9

How did *Homo erectus* reach Java? Least-cost pathway models and a consideration of possible Sumatran routes

Julien Louys and Shimona Kealy

Abstract

The earliest *Homo erectus* remains in Southeast Asia are in opposite reaches of this geographical region. *H. erectus* material from Gongwangling, China, and Mojokerto, Java, represent some of the earliest body fossils recovered for this species, but very few *H. erectus* records exist from between these regions. We examine possible routes that *H. erectus* could have taken on their journey southward, using a least-cost pathway analysis. Our models suggest that the easiest pathway ran through the centre of Sundaland, an area now almost entirely submerged. During periods of higher sea-levels, however, the pathway moved west and could coincide with emergent areas on or just off the east coast of Sumatra. Geological conditions on the east coast of Sumatra, while of the right age to contain early hominin remains, are not conducive to the preservation of fossil material or the retention of suitable quarries for stone artefact production. The Riau archipelago also lies on probable migration routes; however, geological outcrops of the right age will probably be difficult to find there.

Keywords: Indomalayan, Indonesia, island Southeast Asia, hominin dispersal, palaeogeographic reconstruction, remote survey, sea-level rise, Sunda Shelf

Abstrak

Peninggalan Homo erectus paling awal di Asia Tenggara secara geografis berada di jangkauan yang berlawanan arah pada wilayah ini. Sisa-sisa Homo erectus dari Gongwangling, Cina, dan Mojokerto, Jawa, mewakili beberapa fosil tubuh paling awal yang ditemukan untuk spesies ini, tetapi sangat sedikit catatan yang ditemukan di antaranya. Kami meneliti kemungkinan rute yang dapat ditempuh Homo erectus dalam perjalanannya ke selatan menggunakan analisis jalur paling optimal dengan upaya paling rendah. Model kami menunjukkan bahwa jalur paling optimum terletak di tengah-tengah Sundaland, daerah yang sekarang hampir seluruhnya terendam di bawah permukaan laut. Namun, selama periode permukaan laut yang lebih tinggi, jalur tersebut bergeser ke barat dan mungkin berhimpitan dengan daerah yang terpapar atau di lepas pantai timur Sumatra. Kondisi

geologi di pantai timur Sumatra, meskipun secara umur sesuai dengan okupansi hominin awal, tidak kondusif untuk pengawetan material fosil atau retensi sumber alat-alat batu yang melimpah. Kepulauan Riau juga terletak pada rute migrasi yang memungkinkan; namun, singkapan geologi dengan umur yang sesuai kemungkinan sulit ditemukan di sini.

Kata kunci: Indomalaya, Indonesia, Kepulauan Asia Tenggara, penyebaran hominin, rekonstruksi paleogeografi, survei jarak jauh, kenaikan muka air laut, Paparan Sunda

Introduction

Situated between China and Java is a region that has, surprisingly, been mostly free of direct physical traces of the first Asian hominin *Homo erectus*. The earliest dated evidence of the presence of hominins in Asia is currently that obtained from the sites of Majuangou in the Nihewan Basin of northern China and Shangchen in the southern Loess Plateau of north-central China. Magnetostratigraphic dating at Majuangou identified geomagnetic events bracketing artefact layers between 1.77 Ma and 1.24 Ma and provides an interpolated age of c. 1.66 Ma for the lowest artefact level (Ao et al. 2013; Zhu R.X. et al. 2004). Shangchen has been dated to approximately 2.1 Ma based on magnetostratigraphic and loess profile correlations (Zhu Z.Y. et al. 2018). However, these sites preserve only Mode 1 chopper–chopping tools, not body fossils, and without the latter, the identity of the tool-makers remains somewhat speculative.

The earliest dated hominin fossils from Asia, assigned to *Homo erectus*, are derived from the paleosol sequences of the Luochuan Sequence in Gongwangling, only about 4 km south of Shangchen, near the base of the Qinling Mountains, north-central China. Although originally correlated with either an upper sandy loess dated to 0.78 Ma or a lower sandy loess dated to 1.2-1.09 Ma, (An and Ho 1989; Liu et al. 1985), these dated fossil beds were recently re-examined and correlated with paleosol sequences dated to 1.65–1.54 Ma (Zhu Z.Y. et al. 2015). The presence of the fossils in these paleosol deposits, in addition to the identity of most mammalian fossils found in association with the Gongwangling hominin, suggests that subtropical to tropical environments were predominant in the region at this time. Such environmental conditions are more reminiscent of the Indomalayan biogeographic realm than of the drier and cooler conditions of the Palaearctic realm where Gongwangling is now located (Chow and Li 1965; Hu and Qi 1978; Louys et al. 2009). Further early Pleistocene hominin material attributable to H. erectus has been recovered from the Chinese sites Yuanmou, in Yunnan Province, and Yunxian, in Hubei Province, both in the Indomalayan realm, and dated to approximately 1.7 Ma and 1.15 Ma (or 0.8 Ma) respectively (Guo et al. 2013; Zhu R.X. et al. 2003, 2008). Most recently, fossil material preserving features typical of H. erectus has been recovered from Hualongdong in Anhui Province, eastern China (Wu Xiu-Jie et al. 2019), dated to 331-271 ka.

H. erectus material has been recovered from the Palaearctic realm as well, most famously from the extensive Zhoukoudian deposits, which may be as old as 0.8 Ma or as young as 230 ka depending on the dating technique favoured (Shen et al. 2009; Wu Xinzhi 2004). However, fossil hominins in southern China share more similarities with the Southeast Asian samples than with those in northern China (Lee and Hudock 2021), suggesting a divergence of evolutionary trajectories between the two biogeographical realms inhabited by *H. erectus* (Kaifu et al. 2005). It would seem, then, that the Indomalayan *H. erectus* fossils probably come from a single evolutionary group who migrated from north to south into Indonesia along the 'Sino-Malayan' route, which is the most parsimonious and probable based on evidence from the biogeography of other Pleistocene mammals (e.g. Kahlke 1972; Long et al. 1996; Tougard 2001).

South of southern China and north of Java, Indonesia, fossils of *H. erectus* are scarce. Isolated dental remains recovered from Tham Khuyen Cave and Tham Hai in northern Vietnam, dated to approximately 475 ka, have been identified as *H. erectus* (Ciochon et al. 1996; Olson and Ciochon 1990), although some of these attributions have been questioned based on the degree of wear on the teeth (Demeter et al. 2004).

The earliest dated *H. erectus* fossil from Java may be the Mojokerto skull, with dates ranging from 1.8 Ma to 1.43 Ma depending on which dating methods and materials are accepted (Morley et al. 2020; Morwood et al. 2003; Swisher et al. 1994). The Sangiran hominin fossil ages, which are more tightly constrained and more accepted, are approximately 1.5–1.3 Ma based on fission-track and uranium-series dating (Matsu'ura et al. 2020). Younger fossils have been recovered from other sites in Java, including Trinil and Sambungmacan, and the youngest ever fossil remains of *H. erectus* were probably found at Ngandong, dated to 117–108 ka (Rizal et al. 2019).

The vast area between southern China and northern Vietnam, which were at the northern extent of the *H. erectus* range in the early Pleistocene, and central and eastern Java, which were at the southern end, can reasonably be expected to preserve evidence of the passage and migration of this hominin. The lack of fossils from this region is probably at least partly due to both limited fieldwork and the subsidence of the Sunda Shelf since the Middle Pleistocene. Even though palaeontological fieldwork has increased dramatically in Southeast Asia in the last 20 years (e.g. review in Smith et al. 2020), the focus of this work has been largely on limestone caves. This makes sense as cave sites often preserve fossil material and are a natural feature of the landscape that are relatively easy to locate, particularly in dense forest (Louys et al. 2017). Nevertheless, the preservation of fossils in these sites is heavily biased towards the late Middle and Late Pleistocene. While deposits of these ages could theoretically host H. erectus fossil material, other than a few teeth only identifiable as Homo sp.such as those found at Tham Wiman Nakin, Thailand (Tougard et al. 1998) and Ma U'Oi, Vietnam (Demeter et al. 2004)—no other hominin material has been recovered. The notable but rare openair Pleistocene fossil mammal deposits from Southeast Asia, such as Khok Sung, Thailand (Duval et al. 2019; Suraprasit et al. 2018), have likewise failed to vield hominin fossils. Stone tools recovered from Southeast Asia, such as the Acheulean-like bifaces from southern Sumatra (Chapter 10, this volume), have yet to be dated or definitively associated with any particular hominin species.

The subsidence of the Sunda Shelf had profound effects on the biogeography and environments of Southeast Asia. The subsidence of the shelf is estimated as beginning at c. 400 ka based on geomorphological observations, numerical simulations of coral reef growth, and shallow seismic stratigraphy (Sarr et al. 2019). The continuous exposure of the shelf prior to 400 ka probably provided a natural savanna corridor for migration, as well as habitats for numerous large-bodied mammals including *H. erectus* (Husson et al. 2020; Louys and Roberts 2020), and these savannah environments may have been a population source for hominin population sinks in northern Asia (Dennell 2020; Louys and Turner 2012).

The eventual loss of the Sundaland corridor and the relatively open forest and savanna ecosystems it promoted probably disrupted gene flow between populations; it is associated with the extinction of several megafauna, including *H. erectus* (Husson et al. 2020; Louys and Roberts 2020). In addition, it is probable that the inundation of the Sunda Shelf submerged many potential archaeological and palaeontological sites, contributing to the dearth of fossil hominin records between southern China and Java. Here, we explore the question of which paths *H. erectus* may have taken through this corridor, paying particular attention to routes possibly taken following the inundation of the Sunda

Shelf. Following previous research examining modern human movements through Southeast Asia (Kealy et al. 2018), we take a least-cost pathway approach to that question in an effort to determine if any pathways may still be at least partially above water today.

Methods

Sea-levels and palaeogeographic reconstructions

We reconstructed the palaeogeography of Southeast Asia for seven time-and-sea-level slices (see Table 9.1) with the aim of covering a random but representative sample of times and sea-levels encompassing the last 400 ka. The first two slices were selected based on sea-levels present during the hypothetical scenario that Sundaland subsidence occurred prior to 400 ka, namely (1) the initial arrival of hominins in the region at 2.1 Ma (a date chosen as indicative of the earliest arrival of *H. erectus* on mainland Asia) and (2) 1.6–1.5 Ma, the earliest secure record of *H. erectus* in Java. The other five reconstructions aimed to account for variations in sea-level that would have significantly influenced land extent during the periods when hominins moved through the region and that cover most scenarios of sea-level and degree of Sundaland subsidence. Plate tectonic models and palaeogeographic reconstructions of the region suggest that, with the exceptions of continuing uplift and volcanism local to the Wallacean islands, Southeast Asia had largely reached the present geographic layout before 2.1 Ma (Hall 2001; Nugraha and Hall 2018). The aim of our sampling strategy was not to capture every time period and its associated sea-levels, but rather to randomly sample across the period after the subsidence of the Sunda Shelf and across fluctuating sea-levels to observe whether any patterns emerged.

Here we used the Miller et al. (2011) sea-level model, which is based on data from the LR04 δ^{18} O stack and provides a continuous model of global sea-level fluctuations for the last 180 Ma. Due to the broad geographic scope (India–New Guinea, China–Indonesia) and temporal range (2.1–0 Ma) of our study, we found the Miller et al. (2011) model to be the most applicable. The only exception to this was for the minimum (i.e. lowest) sea-level from the last 2.1 Ma, the Last Glacial Maximum (LGM). For our LGM sea-level reconstruction we used the most extreme depth of –135 m (135 m below present sea-levels), from the model by Lambeck et al. (2014), which is based on more detailed and regionally relevant data from the nearby Huon Peninsula, New Guinea. Thus, our LGM reconstruction represents an absolute maximum land extent scenario.

Our five additional time-and-sea-level slices were therefore developed based on these sea-level models. The additional five are: (3) 25–22 ka, the LGM and maximum sea-level lowstand, (4) 123 ka, the maximum sea-level highstand, (5) 2.1–0 Ma mean sea-level; (6) 2.1–0 Ma upper quartile (75th percentile) sea-level; and (7) 2.1–0 Ma lower quartile (25th percentile) sea-level. All seven slices are shown in Table 9.1.

Seven palaeogeographic reconstructions were then developed based on the slices' sea-levels (shown in Table 9.1). We used the General Bathymetric Chart of the Oceans (GEBCO_19) dataset (Smith and Sandwell 1997) to extract contours corresponding to each of our seven different sea-levels. These contours were then used to define the relevant palaeoland extent, and the corresponding sea-level difference was added to the GEBCO_19 dataset to model the palaeotopography.

Model number	Name	Time period	Sea-level m bpl ¹	Ages² ka
1	Asia	2.1 Ma	-14	415-414, 400-397, 323, 240-237, 118, 8
2	Java	1.6–1.5 Ma	-46*	394–388, 217, 287, 219, 195–193, 129, 113, 104–98, 93, 85–80, 75, 12
3	LGM, lowstand	25-22 ka	-135	27-21
4	Highstand	123 ka	+9	405, 123
5	Mean	2.1–0 Ma	-54	386-382, 306-300, 289-288, 244, 229, 112-107, 91-86, 79-76, 74, 13
6	75%	2.1–0 Ma	-33	418, 396, 335, 311, 235, 218-197, 128, 115, 96
7	25%	2.1–0 Ma	-75	374-364, 294, 275-246, 222, 183-173, 64-45

Table 9.1: Sea-level slices used for palaeogeographic reconstructions.

Note: LGM = Last Glacial Maximum.

¹ Depth in metres relative to present sea-levels.

² Approximate ages, over the last c. 400 ka, that correspond with the reconstructions.

* Averaged measurement.

Source: Authors' analysis.

We then used our palaeotopography to model river and lake systems for each of these scenarios. Each reconstructed digital elevation model (DEM) was hydrologically conditioned using the 'sink' and 'fill' tools in ArcGIS v10.7 (ESRI 2018) to smooth out depressions and small errors in the dataset. This enabled us to clearly establish flow direction and accumulation across our DEM's using the Hydrology toolset in ArcGIS v10.7. A drainage threshold of 1,000 cells was applied to the flow accumulation model to delineate major palaeostreams and rivers. A surface area threshold of >100 km² was also applied to the modelled palaeolakes. Both these thresholds were employed to minimise overestimations of reconstructed waterways and focus on those most likely to represent major, permanent water bodies in the palaeolandscape.

Least-cost pathway models

The construction of our least-cost pathway models for the seven different palaeogeographic reconstructions largely followed the methodology of Kealy et al. (2018). 'Slope cost' and 'river distance cost' were both calculated per Kealy et al. (2018: table 1). We also added an additional cost variable not considered by Kealy et al., that of lakes. While the Kealy et al. models focused on the island region of Wallacea, where lakes are generally both rare and small, in our region of interest, lakes comprise a more substantial proportion of the landscape. Therefore, we included lakes with a surface area >100 km² in our modelling.

As *Homo erectus* is not generally considered to have possessed the capabilities required for purposeful crossing of major water bodies, and presumably avoided such activity where possible, we assigned our lakes a cost value of 15. This value corresponds to Field and Lahr's (2005) 'sand seas' value that means crossings are unlikely, but remotely possible for short distances. However, while lake surface was assigned a high cost, we consider lake edges to represent particularly attractive zones, similarly to river systems but to a greater extent (see also Shipton et al. 2018). We therefore assigned a cost value of zero to a 0.5 km buffer extending outwards from our lake edges. These additional lake cost values were combined with the existing river cost values to create a 'waterways cost' surface. The equations used are shown in Table 9.2.

Output	Code	Formula		
Distance from rivers (km) DR		Euclidean distance calculated in ArcGIS 10.5.1		
River distance cost RC		$RC = (TfExp(DR, 0.1, maxDR)) + (\frac{DR}{10})$		
		TfExp base factor calculated in ArcGIS based on upper and lower values		
Lake surface cost LC		LC = 15		
Lake distance cost LDC		<i>LDC</i> = 0.5 km buffer from lake edge = 0		
Waterways cost surface WC		WC = RC + LC + LDC		
Slope (degrees) S		Slope function in ArcGIS 10.5.1 calculated in degrees		
Slope cost	SC	$SC = \frac{\tan \tan S}{\tan \tan 1^{\circ}}$		
Total cost surface TCS		TCS = SC + WC		

Table 9.2: Equations used in the development of the cost surfaces for the seven palaeogeographic reconstructions modelled.

Source: Authors' analysis; table modified from Kealy et al. (2018: table 1).

In contrast to the modelling by Kealy et al. (2018), which was focused on *Homo sapiens* crossing the seas of Wallacea, here we returned to the Field and Lahr (2005) model and classified the ocean as impermeable. This classification had the additional effect of halting the least-cost paths at the coast, making direct access to the islands of Sumatra or Java impossible (according to our model) when the Sunda Shelf was submerged. In these scenarios, we also followed the example of Field and Lahr (2005) to simply pause our pathway model at the coast and restart it at the closest point on the opposite landmass, chosen based on a direct line across the channel.

Numerous studies suggest archaic hominins were incapable of purposeful voyaging (O'Connor et al. 2017; Shipton et al. 2021), unlike *H. sapiens* (Bird et al. 2019; Kealy et al. 2018). Archaic hominins were, however, clearly capable of accidental sea crossings, as evidenced by the early records of Flores, Sulawesi and the Philippines (Brumm et al. 2010; Ingicco et al. 2018; van den Bergh et al. 2016). Recent efforts by D'Cunha et al. (2021) attempted to model such drift dispersal routes, but their study focused on the major crossing of the Makassar Strait (i.e. Wallace's Line) and interactions with the Indonesian Throughflow. For our study, the longest sea crossing required is c. 26 km (across the Sunda Strait between Sumatra and Java) during the period of highest sea-level, significantly shorter than the narrowest point of the Makassar Strait. Our methodology reflects this scenario: sea crossings are not considered by our pathway model, but minor accidental dispersal across short distances is accounted for by the abovementioned 'stop-start' approach of Field and Lahr (2005), thus allowing path continuation across regions which would otherwise be unreachable within the model's parameters.

To capture migration pathways hypothesised from large-mammal biogeography, namely the Siva-Malayan and Sino-Malayan routes (de Vos et al. 1999; Tougard 2001; von Koenigswald 1935, 1939), least-cost pathway models were run from India and China towards Java (specifically, the sites of Narmada in India, Gongwangling in China and Sangiran in Java). Not only did we then model our least-cost path from these two sources to the Java destination—as in the cases of both Kealy et al. (2018) and Field and Lahr (2005)—but we also ran our pathway model in reverse to detect any differences between the favourabilities of potential pathways for travel back from Java. Unlike the southward paths, the reverse models were not forced to return to particular destinations (i.e. Narmada or Gongwangling) as we felt it more realistic to let the model choose its own path with a termination option anywhere along the outer rim of our modelled region. This also provided



useful ways to compare fixed-destination and non-fixed-destination models. The analysis used the Cost Distance, Cost Back-Link and Cost Path tools in the ArcGIS 10.7 (ESRI 2018) Spatial Analyst Toolbox.

Results

Palaeogeographic reconstructions

The ages covered by the sea-levels examined, which ranged over the last 400 ka, follow a Poisson distribution for point events (p = 0.087) with no density trend detected (Laplace test, U = -1.3447, p = 0.179). This means our sea-level sampling covers an even spread of the palaeogeographic scenarios of the last 400 ka, including maximum and minimum extent of sea-level changes. Because we also examined the mean and quartiles for sea-levels over the last 2.1 Ma, we feel confident that the variable palaeogeography experienced by *H. erectus* in Southeast Asia has been captured by our sampling approach.

The seven palaeogeographic reconstructions (Figures 9.1–9.7) included three scenarios in which portions of the Sunda Shelf are submerged to the extent that Java is not connected by land to mainland Southeast Asia: *Asia* (Figure 9.1); *Highstand* (Figure 9.4), and *75%* (Figure 9.6). In these scenarios, the Sunda Strait would have to be crossed to reach Java from mainland Southeast Asia. However, unlike *Asia* and *Highstand*, the *75%* reconstruction does model land connectivity between mainland Southeast Asia and Sumatra, so it does not include the additional necessity of crossing the Malacca and Singapore Straits. In our four other scenarios, sufficient expanses of the Sunda Shelf are exposed to allow travel by land at all times between Java and mainland Asia.



Figure 9.1: Least-cost pathways from India (left) and China (right) to Sangiran, Java (red), and return pathways (pink) for the *Asia* **scenario with sea-level –14 m relative to present.** Source: doi.org/10.6084/m9.figshare.25255141. Map by authors.



Figure 9.2: Least-cost pathways from India (left) and China (right) to Sangiran, Java (red), and return pathways (pink) for the *Java* scenario with sea-level –46 m relative to present. Source: doi.org/10.6084/m9.figshare.25255141. Map by authors.



Figure 9.3: Least-cost pathways from India (left) and China (right) to Sangiran, Java (red), and return pathways (pink) for the *LGM* **scenario with sea-level –135 m relative to present.** Source: doi.org/10.6084/m9.figshare.25255141. Map by authors.



Figure 9.4: Least-cost pathways from India (left) and China (right) to Sangiran, Java (red), and return pathways (pink) for the *Highstand* **scenario with sea-level +9 m relative to present.** Source: doi.org/10.6084/m9.figshare.25255141. Map by authors.



Figure 9.5: Least- cost pathways from India (left) and China (right) to Sangiran, Java (red), and return pathways (pink) for the *Mean* **scenario with sea-level –54 m relative to present.** Source: doi.org/10.6084/m9.figshare.25255141. Map by authors.



Figure 9.6: Least-cost pathways from India (left) and China (right) to Sangiran, Java (red), and return pathways (pink) for the 75% scenario with sea-level –33 m relative to present. Source: doi.org/10.6084/m9.figshare.25255141. Map by authors.



Figure 9.7: Least-cost pathways from India (left) and China (right) to Sangiran, Java (red), and return pathways (pink) for the 25% scenario with sea-level –75 m relative to present. Source: doi.org/10.6084/m9.figshare.25255141. Map by authors.

The validity of the models is supported by comparisons with known *Homo erectus* traits. In particular, the degree to which our modelled pathways follow river corridors to move inland while avoiding regions of high elevation and slope corresponds with observations from studies of various Acheulean assemblages in western Asia (e.g. Shipton et al. 2018). Unlike the more coastal and maritime-focused pathways of Kealy et al.'s (2018) models of *H. sapiens* Wallacea crossings, our models appear to mirror the more terrestrial, inland focus that has been observed for *H. erectus* (Louys and Roberts 2020; O'Connor et al. 2017; Shipton et al. 2021). This comparison is not being made to provide circular support for previous *H. erectus* lifestyle hypotheses, but to demonstrate that our choice and weighting of cost variables successfully reflect what current research suggests were the probable parameters of *H. erectus* movement. Thus, our models represent potential paths taken by *H. erectus* based on our current understanding of the palaeolandscape and *H. erectus* capabilities and preferences.

Three general observations arise from our least-cost pathway scenarios. First, within our region of interest (mainland Southeast Asia), the routes to and from Java are almost always the same as one another—in other words, it makes little difference in our models if the path followed was from north to south or from south to north. Significant divergence only occurred in India and northern China, both of which lie outside the Southeast Asian biogeographic realm. In only two scenarios, the *LGM* and *Mean* sea-level models (Figures 9.3 and 9.5), did the path back from Java to China diverge temporarily from the China-to-Java path; this occurred in the eastern part of the Indochinese region.



Figure 9.8: Least-cost pathways along the east coast of Sumatra under different sea-level conditions.

Note: The major basins of central and southern Sumatra are shown relative to the Air Tawar and Air Semuhun stone artefact sources.

Source: Map by authors. Basin locations after Barber and Crow (2005).

Second, paths from either India or China eventually converge in Southeast Asia, although the point of convergence differs between sea-level scenarios. In most instances, the higher the sea-level, the further north and west this point of convergence occurs. At its most northern occurrence, in the *Highstand* model (Figure 9.4), it is near the Kanchanaburi Province of Thailand. Its most southern, in the *LGM* model (Figure 9.3), occurs in the now-submerged Johore basin.

Finally, the major difference between the sea-level scenarios occurs in the Siam and East Sunda Basins. In the *LGM* scenario, the least-cost pathway runs through central Sundaland, in a region that is now almost entirely submerged. As the sea-level approaches modern levels, however, the pathway shifts noticeably west, towards and along the east coast of Sumatra (see Figure 9.8). Although the individual pathways through eastern Sumatra differ considerably between the scenarios, this trend suggests that eastern Sumatra may have been occupied or traversed (based on the variables included in our analysis).

Discussion

The most probable route taken by early hominins and associated megafauna southward into Java is indicated by the model with maximum connectivity between landmasses and would thus have been in the middle of the now-submerged Sunda Shelf. Such a route would also have gone through more open environments, particularly during the early to Middle Pleistocene (Louys and Roberts 2020). Unfortunately, identification and recovery of any material from this region will be difficult, although, as demonstrated by underwater recovery efforts elsewhere in the world (e.g. Bailey et al. 2007; Benjamin et al. 2020), perhaps not impossible. Nevertheless, any such sites, if they exist, are unlikely to be found in the near future. Therefore, it is useful to examine areas that are currently emergent and which have some support in the literature for their having been used as a migration corridor.

Recently, Salles et al. (2021) reported on landscape evolution and connectivity models of the Late Pleistocene of Southeast Asia. While the focus of Salles et al.'s (2021) study was on the drivers of increase in Southeast Asian biodiversity, their results have two important implications related to our modelling. First, their modelling showed high-connectivity migration corridors along the east coast of Sumatra coinciding with our westward least-cost pathways (Salles et al. 2021: figure 5). High connectivity exists regardless of whether rainforests were considered corridors or barriers to migration. The east coast of Sumatra appears to become a migration highway for many species over the Late Pleistocene, and, by extrapolation, even during periods of maximum continental shelf connectivity, such as the LGM, and the Pleistocene before 400 ka. This is supported by the recovery of Acheulean-type artefacts in the Air Tawar and Air Semuhun rivers (Chapter 10, this volume), which lie in the regions of high connectivity suggested by Salles et al. (2021), and just west of the pathways predicted by our least-cost modelling.

This area, encompassing the piedmont plains and peneplains of southern and eastern Sumatra, would therefore appear to be ideal for the recovery of early hominin material in Sumatra. Here, however, is where the second implication of the Salles et al. (2021) study for our question is relevant, notably the high net cumulative erosion of the east coast of Sumatra they record (Salles et al. 2021: figure 1). Structurally, southern and eastern Sumatra are characterised by two major basin systems: the South Sumatra Basin and the Central Sumatra Basin, which are separated by the Tigapuluh Hills, an upfaulted pre-Neogene block (Barber and Crow 2005; Figure 9.8). The uppermost formations in these basins, the Plio-Pleistocene-to-recent Kasai Formation in the South Sumatra Block and

the similarly aged Minas Formation in the Central Sumatra Basin, unconformably overlie older marine sediments. It is these formations that are likely to preserve material of the right age for early hominins.

Extensive faulting in the Central Sumatra Basin largely controls drainage patterns in this region, which follow a northwest–southeast direction (Verstappen 1973). In the South Sumatra Basin, numerous anticlines control drainage, which is directed more east–west than in the Central Sumatra Basin. Denudation following major orogenic events, such as the uplift and volcanism of the Barisan Mountains, has produced intense base-levelling of high topographic features. Verstappen (1973) reports the loss of 1,000 m, but perhaps up to 5,000 m, of sediment from uplifted blocks and anticlines. Weathering of host rock is largely chemical rather than physical due to the region's high rainfall and dense rainforest vegetation, so that scree fans and coarse alluvial fans are rare, particularly in the area furthest east of the Barisan Mountains (Verstappen 1973). Most fluvial sediment load in the eastern lowlands is therefore composed of silts and clays, and there is extensive erosion, alteration of sediment, and rapid formation of soils, fuelling the growth of the eastern and southern alluvial plains (Verstappen 1973), with outcrops being rare (Katili 1974).

The least-cost pathways through eastern Sumatra (see Figure 9.8) remain relatively close to the east coast—in most instances less than 150 km away. Although some previous authors (e.g. Coleman et al. 1970; Keller and Richards 1967) suggested that a large sediment supply came to the east coast from inland river sources, a convincing study by Cecil et al. (1993) instead suggests that the east coast is an area of net erosion, with the little sedimentation that remains being primarily estuarine and marine rather than alluvial. They suggest that most of the sediment currently exposed in the east is the result of a marine transgression possibly occurring as recently as 5,000 years ago. How far this extends inland is locality-dependent; however, Cecil et al. (1993) suggest that the Kampar estuary is tidally influenced for up to 180 km, and flood tide-dominated more than 100 km inland. This is consistent with other studies that constructed this zone as a humid, tropical deltaic system (Boyd and Peacock 1986; Louys et al. 2021). Any early Pleistocene outcrops within the area identified by our modelling were exposed to repeated marine transgressions and regressions, with concomitant erosional events and marine sedimentation, over the last 400 ka. Thus, while the area of eastern Sumatra is very likely, from a modelling perspective, to preserve remains of early hominins in conditions that are today emergent, geological conditions are not highly favourable for such deposits. Both sedimentological constraints on preservation and the lack of suitable outcrops for stone tool production (e.g. Dennell 2008), as much as a lack of active exploration, probably explain why no Pleistocene early hominin fossil material has been recovered from this region.

These factors may also help to explain the absence of hyena fossils from Sumatra. Two species of hyena were widespread in Southeast Asia throughout the Pleistocene (Louys 2014). These hyenas probably fed in open environments on medium and large herbivores, especially rhinocerotids and bovids (Bacon et al. 2015, 2018), but potentially also including Southeast Asian hominins. Nevertheless, no hyena fossils have been recovered from any of the cave sites in Sumatra. As predators tend to follow prey closely, hyenas, like *Homo erectus*, may have been restricted to regions currently submerged. However, as noted in Chapter 5, more open areas may have existed in the Padang Highlands during the Middle Pleistocene, and the possibility remains that *Homo erectus* and hyena fossils may yet be recovered from the western side of Sumatra.

One final possible emergent area that our models identified as likely to have been traversed by *Homo erectus* and its potential predators and prey—one with less cumulative erosion than the east coast of Sumatra (Salles et al. 2021: figure 1)—is the Riau archipelago. Four of our seven models suggest pathways close to these islands, with two (*High* and *Asia*) suggesting pathways that traverse the

modern, emergent islands of Karimun Besar and Bulan. Prospecting difficulties do arise in the Riau archipelago due to the age of the rocks there (they are mostly Mesozoic). Other factors, such as the ready availability of geological resources for tool manufacture (e.g. Dennell 2008) or the distribution of regional topographic and edaphic constraints (e.g. Devès et al. 2014; Kübler et al. 2016), may be equally important in determining the success for the recovery of early hominins and associated faunas from these islands.

Conclusion

Our least-cost pathway modelling suggests that the most probable route southward through Sundaland would have been through the middle of the now-sunken continental shelf. This route would have benefited hominins such as *Homo erectus* by being much more open than today's tropical rainforests (Louys and Roberts 2020). Nevertheless, any material preserved by these early hominins is currently submerged and inaccessible. The presently unsubmerged (and hence accessible) areas that are potentially on a major migration route southward into Java are mostly situated on the east coast of Sumatra. As sea-levels approach the highs seen today, our least-cost modelling moves the most probable such route westward within Sumatra, towards the Barisan Mountains. These routes coincide with biodiversity connectivity corridors identified through other researchers' landscape evolution modelling (Salles et al. 2021). Unfortunately, these areas are also net erosive regions, highly susceptible to chemical erosion and pedogenesis, hosting relatively few outcrops, and largely overlaid with marine sedimentation, particularly along the east coast. In such conditions, long-term preservation of early Pleistocene material is unlikely, so such material will continue to be difficult to find. Based on our modelling results and previously established erosion patterns, the islands of the Riau archipelago may be an alternative option for future research efforts.

Acknowledgements

Funding for this research was generously provided by the Australian Research Council (FT160100450) and the National Geographic Society (NGS-59859R-19). We thank Paul Albers, Alexandra van der Geer and two anonymous reviewers for helpful comments on this manuscript.

References

- An, Z.S. and C.K. Ho 1989. New magnetostratigraphic dates of Lantian Homo erectus. Quaternary Research 32(2):213–221. doi.org/10.1016/0033-5894(89)90077-X
- Ao, H., M.J. Dekkers, Q. Wei, X. Qiang and G. Xiao 2013. New evidence for early presence of hominids in North China. *Scientific Reports* 3:2403. doi.org/10.1038/srep02403
- Bacon, A.M., K. Westaway, P.O. Antoine, P. Duringer, A. Blin, F. Demeter, J.L. Ponche, J.X. Zhao, L.M. Barnes, T. Sayavonkhamdy, N.T.K. Thuy, V.T. Long, E. Patole-Edoumba and L. Shackelford 2015. Late Pleistocene mammalian assemblages of Southeast Asia: New dating, mortality profiles and evolution of the predator–prey relationships in an environmental context. *Palaeogeography, Palaeoclimatology, Palaeoecology* 422:101–127. doi.org/10.1016/j.palaeo.2015.01.011

- Bacon, A.M., P. Duringer, K. Westaway, R. Joannes-Boyau, J.X. Zhao, N. Bourgon, E. Dufour, S. Pheng, S. Tep, J.L. Ponche, L. Barnes, A. Blin, E. Patole-Edoumba and F. Demeter 2018. Testing the savannah corridor hypothesis during MIS2: The Boh Dambang hyena site in southern Cambodia. *Quaternary International* 464(Part B):417–439. doi.org/10.1016/j.quaint.2017.10.047
- Bailey, G.N., N.C. Flemming, G.C. King, K. Lambeck, G. Momber, L.J. Moran, A. Al-Sharekh and C. Vita-Finzi 2007. Coastlines, submerged landscapes, and human evolution: The Red Sea Basin and the Farasan Islands. *The Journal of Island and Coastal Archaeology* 2(2):127–160. doi.org/10.1080/155648907016 23449
- Barber, A.J. and M.J. Crow 2005. Structure and structural history. In A.J. Barber, M.J. Crow, J.S. Milsom (eds), *Sumatra: Geology, Resources and Tectonic Evolution*, pp. 175–233. Geological Society Memoir No. 31. Geological Society, London. doi.org/10.1144/GSL.MEM.2005.031.01.13
- Benjamin, J., M. O'Leary, J. McDonald, C. Wiseman, J. McCarthy, E. Beckett, P. Morrison, F. Stankiewicz, J. Leach, J. Hacker, P. Baggaley, K. Jerbić, M. Fowler, J. Fairweather, P. Jeffries, S. Ulm and G. Bailey 2020. Aboriginal artefacts on the continental shelf reveal ancient drowned cultural landscapes in northwest Australia. *PLoS ONE* 15:e0233912. doi.org/10.1371/journal.pone.0233912
- Bird, M.I., S.A. Condie, S. O'Connor, D. O'Grady, C. Reepmeyer, S. Ulm, M. Zega, F. Saltré and C.J. Bradshaw 2019. Early human settlement of Sahul was not an accident. *Scientific Reports* 9:8220. doi.org/10.1038/s41598-019-42946-9
- Boyd, J.D. and S.G. Peacock 1986. Sedimentological analysis of a Miocene deltaic systems: Air Benakat and Muaraenim Formations, Central Merangin Block, South Sumatra. *Proceedings of the Indonesian Petroleum* Association 15th Annual Convention 1986, pp. 245–258. Indonesian Petroleum Association, Jakarta. ipa. or.id/en/publications/sedimentological-analysis-of-a-miocene-deltaic-systems-air-benakat-and-muaraenim-formations-central-merangin-block-south-sumatra
- Brumm, A., G.M. Jensen, G.D., van den Bergh, M.J. Morwood, I. Kurniawan, F. Aziz and M. Storey 2010. Hominins on Flores, Indonesia, by one million years ago. *Nature* 464(7289):748–752. doi.org/10.1038/ nature08844
- Cecil, C.B., F.T. Dulong and J.C. Cobb 1993. Allogenic and autogenic controls on sedimentation in the Central Sumatra basin as an analogue for Pennsylvanian coal-bearing strata in the Appalachian basin. In J.C. Cobb and C.B. Cecil (eds), *Modern and Ancient Coal-Forming Environments*, pp. 3–22. GSA Special Papers 286. Geological Society of America, Boulder, CO. doi.org/10.1130/SPE286-p3
- Chow, M.C. and C.K. Li 1965. Mammalian fossils in association with the mandible of Lantian Man at Chenchiaou, in Lantian, Shensi. *Vertebrata PalAsiatica* 9:377–393.
- Ciochon, R., V.T. Long, R. Larick, L. González, R. Grün, J. de Vos, C. Yonge, L. Taylor, H. Yoshida and M. Reagan 1996. Dated co-occurrence of *Homo erectus* and *Gigantopithecus* from Tham Khuyen cave, Vietnam. *Proceedings of the National Academy of Sciences of the USA* 93(7):3016–3020. doi.org/10.1073/ pnas.93.7.3016
- Coleman, J.M., S.M. Gagliano and W.G. Smith 1970. Sedimentation in a Malaysian high tide tropical delta. In J.P. Morgan (ed.), *Deltaic Sedimentation, Modern and Ancient*, pp. 185–197. Society of Economic Paleontologists and Mineralogists Special Publication 15. Society for Sedimentary Geology, Tulsa, OK. doi.org/10.2110/pec.70.11.0185
- D'Cunha, M.G.T., A. Montenegro and J.S. Field 2021. Modeling water crossings leading to the arrival of early *Homo* in Sulawesi, Indonesia, via paleoclimate drift experiments. *Journal of Archaeological Science: Reports* 40(Part A):103194. doi.org/10.1016/j.jasrep.2021.103194

- Demeter, F., A. Bacon, N. Thuy, V. Long, H. Matsumura, H. Nga, M. Schuster, N. Huong and Y. Coppens 2004. An archaic *Homo* molar from northern Vietnam. *Current Anthropology* 45(4):535–541.
- Dennell, R.W. 2008. The taphonomic record of Upper Siwalik (Pinjor stage) landscapes in the Pabbi Hills, northern Pakistan, with consideration regarding the preservation of hominin remains. *Quaternary International* 192(1):62–77. doi.org/10.1016/j.quaint.2007.06.024
- Dennell, R.W. 2020. From Arabia to the Pacific: How Our Species Colonised Asia. Routledge, London. doi.org/ 10.4324/9781003038788
- Devès, M., D. Sturdy, N. Godet, G.C.P. King and G.N. Bailey 2014. Hominin reactions to herbivore distribution in the Lower Palaeolithic of the Southern Levant. *Quaternary Science Reviews* 96:140–160. doi.org/10.1016/j.quascirev.2014.04.017
- de Vos, J., F. Aziz, P.Y. Sondaar and G.D. van den Bergh 1999. *Homo erectus* in S.E. Asia. Time, space and migration routes; a global model III. Migration routes and evolution. In J. Gibert, F. Sanchez, L. Gibert and F. Ribot (eds), *The Hominids and Their Environment During the Lower and Middle Pleistocene of Eurasia*, pp. 369–381. Proceedings of the International Conference of Human Paleontology, Orce 1995. Museo de Prehistoria y Paleontología, Orce, Granada, Spain.
- Duval, M., F. Fang, K. Suraprasit, J.J. Jaeger, M. Benammi, C. Yaowalak, J. Iglesias Cibanal and R. Grün 2019. Direct ESR dating of the Pleistocene vertebrate assemblage from Khok Sung locality, Nakhon Ratchasima Province, Northeast Thailand. *Palaeontologia Electronica* 22.3:69. doi.org/10.26879/941

Environmental Systems Research Institute (ESRI) 2018. ArcGIS 10.7 for Desktop. ESRI, Redlands, California.

- Field, J.S. and M.M. Lahr 2005. Assessment of the southern dispersal: GIS-based analyses of potential routes at oxygen isotopic stage 4. *Journal of World Prehistory* 19:1–45. doi.org/10.1007/S10963-005-9000-6
- Guo, Y., C.C. Huang, J. Pang, X. Zha, Y. Zhou, Y. Zhang and L. Zhou 2013. Sedimentological study of the stratigraphy at the site of *Homo erectus yunxianensis* in the upper Hanjiang River valley, China. *Quaternary International* 300:75–82. doi.org/10.1016/j.quaint.2012.12.036
- Hall, R. 2001. Cenozoic reconstructions of SE Asia and the SW Pacific: Changing patterns of land and sea. In I. Metcalfe, J.M. Smith, M. Morwood and I. Davidson (eds), *Faunal and Floral Migration and Evolution in SE Asia-Australasia*, pp. 35–56. A.A. Balkema Publishers, Lisse.
- Hu, C. and T. Qi 1978. Gongwangling Pleistocene mammalian fauna of Lantian, Shaanxi. *Palaeontologia Sinica* 155:1–6.
- Husson, L., F.C. Boucher, A.C. Sarr, P. Sepulchre and S.Y. Cahyarini 2020. Evidence of Sundaland's subsidence requires revisiting its biogeography. *Journal of Biogeography* 47(4):843–853. doi.org/10.1111/jbi.13762
- Ingicco, T., G.D. van den Bergh, C. Jago-On, J.J. Bahain, M.G. Chacón, N. Amano, H. Forestier, C. King, K. Manalo, S. Nomade, A. Pereira, M.C. Reyes, A.-M. Sémah, Q. Shao, P. Voinchet, C. Falguères, P.C.H. Albers, M. Lising, G. Lyras, D. Yurnaldi, P. Rochette, A. Bautista and J. de Vos 2018. Earliest known hominin activity in the Philippines by 709 thousand years ago. *Nature* 557(7704):233–237. doi.org/ 10.1038/s41586-018-0072-8
- Kahlke, H.D. 1972. A review of the Pleistocene history of the orangutan (*Pongo* Lacepede, 1799). Asian Perspectives 15:5–14.
- Kaifu, Y., H. Baba, F. Aziz, E. Indriati, F. Schrenk and T. Jacob 2005. Taxonomic affinities and evolutionary history of the early Pleistocene hominids of Java: Dentognathic evidence. *American Journal of Physical Anthropology* 128(4):709–726. doi.org/10.1002/ajpa.10425

- Katili, J.A. 1974. Sumatra. In *Geological Society, London, Special Publications*, Volume 4, pp. 317–331. Geological Society, London. doi.org/10.1144/GSL.SP.2005.004.01.18
- Kealy, S., L. Louys and S. O'Connor 2018. Least-cost pathway models indicate northern human dispersal from Sunda to Sahul. *Journal of Human Evolution* 125:59–70. doi.org/10.1016/j.jhevol.2018.10.003
- Keller, G.H. and A.F. Richards 1967. Sediments of the Malacca Strait, Southeast Asia. Journal of Sedimentary Petrology 37:102–127. doi.org/10.1306/74D7166D-2B21-11D7-8648000102C1865D
- Kübler, S., S. Rucina, S. Reynolds, P. Owenga, G. Bailey and G.C.P. King 2016. Edaphic and topographic constraints on exploitation of the Central Kenya Rift by large mammals and early hominins. *Open Quaternary* 2:1–18. doi.org/10.5334/oq.21
- Lambeck, K., H. Rouby, A. Purcell, Y. Sun and M. Sambridge 2014. Sea level and global ice volumes from the Last Glacial Maximum to the Holocene. *Proceedings of the National Academy of Sciences of the USA* 111(43):15296–15303. doi.org/10.1073/pnas.1411762111
- Lee, S.H. and A. Hudock 2021. Human evolution in Asia: Taking stock and looking forward. Annual Review of Anthropology 50:145–166. doi.org/10.1146/annurev-anthro-101819-110230
- Liu, T., Z. An, B. Yuan and J. Han 1985. The loess-paleosol sequence in China and climatic history. *Episodes* 8:21–28. doi.org/10.18814/epiiugs/1985/v8i1/003
- Long, V.T., J. de Vos and R. Ciochon 1996. The fossil mammal fauna of the Lang Trang caves, Viet-nam, compared with Southeast Asian fossil and recent mammal faunas: The geographical implications. *Bulletin* of the Indo-Pacific Prehistory Association 14:101–109.
- Louys, J. 2014. The large terrestrial carnivore guild in Quaternary Southeast Asia. *Quaternary Science Reviews* 96:86–97. doi.org/10.1016/j.quascirev.2013.06.014
- Louys, J., S. Kealy, S. O'Connor, G.J. Price, S. Hawkins, K. Aplin, Y. Rizal, Y. Zaim, Mahirta, D.A. Tanudirjo, W.D. Santoso, A.R. Hidayah, A. Trihascaryo, R. Wood, J. Bevitt and T. Clark 2017. Differential preservation of vertebrates in Southeast Asian caves. *International Journal of Speleology* 46:379–408. doi.org/ 10.5038/1827-806X.46.3.2131
- Louys, J. and P. Roberts 2020. Environmental drivers of megafauna and hominin extinction in Southeast Asia. *Nature* 586:402–406. doi.org/10.1038/s41586-020-2810-y
- Louys, J., K.J. Travouillon, M. Bassarova and H. Tong 2009. The use of natural protected areas in palaeoecological analyses: Assumptions, limitations and application. *Journal of Archaeological Science* 36(10):2274–2288. doi.org/10.1016/j.jas.2009.06.012
- Louys, J. and A. Turner 2012. Environment, preferred habitats and potential refugia for Pleistocene *Homo* in Southeast Asia. *Comptes Rendus Palevol* 11:203–211. doi.org/10.1016/j.crpv.2011.03.003
- Louys, J., Y. Zaim, Y. Rizal, G.J. Price, Aswan, M.R. Puspanigrum, H. Smith and A. Trihascaryo 2021. Palaeontological surveys in Central Sumatra and Bangka. *Berita Sedimentologi* 47: 50–56.
- Matsu'ura, S., M. Kondo, T. Danhara, S. Sakata, H. Iwano, T. Hirata, I. Kurniawan, E. Setiyabudi, Y. Takeshita, M. Hyodo, I. Kitaba, M. Sudo, Y. Danhara and F. Aziz 2020. Age control of the first appearance datum for Javanese *Homo erectus* in the Sangiran area. *Science* 367(6474):210–214. doi.org/10.1126/ science.aau8556
- Miller, K.G., G.S. Mountain, J.D. Wright and J.V. Browning 2011. A 180-million-year record of sea level and ice volume variations from continental margin and deep-sea isotopic records. *Oceanography* 24(2):40–53. doi.org/10.5670/oceanog.2011.26

- Morley, R.J., H.P. Morley, Y. Zaim and O.F. Huffman 2020. Palaeoenvironmental setting of Mojokerto *Homo erectus*, the palynological expressions of Pleistocene marine deltas, open grasslands and volcanic mountains in East Java. *Journal of Biogeography* 47(3):566–583. doi.org/10.1111/jbi.13770
- Morwood, M.J., P. O'Sullivan, E.E. Susanto and F. Aziz 2003. Revised age for Mojokerto 1, an early *Homo erectus* cranium from East Java, Indonesia. *Australian Archaeology* 57(1):1–4. doi.org/10.1080/03122417 .2003.11681757
- Nugraha, A.M.S. and R. Hall 2018. Late Cenozoic palaeogeography of Sulawesi, Indonesia. *Palaeogeography, Palaeoclimatology, Palaeoecology* 490:191–209. doi.org/10.1016/j.palaeo.2017.10.033
- O'Connor, S., J. Louys, S. Kealy and S.C. Samper Carro 2017. Hominin dispersal and settlement east of Huxley's Line: The role of sea level changes, island size, and subsistence behavior. *Current Anthropology* 58(S17):S567–S582. doi.org/10.1086/694252
- Olsen, J.W. and R.L. Ciochon 1990. A review of evidence for postulated Middle Pleistocene occupations in Viet Nam. *Journal of Human Evolution* 19(8):761–788. doi.org/10.1016/0047-2484(90)90020-C
- Rizal Y, K.E. Westaway, Y. Zaim, G.D. van den Bergh, E.A. Bettis III, M.J. Morwood, O.F. Huffman, R. Grün, R. Joannes-Boyau, R.M. Bailey, Sidarto, M.C. Westaway, I. Kurniawan, M.W. Moore, M. Storey, F. Aziz, Suminto, J.-X. Zhao, Aswan, M.E. Sipola, R. Larick, J.-P. Zonneveld, R. Scott, S. Putt and R.L. Ciochon 2019. Last appearance of *Homo erectus* at Ngandong, Java, 117,000–108,000 years ago. *Nature* 577:381–385. doi.org/10.1038/s41586-019-1863-2
- Salles, T., C. Mallard, L. Husson, S. Zahirovic, A.C. Sarr and P. Sepulchre 2021. Quaternary landscape dynamics boosted species dispersal across Southeast Asia. *Communications Earth & Environment* 2:240. doi.org/10.1038/s43247-021-00311-7
- Sarr, A.C., L. Husson, P. Sepulchre, A.M. Pastier, K. Pedoja, M. Elliot, C. Arias-Ruiz, T. Solihuddin, S. Aribowo and Susilohadi 2019. Subsiding Sundaland. *Geology* 47(2):119–122. doi.org/10.1130/G45629.1
- Shen, G., X. Gao, B. Gao and D.E. Granger 2009. Age of Zhoukoudian *Homo erectus* determined with ²⁶Al/¹⁰Be burial dating. *Nature* 458:198–200. doi.org/10.1038/nature07741
- Shipton, C., J. Blinkhorn, P.S. Breeze, P. Cuthbertson, N. Drake, H.S. Groucutt, R.P. Jennings, A. Parton, E.M. Scerri, A. Alsharekh and M.D. Petraglia 2018. Acheulean technology and landscape use at Dawadmi, central Arabia. *PLoS ONE* 13(7):e0200497. doi.org/10.1371/journal.pone.0200497
- Shipton, C., S. O'Connor and S. Kealy 2021. The biogeographic threshold of Wallacea in human evolution. *Quaternary International* 574:1–12. doi.org/10.1016/j.quaint.2020.07.028
- Smith, H.E., M.W. Morley and J. Louys 2020. Taphonomic analyses of cave breccia in southeast Asia: A review and future directions. *Open Quaternary* 6(1).
- Smith, W.H.F. and D.T. Sandwell 1997. Global sea floor topography from satellite altimetry and ship depth soundings. *Science* 277(5334):1956–1962. doi.org/10.1126/science.277.5334.1956
- Suraprasit, K., H. Bocherens, Y. Chaimanee, S. Panha and J.J. Jaeger 2018. Late Middle Pleistocene ecology and climate in northeastern Thailand inferred from the stable isotope analysis of Khok Sung herbivore tooth enamel and the land mammal cenogram. *Quaternary Science Reviews* 193:24–42. doi.org/10.1016/ j.quascirev.2018.06.004
- Swisher, C.C. III, G.H. Curtis, T. Jacob, A.G. Getty, A. Suprijo and Widiasmoro 1994. Age of the earliest known hominids in Java, Indonesia. *Science* 263(5150):1118–1121. doi.org/10.1126/science.8108729

- Tougard, C. 2001. Biogeography and migration routes of large mammal faunas in South–East Asia during the Late Middle Pleistocene: Focus on the fossil and extant faunas from Thailand. *Palaeogeography*, *Palaeoclimatology*, *Palaeoecology* 168(3–4):337–358. doi.org/10.1016/S0031-0182(00)00243-1
- Tougard, C., J.J. Jaeger, Y. Chaimanee, V. Suteethorn and S. Triamwichanon 1998. Discovery of a *Homo* sp. tooth associated with a mammalian cave fauna of Late Middle Pleistocene age, northern Thailand. *Journal of Human Evolution* 35(1):47–54. doi.org/10.1006/jhev.1998.0221
- van den Bergh, G.D., B. Li, A. Brumm, R. Grün, D. Yurnaldi, M.W. Moore, I. Kurniawan, R. Setiawan, F. Aziz, R.G. Roberts and M. Storey 2016. Earliest hominin occupation of Sulawesi, Indonesia. *Nature* 529:208–211. doi.org/10.1038/nature16448
- Verstappen H.T. 1973. A Geomorphological Reconnaissance of Sumatra and Adjacent Islands (Indonesia), Volume 1. Wolters-Noordhoff, Groningen.
- von Koenigswald G.H.R. 1935. Die fossilen Säugetierfaunen Javas. Proceedings of the Koninklijke Nederlandse Akademie van Wetenschappen 38:188–198.
- von Koenigswald G.H.R. 1939. The relationship between the fossil mammalian faunae of Java and China, with special reference to early man. *Peking Natural History Bulletin* 13:293–298.
- Wu Xinzhi 2004. On the origin of modern humans in China. *Quaternary International* 117:131–140. doi.org/ 10.1016/S1040-6182(03)00123-X
- Wu Xiu-Jie, S.W. Pei, Y.J. Cai, H.W. Tong, Q. Li, Z. Dong, J.C. Sheng, Z.T. Jin, D.D. Ma, S. Xing, X.L. Li, X. Cheng, H. Cheng, I. de la Torre, R. L. Edwards, X.C. Gong, Z.S. An and E. Trinkaus 2019. Archaic human remains from Hualongdong, China, and Middle Pleistocene human continuity and variation. *Proceedings of the National Academy of Sciences of the USA* 116(20):9820–9824. doi.org/10.1073/pnas. 1902396116
- Zhu, R.X., Z. An, R. Potts and K.A. Hoffman 2003. Magnetostratigraphic dating of early humans in China. Earth-Science Reviews 61(3–4):341–359. doi.org/10.1016/S0012-8252(02)00132-0
- Zhu, R.X., R. Potts, F. Xie, K.A. Hoffman, C.L. Deng, C.D. Shi, Y.X. Pan, H.Q. Wang, R.P. Shi, Y.C. Wang, G.H. Shi and N.Q. Wu 2004. New evidence on the earliest human presence at high northern latitudes in northeast Asia. *Nature* 431:559–562. doi.org/10.1038/nature02829
- Zhu, R.X., R. Potts, Y.X. Pan, H.T. Yao, L.Q. Lü, X. Zhao, X. Gao, L.W. Chen, F. Gao and C.L. Deng 2008. Early evidence of the genus *Homo* in East Asia. *Journal of Human Evolution* 55(6):1075–1085. doi.org/ 10.1016/j.jhevol.2008.08.005
- Zhu, Z.Y., R. Dennell, W.W. Huang, Y. Wu, Z.G. Rao, S.F. Qiu, J.B. Xie. W. Liu, S.Q. Fu, J.W. Han and H.Y. Zhou 2015. New dating of the *Homo erectus* cranium from Lantian (Gongwangling), China. *Journal of Human Evolution* 78:144–157. doi.org/10.1016/j.jhevol.2014.10.001
- Zhu, Z.Y., R. Dennell, W. Huang, Y. Wu, S. Qiu, S. Yang, Z. Rao, Y. Hou, J. Xie, J. Han and T. Ouyang 2018. Hominin occupation of the Chinese Loess Plateau since about 2.1 million years ago. *Nature* 559:608–612. doi.org/10.1038/s41586-018-0299-4

This text is taken from *Quaternary Palaeontology and Archaeology of Sumatra*, edited by Julien Louys, Paul C.H. Albers and Alexandra A.E. van der Geer, published 2024 by ANU Press, The Australian National University, Canberra, Australia.

doi.org/10.22459/TA56.2024.09