## Title

# Mid-Holocene coastline reconstruction from geomorphological sea level indicators in the Tràng An World Heritage Site, Northern Vietnam


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## Abstract

In this paper we present a high resolution palaeo coastline model for the isolated limestone massif of Tràng An, Ninh Bình province, Vietnam. The archaeological and palaeoecological record here comprise rich archives of human activity set within a landscape that was cyclically transformed between inland and archipelagic states under the influence of past sea level changes. These records have become informative proxies in the study of current sea level rise. Well-preserved notches along the vertical limestone cliffs within the study property reveal several phases of prolonged stable sea levels that likely pertain to the Mid-Holocene marine transgression 8 ka BP to 4 ka BP and allow for detailed coastline reconstructions for parts of the Red River Delta (RRD). The resulting coastline model facilitates a closer look at past human responses to landscape and environmental changes at local and individual site-level, which improves our understanding of past human adaptations to climate-change induced sea level rise. These data also stand to inform current coastal vulnerability assessments and climate change response models.

**Keywords**

Holocene; Pleistocene; Climate dynamics; Sea Level changes; Southeast Asia; Geomorphology, coastal; Data treatment, data analysis

## 1. Introduction

More than 23% of the world's population live on the coast; a figure heavily weighted towards populations in South, Southeast and East Asia (Small and Nicholls, 2003). Coastal communities in this part of the world are facing an urgent threat from above-average climate-driven sea level rise (Nicholls and Cazenave, 2010; Hens et al., 2018). Global and regional models are now seeking to assess future coastal vulnerability in increasingly complex ways. This has included a drive towards incorporating natural and social science data into economic integrated assessment models. The Dynamic and Interactive Vulnerability Assessment (DIVA) tool (Hinkel, 2005), has found particular utility across a range of models at different scales (e.g. Vafeidis et al., 2008; Hinkel et al., 2010; Brown et al., 2016; Diaz, 2016; Muis et al., 2017; Tamura et al., 2019). Equally fundamental to impact projections is an understanding of changes in relative sea level, geological processes and punctuated extreme events (e.g. tsunami or storms). The study of these variables and their effects on coastal areas, people and biodiversity have been the subject of several initiatives sponsored by the International Geoscience Programme (formerly the International Geoscience Correlation Programme (IGCP) since the 1970s, including the recent projects IGCP437 (1999 – 2003) 'Coastal environmental change during sea-level highstands: a global synthesis with implications for management of future coastal changes' (Murray-Wallace et al., 2003) and IGCP588 (2010 – 2014) and 'Preparing for Coastal Change' (Sloss et al., 2012). Palaeoenvironmental data, such as that provided by sedimentary sequences, relic coral reefs and notches also have a significant contribution to make by providing detailed records of how sea levels have changed in the past, where shorelines lay and how coastal settings previously responded to these changes (e.g. Liew et al., 1993; Hanebuth et al., 2000; Wang et al., 2008; Murray-Wallace and Woodroffe, 2014; Kelsey, 2015). In Southeast Asia, palaeoenvironmental proxies have been used to track inundation of the Sunda and adjacent continental shelves after the Last Glacial Maximum (LGM: 26 – 18 ka BP), which not only submerged more than 1.8 million km$^2$ between Indonesia and Vietnam but reshaped coastlines and entire river and deltaic systems (Hanebuth et al., 2000; Hanebuth et al., 2009; Rabett and Jones, 2014).

Past coastal inundations driven by rising sea level contributed to dramatic changes to coastal landscapes, particularly in river deltas where low-gradient flood plains were inundated for hundreds of kilometres, triggering changes in habitats, biodiversity and human culture over prolonged periods of time (Stanley and Warne, 1994; Stanley and Warne, 1997). Sediment cores, geomorphological sea level markers, alongside archaeological and historical records, are used to develop coastline models that satisfy a general understanding of the impact of sea level changes on coastal landscapes at regional and global scales (Pirazzoli, 1991). While such models can inform models of past cultural adaptation and environmental changes, and in a broader sense what triggers them, they provide insufficient detail to study these mechanisms at local and site levels. Palaeoenvironmental samples from sediment cores and archaeological sites are of limited spatial extent, and their formation is determined by the immediate conditions that surround a site. As such, detailed coastal models of geographically limited extend improve the overall understanding of the conditions at a site at a specific point in time and remove uncertainties surrounding site formation processes (e.g. Surakiatchai et al., 2018; O'Donnell et al., 2020). Feedback from these punctuated studies can then be applied to large-scale coastal reconstructions to improve their overall accuracy.

In this paper we present a relative time-series coastline reconstruction and distribution maps for part of the Red River Delta (RRD) in northern Vietnam during the Mid-Holocene sea transgression. Our model is based on a survey of 27 notches all taken within an isolated karst massif within the RRD, which act as indicators for past relative sea levels (here, rsl pertains to past topographic conditions relative to modern elevation above sea level, not adjusted for isostatic and eustatic changes (Rovere et al., 2016). In particular, we illustrate how variations in sea level at the metre-scale have impacted this topographically complex landscape, providing detailed landscape-scale spatial evidence to reconstruct past human activity and ecosystem development in this part of the RRD. Our data also exemplify the detail that can be lost to current assessment models of contemporary coastal vulnerability when spatial structuring and time-depth dimensions are not considered. At present, the lack of a high-resolution chronology prevents immediate incorporation of our data into the regional sea level curve (e.g. Hanebuth et al., 2011); however, this remains an achievable future aim.

*1.1 Notch formation*

During periods of eustatic sea level rise, isolated upland formations set in coastal alluvial plains may become inundated and temporarily transformed into islands or archipelagos. Under such conditions marine notches may form and their morphology indicates the extent and duration of past marine transgressions along with local coastal conditions (Pirazzoli, 1986; Boyd and Lam, 2004; McDonald and Twidale, 2011; Moses, 2012; Trenhaile 2015). Their use as eustatic sea level markers is accompanied by sometimes wide error margins and uncertainty due to absence of direct dating material. Geological, geomorphological, biological and marine factors that influence sea level estimations from notch morphology (Woodroffe and Horton, 2005; Trenhaile 2014, 2015, 2016), however, can still be used effectively in the reconstruction of local and regional rsl and coastlines (Surakiatchai et al., 2018). Indeed, the development of notches plays an important role in the life-cycle of lowland and coastal karst landscapes in tropical South and Southeast Asia (Scheffers et al., 2012; Mann et al., 2019) and, where preserved, serve as excellent past rsl indicators (Pirazzoli, 1986).

Notches considered in this study form in two principal environments: 1) marine notches, which form within coastal littoral zones; 2) basal or swamp notches, which form along the water table in freshwater or brackish environments. Used in conjunction with terrestrial and marine sediment cores, and radiometric dating, the extent, composition and chronology of palaeo-coastlines can be modelled, and then utilised in a variety of contexts including reconstruction of past human activity and ecosystem development; refinement of local and regional sea level curves; and development of risk mitigation strategies against future coastal inundation (Liew et al., 1993; Hanebuth et al., 2000; Wang et al., 2008; Murray-Wallace and Woodroffe, 2014; Kelsey, 2015).

Along the carbonate rock coasts of Vịnh Bắc Bộ (Gulf of Tonkin), the islands of Hạ Long Bay/ Cát Bà and on the terrestrial southwestern margins of the RRD (Figure 1), well preserved notches are reported at elevations ranging between 2 and 9 m above sea level (here, asl pertains to elevation above modern sea level relative to a global geoid and/or local datum such as EGM96) indicative of Quaternary sea levels that were at times above those of today (Boyd and Lam, 2004; Pham et al., 2013). Radiometric dates obtained from material recovered from notches in Hạ Long Bay and in the Tràng An massif (Figure 1) suggest that the majority formed during the Mid-Holocene transgression between 6 and 3 ka BP (dates quoted as ka BP = "thousands of years before present", where "present" is 1950. Where available, calibrated dates are shown with 2σ ranges, unless otherwise stated) (Boyd and Lam, 2004; Tran et al., 2013). Post-6 ka BP transgressions were also proposed by Pedoja (2008) - citing Xie et al. (1985) - and Zhang et al. ( 2003) at 5 ka BP and 3 ka BP, reaching 4 ±1 m asl and 1.5 ±1 m asl respectively for the South China Sea. Notches at 1.5 – 2 m asl have been recorded in the RRD (Nguyen et al., 2012a; Pham et al., 2013; Tran et al., 2013), dated to 2.5 – 1.5 ka BP, and interpreted as evidence for a Late-Holocene high stand.

Using deltaic sediments as past sea level markers poses challenges due to complex formation processes such as erosion, reworking, bioturbation and compaction that cause highly localised variability in lithological sequences and chronology (Mann et al., 2019). This can lead to misinterpretation of results or loss of resolution in data. For example, evidence from marine terraces, marine notches, corals, molluscs and crustacea has been observed across Southeast Asia and attributed to a late Holocene high stand (Tjia, 1996; Baker and Haworth, 2000; Liew and Hsieh, 2000). Sequences covering the same period from three sediment cores taken c. 30 – 50 km east and north of Tràng An lacked this evidence. Instead, a floodplain environment with constantly decreasing sea level has been proposed until modern sea levels were attained (Tanabe et al., 2003a; Tanabe et al., 2003b; Hori et al., 2004; Tanabe et al., 2006).

In this paper, we expand the record of notches recorded in Tràng An (Boyd and Lam, 2004; Nguyen et al., 2012a; Tran et al., 2013; UNESCO, 2014b) (Figure 1) to retrace the palaeo-coast on the southwestern margin of the RRD. Using the work of Boyd and Lam (2004) as a baseline, we examine the extent to which variable karst topography may be implicated in altering tidal hydrology and therefore notch formation. We also propose minimum and maximum Mid-Holocene coastlines for Tràng An, extending the transgression of the south-western lower RRD further west than previously assumed (Tanabe et al., 2003b; Tanabe et al., 2006; Tran et al., 2013), a finding that changes the current interpretation of the central massif of Tràng An during that time from a peninsula to the largest island of a Tràng An archipelago.

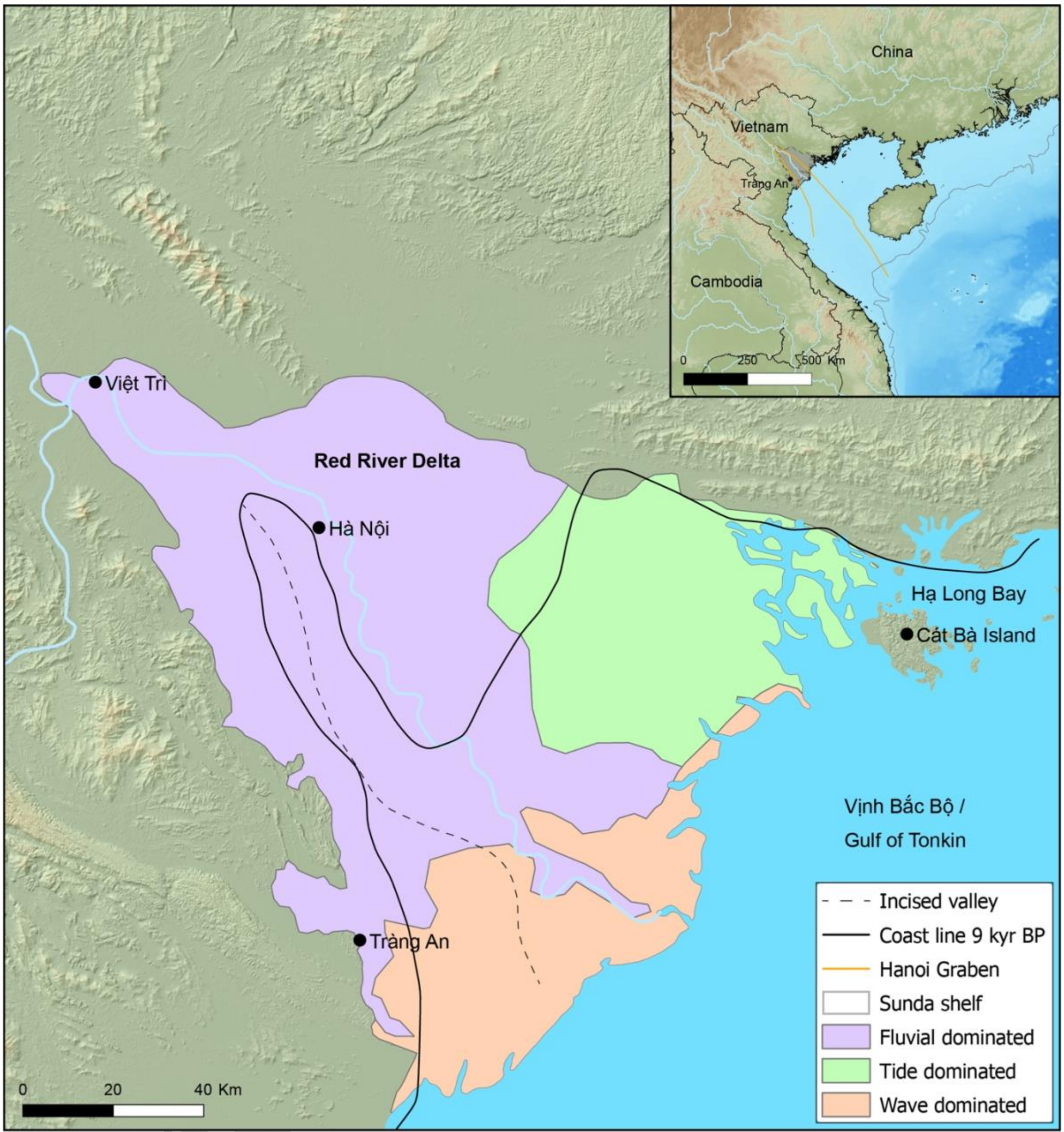



*Figure 1: Red River Delta divided into its three principal sedimentary zones overlain by the location of the incised valley and palaeo coastline at 9 ka BP (after Tanabe et al., 2006). Inset depicting location of RRD in its wider geographic context and Hanoi Graben (after Nielsen et al., 1999).*

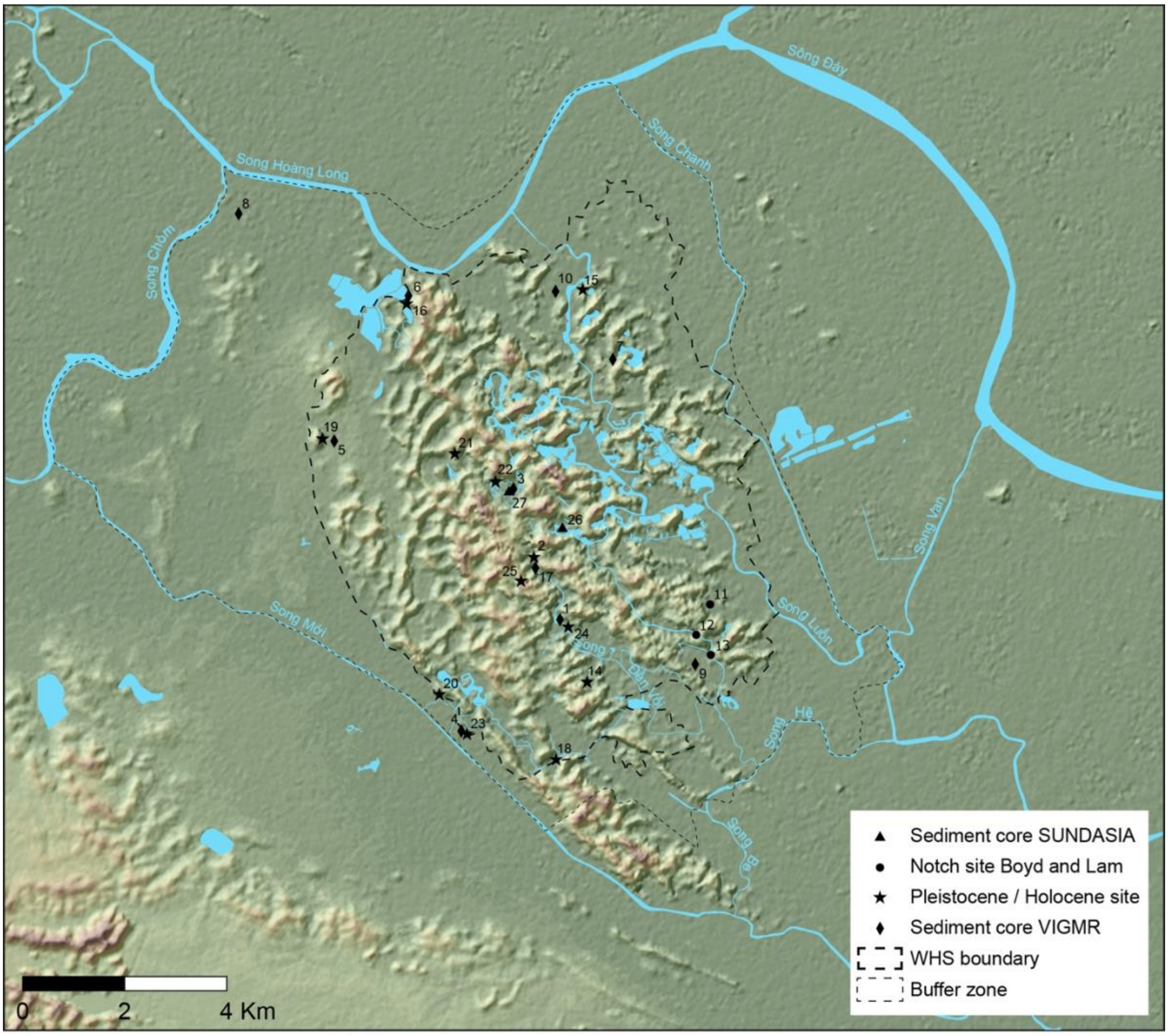
### *1.2 Geographic and geological setting*

Tràng An was inscribed as a mixed natural and cultural UNESCO World Heritage Site (WHS) in 2014, currently the only site in Southeast Asia to receive this status. This isolated limestone massif lies in the Province of Ninh Bình, immediately west of the provincial capital of the same name. The inscription marks Tràng An as an outstanding area of tropical limestone karst with a human presence for the last 30 ka that illustrates adaptation to extreme environmental changes (UNESCO, 2014b). The RRD itself extends c. 180 km northwest to southeast and spans c. 150 km along the North Vietnam coast (Mathers et al., 1996; Mathers and Zalasiewicz, 1999). The delta covers an area of c. 10,000 $km^2$ (Tanabe et al., 2003b) and has a population density in excess of 430 persons/$km^2$, making it one of the most densely populated river deltas in the region (Fanchette, 2002; Labbé, 2019). The delta has formed within the seismically active Red River Graben, a major fault that divides the North Vietnam and Sông Đà terranes. The Red River Graben is controlled by a complex of fault systems; the southern-most of which being the Red River fault that also controls the course of the Sông Đáy (Phach et al., 2020). The Red River Graben is filled with Neogene and Quaternary sediments to a depth of up to 3 km and limited by Pre-Quaternary mountainous uplands (Mathers et al., 1996). These deposits are overlain by alluvial and marine sediments laid during delta initiation from *c.* 9 ka BP (Tanabe et al., 2003b) (see also Appendix A.1). Surface topographical and geological studies indicate three sub-systems that influenced delta morphology (Mathers and Zalasiewicz, 1999). The inland western section of the delta is alluvial-dominated, the northern section is tide-dominated and the southern section is wave-dominated (Figure 1). The Leizhou Peninsula and Hainan Island afford a degree of protection for the northern coast to direct wave action contributing to the development of these contrasting systems.

Situated c. 85 km south of Hanoi and 45 km west of the coast of Vịnh Bắc Bộ, the Tràng An massif lies adjacent to the infilled Sông Hồng valley, an incised river valley that was inundated after the LGM and had been infilled with tide-influenced channel sediments by 6 ka BP (Tanabe et al., 2003b). To its west, Tràng An is adjoined by an elevated Pleistocene fluvial terrace that rises above the otherwise low-lying Holocene marine-influenced and alluvial plains. The former is currently used to indicate the maximum extent of the Mid-Holocene sea transgression (Tanabe et al., 2003b). Its full extent, however, has not yet been established.

An interconnected river–canal system that has been intensely modified for transport and irrigation flows through and around Tràng An, with the Sông Đáy being the largest river. To the west, a 1 – 4 km wide poljie separates Tràng An from the eastern fringe of the Annamite Mountains and forms a flood plain for the Sông Mới as it follows the western margin of the Tràng An massif.

Previous investigations in Tràng An comprise studies that preceded the WHS inscription and which included a series of sediment cores (see Appendix A.1), and geological, geomorphological and archaeological assessments (UNESCO, 2014b). A limited notch survey has also formed part of a broader project that investigated sea level changes in the RRD (Lam and Boyd, 2001; Lam and Boyd, 2003; Boyd and Lam, 2004). Between 2007 and 2014 the Tràng An Archaeological Project (Rabett et al., 2009, 2011) conducted a targeted assessment of three prehistoric cave sites within the massif. Most recently, SUNDASIA (2016-2021) has been investigating human adaptation to cycles of sea transgression and regression during the past 60 ka (Rabett et al., 2017a; Utting, 2017; Rabett et al., 2019; Stimpson et al., 2019; O’Donnell et al., 2020) (Figure 2).




| ID | Name | Site type | ID | Name | Site type | ID | Name | Site type |
|---|---|---|---|---|---|---|---|---|
| 1 | TAK1 | Sediment core | 10 | TAK10 | Sediment core | 19 | Hang Thung Bình 1 | Relict cave |
| 2 | TAK2 | Sediment core | 11 | WK-8269 | Notch date | 20 | Động Thiên Hà | Relict cave |
| 3 | TAK3 | Sediment core | 12 | WK-8268 | Notch date | 21 | Hang Bói | Relict cave |
| 4 | TAK4 | Sediment core | 13 | WK-8267 | Notch date | 22 | Hang Mòi | Relict cave |
| 5 | TAK5 | Sediment core | 14 | Hang Công Binh | Relict cave | 23 | Mái Đá Ốc | Rock shelter |
| 6 | TAK6 | Sediment core | 15 | Hang Quàn | Relict cave | 24 | Mái Đá Vàng | Rock shelter |
| 7 | TAK7 | Sediment core | 16 | Hang Vòng | Relict cave | 25 | Mái Đá Ông Hay | Rock shelter |
| 8 | TAK8a | Sediment core | 17 | Mái Đá Chợ | Relict cave | 26 | Vụng Chạy | Sediment core |
| 9 | TAK9 | Sediment core | 18 | Hang Chùa | Water cave | 27 | Vụng Thắm | Sediment core |

*Figure 2: Overview of Tráng An WHS property with sediment cores, radiocarbon dated notch sites and Pleistocene and Early- to Mid-Holocene sites indicated. [1]) after O'Donnell et al. (2020) [2]) after Boyd and Lam (2004) [3]) after UNESCO (2014a).*

The Tràng An massif is part of the North Vietnam orogenic belt and is composed of thinly bedded to massive Triassic limestone of the Đồng Giao and Pa Khõm formations that have undergone extensive uplift and deformation following the collision of the Indian subcontinent with Eurasia and subsequent activation of the Red River fault (Metcalfe, 2017). After denudation, karstification took place under the influence of tropical and sub-tropical climate regimes during which extensive cave systems and deep river valleys formed along faults and fissures in the bedrock. Ongoing erosion caused by high-volume precipitation resulted in the collapse of the cave systems and the formation of a fengcong landscape, comprising enclosed dolines separated by cone and saddle karst formations. Planation was further driven by sea inundations and seasonal flooding that transformed the fengcong into a fenglin topography of karst towers up to 245 m in height and deep intersecting alluvial valleys (Figure 3 a). Today, both these landforms exist side-by-side in Tràng An, illustrating different stages of tropical karst evolution, with fengcong topography dominating in the west (Figure 3 c) and fenglin prevalent in the east. Isolated and heavily eroded karst remnants in the west and northwest frame the central formations and constitute the final stages of a mature karst (Waltham, 2009; Pham et al., 2013) (Figure 3 b).

Triassic limestone of the Pa Khõm formation, which underlies the Đồng Giao sequence is exposed in the northwest of the massif where it forms a series of isolated outcrops that rise to a height of 177 m asl. The highest of these outcrops, Núi Dinh, is capped by the Đồng Giao formation (Do et al., 2012). An elevated Quaternary marine terrace, covered by undivided Quaternary sediments, is situated between these formations (Mathers et al., 1996; Tue et al., 2018). This locally unique area rises up to 15 m above the surrounding floodplain and constitutes the only plain that remains unaffected by seasonal flooding (Figure 3 c).


*Figure 3: Karst landforms of Tràng An. a: karst valley formed in the fenglin or tower karst dominated south and southeast of Tràng An. b: isolated karst towers in the final stage of planation in the southeast of Tràng An. c: 180˚ panoramic image (left = north, right = south) of the west and northwest extent of the Tràng An massif. A marine terrace stands at 15 m asl and extends along the fengcong dominated western edge with Núi Dinh visible in the distance. The photo was taken after a heavy monsoon rain fall that flooded much of the alluvial plains but left the elevated area that approximates the marine terrace unaffected. [photo credit: TK]*

Prior to delta initiation at the end of the LGM (Stanley and Warne, 1994), the Sông Hồng basin extended towards the southeast into a landmass that occupied the Vịnh Bắc Bộ and extended past Hainan island (Yao et al., 2009). Rapid sea level rise at the beginning of the Holocene drowned most of this landmass and by 9 ka BP the sea had transgressed into the Sông Hồng basin and reached the western fringe of the Tràng An massif. Local sea level curves for the area place Tràng An at the margin of the maximum extent of the Mid-Holocene transgression with coastlines extending as far as the western edge of the massif (Mathers et al., 1996; Mathers and Zalasiewicz, 1999; Lam and Boyd, 2003; Tanabe et al., 2003a; Tanabe et al., 2003b; Boyd and Lam, 2004; Hori et al., 2004; Tanabe et al., 2006; Funabiki et al., 2007; Yao et al., 2009; Tue et al., 2018) (see also Appendix A.2). The uncertainty surrounding the exact extent of the transgression, which affected interpretations of palaeoenvironmental reconstructions (O'Donnell et al., 2020) and archaeological findings within Tràng An, prompted the detailed coastline construction presented here.

## 2. Methodology

### *2.1 Field methods and materials*

Notch elevations and locations were recorded over three field seasons in September 2017, April 2018 and November 2018 using a Leica GS 15 nRTK (network Real Time Kinematic) GNSS (Global Navigation Satellite System) receiver and Leica TS06 total station accompanied by photographic documentation of each site. The GNSS receiver was connected to the Nam Dinh reference station NTRIP (Networked Transport of RTCM via Internet Protocol) caster. Topography frequently reduced the visible horizon, which resulted in poor Position Dillution of Precision (PDOP) and Geometric Dillution of Precision (GDOP). The distance to the NTRIP caster also resulted in frequently longer-than-ideal lead times to signal fixing. To ensure measurement integrity, control measurements were taken at a local datum point (National Benchmark 140411, U Bò mountain) and an arbitrary fixed point at the project fieldwork base. Multiple, repeated control measurements were also taken at a subset of notch locations. Where a nRTK measurement via NTRIP was not available, measurements were post-processed in Leica Geo Office using Rinex data from a reference station at Nam Định.

To enhance measurement accuracy at notch sites, three reference points were recorded for each total station setup near a notch site or centrally within a cluster of notch sites and oriented to the GNSS point locations. In the case of Động Thiên Hà, the notch was inside a cave and the total station was traversed from the GNSS reference points at the boat landing into the cave (Figure 4).

*Figure 4: Survey of Động Thiên Hà notch site. Left: traversing elevation along the access path into the cave. [photo credit: Fiona Coward] Right: surveying the notch inside the cave. [photo credit: TK]*

Observations were recorded using a standard reflector where possible and in reflectorless mode when notches were out of reach. Measurements were taken at the roof edge, apex and floor edge of each notch to obtain elevation of tidal maximum, minimum and mean water level following standards established by Pirazzoli (1986) and Trenhaile (2015). With respect to multi-layered compound notches, the intersection between each component was recorded as floor of upper notch and roof of lower notch. In some cases, the notch apex could not be determined. Such sites were subsequently excluded from coastline reconstruction.

*2.2 Data processing*

Survey results were collated in a single spreadsheet and calibrated to present sea level using a direct measurement at the Hòn Dấu Vietnam Local Vertical Datum set at 0 m national Mean Sea Level (1.41 m EGM96), which enabled our observations to be aligned with previous notch surveys (e. g. Boyd and Lam, 2004; Nguyen et al., 2012a; UNESCO, 2014a). Current tidal range at Hơn Đau is between 0.4 and 3.7 m (Boyd and Lam, 2004). A minimum tidal range was calculated, based on the difference between elevations of notch floor and roof.

Observations were classed into “notch floor”, “apex” and “notch roof” (see also Appendix B.1).

Apart from the apex indicating rsl at the time of formation, the elevation difference between the roof of a notch and its floor also indicates tidal range (Pirazzoli, 1986). Notch morphology is influenced by multiple factors that may offset the apex from mean water level. Only three notches had both a clearly defined roof and floor that were neither deteriorated nor modified, which limited data analysis to a single variable of notch apex as the closest indicator for mean sea level.

Notch sites across the massif were found to feature different morphological traits, such as the occurrence of more than one notch at different elevations at a single site (compound notch) or variations in the notch profile and depth. Such characteristics are common and may indicate multiple cycles of sea level changes; intermittent still stand in sea level rise/fall; vertical displacement of the notch site; or variation in erosion caused by hydrological, geological, chemical and biological factors. For example, if bioerosion was a driving factor in notch formation, then the eroding species may have caused more erosion within their habitation zone (apex, floor, roof). Other factors, such as chemical, mechanical erosion and salt weathering may have had similar effects (Liew et al., 1993; Boyd and Lam, 2004; Bird et al., 2010; Trenhaile, 2014, 2015, 2016). *In lieu* of radiocarbon dates, we used the elevation of the notch apex and morphological traits to group them into likely phases of stable sea levels. The mean elevation of these groups could then be associated with existing sea level curves (Pirazzoli, 1991; Hori et al., 2004) and dates from previous work in the region (UNESCO, 2012, Boyd and Lam, 2004).

To determine the optimal number of clusters ($N_C$), hierarchical clustering (Anderberg, 1973) was performed in R (R Core Team, 2018) using the ‘cluster’ package (Maechler et al., 2019) on a single variable of notch apex elevation. Dunn’s Index (DI) (Dunn, 1974) was used to assess best separation between individual clusters using the 'clValid' package (Brock et al., 2008) with a higher DI indicating a better separation. A dendrogram was generated and modified for style in 'dendextend' (Galili, 2015). Cluster assignments were exported as CSV and appended to the geospatial notch database in ArcGIS Pro. Descriptive statistics were carried out in SPSS 26 using the 'means' function to determine range, min, max, mean, mean error, variance and standard deviation. Proposed clusters were visually assessed for underlying spatial autocorrelation, as these could potentially cause bias in cluster generation and skew rsl predictions. For example, a cluster that contained a small number of sites with a low variance in close proximity to one another was deemed to be spatially correlated and thus aggregated into a single data point. Where individual components within a compound notch were assigned to the same cluster, the survey data were revisited and re-evaluated for ambiguous measurements. Complex compound notches with two individual components may represent the same temporary still-stand with two different tidal amplitudes or a vertical displacement of the geomorphological marker. Long distance measurements that may not have been targeted correctly onto the notch apex, measurements on notches that did not have a clearly developed apex or where a geological feature was erroneously classed as a notch were subsequently excluded from the data set. The process of clustering was then repeated on the resulting final dataset. Once the final clusters were established, the measurements from the individual clusters were summarised and their means were used as the base lines for coastline reconstruction.

*2.3 Coastline reconstruction*

Mid-Holocene coastlines for Tràng An were reconstructed on the basis of relative sea level change, not detailing isostatic and eustatic contributions, illustrating the extent of the Mid-Holocene sea transgression rather than contemporaneous eustatic sea level. A generalised vertical offset to adjust for isostasy could be applied to calibrate to contemporaneous eustatic sea levels. Most recently, Nguyen and Takewaka (2020) identified variable subsidence and uplift of the Nam Định area of between 1.2 and 1.9 mm/pa in the south and subsidence in the north along a 72 km stretch of the southern half of the RRD coast. Post-Mid-Holocene sediments, predominantly of alluvial origin, were accounted for by averaging depth from published core data from inside and outside the massif (Tanabe et al., 2003a; Tanabe et al., 2003b; Hori et al., 2004; Tanabe et al., 2006; Tran et al., 2013; UNESCO, 2014a; O'Donnell et al., 2020) by adding them as offsets to predicted relative sea levels. Ultimately, we identified three principal areas within the Tràng An massif that were likely to have been differentially affected by alluvial processes and therefore required the application of different offsets (see also Appendix A.4). Palaeo-coastlines for a given sea level were modelled along the contour lines of the SUNDASIA DSM (digital surface model) by automated extraction of contours using adjusted rsl values (contour = predicted rsl + offset). Contours were extracted as polygons using the contour function in ArcGIS Pro with the calculated contour value set as the base and an interval greater than the highest peak of the DSM. A smoothing algorithm was applied to each rsl-contour followed by manual adjustments to eliminate irregularities in the topography, such as buildings, roads and trees. A large-scale coastline model for the southeast section of the RRD was derived from a sentinel SRTM DEM by applying the same workflow as for the smaller-scale model.

## 3. Results

### *3.1 Survey results*

A total of 172 measurements were taken at 42 individual sites (Table 1, Appendix B.1) distributed within the massif, around its edge and at some isolated outcrops. Ninh Bình city was the only notch site located outside the WHS property. Of these measurements, 72 were of the elevation of the notch apex. Roof and floors were preserved at 21 notches, roofs only at 30 notches and floors only at 2 notches (see Appendix B.2).

| Feature type | Mean asl | N | Std. Deviation | Std. Error of Mean | Minimum | Maximum | Range |
|---|---|---|---|---|---|---|---|
| **Notch base** | 4.5376 | 70 | 1.02434 | 0.12243 | 2.59 | 6.30 | 3.71 |
| **Notch apex** | 3.9132 | 72 | 1.04311 | 0.12293 | 2.07 | 5.95 | 3.88 |
| **Notch roof** | 3.9137 | 30 | 0.94144 | 0.17188 | 1.93 | 5.43 | 3.50 |
| **Total** | 4.1674 | 172 | 1.05833 | 0.08070 | 1.93 | 6.30 | 4.37 |

*Table 1: Summary statistics of all measurements by feature type.*

## *3.2 Cluster analysis*

Initial clustering on the full data set (N=72) in R returned greatest distance between clusters at $N_C = 3$ (DI = 0.123), closely followed by a 4-cluster division (DI = 0.107) (Appendix B.3). Spatial correlation and ambiguous measurements were identified at 39 sites, leaving 33 sites for the final clustering.

Final clustering at N = 33 (Figure 5) also produced the greatest distance between clusters at $N_C = 3$ (DI = 0.235) resulting in three distinct notch sequences with mean elevations of 3.2 m (N = 22, SD = 0.430), 4.6 m (N = 7, SD = 0.243) and 5.6 m (N = 4, SD = 0.092) (Table 2). Clustering of 22 notches into the lower sequence, however, resulted in the inclusion of multiple components of compound notches into the same cluster. This conflict was partially resolved by increasing the number of clusters to $N_C = 4$ (DI = 1.446) (Table 3).

| **Sequence** | **Lower** | | | **Upper** | | | **High** | | |
|---|---|---|---|---|---|---|---|---|---|
| **Level** | *Floor* | *Apex* | *Roof* | *Floor* | *Apex* | *Roof* | *Floor* | *Apex* | *Roof* |
| **N** | 7 | 22 | 21 | 5 | 7 | 7 | 3 | 4 | 4 |
| **Mean** | 3.1 | 3.2 | 3.8 | 4.1 | 4.6 | 5.2 | 4.9 | 5.6 | 6.0 |
| **Std dev.** | 0.583 | 0.430 | 0.349 | 0.237 | 0.243 | 0.422 | 0.379 | 0.092 | 0.284 |
| **Std. Error** | 0.220 | 0.092 | 0.076 | 0.106 | 0.092 | 0.160 | 0.219 | 0.046 | 0.142 |
| **Min** | 1.99 | 2.49 | 3.03 | 3.74 | 4.33 | 4.60 | 4.64 | 5.44 | 5.57 |
| **Max** | 3.63 | 3.98 | 4.31 | 4.38 | 5.01 | 5.64 | 5.34 | 5.65 | 6.23 |

*Table 2: Summary of averaged notch metrics after classification into three clusters.*

| Sequence | Lower 1 | | | Lower 2 | | |
|---|---|---|---|---|---|---|
| **Level** | *Floor* | *Apex* | *Roof* | *Floor* | *Apex* | *Roof* |
| **N** | 2 | 10 | 10 | 5 | 12 | 11 |
| **Mean** | 2.3 | 2.8 | 3.5 | 3.3 | 3.6 | 4.0 |
| **Std dev.** | 0.499 | 0.173 | 0.300 | 0.310 | 0.271 | 0.237 |
| **Std. Error** | 0.353 | 0.055 | 0.095 | 0.139 | 0.078 | 0.071 |
| **Min** | 1.99 | 2.49 | 3.03 | 2.96 | 3.15 | 3.60 |
| **Max** | 2.70 | 3.03 | 3.85 | 3.63 | 3.98 | 4.31 |

*Table 3: Summary of averaged notch metrics after subdivision of lower notch sequence.*

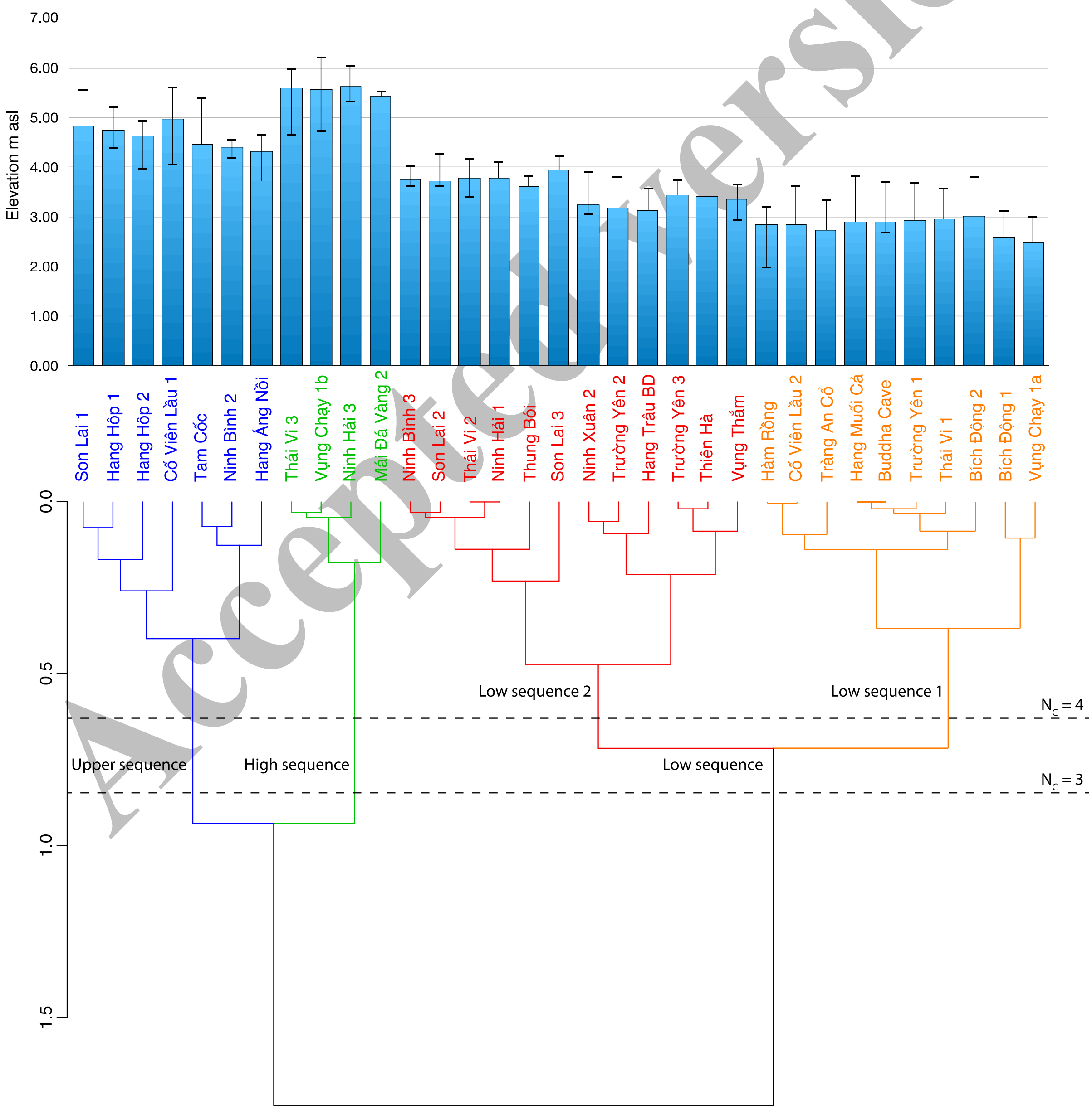


*Figure 5: Final dendrogram of aggregated measurements on notch apex (N = 33). Optimal clustering was achieved at $N_C$ = 3. At $N_C$ = 4 a possible subdivision of the low sequence partially resolves grouping individual components of compound notches into the same cluster. The bar diagram shows the elevation of notch apices whilst whiskers indicate elevations of notch floor and roof (where present).*

### *3.3 Notch distribution*

Notches were found to be most frequently distributed along karst towers and cones on the eastern and southern extent of the Tràng An massif and its eastern open karst valleys, where they continuously extended in excess of 100 m along the vertical cliffs. Some central open and enclosed dolines also featured notches, such as Vụng Thắm, Thung Bói and Vụng Chạy. Notches also occurred, albeit less frequently, in the west and north of the massif where they were observed on limestone boulders or as short sections on isolated karst remnants. Notches were found to be absent on the north-western Pleistocene marine terrace. An area within the western and central part of the property including a group of enclosed dolines with a potential for further notches remains unexplored due to limited accessibility and time-constraints (Figure 6). The higher density of notch sites in the east of the massif is likely due to its orientation towards the coast. Beach ridges as near as 1 km from the edge of the massif are detectable in elevation maps and illustrate that the eastern part was exposed to wave action. Here, planation is more advanced than in the west, which may also be attributable to its exposure to wave action during inundation. Inundations would have also advanced westwards, leaving the east submerged for longer than the west. All these factors would have favoured the formation of notches in the east over the sheltered west, where hills and ridges also have lower gradients and dolines are more frequently closed and have more elevated floors than in the east, limiting or prohibiting flooding.

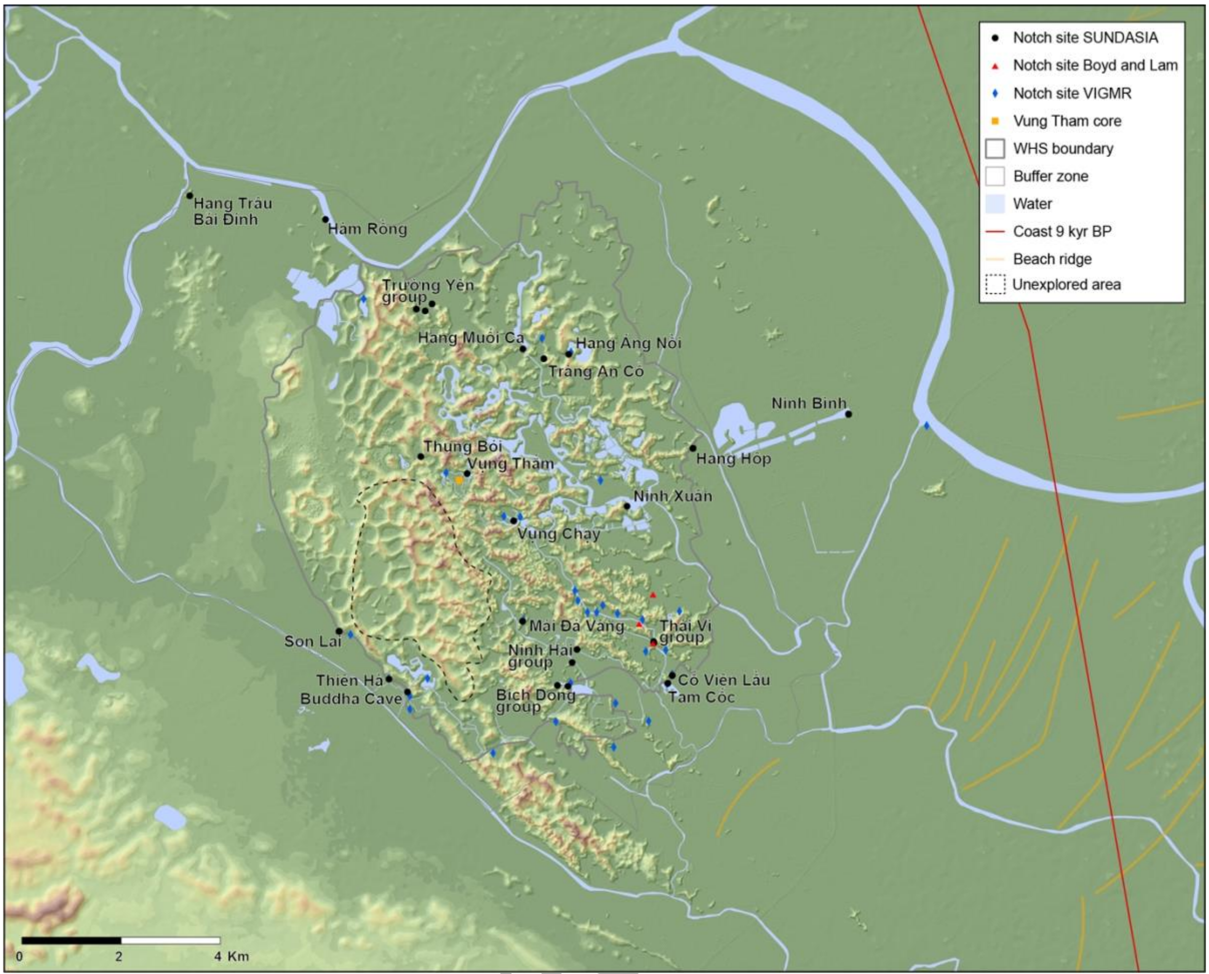



*Figure 6: Distribution of surveyed notch sites today in relation to Vụng Thắm core at the centrer of Tràng An (O'Donnell et al. 2020). Notches are more abundant, more developed and found at higher elevations in the palaeoshore-facing southeast of the massif. Notch sites VIGMR after (Nguyen et al., 2012a; Pham et al., 2013; UNESCO, 2014b). Coast 9 ka BP after Tanabe et al. (2003b).*



Two notches were recorded at Ninh Nhật and Ninh Xuân with respective elevations of 32.83 m and 32.44 m asl. These notches only survive as faint marks in tall vertical cliffs. Such notches likely pertain to earlier Quaternary transgressions and illustrate the amount of uplift the area has undergone since their formation.

### *3.4 Notch morphology*

The notches of Tràng An are morphologically varied with morphotypes encompassing simple single element types as well as complex multiple element compound notches. Some feature irregular corrosion patterns whereas others show polycyclic corrosion patterns in the form of completely separated or superimposed compound notches. Erosion along vertical fissures and between bedding planes at some sites obscured notch features, which made identification and classification challenging. This was particularly evident at Thái Vi 2/3 (Figure 7). These two complex compound notches comprise closely spaced, partially overlaying bands with disturbance from eroded horizontal bedding planes, widened fissures and partial cliff collapse. Their upper and middle sequences consist of two individual and slightly overlapping components both in the upper sequence at 5.9 m, 5.4 m and 4 m, and in the lower sequence at 3.6 m. Thái Vi 1 and 4 are of a simpler morphology with Thái Vi 1 consisting of two discernible erosional sequences that were recorded at the same elevation as the lower component of the upper and the upper component of the lower sequences of Thái Vi 2. Thái Vi 4 consists of only one sequence at the same elevation as the upper component of the lower sequence of Thái Vi 2.

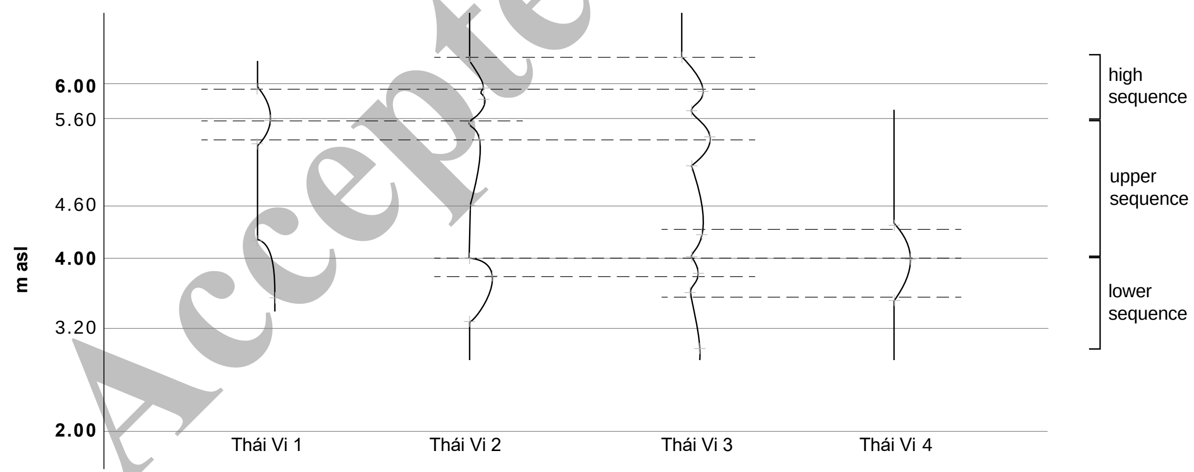



*Figure 7: Schematic profiles of Thai Vi 1 – 4, their elevations and attribution to the identified three stable sea level sequences.*

Continuous erosion has reduced notch depth and height particularly in the upper and high sequences, which had a direct impact on tidal range estimations. Collapse of undercut cliff sections also led to fragmentation of notches or partially missing notch roofs. This type of mechanical erosion is observable at Vụng Chạy, Thái Vi, Tràng An Cổ, Son Lai and Hang Hộp. Freshly exposed limestone is visible as bright and frequently orange- to brown-coloured sections in the otherwise grey to dark grey patinated limestone cliffs. The collapse sites observed in Tràng An were all patinated and lacked basal collapse piles, indicating that the cliff sections broke away some time ago. In contrast, examples of fresh collapses were observed in Cát Bà/ Hạ Long Bay with collapse piles at their bases (Figure 8). At Hang Áng Nồi and Mái Đá Vàng similar processes are likely responsible for the survival of only short and shallow sequences of formerly more substantive notches.

*Figure 8: left: Collapse at Thái Vi notch by ongoing planation through undercutting of the cliff by notches. The collapse most likely occurred during the Mid-Holocene highstand as some superficial erosion marks are visible within the collapse scar in-line with the uppermost notch sequence. Right: Recent collapse of section of limestone cliff at Cát Bà by the same process. [photo credit: TK]*

Post-formation vertical erosion was more prevalent in the upper and high notch sequences than in the lower, being well advanced at Cố Viên Lầu, Tam Cốc and Vũng Chạy but less pronounced at Bích Động and Thái Vi (Figure 9). Much of the notch surfaces were heavily obscured, but the upper edges were visible as a horizontal line that was more noticeable where it crossed non-horizontal bedding planes.

*Figure 9: Notch types observed at Tràng An (top left to bottom right): deep notch at Tam Cốc, single single U-shaped notch at Vụng Thắm, shallow notch at Ninh Hải (3), V-shaped notch at Trường Yên 2, bioerosion scars on single U-shaped notch*

*at Tràng An Cổ, V-shaped notch formed in foot cave at Hàng Muối Ca, polycyclical notch with two distinct phases at Hang Hộp, multi-sequence polycyclical notch at Thái Vi 2 (left) and 3 (right). [photo credit: TK]*

A notch with a bench of 1 – 2 m depth had formed in the base of a sloping limestone ridge at Son Lai (Figure 10). The site is located in a protruding outcrop along the western margin of the massif, just south of the elevated Pleistocene terrace. The lateral offset between notch floor and roof roughly coincides with the slope of the limestone outcrop. The base of the bench, however, is vertical and does not follow the slope above. The notch has a height of 1.5 m with an irregular profile caused by large scallop-like pits, which measure c. 20 – 30 cm in length. The morphology of the Son Lai notch is unique within Tràng An and its features may be attributable to its location. A narrow eastward-oriented channel that separated Tràng An from the surrounding main land during the Mid Holocene likely drained some of the tidal flats west of massif. During low tide, the increase in water volume passing through the channel would have caused an increase in water flow as well as some turbulences where the water flow was redirected from an easterly to a southerly direction where the outgoing tide met the limestone massif at the level of Son Lai.



*Figure 10: A notch formed in a limestone hill at Son Lai. The sloping rockface has left the notch roof recessed from the protruding notch floor, following the gradient of the hill. Irregular pits or scallops line the back of the notch [Photo credit: TK]*

### *3.5 Lower notch sequence*

Notch profiles were found to be either V-shaped or U-shaped with an almost horizontal roof and, where exposed, an outwards sloping floor. Notches at 2 – 3 m asl were frequently filled with alluvium to just above the notch floor. Being subject to flooding during the monsoon season, their lateral development is likely to be ongoing. Notches at 3 – 4 m asl were found to be frequently equipped with concrete or mottled floors and used as storage, habitation, or places of worship, which prevented us from obtaining a floor elevation measurement.

Notches that horizontally extend more than 2 m into the bedrock are uncommon but were recorded at Tam Cốc, Ninh Bình, Buddha Cave, Ninh Xuân and Hang Muối Cả. The latter is the most extensive notch in our data set. Classed as a cave, it extends over 59 m into Cái Hạ Mountain at an elevation of 2.9 m asl with a maximum height of 4.8 m, measured from an artificial floor that covers the entire space. The surface of this feature is entirely covered with small, c. 5 cm long, scallop-shaped erosional pits. Scalloping occurs on notches in the supratidal zone and can be caused by grazing limpets (Kazmer and Taborosi, 2012; Kazmer et al., 2015), but a purely solutional origin, however, may also be possible. Scalloping was frequently observed in notches belonging to the lower sequence.

Vertical ridges that frame the enclosed doline of Vụng Thẳm feature a series of well-developed basal notches that are partially below the current ground surface. Their almost horizontal roof could measure up to 1.5 m in depth with a slightly outward declining floor.

Notches in the lower sequence frequently occur as fragments on peripheral outcrops and isolated boulders inside enclosed and open dolines. In Thung Bói, numerous boulders with notches at 3.6 m asl were found distributed across the doline floor (Figure 11). Similar observations of erosional features on isolated boulders were made in Lau valley, just north of the Son Lai notch. These erosional features are not well-developed and may not be *in situ* but they serve as indicators for the presence of water over a prolonged period of time. A poorly defined notch at c. 3.4 m is located near Hang Trâu Bái Đính in an isolated karst outcrop (Figure 12). Its base was entirely embedded in sediments but its roof suggests a v-shaped profile with scalloping occurring on the exposed surface. It is the most north-western notch of our survey and provides a minimum extent of marine transgression for the northern part of the massif.

*Figure 11: One of numerous notch-incised boulders strewn across the doline floor of Thung Bói.*

*Figure 12: A poorly defined notch in a small limestone outcrop near Hang Trâu Bái Bính in the northwest of the property.*

*3.6 Upper notch sequence*

Notches that fall within the 4 – 6 m bracket were found to be laterally less developed compared to the lower notch sequence and reached a depth of less than 1 m. Their mean height does not differ significantly from the lower sequence but shows greater morphological variation.

Notches at the highest elevations of 5 – 6 m are frequently compound notches and of shallow depth. Those that line the northern cliffs of the broad and open lower Bích Động valley are U-shaped with a single component which is less than 0.5 m high and equally deep. They incise the cliffs at a mean elevation of 5.6 m asl. Further upstream and near the archaeological site of Mái Đá Vàng, a faint secondary notch at 5 m asl was visible below a shallow notch at 5.4 m asl.

Notches at Thái Vi show the highest complexity among the surveyed notches, with up to four individual overlapping notches discernible over the full height of the compound notch of 4.6 – 6.3 m asl. These cut laterally up to 1 m into the south-facing cliff of Núi Voi Phục mountain and the cliffs along the adjacent valley and can be followed for several hundred meters.

While the separation of the individual components into a lower and upper sequence is also observable in other notches in the immediate area, the complexity of the upper components will require dating evidence to establish the chronological relationship between them which can offer a clue into their development.

*3.7 Coastlines*

Based on our dendrogram outputs, we reconstructed five different surfaces that model the coastlines derived for the lower (3.2 m), upper (4.6 m) and high (5.6 m) sequences. Additional surfaces were constructed at 2 m and 6 m to illustrate observed tidal maximum at Vụng Chạy 1b (6.2 m) and minimum at Hàm Rồng (2 m). Relative mean sea level values varied by 0.67 m for the upper sequence and 1.49 m for the lower sequence (Figure 13). Direct observations of tidal ranges where floors and roofs were exposed and/or preserved well enough for measurements were made at 15 sites. The tidal range for the lower sequence was 20% less than that of the combined upper and high sequences. The difference in tidal range between the upper and high sequences was negligible (Table 4).

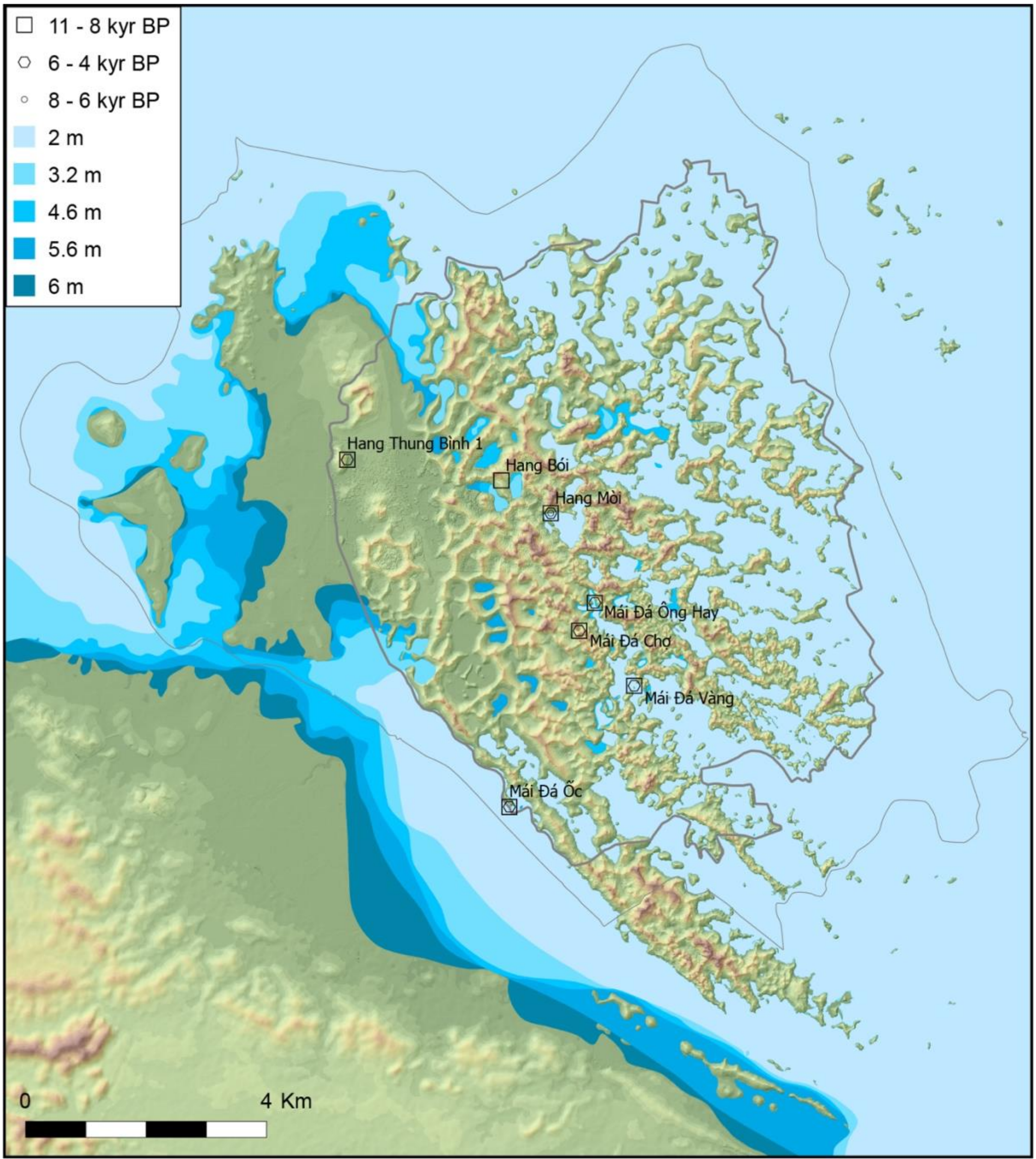



*Figure 13:Coastline model during Middle-Holocene trangression in context with radio carbon dated archaeological sites that fall between 11 ka and 4 ka BP.*

| Sequence | Lower | Upper | High |
|---|---|---|---|
| **N** | 7 | 5 | 3 |
| **Mean Tidal Range** | 0.8 | 1.0 | 1.2 |
| **Std. Dev.** | 0.257 | 0.421 | 0.405 |
| **Std. Error** | 0.097 | 0.188 | 0.234 |
| **Variance** | 0.066 | 0.177 | 0.164 |

*Table 4: Tidal range estimation for notch sequences.*

Based on our model, landscape inundation progressed from east to west across Tràng An and rapidly progressed into the east of the massif with its valleys, poljes and open dolines, such as the Bích Động and Thái Vi valleys, most of which comprise near-vertical cliffs (Figure 14). After initial flooding, the shoreline within this part of the massif remained relatively stable throughout the Mid-Holocene transgression. Lateral shoreline progression in the northwest of Tràng An was more dynamic due to the Pleistocene terrace and its low graduated slopes. Standing at 10-15 m asl, the terrace extends southwards along the western extent of the karst and into the polje east of Thung Chùa. Here, the shoreline gradually advanced with rising sea level. The topography between the Tràng An massif and the western uplands is lowest along the Sông Mới channel which became flooded as the sea level exceeded 4.6 m rsl, separating Tràng An from the main land. As the sea level reached its maximum, the channel reached a width of up to 1 km.



*Figure 14: Landloss in valleys with steep cliff faces was marginal and did not significantly alter the coastline as sea levels rose.*

Enclosed dolines in the west and central massif with floor levels near or below 5 m became increasingly affected by rising sea levels. The internal environment changed from dry to brackish swamp, saltmarsh, tidal and finally fully flooded hong (marine lake). A general trend was observed wherein enclosed central dolines were flooded from the northeast and southeast, with those adjacent to the Pleistocene terrace found to be above the highest predicted sea level of 6 m. Notches with apex levels of around 3.5 m were recorded at Vụng Thắm and Thung Bói, indicating permanent flooding under a tidal regime during the Mid-Holocene.

Compound notches were more common along the cliffs of open karst valleys and poljes in the south and southeast, indicating that this area was affected most and the longest by inundations. Here, relative sea levels reached a maximum of at least 5.6 m but could have potentially reached 6 m asl. The high sequence has, however, not been securely dated yet thus leaving the possibility of an earlier Pleistocene date for some of the notches. The complex morphology of the lower two sequences indicates that either transgression or regression was not linear but underwent phases of stagnation allowing for the formation of compound notches with two distinct apexes within one larger notch. These notches have been previously dated from cemented oyster shells (Boyd and Lam, 2004; UNESCO, 2014).

## 4. Discussion

### *4.1 Dating marine inundation at Tràng An*

The presence of at least three, possibly four sequences of notches suggests that Tràng An has experienced multiple phases of prolonged and relative stable sea levels of +3.2 m, +4.6 m and +5.6 m. As there are no new dates from the notches at this stage, a chronology had to be estimated by association with previous work. Boyd and Lam (2004) radiocarbon dated oyster shells from notches in the Tam Cốc area at 5.4 m asl to 5740 – 5500 cal BP (Wk-8267) and at

4 m asl to 5550 – 5270 cal BP (Wk-8268) BP, which coincide with the upper and high notch sequences from our model. While those authors do not state the exact location of the dated notch, the given name likely pertains to the Tam Cốc / Bích Động area, which was also included in the present survey. Similar dates were established during a geomorphological survey for the UNESCO WHS dossier (table 5) (UNESCO, 2014). The elevations stated in the dossier were taken from the base of the notch and do not coincide with the elevations of our surveys. The associations with individual samples from within compound notches, particularly Thai Vi, therefore carry some uncertainty. On the basis of the available dating evidence, the upper sequence of our model is cautiously attributed to the peak of the Mid-Holocene transgression, while the lower sequence likely pertains to the later Holocene. An extensive sampling and dating campaign of palaeo-sediments from notch sites is needed to provide a clearer picture of the time frames involved. The presence of the lower sequence at most of the surveyed sites indicates that much of the plains in and around Tràng An were almost certainly fully submerged for an extended period of time during the Mid- to later Holocene.

| Site | Sample location | ASL | $^{14}C$ Age | Cal. BP |
|---|---|---|---|---|
| **Thái Vi 2** | Notch base | 3.3 | 4390 ± 310 | 4530 ± 320 |
| **Tam Cốc** | Notch base | 2.2 | 4220 ± 290 | 4350 ± 300 |
| **Đồng Thiên Hà** | Notch base | 2.3 | 5230 ± 310 | 5390 ± 320 |
| **Đồng Thiên Hà** | Notch base | 2.3 | 5430 ± 315 | 5500 ± 325 |
| **Đồng Thiên Hà** | Notch base | 2.3 | 5110 ± 230 | 5260 ± 240 |

*Table 5: Radiocarbon dates from Oyster samples taken during a geomorphological survey for the UNESCO WHS dossier (UNESCO, 2014). Elevations were re-taken for this study.*

### *4.2 Within-sequence variation of notch elevations*

The variation of sea level values within the upper sequences of 0.67 m, or 1.23 m including the upper Tam Cốc / Bích Động notch sequence, and 1.49 m for the lower sequence adds some ambiguity to our coastline reconstructions.

Within-sequence variation in notch elevations may be caused by hydro-geomorphological factors such as restrictions to water flow, which may have influenced water-levels in some enclosed flooded dolines (hongs). Water flow in these hongs was likely controlled by foot caves, subaerial caves and other small conduits. While some foot caves were large enough to provide sufficient flow during a tidal cycle, some hongs may have experiencing a reservoir effect where retention times were larger than the tidal period. Experiencing permanently raised water levels would have influenced notch formation, with an elevated notch apex and potentially decreased notch height. High-volume precipitation during monsoons would have added to the water volume in a hong, amplifying the tidal reservoir effect and potentially further altering notch morphology. Such reservoir effect in a hong was observed at Cát Bà Island/ Hạ Long Bay, Vietnam and corroborated by local informants (Leonard 2020, pers. comm.) (Figure 15) and is known to take place in choked coastal lagoons (Kjerfve, 1994).



*Figure 15: Small cave draining a series of interconnected tidal on Cát Bà Island. The restrcited flow rate causes a permanent elevasted water level inside the dolines.*

Changes in pH, salinity and temperature would have also impacted the biodiversity in a hong. The effects of these factors were documented in Cát Bà/ Hạ Long Bay by Cerrano et al. (2006) and may be detectable in corresponding sediment core profiles. A core obtained by the SUNDASIA project within the enclosed Vụng Thắm doline, near to the Hang Mòi archaeological site, did not contain a Mid-Holocene sequence (O'Donnell et al., 2020); however a second core obtained by the project from the Vụng Chay open doline is under analysis and may contain a more complete stratigraphy.

Several possible interpretations of our notch data must be considered. Whilst our model focuses on the Mid- to Late Holocene transgressions as the main cause for notch formation, earlier Pleistocene sea transgressions are likely to have formed marine notches in this massif. Late-Pleistocene transgressions that occurred between 120 – 30 ka BP with rsl at or below Mid-Holocene levels in conjunction with subsequent uplift (Lambeck, 1990; Lambeck and Chappell, 2001) could have left notches at similar elevations that were then re-occupied during the Mid-Holocene transgression. MIS-5 notches at 4 – 6 m asl were recorded in the Mekong delta and Palawan (Lap et al., 2000; Omura et al., 2004) and notches at this level in the southeast of Tràng An may have formed during that period. Resolving the complex processes observed in the Tràng An notches requires the establishment of a comprehensive chronology for the Tràng An notches.

*4.3 Implications for archaeology*

Several historic communities, most notably the 10th century Hoa Lư ancient capital and, more recently, the provincial capital have been established on the edge of the massif. Archaeological evidence from Tràng An indicates human presence within the massif that extends back to at least 30 ka BP (Rabett et al., 2009; Rabett et al., 2011; Nguyen, 2012; Nishimura and Phan, 2012; Reinecke, 2016; Rabett et al., 2017b). While the vegetation within the upland karst remained mostly stable throughout that time (Rabett et al., 2017b), relative sea level rise from the Early-Holocene through to the Mid-Holocene inundated much of the surrounding plains (Tanabe et al., 2003b) introducing marine taxa, notably mangrove plants, marine-molluscs and crabs to the massif (O'Donnell et al., 2020).

The absence of Pleistocene archaeological sites within the plains of the RRD is likely due to Holocene delta progradation and sea transgression, which led to a loss of much of the Pleistocene landmass that extended hundreds of kilometres east of the modern Vietnamese coastline while the remaining delta has been intensively reshaped by fluvial processes. Excavated evidence suggests that Pleistocene hunter-gatherers in this region tended to favour a terrestrial-based diet (Oxenham et al., 2018; Jones et al., 2019) and the archaeological evidence from Tràng An is largely consistent with this (Rabett et al., 2009; Stimpson et al., 2019). The recovery of perforated neritid shells from three archaeological cave sites in the massif implies, however, that while there is negligible evidence for marine resource use on-site prior to the Mid-Holocene, long-standing links appear nonetheless to have existed with the coast, extending back to as early as c. 17 ka cal BP (Rabett et al., 2019). Changes in the range of lithic raw materials utilised through time, from greater diversity before the LGM to reduced diversity thereafter (Phan, 2014; Utting, 2017), also hints that greater mobility may have been a feature of late Pleistocene communities; a contention that finds further support from preliminary lithic provenancing work and geological survey (Nguyen et al., 2012b). As such, the hunter-gatherer groups that frequented Tràng An may also have incorporated sites along the palaeo-coast in their annual or super-annual movements.

The Mid-Holocene sea transgression coincided with the establishment of local ceramic technocomplexes, most notably the Đa Bút, which is believed to have emerged as an adaptation to the transformation of the RRD basin from an inland to a coastal environment (Oxenham et al., 2018). While the Đa Bút is commonly attributed to open air sites (Nguyen, 2005), excavations in Tràng An, particularly at the site of Hang Mòi, demonstrate that caves continued to form an important part of funerary activities (Rabett et al., 2017a). The zooarchaeological data recovered from Hang Mòi relate to a shift in subsistence strategy to include marine resources in addition to staples from the forest interior and upland habitats (O'Donnell et al. 2020).

Our model suggests that Tràng An was separated from its surrounding uplands in the west and north by 300 m to 700 m of water during the Mid-Holocene high stand, between 6 ka and 5 ka BP. Notches at Hang Trâu Bái Đính and Son Lai show that the sea transgressed past previously proposed shorelines, which have suggested that only the east of Tràng An was affected by inundation (Tanabe et al., 2003b). Inhabitants of the Tràng An massif would have been isolated from or had only limited access to the mainland for the most part of the 6th millennium BP. Locations for habitation would have been dictated by the advancing sea, cutting off much of the isolated peaks and ridges in the east and northeast and submerged previously occupied sites like Mái Đá Ông Hay and Mái Đá Ốc (Figure 16).

*Figure 16: The limestone outcrop that accommodates Mái Đá Ốc (indicated) is almost entirely surrounded by flood plains. The rockshelter would have been either entirely surrounded or, more likely, submerged during the Mid-Holocene highstand.*

Sites located either within or with land-access to the north-western marine terrace during the Mid-Holocene high stand, such as Hang Mòi, Hang Bói, Hang Thung Bình 1, Mái Đá Ốc, Mái Đá Chợ, Mái Đá Ông Hay and possibly Hang Trống, were occupied during the Pleistocene/Holocene transition but with an unclear chronology for the Mid-Holocene. A general absence of $^{14}C$ dates between 8 ka and 6 ka BP from the available archaeological record (with the exception of two dates from Hang Mòi from around 7 ka BP) may be related to a shift in site location choice in the light of the changing environment but could also be related to heightened monsoon precipitation that may have caused erosion of archaeological strata. Remnants of sediments can be found adhered to the cave wall more than 1 m above the current floor level in Hang Thung Bình 1, Hang Mòi and Hang Bói, with the latter suggesting recurring activity that reaches back as far as the Upper Pleistocene but can also be observed today (Rabett et al., 2011). Such features and observations demonstrate that some relict caves still experience phases of hydrological activity with significant erosion of sediments.

At Hang Thung Bình 1, some form of hydrological activity of this otherwise inactive cave was evident in a phase of disturbed sediments overlying late Pleistocene deposits, in turn overlaid by Neolithic (Mán-Bạc) strata. This context comprised of a layer of sediments mixed with Đa Bút pottery sherds that were exposed to flowing water, giving them a distinct 'water-rolled' appearance. The paucity of Mid-Holocene evidence is most likely a result of increased precipitation and a wetter environment eroding sediments from the cave rather than a decrease of human activity during that time. Thung Bình Hill is located at the centre of the Pleistocene terrace and its caves overlook the plains that lie between the hill and the edge of the limestone massif, affording superior views across the only remaining plain in a Mid-Holocene marine archipelago, making it an ideal habitation site (Figure 17). Faunal remains from lower occupation layers contain several species of deer (Cervidae**)**, which inhabited the plains that surrounded Thung Bình Hill and likely persisted into the Holocene. Along with access to terrestrial resources, the coast would have been within walking distance in most directions, giving access to marine resources. Palynological assessment of the TAK5 sediment core that was taken at the foot of Thung Bình Hill revealed the presence of true mangrove taxa (*Rhizophora* spp., *Sonneratia* spp.) along with backmangrove associated types make up 2.5 – 15% of the pollen, suggesting a weak marine influence on the area. Grasses dominate the assemblage (85%) with ferns as well as coniferous and temperate trees also evident. Given that the marine terrace stood more than 10 m above the Mid-Holocene high-tide level it is likely that mangrove pollen in this elevated area originate from the near-by shore.

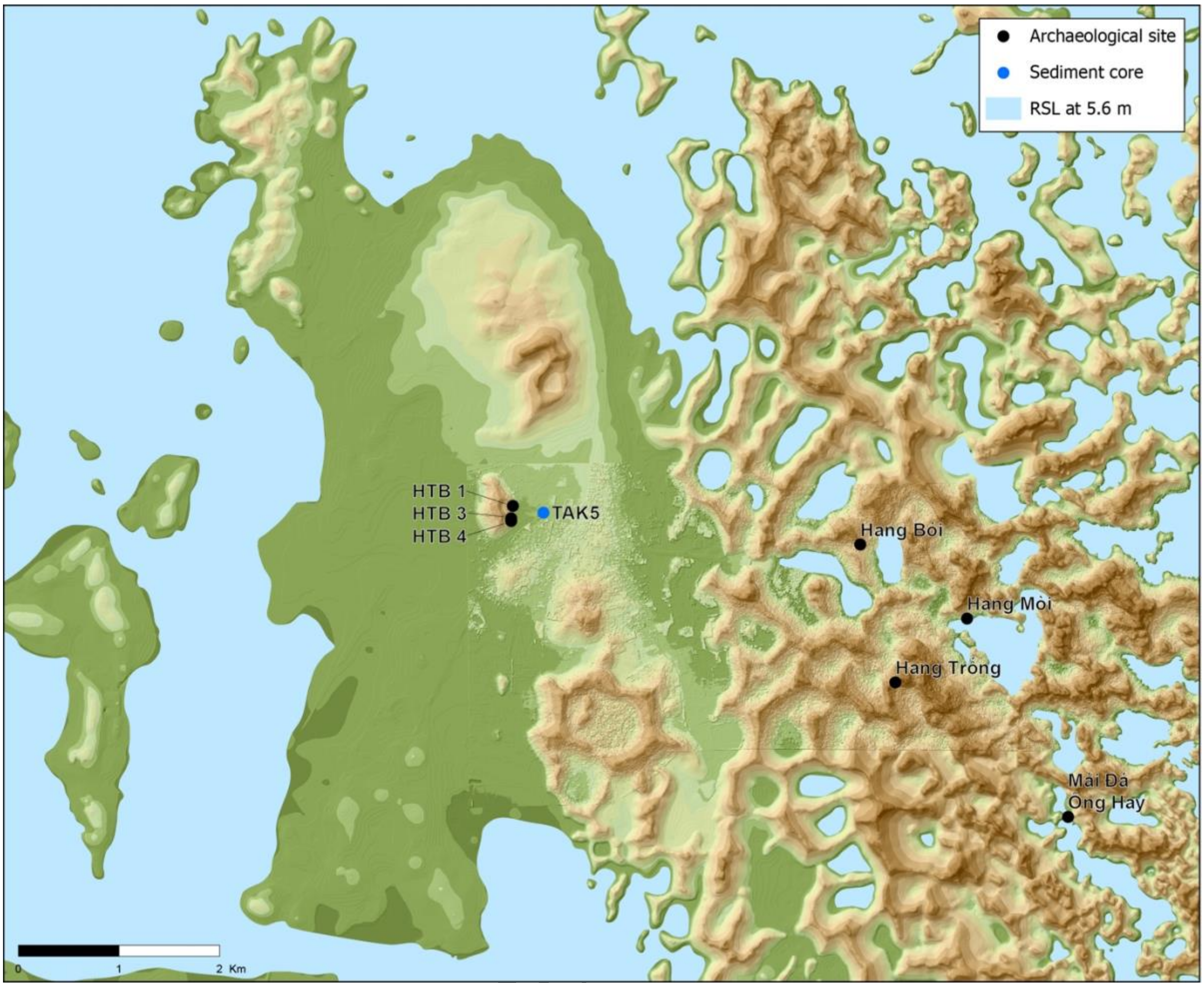



*Figure 17: Pleistocene terrace at proposed Mid-Holocene highstand, with relevant caves and TAK5 sediment core marked. (Abbreviation HTB = Hang Thung Bình).*

Higher elevation sites such as Hang Bói (Rabett et al., 2009) and Hang Trống (Rabett et al., 2017) appear to have been abandoned as the coastline encroached onto the massif, perhaps coinciding with a shift in subsistence strategy away from terrestrial to marine resources. Low elevation rock shelters such as Mái Đá Ốc and Mái Đá Ông Hay that were occupied prior to the transgression were abandoned as they became affected by rising sea levels (Figure 18). Elevated cave sites and rock shelters such as Hang Mòi, Mái Đá Vàng and Mái Đá Chợ continued to be occupied throughout the transgression cycle, with the introduction of a marine component to forager diet, reflected in an increase of marine taxa in the archaeological record (Nguyen, 2012; Nguyen and Nguyen, 2012). Hang Mòi, located in an enclosed doline in the centre of the massif that was flooded during the high stand, produced evidence for occupation spanning from the late Pleistocene through to the late Holocene. The cultural assemblage from the Mid-Holocene layers was dominated by Đa Bút ceramics with an under-representation of lithics, whilst faunal remains indicate a mix of inland terrestrial and marine-based subsistence (Rabett et al., 2019; O'Donnell et al., 2020).

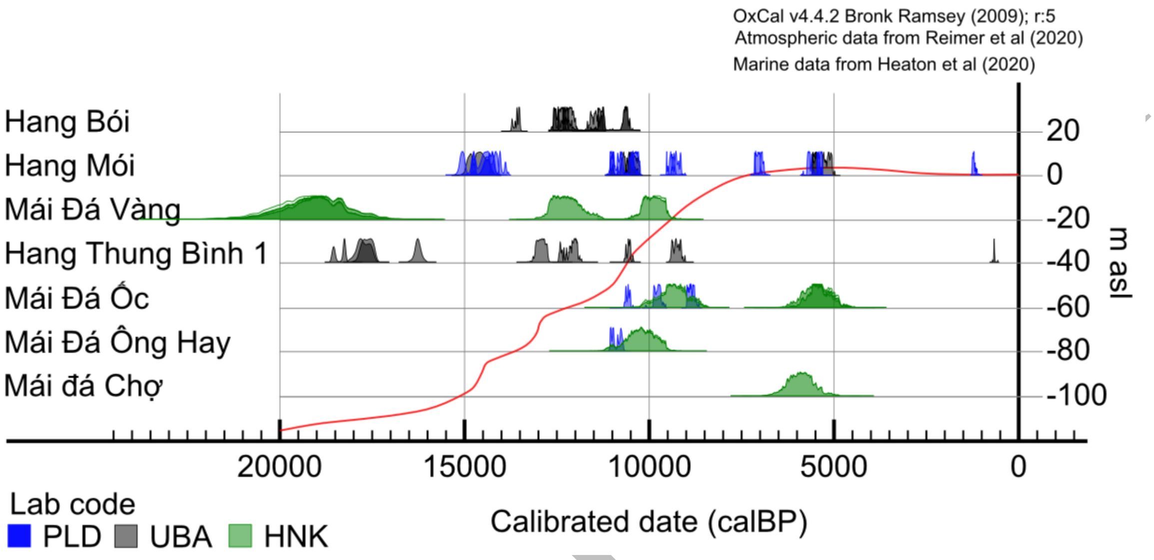



*Figure 18: Clustered view of radiocarbon dates from excavated archaeological sites with Holocene dates in Tràng An and calibrated sea level curve for the RRd delta (after Tanabe et al., 2006).*



With the possibility of a temporary isolation of Tràng An from the mainland, procuring non-local raw materials, such as lithics for stone tool production would have posed a challenge. Evidence that raw materials were imported or exchanged over long distances comes from lithic assemblages from Tràng An. Whilst primarily composed of unretouched expedient limestone tools (60 – 95%), these contain a significant minor proportion of tools made of igneous raw material. The ratio of igneous tools to limestone tools can vary greatly, even between sites in the same karst tower. At Hang Thung Bình 1 igneous tools account for 14.6% of the assemblage (N = 260), compared to 39.2% at Hang Thung Bình 3 (N = 265). This difference suggests significant variability in occupation or use between sites that are less than 100 meters from each other. Overall raw material composition at other sites throughout the complex varies but changes in assemblage raw material proportions associated with the

LGM suggest major shifts in site use or occupation associated with lowering sea levels (e.g. Utting, 2017). There are no known outcrops of igneous rock in the general vicinity of Tràng An, and various sources place the closest igneous outcrops between 50 and 80 km from the landscape complex (Nguyen *et al*. 2012b, Tran, T.V., pers. comm).

*4.4 Sea level proxies in the RRD*

Conflicting chronologies for the Mid-Holocene transgression in the RRD from different sediment cores as identified by Mann et al. (2019) can be resolved by considering notches in Tràng An. Mann et al. (2019) report a difference between marker and index points of 20 m in sea level around 10 ka BP and a discrepancy of 1000 years for the Mid-Holocene high stand (Tanabe et al., 2003a; Tanabe et al., 2003b; Hori et al., 2004). A subsequent paper by Tanabe et al. (2006) presented further data from three cores from the southern coastal area of the delta, which do not occur in the SEAMIS database. Contextualising and summarising the various core data sets, they proposed a rsl of -40 m sometime after 11 – 12 ka BP based on the fluvial/estuarine contact in ND-1. Whilst our survey cannot provide direct insight into sea levels below modern mean sea level, a consideration of data from our notch surveys and from Boyd and Lam (2004) is informative. Here we assume that sediments and geomorphological markers in relatively close proximity to each other underwent similar vertical displacement since the Mid-Holocene, with the south of the coastal RRD being uplifted while the north subsided at a rate of 1 – 2mm pka for the past 20 years (Hai and Liem, 2011; Nguyen and Takewaka, 2020). This rate, however, is unlikely to have been maintained over the last 5 – 7 ka and a comparison between contemporaneous sample sites from Hạ Long Bay and Tràng An suggest a net vertical displacement of 0.5 (WK-8260/WK-8269) – 0.55 m (WK-8255/WK-8267) since the Mid-Holocene. The upper bound may be reduced to 0.5 m if the upper notch band of 5.6 m rsl from our survey is representative of the Mid-Holocene high stand across the massif. A dedicated dating programme for notches in Tràng An and Hạ Long Bay would reduce temporal ambiguity in the data sets and make them directly comparable. As a whole, however, the notch data from Tràng An suggests that sea levels were still rising at 7 ka BP, remaining significantly above modern sea level at around 6 ka BP rsl, and not reaching present day sea level until at least 4 ka BP.

*4.5 Implications for modelling coastal vulnerability*

For over a decade, the Dynamic and Interactive Vulnerability Assessment (DIVA) model (Hinkel and Klein, 2009), which was developed as part of the DINAS-COAST project, has been particularly influential in predicting impacts from future sea level rise (e.g. Vafeidis et al., 2008; Hinkel et al., 2014; Brown et al., 2016; Diaz, 2016; Muis et al., 2017; Tamura et al., 2019). DIVA partitioned global coastlines (excluding Antarctica) into 12,148 linear segments with uniform vulnerability to sea level rise and examined c. 80 different biophysical and socio-economic parameters. This provision of semi-localised units of assessment (median coastal segment: 18 km) with global coverage has been one of the strengths of the approach, though it also inevitably introduces compromises; the potential impact from two of these in particular is highlighted by the results of our study.

Coastal segments assessed through DIVA-based models, even when these are highly detailed are constrained by a lack of time-depth. Future impact scenarios are extrapolated primarily from a snapshot of current conditions with limited attention to the past. Deep-time records such as those from Tràng An emphasise changes to coastal character (and hence potentially also to segment classification), as well as the complexity of transgression and still-stand episodes.

Our research also highlights the compromise that DIVA-based models make by excluding or limiting changes to spatial structure (especially where these are also time-relative) in favour of linear representations of the coastal zone. O'Donnell et al. (2020) demonstrated the survival of mangrove forest elements within the Tràng An massif millennia after the Mid-Holocene high stand had ended and the coastline had retreated. In this study, we have shown how local conditions and specific hydromorphological features may have supported that continuity. Coastal conditions need not be spatially confined to the linear transition zone between terrestrial and marine environments that DIVA models track; nor do they necessarily change in-step with changes to sea level.

The incorporation of a time-series and/or spatial structure into each defined coastal segment is logistically and computationally impractical at a global scale, though it potentially holds greater feasibility at a regional scale – as the recent Mediterranean study by Wolff et al. (2018) demonstrates. We propose that targeted incorporation of anchor-point datasets that utilise both dimensions, with particular reference to coastal areas of pronounced vulnerably to sea level change, such as deltas, would be a valuable refinement to future regional models.

## 5. Conclusions

Detailed palaeo-coastline reconstruction for the Mid-Holocene marine transgression has been carried out for the south-western extent of the RRD. The UNESCO World Heritage Site of Tràng An stood at the centre of the investigation and modelling results have shown that existing large-scale models underestimate the extent of the inundation in this area. Whilst sufficient for regional and global coastal reconstructions, the error-margins attached to such models potentially lead to misinterpretations of past human-landscape interactions.

Our current interpretation, supported by previous work (Lam and Boyd, 2001), places the observed highest rsl at the Mid-Holocene high stand between 6 – 4 ka BP, turning Tràng An into isolated near-shore archipelago. Under this scenario the central massif with its elevated Pleistocene marine terrace constituted the only open plain within the archipelago that was accessible from all contemporaneous archaeological sites. Hang Thung Bình and its five principal caves stood in the centre of this plain. Mid-Holocene strata from its largest cave, Hang Thung Bình 1, has only partially survived in excavated trenches but its advantageous position in the landscape and its extensive use during the Pleistocene, makes this outcrop a primary target for further investigation. This should certainly be extended to the plains surrounding the hill in search for sites similar to the open-air Đa Bút sites that were found at elevated terraces some 30 km southeast of Tràng An (Nguyen, 2005; Oxenham et al., 2018). Finds here would extend the high density of archaeological sites from Early to Mid-Holocene date, which are of considerable significance for Southeast Asian archaeology and the cultural changes that took place at the Late-Pleistocene/ Early Holocene interface.

Our detailed study of notches as indicators for past rsl has established three, possibly four discrete phases of stable sea levels above current mean sea level. These could indicate either multiple transgressions or intermittent still-stands during transgression/ regression events and highlight the complexity of sea level evolution.

In that context, we have clarified observed discrepancies between index and marker points for water depth in existing palaeoecological reconstructions of the RRD and contributed a new dataset that can be incorporated into the regional sea level curve. We have also recommended that time-depth and spatial variability should be closely considered in the preparation of future DIVA-based modelling in this and other regions. The research presented here has demonstrated the potential importance of these dimensions not only to archaeological reconstruction but also to modern coastal modelling and mitigation strategies.

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## Author contributions

**Thorsten Kahlert:** Conceptualisation, Methodology, Software, Investigation, Formal analysis, Data curation, Visualisation, Writing – Original draft preparation, Review & Editing **Shawn O'Donnell:** Conceptualisation, Methodology, Investigation – Vung Tham core, Writing – Original draft preparation, Review & Editing **Christopher Stimpson:** Conceptualisation, Investigation – Archaeological excavation director, Zooarchaeology, Writing – Review & Editing **Nguyễn Thị Mai Hương:** Conceptualisation, Investigation – TAK5 core, Writing – Review & Editing **Evan Hill:** Conceptualisation, Formal analysis – Radiocarbon date calibration, Visualisation **Benjamin Utting:** Conceptualisation, Methodology, Formal analysis, Writing – Original draft preparation, Review & Editing **Ryan Rabett:** Conceptualisation, Methodology, Investigation, Writing – Original draft preparation, Review & Editing, Supervision, Project Management, Funding acquisition, Resources

## Declaration of competing interest

The authors declare that they have no competing interests that could have influenced the work reported in this article.

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