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1   **Title**

2   Holocene development and human use of mangroves and limestone forest at an ancient

3   *hong* lagoon in the Tràng An karst, Ninh Bình, Vietnam

4

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29 **Abstract**

30 How past environments and communities responded to episodes of coastal inundation can

31 inform preparations for future resilience to predicted rises in sea level. Southeast Asia's

32 extensive coastlines and expanding coastal populations mean vast natural and human

33 capital is at risk from future sea level rise. Regional mangroves provide many ecosystem

34 services that can help mitigate such risks, but deforestation has left them threatened and

35 compromised. The present study examines the Holocene development and human use of

36 mangrove forest in northern Vietnam, where existing palaeo-records derive from

37 sedimentary archives in tidal flat, estuarine and deltaic settings. Here, we expand that

38 coverage by describing conditions at an enclosed doline within the Tràng An limestone karst

39 in Ninh Binh province that would have been sheltered from deltaic and marine processes.

40 We present a multi-proxy assessment incorporating pollen analysis of the 8125-year-old

41 discontinuous sediment core obtained from the doline floor, combined with inferences from

42 erosional tidal notches in the enclosing limestone, and analyses of phytolith, vertebrate and

43 mollusc assemblages from an adjacent archaeological cave site with deposits of comparable

44 age. The results provide a detailed example of how enclosed coastal environments and

45 communities responded to Middle Holocene marine inundation. High percentages of pollen

46 from mangroves (17-57%) suggest their colonisation of the doline from ~8100 cal. BP and

47 persistence until ~250 cal. BP, well after the intertidal zone regressed seaward beyond the

48 massif. Archaeological assemblages dating to ~5500 cal. BP and containing palm and woody

49 eudicot phytoliths and sponge spicules, neurocrania of the fish genus *Pomadasys* ('grunts',

50 'grunters' or 'javelins') and brackish-water molluscs *Sermyla riqueti* and *Neripteron*

51 *violaceum* support the persistence of mangrove environments through the Middle Holocene

52 high-stand, a period of hiatus within the core, and indicate human foraging and fishing

53 activities took place in mangrove and lagoonal habitats alongside hunting in the surrounding

54 limestone forest. Subsequent structural opening of this latter forest formation from ~1075

55 cal. BP (875 CE), evident in the pollen record, coincides with the Medieval Climate Anomaly

56 and with the adjacent development of the ancient capital at Hoa Lu. We propose that given

57 the long-term persistence of mangrove habitats and associated resources documented in

58 this study, regional initiatives aimed at rehabilitating mangroves (with the positive

59 consequences that this holds for biodiversity and socio-economic conditions) may wish to

60 consider selective restorative measures within Tràng An and similar sheltered sub-coastal

61 karst settings.

62

63 **Keywords**

64 Holocene; Palaeoecology; Pollen; Phytoliths; Vegetation dynamics; Zooarchaeology; Sea

65 Level changes; Southeast Asia

66

67 **1.   Introduction**

68   Past eustatic changes in sea level throughout the Quaternary have cyclically drowned

69 and exposed up to 2.5 million km^2 of Southeast Asia's Sunda Shelf (Sathiamurthy & Voris,

70   2006), repeatedly fragmenting and reconnecting landmasses and the ecosystems they

71   support (Cannon et al., 2009). Rising sea levels in the Early-Middle Holocene drove the

72   development of river deltas (e.g. Funabiki et al., 2007; Hori et al., 2004) and the expansion of

73   mangroves across the region (Allen, 1996; Ellison, 2008; Li et al., 2012). Archaeological and

74   palaeoecological evidence for human interaction with mangroves coincides with this

75   expansion (Boulanger et al., 2019; Hunt & Rushworth, 2005; Nguyen, 2005; Rabett, 2005).

76   Today, Southeast Asia's extensive coastlines and low-lying hinterland, combined with large

77   and expanding human populations reliant upon rapidly developing coastal economies,

78   infrastructure and cities, make this region especially vulnerable to predicted future sea level

79   rise (Hijioka et al., 2014). Global rates of mangrove deforestation now stand at <0.4% yr^{-1}

80   (Friess et al., 2019); however, the rate of loss in Southeast Asia remains considerably higher

81   (e.g. 3.58-8.08% for the period 2000-2012) (Hamilton & Casey, 2016). Regional restoration of

82   this habitat and the valuable ecosystem services and socio-economic resources it can provide

83   to mitigate the impact of sea level rise depends on robust evidence-based programmes of

84   replanting and restoration with careful site and species selection (Lee et al., 2019).

85   Quaternary scientists are increasingly highlighting the utility of palaeoenvironmental

86   records to inform present and future biodiversity conservation and sustainable development

87   decisions (e.g. Birks, 1996; Davies & Bunting, 2010; Froyd & Willis, 2008; Gillson, 2015; Grace

88   et al., 2019; Nogue et al., 2017; Vegas-Vilarrubia et al., 2011; Willis et al., 2007; Wingard et

89   al., 2017). In this context, we briefly review the Holocene history of mangrove forests in

90   Southeast Asia and then employ palaeoenvironmental evidence obtained from the Tràng An

91   limestone massif, northern Vietnam, to consider both the human use of mangroves in

92   prehistory, and the current position of these habitats in preparations for human and ecological

93   resilience to future sea level rise.

94

95   *1.1. Mangroves of Southeast Asia and Vietnam*

96   Mangrove forests are distinctive coastal vegetation communities in intertidal zones

97   within the tropics and subtropics where sediments are actively accumulating (van Steenis,

98   1958). Such conditions occur along low-gradient coastlines and tidally influenced low-lying

99   hindshores, often near river mouths and deltas (Giesen et al., 2006/7; Woodroffe et al., 2016).

100 Single-stratum architecture and physiological adaptations to periodic inundation by saline

101 water, such as stilt roots, pneumatophores, salt excretion glands or capacity to sequester

102 excess salts within tissues, vivipary and water-dispersed disseminules, are common

103 mangrove characteristics (Tomlinson, 2016).

104   Across the Southeast Asian tropics, the world's most species-diverse and extensive

105 mangroves underpin and sustain productive intertidal ecologies and the coastal economies

106 that depend upon their resources (Giesen et al., 2006/7). Mangrove forests provide habitat

107 and act as nurseries for a diverse range of fishes, molluscs, crustaceans, insects, reptiles,

108 birds and mammals (MacNae, 1968). They yield timber, food and medicines to local

109 communities, whilst indirectly sustaining nearshore fisheries through their ecological role as

110 protection and breeding grounds for economically important species (Orchard et al., 2016).

111 Mangroves also sequester ~1.5 metric tons of carbon per hectare per year in their organic

112 soils and in their biomass (Ong, 1993); and they buffer coastlines against the erosive power

113 of tropical storms and tsunamis (Alongi, 2008; 2015).

114   Mangroves are less diverse and more restricted in extent in the Song Hong (Red River)

115 Delta region in the north of Vietnam than they are around the more tropical Mekong Delta in

116 the south (Hong & San, 1993). Despite this, 31 species of 'true mangroves' – defined as those

117 species that are found in mangrove habitat only (Giesen et al., 2006/7) – as well as a

118 significant proportion of the 216 'mangrove associates' recorded regionally within mangrove

119 and adjacent non-mangrove habitats, occur within northern Vietnamese mangrove vegetation.

120 Rhizophoraceae (*Bruguiera*, *Ceriops*, *Kandelia* and *Rhizophora*) is the dominant plant family,

121 while species of *Avicennia* (Acanthaceae), *Sonneratia* (Lythraceae), *Aegiceras* (Primulaceae),

122 *Lumnitzera* (Combretaceae) and *Xylocarpus* (Meliaceae) are also abundant woody elements.

123 The mangrove palm *Nypa fruticans* and mangrove fern *Acrostichum aureum* are conspicuous

124 non-woody components. The remainder of taxa recorded in northern Vietnamese mangroves

125 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

154   of success. Both the impacts from shrimp aquaculture, the construction of flood control

155   infrastructure and growing tourist numbers though leave the future of Vietnam's mangroves

156   uncertain (Marchand, 2008).

157

158   *1.2.   Mangroves and the Song Hong Delta throughout the Holocene*

159   The Holocene development of the Song Hong Delta and the palaeoenvironments it

160   supported have been examined through sedimentological and microfossil analyses of at least

161   20 deep boreholes across the delta plain, largely following the path of the Song Hong and Red

162   River Fault (Duong et al., 2020; Funabiki et al., 2007; Hori et al., 2004; Li et al., 2006a; Tanabe

163   et al., 2006). Geomorphic processes, delta morphology and its palaeoenvironments have

164   changed markedly across this time period, driven primarily by the effects of eustatic sea level

165   changes tied to patterns of deglaciation. The Holocene portion of the regional sea level curve

166   synthesised by Tanabe et al. (2003b) shows a steep rise from -60 m at the beginning of the

167   Holocene to near present-day levels by ~7500 cal. BP. The rate of subsequent sea level rise

168   slowed, reaching a high-stand of +3-5 m centred around 5500 cal. BP and remained relatively

169   stable until ~4000 cal. BP before gradually returning to present-day levels after 2000 cal. BP.

170   Geomorphologic and palaeoenvironmental inferences drawn from sedimentological and

171   microfossil analyses show that deglacial sea level rise drowned an ancient valley incised by

172   the Song Hong during the preceding glacial low-stand (Duong et al., 2020; Funabiki et al.,

173   2007; Hori et al., 2004; Li et al., 2006a; Tanabe et al., 2006). Early Holocene portions of cores

174   from as far northwest as the vicinity of Hanoi (i.e. cores PD and DA from Funabiki et al., 2007;

175   core HN from Duong et al., 2020) provide evidence for estuarine and tidal flat depositional

176   environments inhabited by mangrove forests and brackish water ecosystems far inland from

177   the present coast despite below-modern sea levels at the time. Delta progradation at the

178   upstream end of the drowned Song Hong valley began ~8500 cal. BP (Hori et al., 2004) while

179   sea level was still rising toward the Middle Holocene high-stand. Estuarine environments

180   ahead of the delta front were infilled progressively seaward through the Middle and Late

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

182   et al., 2006a).

183   Existing palaeoenvironmental records of mangroves derive from deltaic, estuarine and

184   tidal mudflat settings exposed to marine and fluvio-deltaic processes and surrounded by other

185   wetland vegetation communities. In this paper we present palaeoenvironmental evidence of

186   past mangrove habitats within an enclosed valley on the southern edge of the Song Hong

187   Delta, sheltered by limestone karst from large-scale marine and fluvio-deltaic processes and

188   surrounded by limestone forest. We examine how these mangrove ecosystems and past

189   coastal communities have responded to episodes of sea level rise across the Holocene, and

190   consider the future utility of sheltered sites to mangrove rehabilitation efforts.

191

192   **2.   Study area**

193   *2.1.   Geography and geology*

194   The Tràng An karst occupies most of the 6226-hectare core zone of the Tràng An

195   Landscape Complex, a mixed-designation UNESCO World Heritage property in Ninh Binh

196   province, northern Vietnam. The massif is situated on the southern margin of the Song Hong

197   Delta, ~30 km inland from the present coast of the Gulf of Bac Bo (Tonkin) at its nearest point

198   (Fig. 1). It is composed of Lower – Middle Triassic thinly bedded – massive limestone (VIGMR,

199   2012). This bedrock has subsequently undergone extensive uplift, deformation and

200   weathering, especially associated with later-Mesozoic closure of the palaeo-Tethys Ocean

201   and early Cenozoic extension and activation of the Red River Fault system after India's

202   collision with Eurasia (Faure et al., 2014; Metcalfe, 2017). Tropical and subtropical climates

203   acting throughout the Cenozoic (66 – 2.58 Ma), and Quaternary (2.58 Ma – present) climatic

204   fluctuations and associated oscillations in sea level, have driven the geologically recent

205   evolution of the massif. Today's karst landscape exhibits predominantly *fenglin* terrain

206   composed of towers, sharp ridges and sheer limestone faces undercut laterally by alluvial

207   planation and marine inundation, but with a small core of *fengcong*-doline topography where

208   doline floors have remained well above the local water table (Waltham, 2009). Under present

209
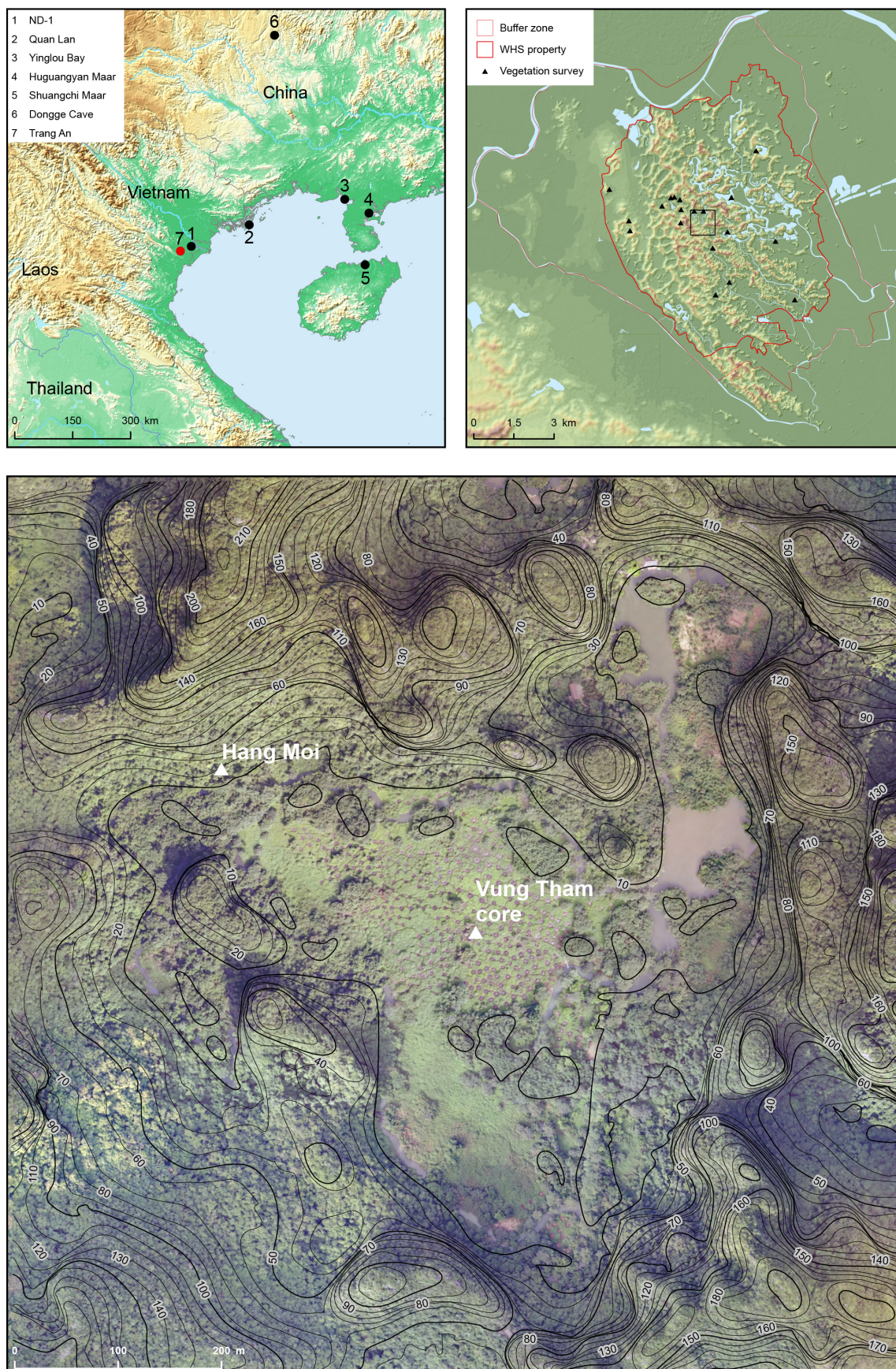
Fig. 1 Study area and sites mentioned in the text, at regional (top-left panel), Tràng An property (top-right panel) and local site scales (bottom panel). Red filled circle in top-left panel denotes Tràng An. Box in top-right panel denotes location of bottom panel. Figure credit: T. Kahlert.

213 hydrological conditions and management many of the deepest dolines within the *fenglin* terrain

214 are flooded with fresh water and interconnected via both natural foot caves and man-made

215 tunnels and waterways.

216

217 *2.2. Climate*

218 The Song Hong Delta region covers more than 15,000 km^2, most of which sits at 2-6 m

219 above present average sea level (a.s.l.; relative to sea level calibrated to the Vietnam National

220 datum at Hon Dau). Today, lowland northern Vietnam experiences a tropical monsoonal

221 climate with warm, wet summers and cool, dry winters (Averyanov et al., 2003), modified by

222 maritime influence (Lawrimore et al., 2016; Li et al., 2006a) (See Supplementary Materials for

223 more detail).

224

225 *2.3. Vegetation*

226 The vegetation of the Song Hong Delta region and surrounding outcrops and uplands of

227 northern Vietnam is composed of a diverse mix of tropical and temperate components

228 (Averyanov et al., 2003; Regalado et al., 2005). The complex and dynamic geological history

229 of the region has created topographic, microclimatic and edaphic heterogeneity which

230 supports seasonal evergreen broad-leaved and mixed forests, with compositional and

231 structural variations according to soil type and along gradients in elevation and continentality

232 (Ashton, 2014; Averyanov et al., 2003). Limestone outcrops and low-gradient coastal

233 landscapes in northern Vietnam also support distinct limestone and mangrove floras

234 (Clements et al., 2006; Giesen et al., 2006/7; Tomlinson, 2016).

235 Whilst the flora of Tràng An has not yet been comprehensively enumerated, a

236 reasonable proxy can be assembled from the literature on the limestone floras of nearby Cuc

237 Phuong and Ben En National Parks (Nguyen, 1997; Hoang, 2009). For the purposes of this

238 study, these expectations were then ground-truthed as part of the SUNDASIA Project using

239 pedestrian surveys and species lists of some of the limestone vegetation found near to focal

240 sites of research interests in Tràng An (Fig. 1). The island-like nature of isolated limestone

241 massifs like Tràng An (*sensu* Kruckeberg, 1991), combined with the thin and usually nutrient-

242 poor soils (Vermeulen & Whitten, 1999), and sharp karstic topographies forming a patchwork

243 of exposed and shaded aspects, creates an array of microhabitats that support a diverse flora

244 (Ashton, 2014; Crowther, 1982; Kruckeberg, 2002; Zhu et al., 2003). In valley bottoms and on

245 shallow-gradient slopes, a tall and closed broad-leaved forest composed predominantly of

246 tropical families occurs (Averyanov et al., 2003). These include Leguminosae (*Erythrophleum*;

247 *Saraca*), Moraceae (*Ficus*; *Streblus*), Datiscaceae (*Tetrameles*), Anacardiaceae

248 (*Cherospondias*; *Dracontomelon*), Meliaceae (*Aglaia*; *Chisocheton*; *Dysoxylum*),

249 Sapindaceae (*Pometia*), Dipterocarpaceae (*Hopea*; *Shorea*; *Vatica*), Malvaceae (*Grewia*;

250 *Pterospermum*; *Sterculia*), Ebenaceae (*Diospyros*) and Sapotaceae (*Madhuca*). In contrast,

251 exposed ridges, vertical walls and steep slopes support a more open and shorter, often

252 drought-adapted and semi-deciduous, mixed vegetation comprised of broad-leaved and

253 gymnospermous elements such as cycads and podocarps, as well as epilithic herbs in

254 Orchidaceae, *Impatiens* (Balsaminaceae), Urticaceae, Gesneriaceae, *Begonia*

255 (Begoniaceae) and Araceae (Clements et al., 2006).

256 Today, alluviated valley floors within the *fenglin* terrain of Tràng An are dominated by

257 development and cultivation of rice, maize, fruit trees and non-native *Acacia mangium*

258 plantations and fringed by ruderal scrub composed largely of agricultural weeds, many of

259 neotropical origin. Where not in cultivation, narrow floodplains and banks of waterways

260 support wetland and riparian communities dominated by grasses (Poaceae), sedges

261 (Cyperaceae), *Ficus* spp. and several species of trees and shrubs in the rubiaceous tribe

262 Naucleeae, as well as rapid colonisers of open ground in Phyllanthaceae (*Sauropus*, *Breynia,*

263 *Glochidion* and *Cleistanthus*) and Euphorbiaceae (*Mallotus* and *Macaranga*).

264

265 *2.4. Study sites*

266 *2.4.1.Vung Tham*

267 Vung Tham is an alluviated doline occupying just over 20 ha near the centre of the

268 massif (105.89745°E, 20.25281°N) (Figs. 1, 2). The modern floor of the doline is relatively flat

269

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

288 cave setting), their incorporation into the current study provides a temporal sequence of

289 comparative, if selected, palaeoenvironmental data that compliments that obtained from the

290 Vung Tham core, and permits a more robust exploration of potential linkages between local

291 habitat change and human agency.

292   Occupied intermittently from at least 15,000 cal. BP, Hang Moi was first excavated in

293 2011 by the Tràng An Archaeological Project (TAAP), followed in 2012 with excavation by a

294 team from the Vietnamese Institute of Archaeology and, since 2016, by the SUNDASIA

295 Project. Three trenches have so far been excavated; herein, we focus on Middle Holocene

296 occupation layers from Trenches 1 and 2 excavated by TAAP and SUNDASIA (Figs. 3, 4).

297 Trench 1 has revealed an in situ hearth sequence and a human burial (Field reports: Rabett

298 et al., unpublished; Stimpson et al., a) & b), unpublished); the upper deposit of Trench 2

299 represents a 1 m-thick 'refuse dump' of ash, coarse-ware potsherds and faunal remains with

300 abundant mollusc and crab. Contemporaneous radiocarbon dates have been recovered from

301 Trenches 1 and 2 and place Middle Holocene occupation at ~5500 cal. BP (Table 1).

302 Underlying the ash-rich material in Trench 2 are two as-yet undated deposits, (6504) and

303 (6509), which also contain comparable coarse-ware ceramics.

304

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.

307
308 **Fig. 4** Hang Moi site plan (A) and representative sections from Trench 1 (B) and Trench 2 (C). Bold
309 trench boundaries in A denote specific sections illustrated in B and C. Drawing credit: C Stimpson.
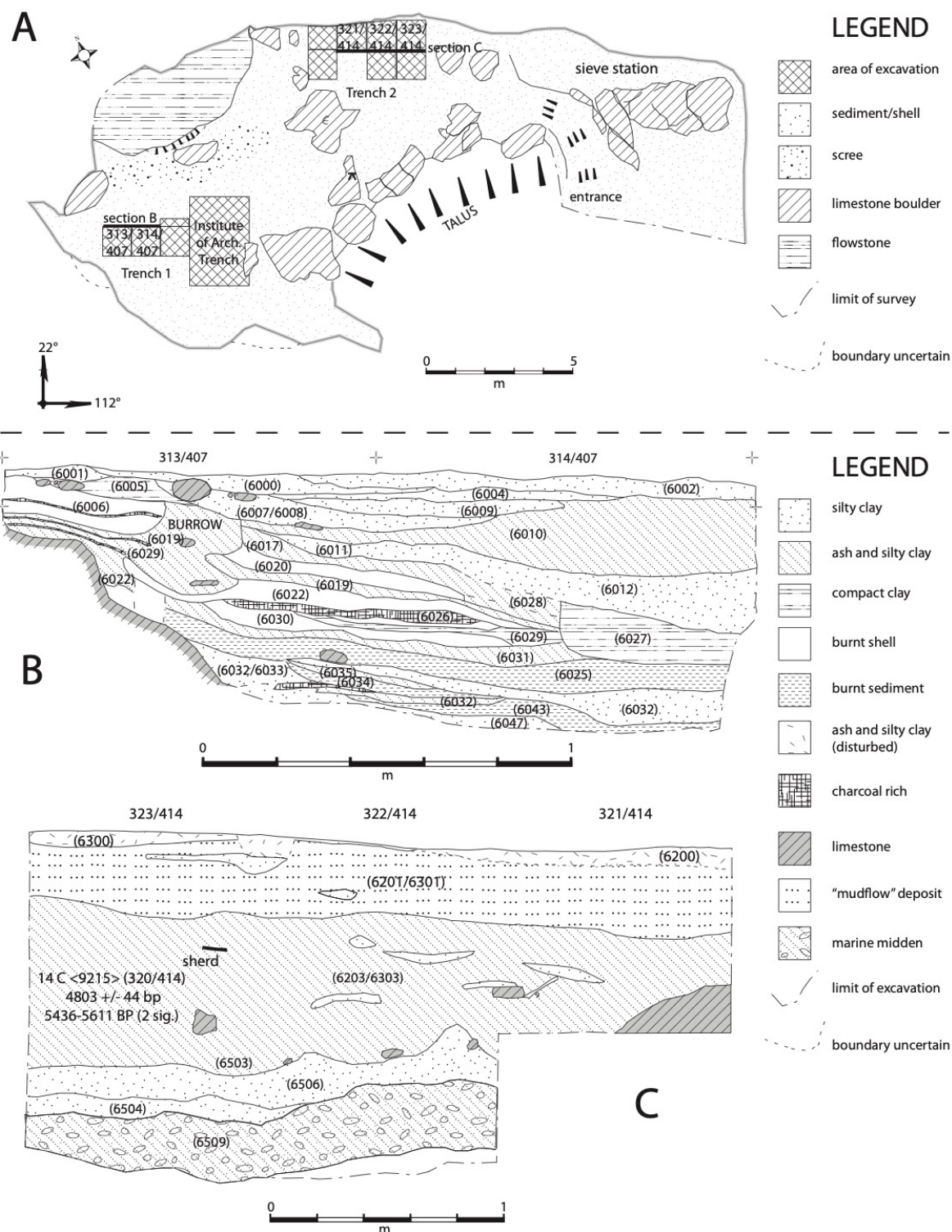
310 **Table 1** Middle Holocene radiocarbon dates from Hang Moi.

Sample # / code	Trench	Context	14C	error	Cal BP[a]
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
[a] 2 sigma ranges are shown					

311

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 [14]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^{-1} (i.e. 1.9 mm yr^{-1}) 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

340   Magnetic susceptibility was measured at 2 cm increments throughout the length of the

341   core using a Bartington MS2C core scanning sensor (Bartington Instruments, 2019). A total

342   of 38 paired subsamples were collected from the core at roughly 10 cm depth-intervals. One

343   set of subsamples was used for loss-on-ignition (LOI) analysis, retaining the parallel set for

344   pollen analysis. LOI analysis followed Cambridge Geography (2018).

345

346   *3.1.4. Pollen analysis*

347   Each of the 38 subsamples collected for pollen analysis were measured to comprise

348   one cc of sediment. One tablet containing a known quantity of exotic marker spores

349   (*Lycopodium*) was then added to each subsample to enable estimation of microfossil

350   concentrations (Stockmarr, 1971). Pollen extraction followed protocols based upon dense-

351   media separation using a sodium polytungstate solution at specific gravity between 1.88 –

352   1.91 g cm^{-3} (Nakagawa et al., 1998; Campbell et al., 2016). Acetolysis was omitted due to low

353   total organic content and anticipated suboptimal pollen and spore preservation. Prior to the

354   dense-media separation step, preliminary slides were made on which to quantify diatom

355   abundances. Final residues were mounted in silicone oil for microfossil identification and

356   counting which were carried out under light microscopy, primarily at 400x magnification. Pollen

357   and spores were identified using keys and images for Southeast Asian taxa (Fujiki et al., 2005;

358   Huang, 1972; Huang, 1981; Mao et al., 2012; Nguyen, unpublished; Semah, unpublished;

359   Thanikaimoni, 1987) and the Australasian Pollen and Spore Atlas (APSA Members, 2007).

360   A target minimum of 300 microfossils per subsample guided the counting process.

361   Relative abundances of taxa and summary groupings were calculated using a 'basic sum',

362   'total sum' or 'dryland sum' depending upon taxon (see Supplementary Materials for details).

363   Stratigraphic diagrams were plotted using C2 version 1.7.7 (Juggins, 2010). Zonation of the

364   stratigraphic diagrams was achieved through adjacency-constrained hierarchical

365   agglomerative clustering analysis using the R packages adjclust (Ambroise et al., 2018) and

366   vegan (Oksanen et al., 2018). Zones and subzones were defined by the branches of the

367   dendrogram that were intersected by lines at arbitrarily selected threshold values of total

368   dispersion. Several principal components analysis (PCA) ordinations were performed on the

369   entire dataset, as well as various subsets of it, in order to reveal possible patterns in the data

370   that are difficult to detect visually in the stratigraphic diagrams.

371

372   *3.2. Vung Tham notches*

373   Marine or tidal notches form in the intertidal zone as horizontal bands along vertical or

374   near-vertical limestone faces as a result of mechanical, biological and chemical erosion. Their

375   formation requires prolonged phases of stable sea levels and their presence is used,

376   alongside sedimentary cores, coral deposits and marine terraces, as past sea level indicators

377   (Boyd & Lam, 2004; Lam & Boyd, 2003; Pirazzoli, 1986; Trenhaile, 2015). Limestone is

378   particularly susceptible to erosion and elevated tidal notches are abundantly found in karst

379   formations along modern and palaeo-coasts of the Thai-Malay Peninsula and in northern

380   Vietnam (Gillieson, 2005; Tjia, 1996).

381   A detailed survey across Tràng An as part of the SUNDASIA Project documented the

382   occurrence of notches at at least four different elevations that are indicative of relative stable

383   sea levels higher than at present and that likely pertain to two marine transgressions of around

384   5.6 m and 3.2 m a.s.l. (Rabett et al., 2018). Previous studies and limited dating of notch sites

385   at Tràng An have produced modelled relative sea levels that fall within established Middle

386   Holocene sea level curves for Southeast Asia and the Song Hong Delta of 5 m (Boyd & Lam,

387   2004; Nguyen et al., 2012).

388   In Vung Tham, notches at the base of the enclosing limestone walls around the interior

389   perimeter of the doline were surveyed using a total station and differential GPS. Geographical

390   coordinates, elevation relative to the sea level datum at Hon Dau, and characteristics of notch

391   morphology (vertical span, depth and shape in profile) were measured for each in situ notch.

392

393   *3.3. Hang Moi archaeology*

394   *3.3.1. Phytolith Analysis*

395   An archived sediment column was taken from the north section of Trench 1 in Hang Moi,

396   from which eleven subsamples were collected to target the series of hearth deposits that date

397   from ~5500 cal. BP (see Table 1). Two grams of sediment from each subsample were

398   processed for phytoliths following Rosen`s protocol (1999) (full methodology in Supplementary

399   Materials).

400   Phytoliths were identified and counted at 400x magnification under light microscopy

401   through a polarising lens. Morphotypes were described using the International Code for

402   Phytolith Nomenclature 1.0 (Madella et al., 2005) and identified using primarily regionally

403   specific published images (e.g. Weisskopf, 2018; Piperno, 2006; Huang & Zhang, 2000;

404   Bowdery, 1999; Kealhofer & Piperno, 1998). Due to poor preservation the aim of counting 300

405   phytoliths per slide was only achieved in one subsample, resulting in most slides being

406   counted in their entirety. Total counts of silica aggregate and sponge spicules were also

407   recorded as an indication of the presence of wood/bark and wet environments. Phytoliths g^{-1}

408   in each sample was calculated after Power et al. (2014).

409

410   *3.3.2.Vertebrate faunal remains*

411   The vertebrate remains recovered from the Middle Holocene hearth (Trench 1) and

412   refuse dump (Trench 2) deposits were highly fragmentary and are parsimoniously the

413   remnants of taxa exploited as food. The remains are principally comprised of broken fish

414   spines and centra, mixed with copious numbers of broken crab chelae and mollusc shells. The

415   bones of terrestrial vertebrate taxa are comparatively rare and are also highly fragmented. As

416   such, only relatively small numbers of vertebrate remains were identifiable. The materials were

417   exported under agreement with the Ninh Binh Peoples Committee and the Tràng An

418   Management Board. Identifications were made using comparative osteological collections at

419   the Oxford University Museum of Natural History.

420   Trench 1 yielded three identifiable teeth from contexts 6011 and 6014 and post-cranial

421   remains from contexts 6032 and 6039. These specimens are associated with a date of 5464

422   – 5591 cal. BP (Table 1). Materials from Trench 2 incorporated two episodes of deposition

423 within the Middle Holocene. Firstly, materials from contexts 6203, 6303 and 6503 (Number of

424 Identified Specimens, or NISP = 15) were of similar age to materials from Trench 1 and date

425 to 5436 – 5611 cal. BP (Table 1). Secondly, materials from contexts 6506 and 6509 (NISP =

426 17) were directly underlying the Middle Holocene deposits but were stratigraphically distinct

427 and represent earlier phases of deposition (Fig. 4C).

428

429 *3.3.3. Molluscs*

430   Mollusc assemblages from six contexts from Trench 2 were analysed under a low-

431 powered binocular microscope and hand lens, and recorded using 'Minimum Number of

432 Individuals' (MNI). Data were plotted stratigraphically using Tilia 2.1.1 (Grimm, 2019).

433 Identifications were made using Vermeulen & Whitten (1998a; 1998b); Vermeulen & Maassen

434 (2003); Phung et al. (2017); Raheem et al. (2017); Sutcharit et al. (2019); as well as modern

435 comparative collections made by the SUNDASIA Project.

436

437 **4.   Results**

438 *4.1.   Vung Tham core*

439 *4.1.1. Lithology*

440   The 382 cm sequence from the Vung Tham core consisted of fine-grained sediments

441 throughout. Constituent units varied in oxidative state and colour as well as presence and

442 composition of inclusions (Table 2). Boundaries between all constituent units below the 21 cm

443 of modern soil were diffuse.

444 **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}C age	Calibrated age (2σ)	Lab. Ref.
54	Leaf tissue	186 ± 22 BP	142 – 289 cal. BP	UBA-40840
119	Wood	1370 ± 46 BP	1183 – 1358 cal. BP	UBA-38672
157	Wood	1398 ± 31 BP	1280 – 1352 cal. BP	UBA-38673
301	Leaf tissue	1655 ± 25 BP	1521 – 1618 cal. BP	UBA-40841
315	Wood	6969 ± 44 BP	7693 – 7928 cal. BP	UBA-38674
378	Leaf tissue	7298 ± 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.

461
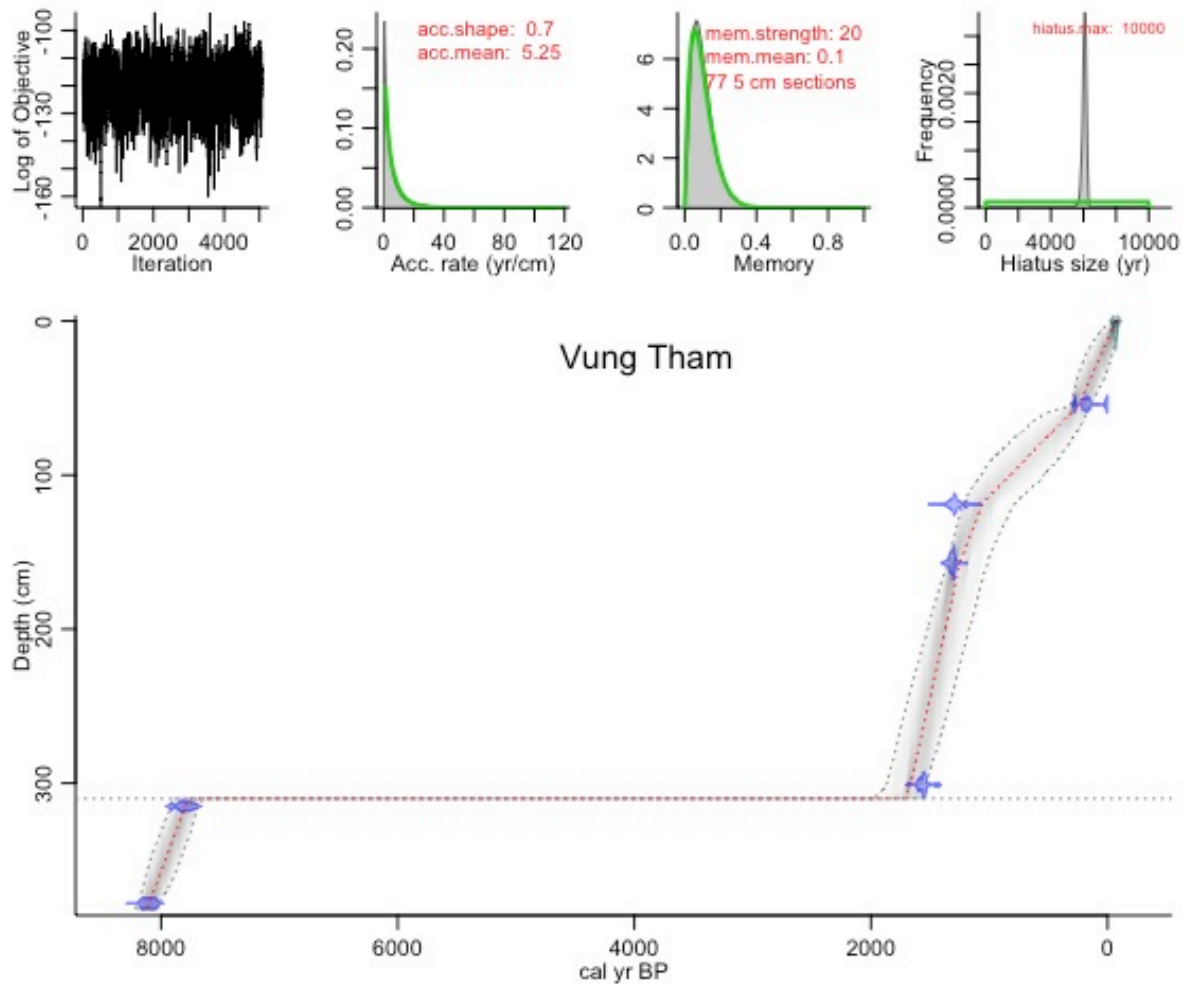
Fig. 5 Bayesian age-depth model for the Vung Tham core sedimentary sequence.

463

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

474   revealed strong positive linear correlations between total organic content and: carbohydrate

475   content ($r = 0.998$; $p < 2.2e^{-16}$; df = 36); and water content ($r = 0.802$; $p = 1.38e^{-9}$; df = 36).

476   Equally strong, though negative, correlations were revealed between mineral content and:

477   total organic content ($r = -0.999$; $p < 2.2e^{-16}$; df = 36); and water content ($r = -0.804$; $p = 1.16e^{-9}$;

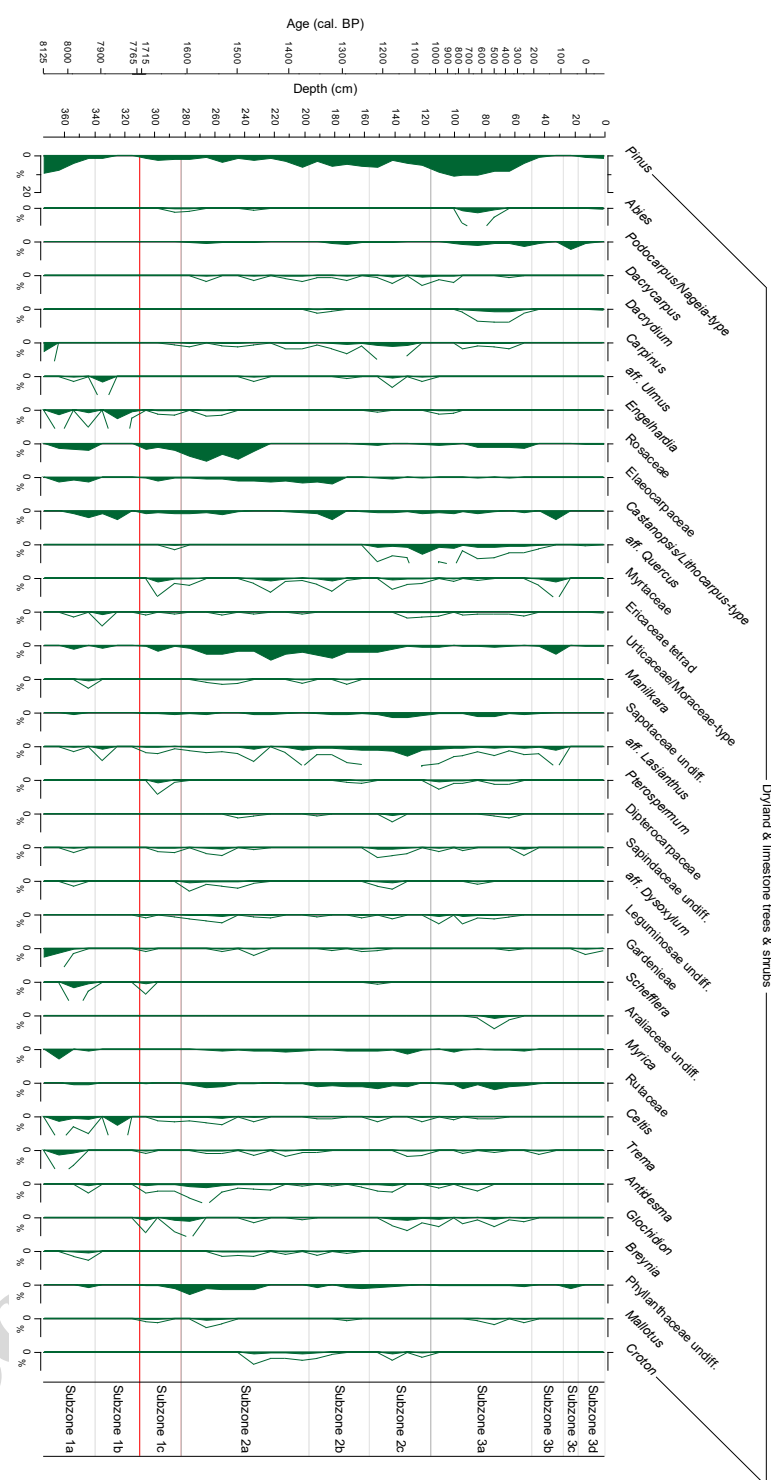478   df = 36).

479

480   *4.1.4. Microfossil assemblages*

481   A total of 141 microfossil taxa were recorded across the 38 assemblages. These

482   comprised pollen grains from seed plants; spores from ferns, fern allies and non-vascular

483   plants; inner casings of foraminifera; diatom frustules; and dinoflagellate cysts. Only 24 of the

484   38 assemblages derive from microfossil counts that exceeded the target minimum of 300, and

485   counts were highly variable ($\mu = 556$; $\sigma = 733$).

486

487   *4.1.4.1.   Zonation*

488   Three zones are defined by the branches of the dendrogram that are intersected by a

489   line drawn at a threshold value of 60,000 total dispersion units (Fig. 6a). Each of these three

490   zones are further divided into subzones by a secondary threshold placed at 15,000 total

491   dispersion units, yielding three subzones each for Zones 1 and 2, whilst Zone 3 is split into

492   four subzones.

493

494

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.

Fig. 6c Stratigraphic diagram of the Vung Tham core showing microfossil relative abundances of dryland and limestone forest non-woody taxa. Colour-coding of curves correspond to life-form summary groupings in Fig. 6d. Outline curves represent 5x exaggeration. Horizontal red line represents the hiatus.

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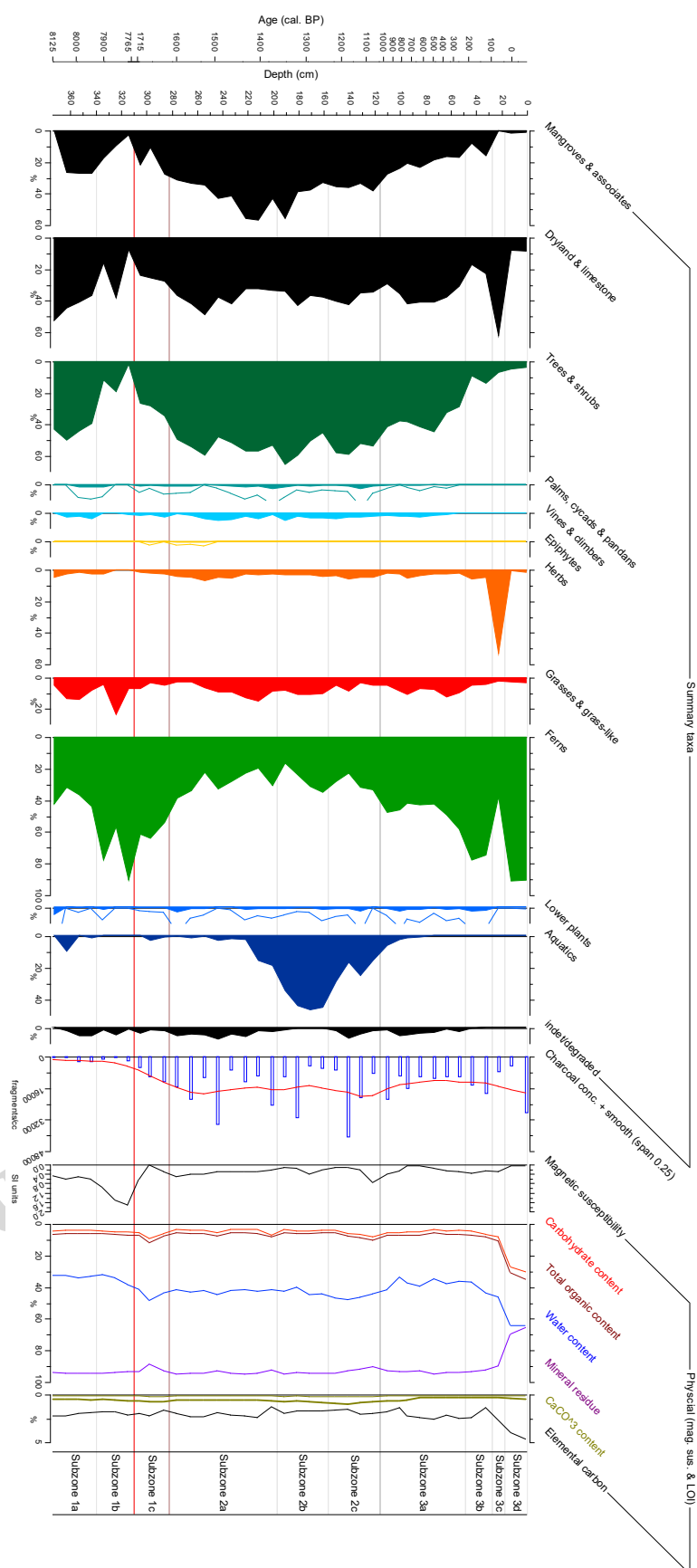
Fig. 6d Stratigraphic diagram of the Vung Tham core showing ecological and life-form summary curves, microcharcoal concentration and physical measures with depth. Outline curves represent 5x exaggeration; CaCO$_3$ curve is 10x exaggeration. Horizontal red line represents the hiatus.

513

4.1.4.2.   Assemblage descriptions by zonation

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

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

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

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

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

540   Microfossil concentrations are at their lowest in the core at 325 cm depth (403 grains cc^{-}

541   ^{1}), and low pollen to fern spore ratios throughout the subzone (μ = 0.41, σ = 0.38) likely indicate

542   a diagenetic biasing of assemblages. Fern spores are the dominant component of all three

543   assemblages, ranging from 57.1 – 90.8%, which includes moderate representation of

544   *Acrostichum*. *Excoecaria* is the only true mangrove seed plant taxon present. Several

545   temperate   or   montane   broad-leaved   taxa,   such   as   *Ulmus*,   *Engelhardia*,

546   *Castanopsis/Lithocarpus*-type, Ericaceae and *Celtis*, show small peaks, as do Poaceae,

547   Cyperaceae, and the saltmarsh or dry-adapted Chenopodioideae.

548

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

550   Despite the 6000-year gap between Subzones 1b and 1c, the three assemblages that

551   comprise Subzone 1c are statistically more similar to those that predate the discontinuity than

552   to those that overlie and follow continuously. This likely reflects the marginal to poor

553   preservation that is common to these Zone 1 assemblages rather than likeness of parent

554   vegetation. While microfossil concentrations are moderate across Subzone 1c (μ = 9443

555   grains cc^{-1}; σ = 952 grains cc^{-1}), pollen to fern spore ratios remain low (μ = 0.70, σ = 0.15).

556   'Ferns' remain the dominant summary taxon, ranging from 54.4 – 64.3%. Several mangrove

557   and associated taxa that were present in Subzone 1a return, such as Rhizophoraceae,

558   *Aegiceras*, Combretaceae/Melastomataceae-type, *Heritiera* and *Ilex*, while *Avicennia*,

559   *Xylocarpus*, *Nypa*, *Casuarina*, *Pandanus*, *Colocasia* and inner casings of undifferentiated

560   foraminifera make their respective first appearances.

561

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

563   Assemblages across this zone collectively suggest persistence of diverse mangrove

564   forest within the doline, as well as development of littoral elements and indicators of open

565   water, particularly in the upper two subzones since 1365 cal. BP.

566   Indices for preservation across the 16 assemblages of Zone 2 are high though variable

567   (ratio of pollen to fern spores: μ = 2.80, σ = 0.96; microfossil concentration: μ

568 = 23,112 grains cc^{-1}; σ = 20,302 grains cc^{-1}). Average concentrations of microcharcoal

569 fragments are higher across this zone than in other portions of the record, but values for

570 individual subsamples vary widely (μ = 16,979 fragments cc^{-1}; σ = 11,179 fragments cc^{-1}).

571

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

573   Relative abundance of the 'Mangrove & associates' summary taxon is at its highest

574 average value within this subzone (μ = 42.49%; σ = 9.61%), rising steadily from 31.50% at

575 277 cm depth to 56.78% at 213 cm before tapering off slightly to 43.22% in the uppermost

576 assemblage. In addition to the mangrove taxa that were already present from Zone 1,

577 *Avicennia*, *Sonneratia*, *Scyphiphora*, *Xylocarpus*, *Casuarina*, *Diospyros*, *Brownlowia*,

578 *Cerbera*, *Barringtonia* and *Pandanus* are all represented in these Subzone 2a assemblages.

579 The 'Grass & grass-like' summary taxon shows a similar trend, rising from 2.56% to 14.83%,

580 driven by Poaceae but with minor representation of Cyperaceae and *Typha*. Additional marked

581 features of summary taxa are the consistently low values for 'Ferns' (μ = 28.66%; σ = 6.69%),

582 as well as the steep increase in 'Aquatics' in the two uppermost assemblages. *Acrostichum* is

583 the dominant fern taxon, whilst the increase in aquatics is due to the first appearance of

584 diatoms. A peak in the 'Dryland & limestone' summary taxon occurs at 255 cm (48.85%), whilst

585 this taxon maintains values from 32.23 – 42.12% throughout the rest of the subzone. Within

586 this summary grouping, prominent taxa are Rosaceae, Urticaceae/Moraceae-type,

587 Phyllanthaceae and Lamiaceae/Verbenaceae-type, with minor representation of the conifers

588 *Abies*, *Podocarpus*/*Nageia*-type and *Dacrydium*, as well as broad-leaved forest taxa such as

589 *Carpinus*, Myrtaceae, *Lasianthus*, Sapotaceae and Rutaceae.

590

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

592   The distinctive feature of this subzone is the very large peak in diatom abundance (μ =

593 38.40%; σ = 7.40%). Diatoms dominate the signal of aquatic taxa in this subzone, though

594 dinocysts and foraminifera maintain significant concentrations. Mangrove and terrestrial taxa

595 remain abundant and diverse, though *Xylocarpus* decreases across the four assemblages.

596 Within the dryland and limestone taxa, *Pinus*, Urticaceae/Moraceae-type, *Lasianthus*,

597 Rutaceae and Poaceae all occur at stable levels, whereas Elaeocarpaceae and

598 *Castanopsis*/*Lithocarpus*-type show minor decreases.

599

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

601   Diatom abundance declines sharply from the high values attained in the underlying

602 subzone, and disappears altogether by the two uppermost assemblages, whilst dinocysts and

603 foraminifera show marked increases. Within the mangrove taxa, Rhizophoraceae, *Aegiceras*

604 and *Excoecaria* occur at high, stable relative abundances, whereas

605 Combretaceae/Melastomataceae-type, *Scyphiphora*, *Acrostichum* and *Heritiera* decrease in

606 abundance. The coastal strand and littoral taxa *Casuarina* and *Pandanus* show minor

607 increases. Of the dryland and limestone components, the wind-dispersed pollen of temperate

608 tree taxa *Carpinus*, *Ulmus* and *Quercus* are relatively abundant, alongside increases in the

609 tropical forest and lowland taxa Sapotaceae, *Lasianthus*, Sapindaceae and *Glochidion*.

610

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

612   The most significant vegetation change within the record occurs with the shift to Zone 3

613 assemblages, at a modelled mean age of 1025 cal. BP (925 CE). While this zone appears to

614 represent a continued though diminished presence of mangroves, structural opening of the

615 dryland and limestone vegetation is evident (beginning with the uppermost assemblage of

616 Subzone 2c at 122 cm and a modelled mean age of 1075 cal. BP), with suggestions of both

617 drought and increased disturbance to vegetation.

618

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

620   Amongst the summary taxa, decreases are marked in 'Trees & shrubs', as well as in

621 'Mangroves & associates', whilst the 'Ferns' and the 'Grasses & grass-like' taxa increase.

622 Though individual mangrove taxa are still represented, relative abundances of all but the back-

623 mangrove fern *Acrostichum* decrease, and many disappear from the record altogether by the

624 uppermost assemblage. Mangrove and associated taxa that do not occur above these

625 Subzone 3a depths include Rhizophoraceae, *Avicennia*, *Sonneratia*, *Scyphiphora*,

626 *Xylocarpus*, *Aegialitis*, *Acanthus*, *Heritiera*, *Pandanus* and *Tristellateia australasiae*.

627 Additionally, foraminifera and dinocysts decrease across the lower three subsamples, and join

628 diatoms in their absence from all assemblages above 85 cm depth. Concurrently, temperate

629 trees, many of which are wind-pollinated and likely extra-local to the site, and drought-tolerant

630 or disturbance-indicative taxa show corresponding increases. These taxa include conifers

631 such as *Pinus*, *Abies*, *Podocarpus*/*Nageia*-type and *Dacrydium*, as well as the largely

632 temperate taxa Rosaceae and Ericaceae, drought-adapted *Pterospermum*, and the often

633 early-successional Rutaceae, *Glochidion*, *Mallotus* and Poaceae, as well as multiple fern taxa.

634

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

636 Poor preservation across the five uppermost assemblages, which comprise Subzones

637 3b – d prevents meaningful interpretation. 'Ferns' dominate the two Subzone 3b assemblages

638 (μ = 76.54%; σ = 2.18%), consisting largely of *Lygodium* and monolete psilate spores, but also

639 with substantial representation of *Acrostichum*. Minor peaks in *Castanopsis*/*Lithocarpus*-type,

640 Myrtaceae, Urticaceae/Moraceae-type, *Lasianthus*, Amaranthaceae and Cyperaceae occur,

641 whilst Poaceae decreases. The single Subzone 3c assemblage at 23 cm is composed of little

642 else apart from a large number of grains of Amaranthaceae pollen, a couple of grains of

643 *Podocarpus*/*Nageia*-type, Phyllanthaceae and Cyperaceae, and a handful of fern spores. The

644 two uppermost assemblages, comprising Subzone 3d, derive from what is presumably

645 modern and recent humus and are dominated by monolete fern spores, though *Acrostichum*

646 is also present in low relative abundance. Some elements of the modern disturbance-

647 indicative flora are also present but not abundant, as are conifers and other likely extra-local

648 wind-pollinated taxa.

649

650 *4.1.4.3.   Ordination*

651   Of the exploratory ordinations that were performed on various subsets of the

652   palynological data, the most informative was the PCA run on a subset of the data that included

653   only the well-preserved assemblages and non-mangrove terrestrial taxa. Analyses performed

654   on data from all subsample levels were skewed by the diagenetically biased, poorly preserved

655   assemblages at the base and top of the sequence. Similarly, whilst presence and relative

656   abundances of mangrove taxa are informative for reconstructing the vegetation occupying the

657   doline floor and for sea level inferences, these data reflect narrowly relevant tidal processes

658   rather than more broadly important palaeoenvironmental parameters such as climatic factors.

659   After the poorly preserved assemblages and the mangrove taxa were temporarily masked,

660   patterns in the dryland and limestone vegetation were revealed.

661   In the PCA (Fig. 7), the summary taxa 'Trees & shrubs' (appearing as 'Trs_shrb') and

662   that of 'Ferns' plot in opposing directions with respect to the primary axis (PC1). This suggests

663   that a structural gradient in the degree of openness of the limestone vegetation has

664   considerable explanatory power in describing differences between assemblages. Like the

665   'Ferns' summary taxon, assemblages from 122 cm and above (the uppermost assemblage of

666   Zone 2, plus Zone 3 assemblages) exhibit negative scores with respect to PC1, implying a

667   structural opening of limestone vegetation from 122 cm and above. The Bayesian model

668   suggests this change in vegetation occurred around 1075 cal. BP (875 CE).

669
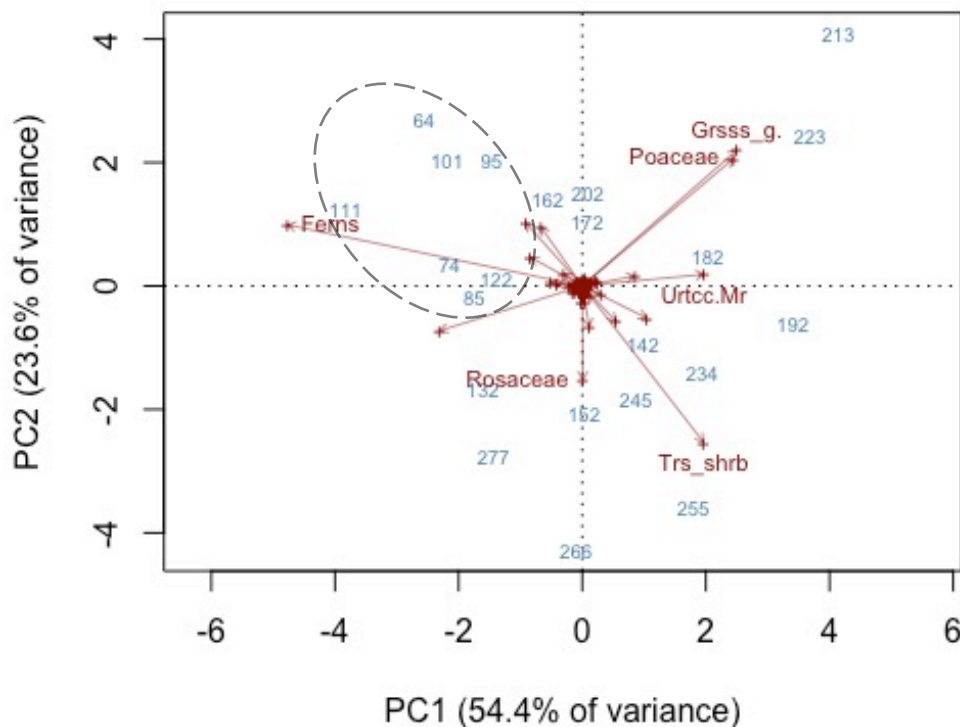
Fig. 7 PCA biplot of the non-mangrove taxa from well-preserved assemblages. Numbers correspond to core depths (cm) of assemblages; vectors correspond to constituent taxa of those assemblages and their loadings. Dashed oval encompasses depths 122 cm and above (uppermost assemblage of Zone 2 plus Zone 3 assemblages).

674

4.2. Vung Tham notches

676   Notches were observed at the base of the vertical cliffs that enclose the doline and in

677   isolated boulders. Their uniform U-shaped profile reaches a depth of 1.5 m with a horizontal

678   roof and a slightly sloping floor which suggests low wave action and a relatively stable mean

679   sea level over at least 1500 years based on an estimated annual planar erosion rate of 1 mm

680   yr^{-1} for tropical karst landscapes (Trenhaile, 2015). Measured notch heights indicate a mean

681   tidal range of ~0.6 m, which is below the observed average of 1.2 m at sites that were exposed

682   to the open sea. This indicates that water flow in and out of the doline during inundations was

683   restricted and may have caused a delay in the tidal cycle and flattening of the tidal amplitude

684   at Vung Tham. A similar effect was observed (by TK) at Cat Ba Island where the water table

685   inside *hongs* was above the prevailing sea level and water was draining at high flow rates

686   through small outlets in the rock.

687

688 *4.3. Hang Moi archaeology*

689 *4.3.1. Phytoliths*

690   Phytoliths were recovered from all contexts sampled, which date to within the Middle

691 Holocene hiatus in the Vung Tham core sequence from the doline floor, though phytolith

692 counts were consistently low. This is likely a result of degradation under alkaline conditions,

693 evidenced by surface pitting on some phytoliths, and as a result of burning. Variation between

694 contexts was still observed, however, with peaks (~2000 – 5000 phytoliths g^{-1}) in the charcoal-

695 rich contexts (6019) and (6026) contrasting with lows of ~500 phytoliths g^{-1} in burnt shell

696 layers.

697   The majority of morphotypes were only coarsely ascribed as being derived from the

698 wood/bark of eudicotyledons (Table 4). These types make up 47% of the entire assemblage

699 and indicate that wood was the main source of fuel used in the hearths. Globular echinate

700 phytoliths from Arecaceae spp. (palms) were also common and relatively abundant in the

701 samples at 17%. At much lower levels (<2%) phytoliths from taxa of Anonnaceae, Asteraceae,

702 *Celtis*, Marantaceae and Poaceae were recovered. Low numbers of sponge spicules were

703 recovered throughout the samples but were more abundant in (6026) and (6019), suggesting

704 that some of the foraged vegetation in the hearths came from wet environments.

705 **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 *Celtis* 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 *Celtis* sp., palms, and trees/shrubs.
HMC11	1	6022	Low phytolith count. Asteraceae sp. platelet recovered only from this context (n = 1). *Celtis* sp. present.
HMC11	1	6026	Increase in the phytoliths from leaves and hair cells. Only occurrence of Annonaceae sp. (n = 1). Sponge spicules, *Celtis* 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.

706

707 *4.3.2. Vertebrate faunal remains*

708   The three identifiable teeth from the Middle Holocene deposits of Trench 1 were

709 attributable to two taxa: chevrotain (*Tragulus* sp.; NISP = 2) and serow (*Capricornis maritimus;*

710 NISP = 1) (Table 5). The specimens are most likely attributable to the lesser Oriental

711 chevrotain, *T. kanchil*. Two post-cranial specimens are attributable to small carnivores and

712 are as-yet unidentified civets (Viverridae).

713   Post-cranial remains of serow were also recovered from the upper deposit from Trench

714 2, as were post-cranial elements of a large species of macaque (*Macaca* sp.), possibly *M.*

715 *assamensis*. The presence of hog deer, *Hyelaphus* (*Axis*) *porcinus*, is indicated by an antler

716 fragment. Carnivore remains include greater hog badger, *Arctonyx collaris*. Avian remains

717 include fish owl (*Bubo* sp.) and Oriental pied hornbill, *Anthracoceros albirostris*. Finally,

718 distinctive vertebrae of *Python* sp. indicate the exploitation of these snakes.

719   Specimens from the lower deposits of Trench 2 comprised several fragmented vertebrae

720 from larger mammals including a large cervid (most likely sambar, *Rusa unicolor*), further post-

721 cranial remains from a large species of macaque and a complete pig distal humerus (*Sus* sp.).

722 Further vertebrae of *Python* sp. were also recovered from this lower deposit.

723   A particularly conspicuous component of the faunal remains from the lower deposit in

724 Trench 2 (6509) was a relatively large discrete collection of distinctive neurocrania of the fish

725 genus *Pomadasys*, variously known as 'grunts', 'grunters' or 'javelins' (MNI = 13). The size of

726 complete specimens (greatest length: *n* = 3: 69.90 mm, 73.34 mm, 62.06 mm; greatest

727 breadth: *n* = 4: 46.93 mm, 52.32 mm, 45.40 mm, 39.06 mm) within this collection indicate the

728 presence of a relatively large species within the genus and fall within the range of *Pomadasys*

729 *argenteus*, the silver 'grunt' or 'javelin' (cf. *Pomadasys* "*fuscas*" in Belcher, 1994).

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

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

741

742 **Fig. 8** Stratigraphic diagram of Middle Holocene mollusc assemblages from Trench 2 at Hang Moi.
743 Figure credit: E. Hill.

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 $\partial^{18}O$ 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 $\partial^{18}O$ 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 Tràng An massif and ~30 km

772 ENE from Vung Tham (see Fig. 1), dates to 9000 – 7700 cal. BP (Tanabe et al., 2003a).

773 Tanabe et al. (2003a; 2003b) interpret the lithology of this portion of the ND-1 core to represent

774 a tidal flat depositional environment near the mouth of the Song Hong. Li et al. (2006a)

775 describe the first peak in mangrove pollen within the ND-1 record to occur at about 9000 cal.

776 BP, while pollen from tropical taxa increase across ND-1-Va at the expense of pollen from

777 previously prevalent conifers and temperate broad-leaved trees. This palynological trend

778 shows greater similarity to that of the insular Shuangchi Maar record than it does to the

779 mainland Huguangyan Maar, likely reflecting the tempering effects of maritime influence

780 shared by the Shuangchi Maar and ND-1 sites, whereas the 8.2 ka event is recorded in the

781 more continental sites of Huguangyan Maar and Dongge Cave.

782   In this context, the hydrological instability inferred from the Subzone 1b assemblages of

783 the Vung Tham pollen record more likely reflects the locally dynamic interplay between

784 transgressive and regressive processes that Funabiki et al. (2007) describe for this portion of

785 the delta infilling the flooded Song Hong valley than it does any large-scale climatic oscillation.

786 It seems probable that the mangrove vegetation that colonised the Vung Tham doline prior to

787 8100 cal. BP was seeded from the more extensive mangroves that existed from 9000 cal. BP

788 on the tidal flats outside the massif. Water-dispersed disseminules are life history traits

789 common to mangrove plants (Tomlinson, 2016), implying that mangrove fruits, seeds and

790 viviparous seedlings were likely brought into the Vung Tham doline on flooding tides via foot

791 caves when Vung Tham was within the intertidal zone. Subsequently, sedimentation within

792 the flooded Song Hong valley outside the massif to the east possibly outpaced relative sea

793 level rise immediately after 8000 cal. BP, leading to a lower relative water table and the

794 temporary development of back-mangrove vegetation within the Vung Tham doline.

795

796 *5.2. Middle Holocene high-stand*

797   A large gap in the Vung Tham record from the doline floor spans 7765 – 1715 cal. BP.

798 Similar Middle-Late Holocene gaps exist in cores from the delta plain outside the Tràng An

799 massif (e.g. cores HN, HT, HD, CD, DP, NP from Duong et al., 2020; cores PD, DA, TL from

800 Funabiki et al., 2007; core CC from Hori et al., 2004; core ND-1 from Tanabe et al., 2003a;

801 core DT from Tanabe et al., 2003b; cores VN, HV, NB, GA from Tanabe et al., 2006). These

802 sequences provide evidence for Middle Holocene delta progradation and infilling of the

803 drowned Song Hong valley leading up to and during the high-stand centred ~5500 cal. BP.

804 Microfossil analyses of Middle Holocene portions of these sequences suggest brackish

805 estuarine environments within the drowned and infilling Song Hong valley, fringed by tidal flats

806 supporting mangrove and other wetland vegetation (Duong et al., 2020). Immediately following

807 the high-stand, sedimentation subsequently slowed and ceased at upstream sites such as

808 PD, HN, DA and HT as sea level began to gradually regress toward that of the present-day;

809 causing a drop in fluvial geomorphic base level and incision by the Song Hong of the

810 sediments deposited during the preceding deglacial marine transgression.

811 While the gap in the Vung Tham sequence fits the pattern of sedimentation displayed

812 by the borehole sequences from across the delta plain, the processes involved are less

813 obvious. Vung Tham is enclosed by the surrounding limestone massif, and the fine-grained

814 sediments throughout the deposit support the expectation that it had remained sheltered from

815 the higher-energy marine and fluvio-deltaic processes acting outside the massif across the

816 broader delta region. The likely prior colonisation of the doline floor by water-dispersed

817 mangrove disseminules, as well as the existence of notches at the base of the enclosing

818 limestone walls, imply that a direct hydrological connection existed with the transgressing sea

819 and associated tidal cycles. Two plausible explanations for the gap in the Vung Tham record,

820 which are not mutually exclusive, are proposed. The doline floor may have been starved of

821 sediment during the Middle Holocene high-stand when Vung Tham appears to have been

822 submerged from wall to wall; and that as the intertidal zone regressed back across the doline

823 following the high-stand, portions of the deposit may have been eroded on ebbing tides.

824 Observations made by SO, NTMH, TK and EH at an analogous modern flooded doline on Cat

825 Ba Island, which is within the present intertidal zone and has hydrological connections to the

826 surrounding sea, confirm that significant flow velocities and erosive potential are achieved on

827 ebbing tides.

828   In the absence of high-stand sediments from the Vung Tham doline floor,

829   palaeoenvironmental inferences for this time period have been drawn from the notches at the

830   base of the enclosing limestone walls within Vung Tham, as well as from Middle Holocene

831   archaeological assemblages from the adjacent cave site of Hang Moi. Data from the notches

832   indicate that the entire doline was inundated to a level of ~3.3 m a.s.l. While there is presently

833   no visible evidence of a connection to the surrounding delta plain, the current presence of

834   water in Vung Tham is most likely facilitated by subterranean conduits that connect to the local

835   aquifer. The microfossil evidence for the past presence of mangroves, discussed above, also

836   implies a hydrological connection with the sea during times of higher sea level.

837   Phytolith analysis of the in situ hearth sequence from Trench 1 at Hang Moi confirmed

838   the presence of Annonaceae, Arecaceae, Asteraceae, *Celtis*, Marantaceae and Poaceae, as

839   well as unidentifiable woody eudicots (trees / shrubs) within the deposit at Hang Moi. The most

840   abundant morphotypes present, that are attributable to trees / shrubs, are not diagnostic.

841   However, previous analysis of charcoal recovered from the same contexts at Hang Moi

842   (Ceron, 2012) attests to the presence of Dipterocarpaceae sp. (prob. *Dipterocarpus* sp.),

843   Dilleniaceae sp. (prob. *Dillenia* sp.) and Sapotaceae sp. (prob. *Manilkara* sp. or *Palaquium*

844   sp.), which are indicative of lowland and limestone forest and likely the source of fuel for the

845   fires.

846   All the taxa recovered are common in Southeast Asian ethnographic examples and

847   archaeobotanical assemblages. Palms are used as fuels, construction, in weaving, wrappings

848   and as food (Haynes & McLaughlin, 2000; Tsuji et al., 2011). *Celtis* sp. fruit are edible; its

849   bark/wood has medicinal properties; and it is suitable for cloth manufacture and for use as

850   timber (Fu et al., 2003; Glover, 1986; Kealhofer & Piperno, 1998). Poaceae is an expansive

851   family with many key economic species, with numerous additional uses which vary from

852   construction to textiles. Whilst many of the families represented in the phytolith assemblages

853   have species that produce edible fruits or nuts, the phytoliths identified mostly come from

854   wood, bark, leaves and stems, and so do not in themselves provide immediate indication for

855   use as foods.

856   Comparisons can be drawn between these assemblages from Hang Moi and existing

857   contemporaneous evidence from subtropical South China. Phytoliths from Xincun attest to the

858   importance of palms in the subsistence strategy of Middle Holocene gatherers (Yang et al.,

859   2013). Similarly, Annonaceae, palms, cucurbits and grasses have been recovered in phytolith

860   assemblages from Dingsishan sites (Chi & Hung, 2012). In this context, the abundance of

861   globular echinates from the Hang Moi samples may indicate the importance of palms in the

862   subsistence strategies of the people who used Hang Moi during the Middle Holocene, although

863   it has been proposed that this morphotype of phytolith is more robust than others, so its high

864   frequency may be a result of preferential preservation (Albert et al., 2008; Cabanes &

865   Shahack-Gross, 2015). The results of the phytolith and charcoal analysis, together with the

866   sponge spicules that were recovered, attest to the presence and exploitation of resources that

867   can occur in a range of habitats, including forests and wetlands, by the people at Hang Moi

868   during the Middle Holocene.

869   The animal bones recovered from Hang Moi overwhelmingly reflect subsistence

870   behaviours of the prehistoric occupants of the cave rather than a comprehensive sampling of

871   available local vertebrate taxa. As such, the zooarchaeological assemblages represent the

872   product of the exploitation of different habitat types. With this caveat in mind, the current

873   identifications of vertebrate taxa permit the following inferences.

874   The identified mammalian taxa from the Middle Holocene hearth and refuse dump

875   deposits indicate the exploitation of serow (*Capricornis maritimus*). These large caprines most

876   parsimoniously occupied the steep terrain of Tràng An (e.g. Castelló, 2016) reflecting the

877   exploitation on the interior of the karst.

878   The ecology and behaviour of Indochinese chevrotains is understudied, but known

879   habitat preferences of the species are a mosaic of riverine, seasonal swamp and drier

880   undulating country. The main vegetation types associated with the lesser Oriental chevrotain

881   (*T. kancil*) are legumes and dipterocarps (Timmins & Duckworth, 2015).

882   Post-cranial elements of primates indicate the exploitation of a large species of macaque

883   (*Macaca* sp.), possibly *M. assamensis*. This is associated with lowland limestone karst forest

884   (Nadler & Brockman, 2014). The presence of hog deer, *Hyelaphus porcinus*, is indicated by

885   an antler fragment. The hog deer is now extinct in Vietnam but is reported to strongly favour

886   more open wet or moist tall grasslands, often associated with riverine habitats. The species is

887   reported to occur in the highest densities in flood plain grasslands. Hog deer favour grazing

888   on young grasses, especially *Imperata cylindrica* and *Saccharum* spp. In addition, herbs,

889   flowers, fruits and some browse are also taken (Timmins et al., 2015).

890   Carnivore remains include as-yet unidentified civets (Viverridae) and greater hog badger

891   (*Arctonyx collaris*). Many basic aspects of the natural history of the greater hog badger are

892   poorly known and require study (e.g. Proulx et al., 2016) but the species is reported to be

893   primarily associated with lowland and hill forests (Hunter & Barrett, 2011).

894   Avian remains include fish owl (*Bubo* sp.) and Oriental pied hornbill (*Anthracoceros*

895   *albirostris*). The species of fish owl that are known from the region today show strong

896   association with forested habitats near water (König & Weick, 2008). The Oriental pied hornbill

897   is a widely distributed species (that remains a conspicuous and noisy resident of Tràng An

898   today) and is predominantly associated with tropical and subtropical wet lowland forests

899   (Kinnaird & O'Brian, 2007). Pythons are known from forested and grassland habitats but are

900   strong swimmers and show a marked affinity for water.

901   Specimens of cervid, pig and macaque from the lower deposits of Trench 2 likely

902   indicate the exploitation of interior habitats. Further vertebrae of *Python* sp. were also

903   recovered from the lower deposit.

904   The assemblage of neurocrania from *Pomadasys* cf. *argenteus* is perhaps the strongest

905   evidence of local high-stand conditions. On the basis of data currently available from Hang

906   Moi this would seem to have occurred prior to 5500 cal. BP. While 'grunts' *per se.* are

907   predominantly associated with marine and coastal habitats, species such as *P. argenteus* are

908   also known to enter mangroves (Dahanukar, 2012).

909   Middle Holocene contexts from Trench 2 yielded mollusc assemblages containing a mix

910   of taxa that inhabit mangrove, estuarine and terrestrial subtropical forest environments.

911   Mangrove and estuarine gastropod taxa such as *Neripteron violaceum*, *Cerithidea obtusa*,

912 *Ellobium* cf. *aurisjudae*, *Sermyla riqueti*, *Brotia* spp. and *Cerithium* spp. predominate alongside

913 shallow mud burrowing bivalves like *Meretrix* sp., various Tellinidae and Arcidae and a variety

914 of small oysters, most likely *Crassostrea* sp., which are present in large numbers alongside

915 several fragmentary *Unio* spp. The terrestrial component, which is significantly smaller than

916 that from other cave assemblages in the area (Hill & Hunt, 2014), is dominated by *Cyclophorus*

917 spp., a small number of which are identifiable to *C. cambodgensis*.

918   The composition of the assemblages within context 6203 reflects human foraging of

919 mangrove and estuarine habitats. Comparative survey of modern intertidal environments on

920 Cat Ba Island (by EH), treated here as an analogue to Middle Holocene Tràng An,

921 demonstrate that many of these species are accessible within the intertidal zone and the

922 edges of mangrove stands. The dominance of mangrove and estuarine taxa within the Trench

923 2 midden assemblages, which make up ~90% of the total across the sequence, suggests a

924 heavy reliance on mangrove and estuarine environments as a foraging location for molluscs.

925 *Sermyla riqueti* are still bought and sold in Vietnamese markets today as an edible species,

926 and this taxon makes up 75% of all molluscs in the Trench 2 Middle Holocene midden layers

927 at Hang Moi. The average size of the archaeological *S. riqueti* shells is 2.7 cm, which are

928 slightly smaller than those sold today, while the largest are 4cm.

929   The reduced terrestrial components of these Middle Holocene mollusc assemblages

930 from Hang Moi as compared to that of earlier Holocene assemblages from other cave deposits

931 across Tràng An (cf. Rabett et al., 2011) suggests that the human groups that used Hang Moi

932 during this period preferred to forage for molluscs in mangrove and estuarine habitats. The

933 vertebrate faunal remains discussed above attest to the persistence and human use of

934 limestone forest habitats within the interior of the karst throughout the Middle Holocene. In this

935 context, it seems that the people who used Hang Moi during the high-stand in sea level

936 preferred to forage for molluscs in the mangrove and estuarine environments that likely existed

937 within the doline in front of the cave, while venturing deeper into the karst to hunt in limestone

938 forest habitats.

939   In total, based upon the inferred subsistence base, combined with the dark coarse-ware

940   potsherds previously recovered from Middle Holocene contexts at Hang Moi (Green, 2018;

941   Nyiri, 2011), the archaeological remains are attributable to the Da But culture. Bui (1991) and

942   Nguyen (2005) describe the Da But's characteristic orientation towards wetland, estuarine and

943   mangrove resources as a cultural adaptation to coastal inundation during the Middle Holocene

944   high-stand in sea level, though the exploitation of interior, forested habitats remained a

945   component of the foraging economy. During this high-stand, the palaeoenvironmental and

946   archaeological evidence presented here suggests that the Vung Tham doline contained an

947   ancient *hong* lagoon enclosed by limestone karst and supported mangroves and surrounding

948   limestone forests, similar to the modern *hongs* of Krabi province in southwestern Thailand and

949   of Cat Ba Island in Hai Phong province of northern Vietnam (Price & Waltham, 2007). The

950   ancient *hong* in Vung Tham appears to have been an attractive location to Da But people

951   during the Middle Holocene.

952

953   *5.3.   Late Holocene*

954   The Late Holocene is defined by Walker et al. (2018) as beginning with the widely

955   detected '4.2 ka event', expressed in many palaeoclimate records by abrupt onset of

956   aridification lasting 200 – 300 years. The Dongge Cave record from south-eastern China

957   documents the 4.2 ka event with a sharp excursion to heavier $\partial^{18}O$ values, suggesting a further

958   weakening of the EASM (Dykoski et al., 2005). This expression of the 4.2 ka event is an

959   acceleration of the weakening trend in the EASM throughout the Middle-Late Holocene, which

960   tracks mid-latitude Northern Hemisphere summer insolation (Wang et al., 2005; Zhang et al.,

961   2019). The subsequent period from ~4 – 2 ka is marked by increasing variability of the El Niño

962   – Southern Oscillation (ENSO) (Dykoski et al., 2005; Haug et al., 2001; Toth & Aronson, 2019),

963   manifest in south-eastern China as hydroclimatic instability (Zhang et al., 2018a; 2019).

964   Palaeo-shoreline reconstructions for the Late Holocene based upon borehole data in

965   Duong et al. (2020) and Tanabe et al. (2006) describe the completion of infilling of the Song

966   Hong valley by ~4 – 3.7 ka, and the resulting establishment of a linear coastline along the

967   delta front ~30 km inland from its present position. While Late Holocene sediments are absent

968   from the ND-1 core (Li et al., 2006a), pollen assemblages from the VN and GA cores located

969   progressively further downstream along the course of the Song Hong record the seaward

970   migration of mangrove-dominated tidal flats as the delta continued to prograde across the Late

971   Holocene (Li et al., 2006b). In pollen zone VN-IV of the VN core, Li et al. (2006b) attribute

972   sharp and sustained decreases in pollen of arboreal taxa at 3340 cal. BP, and their

973   replacement by pollen of non-arboreal and secondary taxa such as large grass grains (greater

974   than 40 μm), aroids, gesneriads, and extra-local *Pinus*, to human clearance of the broad-

975   leaved lowland tropical forest that they suggest occurred during the Middle-Late Holocene at

976   the site. This dominance in non-arboreal pollen remains a consistent feature through the

977   remainder of the record, suggesting sustained forest reduction on the delta plain across the

978   past three millennia.

979   The majority of the Vung Tham core sequence dates to the past ~1715 years (i.e. the

980   upper 310 cm). Thirty-one of the 38 pollen assemblages derive from this portion of the

981   sequence. These comprise the uppermost assemblage from Subzone 1c, as well as all Zone

982   2 and Zone 3 assemblages. Two dominant trends in local vegetation dynamics are suggested

983   by the sequence of these assemblages: long-term persistence of mangrove forests on the

984   doline floor until well after the intertidal zone had regressed seaward at the edge of the

985   prograding delta front; and a structural opening of the dryland and limestone forest on the

986   surrounding karst beginning from a modelled date of 1075 cal. BP (875 CE).

987   While mangrove plants overwhelmingly occur within intertidal zones in coastal settings

988   and display various physiological adaptations to periodic inundation by saline water

989   (Tomlinson, 2016), numerous published accounts exist of mangroves occurring tens of

990   kilometres inland and even associated with freshwater (e.g. Beard, 1967; Brinson et al., 1974;

991   Ellison & Simmonds, 2003; Flores-Verdugo et al., 1987; Lugo, 1981; Lugo & Snedaker, 1974;

992   Patel & Agoramoothy, 2012; Stoddart et al., 1973; Taylor, 1986; van Steenis, 1963; 1984).

993   These inland mangroves are frequently described as relictual, likely persisting at these sites

994   from antecedent populations that established when the sites were within the intertidal zone.

995 While local environments supporting mangroves may change on centennial-millennial

996 timescales due to subsequent eustatic drops in sea level, or isostatic or tectonic uplift of the

997 ground surface, it is apparent that mangroves are able to persist outside of the intertidal zone.

998 It is unclear what set of conditions permit these occurrences. Nonetheless, this phenomenon

999 is a possible explanation for the persistence of mangrove vegetation on the doline floor of

1000 Vung Tham until as late as 250 cal. BP (1700 CE), which is the modelled age of the uppermost

1001 assemblage (54 cm depth) that contains pollen from woody mangrove elements such as

1002 *Excoecaria* and *Aegiceras* as well as substantial representation of the summary taxon

1003 'Mangroves & associates' (~17%). The palaeoenvironmental records from the VN and GA

1004 cores (Li et al., 2006b) provide evidence that the palaeo-shoreline on the delta outside the

1005 Tràng An massif had already regressed substantially seaward beyond Tràng An by the time

1006 the Vung Tham record resumes from 1715 cal. BP (Duong et al., 2020).

1007 An additional major trend in vegetation dynamics evident in the Vung Tham pollen record

1008 is the structural opening of the dryland and limestone vegetation after ~1075 cal. BP (875 CE).

1009 Rabett et al. (2017) inferred the long-term resilience of limestone forest at Tràng An throughout

1010 the climatic stresses of the LGM and terminal Pleistocene deglaciation using several

1011 palaeoenvironmental proxies from archaeological cave sites across the massif (see also

1012 Stimpson et al., 2019, for discussion). Pollen Zone 1 and all but the uppermost assemblage

1013 from Zone 2 of the Vung Tham core, as well as the archaeological remains from Hang Moi,

1014 provide evidence for the continued presence of limestone forest habitats throughout the

1015 Middle and into the Late Holocene. Pollen assemblages from the Vung Tham core above 122

1016 cm depth, estimated to date to the most recent 1075 years (since 875 CE), then show marked

1017 increases in the representation of ferns and grasses at the expense of previously prevalent

1018 woody dryland and limestone forest elements such as *Dacrycarpus*, Rosaceae,

1019 Elaeocarpaceae and Urticaceae/Moraceae-type. Likely extra-local wind-pollinated taxa such

1020 as *Pinus*, *Podocarpus/Nageia*-type and *Quercus* also increase in these assemblages from the

1021 last 1075 years, implying an expansion of the pollen catchment (Davis, 2000) as surrounding

1022 vegetation became more open. These changes coincide with the onset of the Medieval

1023 Climate Anomaly (Mann et al., 2009), which is expressed across East Asia as a ~300-year

1024 warm period (Zhang et al., 2018b) and at Quan Lan in coastal northern Vietnam as aridity and

1025 drought (Briles et al., 2019). In addition to this potential climatic driver of the dryland and

1026 limestone vegetation changes inferred at Tràng An, and perhaps also related to associated

1027 climatic stresses, hydrological manipulation of surrounding river networks and development

1028 at the adjacent city of Hoa Lu intensified around the same time.

1029   In 968 CE, Hoa Lu was chosen to be the capital city of Vietnam. According to historical

1030 records, the King ordered the building of walls, canals and palaces in the Citadel (Ngo, 1697).

1031 Archaeological research since the 1970s has added information about the existence of the

1032 Citadel with walls, temples and palaces (Nguyen, 1970; Pham & Nguyen, 1970; Tong et al.,

1033 1998; Nguyen et al., 2010). Recent research has investigated the large boundary around the

1034 Hoa Lu Citadel (Vo et al., in review). This boundary was formed by the Citadel walls to the

1035 north, north-east and east – the Eastern Wall was excavated in 1970 (Pham & Nguyen, 1970),

1036 the Northern Wall was recently excavated in 2018 (Nguyen et al., 2018) – and the rivers on

1037 the east and the canals at the south and south-east, combined with the Tràng An massif to

1038 the west. The enclosure not only protected the central Citadel but also separated the inner

1039 area from the outer parts of the city. The Northern Walls protected the Citadel and stopped

1040 flooding and deposits from the brackish Hoang Long River to the north. The Van River, an

1041 important waterway to the Citadel from the south and south-east, was built to protect, but also

1042 disconnect, the Citadel from the sea. The formation of this enclosed boundary, and the

1043 associated modifications of the river system and local drainage networks, created an extended

1044 urban area which likely had a significant impact on the environment of the area within the

1045 Tràng An massif and on the vegetation of the limestone landscape. Aquatic taxa in particular

1046 would have been impacted through altered hydrology.

1047

1048 *5.4. Conclusions: implications for conservation and sustainable development*

1049   The data presented here provide evidence for the Middle Holocene colonisation of the

1050 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^{-1} 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

1079 coastlines against the effects of storm damage, the filtering and trapping of pollutants, as well

1080 as significant socio-economic value (Wells et al., 2006). Efforts to restore degraded mangrove

1081 areas that have demonstrated resistance or resilience to climate change are also highlighted

1082 as a strategy that the managers of protected areas could instigate to help build mangrove

1083 resilience to future climate change (McLeod & Salm, 2006). The long-term survival of

1084 mangrove components within the Vung Tham doline offers an opportunity for restorative

1085 measures to be instigated within this and similar sheltered sites within Tràng An, as well as

1086 elsewhere around the edge of the Song Hong Delta. Further research is required, for example

1087 into the relationship and interactions between mangrove and limestone forest formations, and

1088 to socio-economic benefits among local communities (see e.g. Nguyen et al., 1998). However,

1089 this palaeoenvironmental study has demonstrated that sites like Vung Tham have the potential

1090 to form stable centres for mangrove rehabilitation that could help mitigate impacts and

1091 optimise socio-economic and environmental responses to future sea level rise.

1092

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