabett et al., 2011) suggests that the human groups that used Hang Moi during this period preferred to forage for molluscs in mangrove and estuarine habitats. The vertebrate faunal remains discussed above attest to the persistence and human use of limestone forest habitats within the interior of the karst throughout the Middle Holocene. In this context, it seems that the people who used Hang Moi during the high-stand in sea level preferred to forage for molluscs in the mangrove and estuarine environments that likely existed within the doline in front of the cave, while venturing deeper into the karst to hunt in limestone forest habitats.



In total, based upon the inferred subsistence base, combined with the dark coarse-ware potsherds previously recovered from Middle Holocene contexts at Hang Moi (Green, 2018; Nyiri, 2011), the archaeological remains are attributable to the Da But culture. Bui (1991) and Nguyen (2005) describe the Da But's characteristic orientation towards wetland, estuarine and mangrove resources as a cultural adaptation to coastal inundation during the Middle Holocene high-stand in sea level, though the exploitation of interior, forested habitats remained a component of the foraging economy. During this high-stand, the palaeoenvironmental and archaeological evidence presented here suggests that the Vung Tham doline contained an ancient *hong* lagoon enclosed by limestone karst and supported mangroves and surrounding limestone forests, similar to the modern *hongs* of Krabi province in southwestern Thailand and of Cat Ba Island in Hai Phong province of northern Vietnam (Price & Waltham, 2007). The ancient *hong* in Vung Tham appears to have been an attractive location to Da But people during the Middle Holocene.

### 5.3. Late Holocene

The Late Holocene is defined by Walker et al. (2018) as beginning with the widely detected '4.2 ka event', expressed in many palaeoclimate records by abrupt onset of aridification lasting 200 – 300 years. The Dongge Cave record from south-eastern China documents the 4.2 ka event with a sharp excursion to heavier  $\delta^{18}\text{O}$  values, suggesting a further weakening of the EASM (Dykoski et al., 2005). This expression of the 4.2 ka event is an acceleration of the weakening trend in the EASM throughout the Middle-Late Holocene, which tracks mid-latitude Northern Hemisphere summer insolation (Wang et al., 2005; Zhang et al., 2019). The subsequent period from ~4 – 2 ka is marked by increasing variability of the El Niño – Southern Oscillation (ENSO) (Dykoski et al., 2005; Haug et al., 2001; Toth & Aronson, 2019), manifest in south-eastern China as hydroclimatic instability (Zhang et al., 2018a; 2019).

Palaeo-shoreline reconstructions for the Late Holocene based upon borehole data in Duong et al. (2020) and Tanabe et al. (2006) describe the completion of infilling of the Song Hong valley by ~4 – 3.7 ka, and the resulting establishment of a linear coastline along the

delta front ~30 km inland from its present position. While Late Holocene sediments are absent from the ND-1 core (Li et al., 2006a), pollen assemblages from the VN and GA cores located progressively further downstream along the course of the Song Hong record the seaward migration of mangrove-dominated tidal flats as the delta continued to prograde across the Late Holocene (Li et al., 2006b). In pollen zone VN-IV of the VN core, Li et al. (2006b) attribute sharp and sustained decreases in pollen of arboreal taxa at 3340 cal. BP, and their replacement by pollen of non-arboreal and secondary taxa such as large grass grains (greater than 40  $\mu\text{m}$ ), aroids, gesneriads, and extra-local *Pinus*, to human clearance of the broad-leaved lowland tropical forest that they suggest occurred during the Middle-Late Holocene at the site. This dominance in non-arboreal pollen remains a consistent feature through the remainder of the record, suggesting sustained forest reduction on the delta plain across the past three millennia.

The majority of the Vung Tham core sequence dates to the past ~1715 years (i.e. the upper 310 cm). Thirty-one of the 38 pollen assemblages derive from this portion of the sequence. These comprise the uppermost assemblage from Subzone 1c, as well as all Zone 2 and Zone 3 assemblages. Two dominant trends in local vegetation dynamics are suggested by the sequence of these assemblages: long-term persistence of mangrove forests on the doline floor until well after the intertidal zone had regressed seaward at the edge of the prograding delta front; and a structural opening of the dryland and limestone forest on the surrounding karst beginning from a modelled date of 1075 cal. BP (875 CE).

While mangrove plants overwhelmingly occur within intertidal zones in coastal settings and display various physiological adaptations to periodic inundation by saline water (Tomlinson, 2016), numerous published accounts exist of mangroves occurring tens of kilometres inland and even associated with freshwater (e.g. Beard, 1967; Brinson et al., 1974; Ellison & Simmonds, 2003; Flores-Verdugo et al., 1987; Lugo, 1981; Lugo & Snedaker, 1974; Patel & Agoramoothy, 2012; Stoddart et al., 1973; Taylor, 1986; van Steenis, 1963; 1984). These inland mangroves are frequently described as relictual, likely persisting at these sites from antecedent populations that established when the sites were within the intertidal zone.

While local environments supporting mangroves may change on centennial-millennial timescales due to subsequent eustatic drops in sea level, or isostatic or tectonic uplift of the ground surface, it is apparent that mangroves are able to persist outside of the intertidal zone. It is unclear what set of conditions permit these occurrences. Nonetheless, this phenomenon is a possible explanation for the persistence of mangrove vegetation on the doline floor of Vung Tham until as late as 250 cal. BP (1700 CE), which is the modelled age of the uppermost assemblage (54 cm depth) that contains pollen from woody mangrove elements such as *Excoecaria* and *Aegiceras* as well as substantial representation of the summary taxon 'Mangroves & associates' (~17%). The palaeoenvironmental records from the VN and GA cores (Li et al., 2006b) provide evidence that the palaeo-shoreline on the delta outside the Trảng An massif had already regressed substantially seaward beyond Trảng An by the time the Vung Tham record resumes from 1715 cal. BP (Duong et al., 2020).

An additional major trend in vegetation dynamics evident in the Vung Tham pollen record is the structural opening of the dryland and limestone vegetation after ~1075 cal. BP (875 CE). Rabett et al. (2017) inferred the long-term resilience of limestone forest at Trảng An throughout the climatic stresses of the LGM and terminal Pleistocene deglaciation using several palaeoenvironmental proxies from archaeological cave sites across the massif (see also Stimpson et al., 2019, for discussion). Pollen Zone 1 and all but the uppermost assemblage from Zone 2 of the Vung Tham core, as well as the archaeological remains from Hang Moi, provide evidence for the continued presence of limestone forest habitats throughout the Middle and into the Late Holocene. Pollen assemblages from the Vung Tham core above 122 cm depth, estimated to date to the most recent 1075 years (since 875 CE), then show marked increases in the representation of ferns and grasses at the expense of previously prevalent woody dryland and limestone forest elements such as *Dacrycarpus*, Rosaceae, Elaeocarpaceae and Urticaceae/Moraceae-type. Likely extra-local wind-pollinated taxa such as *Pinus*, *Podocarpus/Nageia*-type and *Quercus* also increase in these assemblages from the last 1075 years, implying an expansion of the pollen catchment (Davis, 2000) as surrounding vegetation became more open. These changes coincide with the onset of the Medieval

Climate Anomaly (Mann et al., 2009), which is expressed across East Asia as a ~300-year warm period (Zhang et al., 2018b) and at Quan Lan in coastal northern Vietnam as aridity and drought (Briles et al., 2019). In addition to this potential climatic driver of the dryland and limestone vegetation changes inferred at Trảng An, and perhaps also related to associated climatic stresses, hydrological manipulation of surrounding river networks and development at the adjacent city of Hoa Lu intensified around the same time.

In 968 CE, Hoa Lu was chosen to be the capital city of Vietnam. According to historical records, the King ordered the building of walls, canals and palaces in the Citadel (Ngo, 1697). Archaeological research since the 1970s has added information about the existence of the Citadel with walls, temples and palaces (Nguyen, 1970; Pham & Nguyen, 1970; Tong et al., 1998; Nguyen et al., 2010). Recent research has investigated the large boundary around the Hoa Lu Citadel (Vo et al., in review). This boundary was formed by the Citadel walls to the north, north-east and east – the Eastern Wall was excavated in 1970 (Pham & Nguyen, 1970), the Northern Wall was recently excavated in 2018 (Nguyen et al., 2018) – and the rivers on the east and the canals at the south and south-east, combined with the Trảng An massif to the west. The enclosure not only protected the central Citadel but also separated the inner area from the outer parts of the city. The Northern Walls protected the Citadel and stopped flooding and deposits from the brackish Hoang Long River to the north. The Van River, an important waterway to the Citadel from the south and south-east, was built to protect, but also disconnect, the Citadel from the sea. The formation of this enclosed boundary, and the associated modifications of the river system and local drainage networks, created an extended urban area which likely had a significant impact on the environment of the area within the Trảng An massif and on the vegetation of the limestone landscape. Aquatic taxa in particular would have been impacted through altered hydrology.

#### 5.4. *Conclusions: implications for conservation and sustainable development*

The data presented here provide evidence for the Middle Holocene colonisation of the enclosed Vung Tham doline by mangrove vegetation, and long-term persistence of

mangroves until well within the most recent millennium. These data also attest to the presence and resilience of tropical limestone forest on the surrounding karst as previously found by Rabett et al. (2017). This study, however, also presents evidence of a more recent structural opening of this limestone vegetation beginning ~1075 cal. BP (875 CE). Alongside these trends in vegetation changes, the erosional notch data, as well as archaeological data from Hang Moi provide palaeoenvironmental insights for the Middle Holocene high-stand, a period of time that is not represented in the Vung Tham core sequence from the doline floor. The zooarchaeological and archaeobotanical data, which reflect human foraging strategies rather than a comprehensive or representative sampling of past environments, suggest that mangrove, wetland and limestone forest habitats and resources all occurred within regular foraging proximity of the cave at this time. These data have implications for present and future conservation and sustainable development.

The Intergovernmental Panel on Climate Change's (IPPC) Fifth Assessment Report (AR5) predicts up to one metre of sea level rise by 2100 (Church et al., 2013). This will likely threaten not only cities and cultivated lands which currently (2010) sustain 270 million people and US\$13 trillion in assets (Jongman et al., 2012; Wong et al., 2014), but will also endanger rich coastal ecosystems and the ecosystem services they provide. Coastal ecosystems are vital components of human and ecological resilience to climate change and associated sea level rise. They support high levels of biodiversity and provide defence against storm surges, flood mitigation, erosion control and provisioning of resources such as food, timber and medicines (UNEP-WCMC, 2011). The average sea level rise (1993-2014) along Vietnam's coastline of 3.3 mm yr<sup>-1</sup> places it above the worldwide average (Hens et al., 2018), with significant portions of coastal provinces within the Song Hong Delta (including Ninh Binh) at risk with the increased impact from associated storm surge events compounding inundation (Neumann et al., 2015). The current study therefore holds potential relevance for local stakeholders as they seek to mitigate the effects of these future impacts on local infrastructure.

The conservation and restoration of mangrove ecosystems are subject to complex factors (Lovelock & Brown, 2019); however, benefits are substantial, including stabilization of

coastlines against the effects of storm damage, the filtering and trapping of pollutants, as well as significant socio-economic value (Wells et al., 2006). Efforts to restore degraded mangrove areas that have demonstrated resistance or resilience to climate change are also highlighted as a strategy that the managers of protected areas could instigate to help build mangrove resilience to future climate change (McLeod & Salm, 2006). The long-term survival of mangrove components within the Vung Tham doline offers an opportunity for restorative measures to be instigated within this and similar sheltered sites within Trảng An, as well as elsewhere around the edge of the Song Hong Delta. Further research is required, for example into the relationship and interactions between mangrove and limestone forest formations, and to socio-economic benefits among local communities (see e.g. Nguyen et al., 1998). However, this palaeoenvironmental study has demonstrated that sites like Vung Tham have the potential to form stable centres for mangrove rehabilitation that could help mitigate impacts and optimise socio-economic and environmental responses to future sea level rise.

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