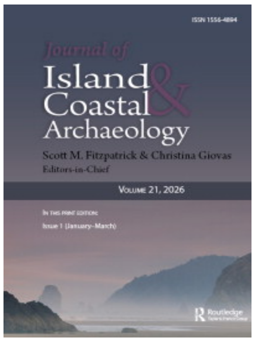

Journal of Island and Coastal Archaeology

ISSN: 1556-4894 (Print) 1556-1828 (Online) Journal homepage: www.tandfonline.com/journals/uica20

Geological controls on the preservation of fossils and archaeology in the islands of the Riau–Lingga Archipelago, Indonesia

Julien Louys, Agus T. Hascaryo, Yinika L. Perston, Mika R. Puspaningrum, Yan Rizal, Aswan, Yahdi Zaim, Benyamin P. Shidqi, Mathieu Duval, Virginia Martínez Pillado & Gilbert J. Price

To cite this article: Julien Louys, Agus T. Hascaryo, Yinika L. Perston, Mika R. Puspaningrum, Yan Rizal, Aswan, Yahdi Zaim, Benyamin P. Shidqi, Mathieu Duval, Virginia Martínez Pillado & Gilbert J. Price (05 Mar 2026): Geological controls on the preservation of fossils and archaeology in the islands of the Riau–Lingga Archipelago, Indonesia, Journal of Island and Coastal Archaeology, DOI: 10.1080/15564894.2025.2576128

To link to this article: https://doi.org/10.1080/15564894.2025.2576128

THE JOURNAL OF ISLAND AND COASTAL ARCHAEOLOGY
https://doi.org/10.1080/15564894.2025.2576128

Geological controls on the preservation of fossils and archaeology in the islands of the Riau–Lingga Archipelago, Indonesia

Julien Louys[a], Agus T. Hascaryo[b], Yinika L. Perston[c], Mika R. Puspaningrum[b], Yan Rizal[b], Aswan[b], Yahdi Zaim[b,d], Benyamin P. Shidqi[a,b], Mathieu Duval[a,e,f], Virginia Martínez Pillado[g], and Gilbert J. Price[h]

[a]Australian Research Centre for Human Evolution, Griffith University, Brisbane, Australia; [b]Department of Geological Engineering, Institut Teknologi Bandung, Bandung, Indonesia; [c]Griffith Centre for Cultural and Social Research, Art, Education and Law, Griffith University, Brisbane, Australia; [d]Department of Geology, Institute of Technology Sumatera (ITERA), Lampung, Indonesia; [e]Centro Nacional de Investigación sobre la Evolución Humana (CENIEH), Burgos, Spain; [f]Palaeoscience Labs, Department of Archaeology and History, La Trobe University, Melbourne, Australia; [g]Centro Mixto UCM-ISCIII sobre Evolución y Comportamiento Humanos, Madrid, Spain; [h]School of the Environment, The University of Queensland, Brisbane, Australia

ABSTRACT

The Riau–Lingga Archipelago, situated south of Singapore and east of Sumatra, holds promise from a modeling perspective for the preservation of *Homo erectus* and other early archaeological material, as hominins traveled south to Island Southeast Asia. The islands in the archipelago are some of the only emergent lands of the now submerged Sunda Shelf, a region ecologically and geographically conducive for early hominin and faunal movements and occupation. On the ground surveys, however, revealed very little potential for the preservation of archaeology or body fossils. This very limited preservation potential can be attributed to geological and anthropogenic controls. The dominant lithology of the archipelago is granite, which provides neither a reliable source for production of lithics nor weathers in a fashion likely to allow for long-term preservation. Chemical weathering of granites produces acidic soils, and clays and sediments produced are prone to sheet erosion which prevents the formation of soil horizons. A geologically long period of peneplanation, especially in the islands in the northern part of the archipelago, exacerbated these processes, as did large-scale deforestation in the eighteenth and nineteenth centuries for gambier cultivation. Nevertheless, this first large-scale field survey of the archipelago identified novel archaeology and fossil remains. The former includes a lithic scatter on Singkep, possibly associated with pottery sherds, as well as potential standing stones on Singkep and Kundur. Karimunbesar preserved recent rock art in addition to a well-known Sanskrit inscription, and a stone adze owned by a local villager in Lingga is of unknown and unlikely local provenance. A single fossil enamel fragment, provisionally identified as bovid, was recovered

ARTICLE HISTORY
Received 1 June 2025
Accepted 12 October 2025

KEYWORDS
Homo erectus; Sundaland; gambier; granite; peneplain

CONTACT Julien Louys j.louys@griffith.edu.au Australian Research Centre for Human Evolution, Griffith University, Brisbane, Australia.

Supplemental data for this article can be accessed online at https://doi.org/10.1080/15564894.2025.2576128.

from Lingga though its age could not be determined. Our study highlights the difficulties in locating archaeological and paleontological material on stable, tectonically inactive continental islands, with implications for efforts to understand the Pleistocene dispersal of *H. erectus*.

Introduction

The Straits of Singapore define the modern southern extent of contiguous Mainland Southeast Asia, south of which lies the Riau Archipelago and the northern limit of Island Southeast Asia. It is therefore a highly significant region for understanding past faunal and human exchanges between these two regions. While the Straits currently prevents overland movement from Mainland to Island Southeast Asia, this is a relatively geologically recent phenomenon. No barriers to dispersal existed in the Straits of Singapore until Marine Isotope Stage (MIS) 5 (ca. 80–130 ka) based on bathymetric data (Bird, Pang, and Lambeck 2006), and reconstructions of past sea levels indicate broad terrestrial connections across Sumatra, Singapore, and Peninsula Malaysia for most of the Quaternary (Louys and Kealy 2024; Salles et al. 2021), although major rivers were present (Voris 2000).

Despite the central paleogeographical position of this region, little is known of its Quaternary vertebrate fossil or archaeological record. Two areas in Singapore, Pulau Ubin and Tanjong Karang (now Tuas), have produced surface finds of ground stone axes considered typical of the Southeast Asian Neolithic (Miksic 2021; Tweedie 1953); however, these have never been formally described or dated. An undated excavation a short distance away at the mainland Malaysian site of Tanjong Bunga, briefly reported by Tweedie (1953), yielded more reliably Neolithic stone tools, including ground axes and quadrangular adzes. On the southern side of the Strait, three substantial shell middens associated with the Hoabinhian have been recognized on the island of Bintan (Simatupang et al. 2017). The Kawal Darat shell middens are approximately 5 km from the modern coastline in the Gunung Kijang District in eastern Bintan Island. Although Kawal Darat Shell Middens II and III have been lost to agriculture, Midden I remains largely intact. It is very large, measuring ca. 4 m thick and 18 m across, and partial excavation showed the midden may span approximately 400 years to 12,000 years ago as indicated by radiocarbon dating (Simatupang et al. 2017), although geochronological uncertainties exist due to limited details on sample origins within the midden as well as unaccounted marine reservoir effects. While mollusks are yet to be taxonomically identified beyond family level, the presence of unifacial discoids identified as sumatraliths in conjunction with other stone artifacts suggests the site is part of the late Pleistocene to Holocene Hoabinhian technocomplex (Simatupang et al. 2017).

Earlier Pleistocene records of either humans or other fauna are non-existent. Despite that, the importance of the region for this earlier period was highlighted by Louys and Kealy (2024), who examined least cost pathway dispersal models for *Homo erectus* and other large faunas between northern Southeast Asia and Java. While central Sundaland was the likely preferred pathway during periods of lowest sea levels and maximum land connectivity (and see Berghuis et al. (2025) for physical evidence of

H. erectus from drowned deposits in Sundaland near Java), in other paleogeographic contexts, the least cost pathways crossed at or near the Straits as well as several islands in the Riau and Lingga archipelagos (Figure 1). The latter were identified as likely areas for further physical exploration (Louys and Kealy 2024, Figure 9.8). The reconstructions of settlements or activity areas and, by inference, populations and migration patterns from the archaeological record require a full understanding of the geological forces and history that have shaped that record (Waters and Kuehn 1996). Here, we detail the results of our survey efforts in this region and use our geological observations to inform on the likely controls for preservation of fossils and archaeology in these small, tectonically stable continental islands.

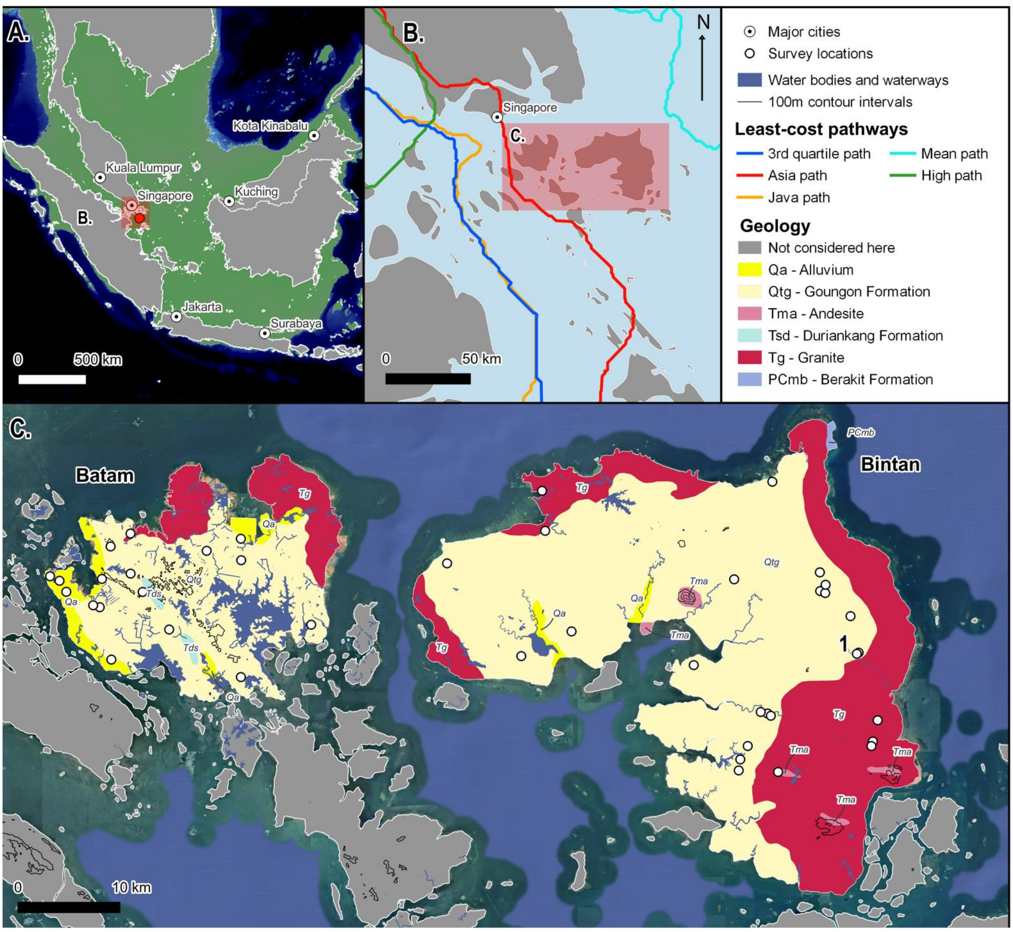

Figure 1. Map of Batam and Bintan in the Riau–Lingga Archipelago. (A) Regional location of study area, with green showing the extent of the exposed Sunda plain during the Last Glacial Maximum. (B) Locations of islands surveyed showing least cost pathway models of *Homo erectus* moving south from Mainland Southeast Asia to Java (from Louys and Kealy 2024). (C) Geological maps of Batam and Bintan showing survey locations (adapted from Kusnama et al. 1994). Specific locations mentioned in the text: 1, Bukit Kerang Kawal Darat. Base map: Natural Earth, Indonesian islands: Hijmans and University of California, Berkeley, Museum of Vertebrate Zoology (2015); contours: SRTM 1 Arc-Second Global, USGS; waterways: Open Street Map; Sea level curves Lambeck et al. (2014); Digital elevation model: GEBCO Bathymetric Compilation Group (GEBCO), 2024).

Geography

The Riau Island Group (Kepulauan Riau) is an administrative province of Indonesia situated south of Singapore, east of Riau and Jambi in Sumatra, and including islands between Kalimantan (Borneo) and the Malay Peninsula (Figures 1–3). It comprises more than 2000 islands, 300 of which are found in the Riau Archipelago (also known as Kepulauan Riau)—the core group of islands found south of Singapore and east of Riau,

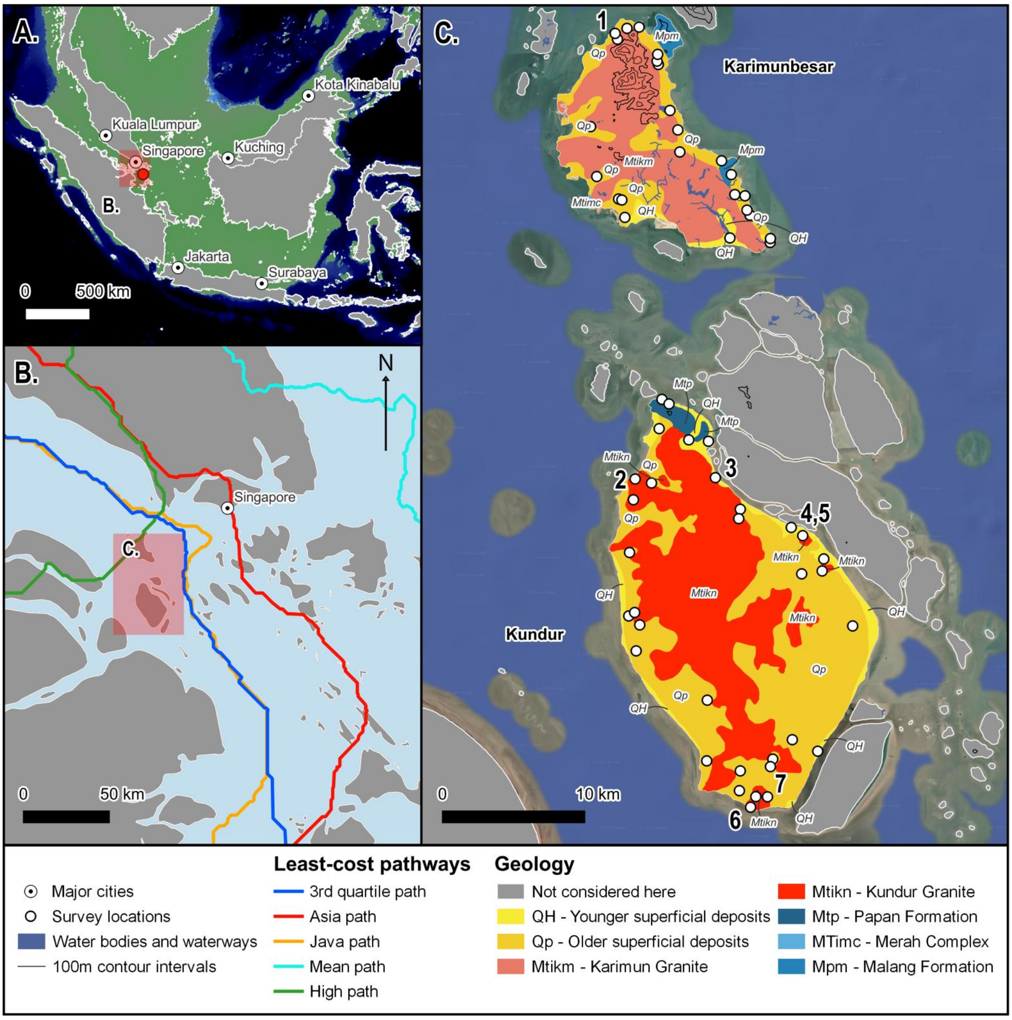

Figure 2. Map of Karimunbesar and Kundur in the Riau–Lingga Archipelago. (A) Regional location of study area, with green showing the extent of the exposed Sunda plain during the Last Glacial Maximum. (B) Locations of islands surveyed showing least cost pathway models of *Homo erectus* moving south from Mainland Southeast Asia to Java (from Louys and Kealy 2024). (C) Geological maps of Karimunbesar and Kundur showing survey locations (adapted from Cameron, Ghazali, and Thompson 1982a, 1982b). Specific locations mentioned in the text: 1, Pasir Panjang and recent rock art; 2–6, Kundur pH sampling locations; 7, Kundur standing stone. Base map: Natural Earth, Indonesian islands: Hijmans and University of California, Berkeley, Museum of Vertebrate Zoology (2015); contours: SRTM 1 Arc-Second Global, USGS; waterways: Open Street Map; Sea level curves Lambeck et al. (2014); Digital elevation model: GEBCO Bathymetric Compilation Group (2024).

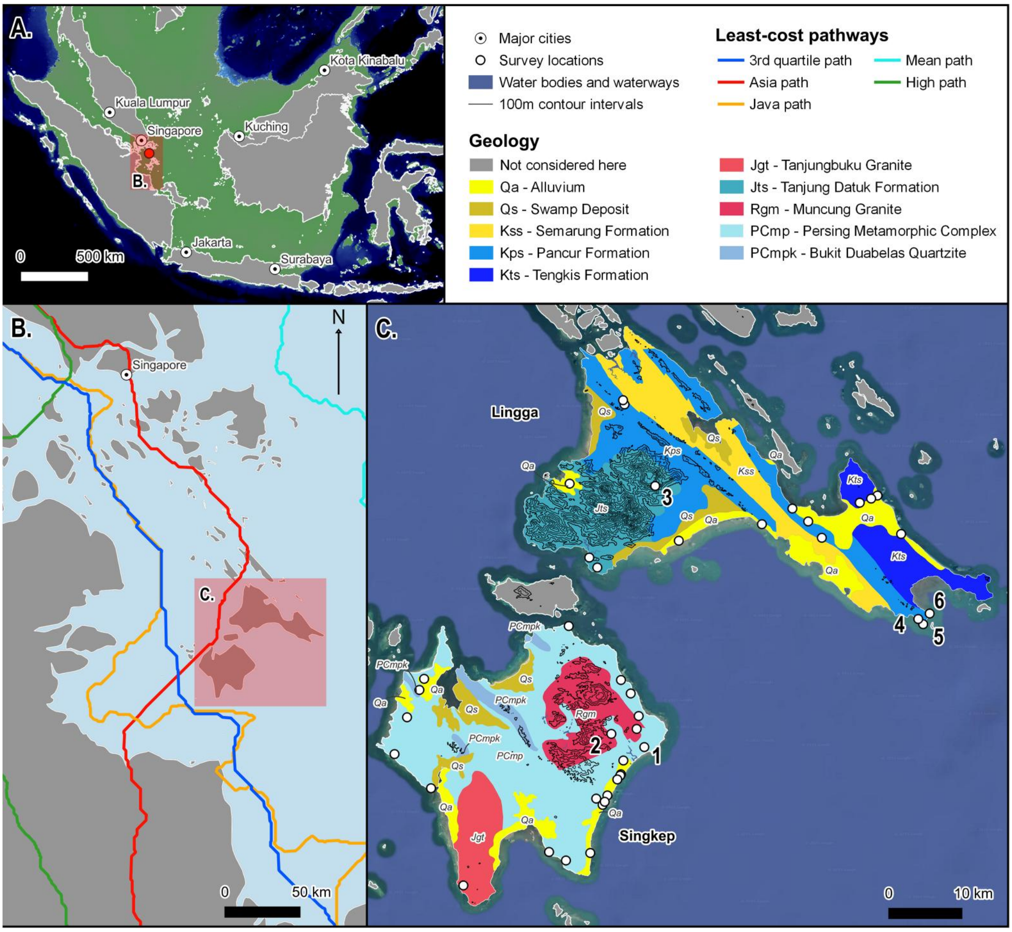

Figure 3. Map of Lingga and Singkep in the Riau–Lingga Archipelago. (A) Regional location of study area, with green showing the extent of the exposed Sunda plain during the Last Glacial Maximum. (B) Locations of islands surveyed showing least cost pathway models of *Homo erectus* moving south from Mainland Southeast Asia to Java (from Louys and Kealy 2024). C. Geological maps of Lingga and Singkep showing survey locations (adapted from Sutisna, Burhan, and Hermanto 1995). Specific locations mentioned in the text: 1, Dabo lithic and pottery scatter; 2, Singkep standing stone; 3, Goa Kelelawar; 4, Goa Pegang; 5, Goa Kukar; 6, Goa Tanjung Kubang. Base map: Natural Earth, Indonesian islands: Hijmans and University of California, Berkeley, Museum of Vertebrate Zoology (2015); contours: SRTM 1 Arc-Second Global, USGS; waterways: Open Street Map; Sea level curves Lambeck et al. (2014); Digital elevation model: GEBCO Bathymetric Compilation Group (2024).

Sumatra. Here, we focus on the Riau Archipelago and Lingga islands (hereafter Riau–Lingga Archipelago), with particular emphasis on the islands of Batam, Bintan, Kundur, Karimunbesar, Singkep, and Lingga.

The Riau–Lingga Archipelago straddles the equator, crossing at the northern part of Lingga Island. The region has a diverse population of more than 2 million people, with Malay, Javanese, Batak, Minangkabau, and Chinese ethnic groups making up most of the population, with the highest density of occupation occurring on the island of Batam, followed by Bintan where the capital of the province is situated. The islands are generally low-lying, with hills commonly separated by broad marshy areas. The highest point is Mount Daik on Lingga (1165 m); in the Riau islands the hills are generally much lower: typically 50–80 m in elevation and not higher than 450 m (Johnson and Marjono 1963; Figures 1 and 2). The province has a wet tropical climate and is affected by strong winds during both the northern and southern monsoons. Average rainfall varies but in normal years no month has less than 100 mm; annual rainfall can vary from approximately ca. 2600 to 3500 mm.

The original vegetation of the islands was tropical rainforest, but large areas have been removed to make way for plantations, agriculture, mining, and urban development (Colombijn 1997). While some areas of cut-over land on the small islands have reverted to secondary forests, on the main islands such as Bintan, rainfall, land use (predominately settlement, followed by farming), and soil type contribute greatly to erosional rates that average 4.7 t/ha/yr (in 2014–2018; Mulyono et al. 2021), well above the maximum amount that would allow for new soil formation (0.5 t/ha/yr; Lehmann 1993). Natural resources are few, but bauxite is currently mined.

Regional geological history

The oldest rocks in the archipelago predate the massive Triassic granitic intrusions that dominate the geology of the region and include possible Permo-Carboniferous outcrops on the islands of Bulan, Batam, and southwest Lingga, in the form of shales with metamorphic rhyolites, dactites, and tuffs (Van Bemmelen 1949). A Permo-Carboniferous age for these units was suggested by correlation with similar Permo-Triassic rocks in Malaysia and those of the Upper Jambi Nappe of Sumatra (Zwierzycki 1930). However, Zeylmans van Emmichoven (1938) suggested that the volcanics were more typical of the Triassic of west Kalimantan, suggesting a later Triassic age for the outcrops. Other Permo-Carboniferous rocks could include phylittic and sandy formations with volcanic intercalations comparable to the Pahang Volcanic Series (Van Bemmelen 1949), found on Batam, Bintan, and other nearby islands, although some of these outcrops may also be Triassic in age (Bothé 1925). Further indications of pre-Carboniferous rocks are represented by crystalline schists in Songkop (Van Bemmelen 1949). Carboniferous rocks could include contact-metamorphic limestones on Karimunbesar (Bothé 1925).

The Permo-Carboniferous outcrops in the Riau Archipelago are likely associated with a major orogenesis during the latest Permian–Middle Triassic interval, interpreted by Metcalfe (2013) to represent collisions between the Sukhothai Arc and Indochina, and between Sibumasu and the Sukhothai Arc. Clastic sediments including sandstones, conglomerates, shales, and greywackes found on Sugi, Combol, and Citlim were thought younger than this orogeny, as they were not associated with regional metamorphic suites and assigned to the Triassic by Van Wessem (1941). They were tentatively associated with the Jurassic by Van Bemmelen (1949), on the presumption that they post-dated this orogeny and were related to greywackes of the Tigapuluh Mountains of Sumatra. Much of the sedimentary units exposed in Kundur, Karimunbesar, Bintan, and Batam are dominated by sandstone but include siltstones, shales, and conglomerates. They are variously interpreted as pre- or post-granitic, and thus Triassic or post-Triassic in age, in relation to the major granitic intrusions formed around 230 Ma (Metcalfe 2017). Rocks intruded by granites or showing regional metamorphism are considered pre-Triassic, while unmetamorphosed sedimentary rocks adjacent to or overlying granites are considered younger (Johnson and Marjono 1963). Unconformable relations between Triassic and post-Triassic rocks have been reported but are considered by some as unreliable (Van Bemmelen 1949). The Triassic sediments are thought to have been largely deposited in shallow marine conditions (Van Bemmelen 1949), while post-intrusive units are lenticular and cross-bedded, arkosic with rare fragments of carbonized wood and plant material indicative of deltaic conditions (Johnson and Marjono 1963).

Most of the granites in the northern islands of the Riau–Lingga Archipelago are of the non-stanniferous I-types and form part of the Indonesian Tin Belt, but stanniferous S-types are also present on the island of Kundur and at the southwest tip of Singkep (Cobbing 2005). The I-type granites are subduction-related Middle Permian to early Late Triassic in age and intrude the Sukhothai Arc and Indochina margin (Metcalfe 2017). S-Type granites, of mainly Late Triassic age, were formed during the Indosinian Orogeny, where a collision between Sibumasu and the Sukhothai Arc and Indochina caused the Sibumasu continental crust to become thickened and melt, producing voluminous magmatic intrusions (Metcalfe 2017). Subsequent weathering of syenitic granites produced extensive bauxite concretions in much of the Archipelago.

A long period of peneplanation followed the Indosinian Orogeny, with the later part of the Mesozoic probably accounting for much of the sandstone and other terrestrial sedimentary outcrops in the Riau islands, while the Paleogene likely saw large-scale movement of sediments from Sundaland to the downwarps of Kalimantan, Java, and Sumatra (Van Bemmelen 1949). Prior to the subsidence of Sundaland around 400 ka (Sarr et al. 2019), the "Old Alluvium of Singapore," a widespread marker of lower sea levels, indicates that considerable relief, seasonal rainfall, and extremely active erosional processes acted on the granites (Gupta et al. 1987; Kamaludin et al. 1993). Paleomagnetic dating suggests that the Old Alluvium was deposited predominantly during the Matuyama reversed Chron (0.78–2.58 Ma; Batchelor 1988, 2015). The Old Alluvium consists of deeply weathered, highly consolidated, but not lithified fluviatile sediments and represents the oldest Quaternary sediments in peninsular Malaysia, Singapore, and the Riau islands; they are widely distributed both onshore and offshore (Gupta et al. 1987). They may correspond to parts of the Goungon Formation found predominately on Batam and Bintan. Following the subsidence of Sundaland, the region would have experienced island conditions, with intermittent periods of connectivity between the Riau–Lingga Archipelago, Singapore, Peninsular Malaysia, and Sumatra during glacial periods. Evidence of inundation of the Sunda plain following the Last Glacial Maximum (LGM) has been recovered from the Putri islands north of Batam, in the form of near-shore GPR evidence of transgression and a corresponding change in depositional facies from fluvial to coastal plains (Hernawan, Geurhaneu, and Zulfikar 2019).

Geology of Palau Batam and Palau Bintan

The geology of Batam and Bintan is summarized by Bothé (1925), Kusnama et al. (1994), Van der Bold and Van der Sluys (1942; Batam), Van Bemmelen (1940, 1941; Bintan), and Hermes and de Vletter (1942; Bintan). The geological map of the island of Batam shows four major geological units: the late Triassic Duriangkang Formation, consisting of shale and alternated with poorly sorted and strongly cemented sandstone; late Triassic granites; the Plio-Pleistocene Goungon Formation, consisting of white tuffaceous sandstone with some reddish white tuff and grey siltstone; and Quaternary alluvium on the north and northwest coast (Kusnama et al. 1994; Figure 1). The geology of Bintan is similar to Batam, except that the Duriangkang Formation is absent from the former, and with small outcrops of andesite present (Kusnama et al. 1994). Both islands are dominated by the Goungon Formation, which may in parts correspond to Roggeveen's "Central Batam Formation" as shown in the map according to Van der Bold and Van der Sluys (1942). This suggests that some of the sedimentary beds observed on the island and marked Plio-Pleistocene on the geological maps are in fact Triassic (Bintan Formation, sensu Jongmans 1951)—these may perhaps be identified by the dips in their formation (Van Bemmelen 1949) as well as plant fossils found in carbonaceous beds of the alternating shale and sandstone layers (Jongmans 1951; Wade-Murphy and van Konijnenburg-van Cittert 2008). No further published details on Quaternary outcrops were found.

Geology of Palau Kundur and Palau Karimunbesar

The geology of Kundur and Karimunbesar is summarized by Cameron, Ghazali, and Thompson (1982a, 1982b), Germeraad (1941; Kundur), and Raadshooven and Swart (1941; Karimunbesar). Kundur is dominated by granite outcrops; along with both older and younger surficial sediments (clays, silts, gravels, granite sands; Cameron, Ghazali, and Thompson (1982a)). The Papan Formation (shales and other granite contacts) have been mapped in the northern tip of the island (Cameron, Ghazali, and Thompson 1982a) and extend along most of Bela Island. The geology of Karimunbesar is very similar to that of Kundur; the only noteworthy differences are older (possibly Permian) schists (Tapanuli Group; Cameron, Ghazali, and Thompson 1982b) found on the Malolo Peninsula in the southeast of the island (Raadshooven and Swart 1941). No further published details on Quaternary outcrops were found.

Geology of Palau Lingga and Palau Singkep

The geology of these two islands is provided by Sutisna, Burhan, and Hermanto (1995). The oldest rocks are low grade metamorphic rocks (phyllite and schist) with alternating quartzite and slate of the Permo-Carboniferous Persing Metamorphic Complex possibly related to the schists found on Karimunbesar. This unit dominates Singkep and is intruded on that island by Triassic granites. In Lingga, a low-grade metamorphic unit, the Tanjungdatuk Formation, is found on the southwest of the island with no evidence of intrusion by the Triassic granites—a Jurassic age for these is suggested, with a series of thick (2000–2500 m) sandstone and shale units overlying this formation unconformably. These are presumed Cretaceous based on stratigraphic grounds, with Quaternary swamp and alluvium situated unconformably on top. Some unconformably deposited Quaternary and swamp units are also noted for Singkep, but no independent age controls for these sediments are available and no further published details on Quaternary outcrops were found.

Field survey

We selected potential geological outcrops from satellite imagery showing obvious exposures. Travel to outcrops was by vehicle and on foot. Outcrop coordinates were recorded by GPS and any relevant geological, paleontological, or archaeological features noted. Samples were taken opportunistically where relevant.

Palau Batam and Palau Bintan

Most sedimentary outcrops on Batam were characterized by red, yellow, and white clays (Figure 4D), with some coarser-grained sediments included, usually in thin bands, but thicker conglomerate beds were observed in the center of the island. The source of sediments is likely from *in situ* and minimally traveled, heavily weathered, and chemically altered granitic outcrops reminiscent of the west coast of Bangka and probably relates to the Plio-Pleistocene Goungon Formation. More lithified outcrops observed share the same characteristics as the unconsolidated sediments described above, except beds show steep inclination, anticlines, etc. of the bedding planes, indicating they likely predate the Triassic granites (Figure 4C). Toward the east of Batam, clays were more massive and heavily lateralized. More recent primary sedimentological contexts observed were swamp/estuarine depositional environments and probably date to the Holocene. In all cases, the sedimentary beds observed were not favorable to Quaternary fossil preservation nor to the generation and preservation of lithics, and none were recorded.

The outcrops on Bintan were likewise characterized by heavily altered granites and minimally transported clays, conditions again not conducive to fossil or archaeological preservation, although extensive rhizoliths and some copal were present on the surface of some outcrops indicating more recent deltaic conditions like those observed in Jambi province in mainland Sumatra (Louys et al. 2021). Rare channel deposits with finely laminated crossbedding sitting unconformably on conglomerate, in turn unconformably atop a weathered granite, were also recorded, but without any evidence of fossil or archaeological inclusions. In the east of Bintan the topography is very flat (Figure 4I), and although we observed some transgressed shorelines, these are likely mid- to late-Holocene based on their proximity and orientation relative to modern shorelines and outcropping unweathered and unconsolidated sands. Previous studies at Tanjungpinang on the island's soil characteristics (Danardono, Taryono, and Ridwan 2024) indicated very acidic soils (pH less than 4.5) with high permeability, and high surface rock values indicating common and widespread sheet erosion. None of these characteristics are conducive for the preservation of faunal remains or archaeological deposits. The only significant archaeology observed on the island is the previously discussed and excavated midden in the central east of the island—Bukit Kerang Kawal Darat (Simatupang et al. 2017).

Palau Karimunbesar and Palau Kundur

The vegetation on Karimunbesar is more open and drier than the more eastern islands of the archipelago. Outcrops are similar to Batam and Bintan, but with more poorly sorted sediments, including coarser sand and gravels, with the addition of prominent

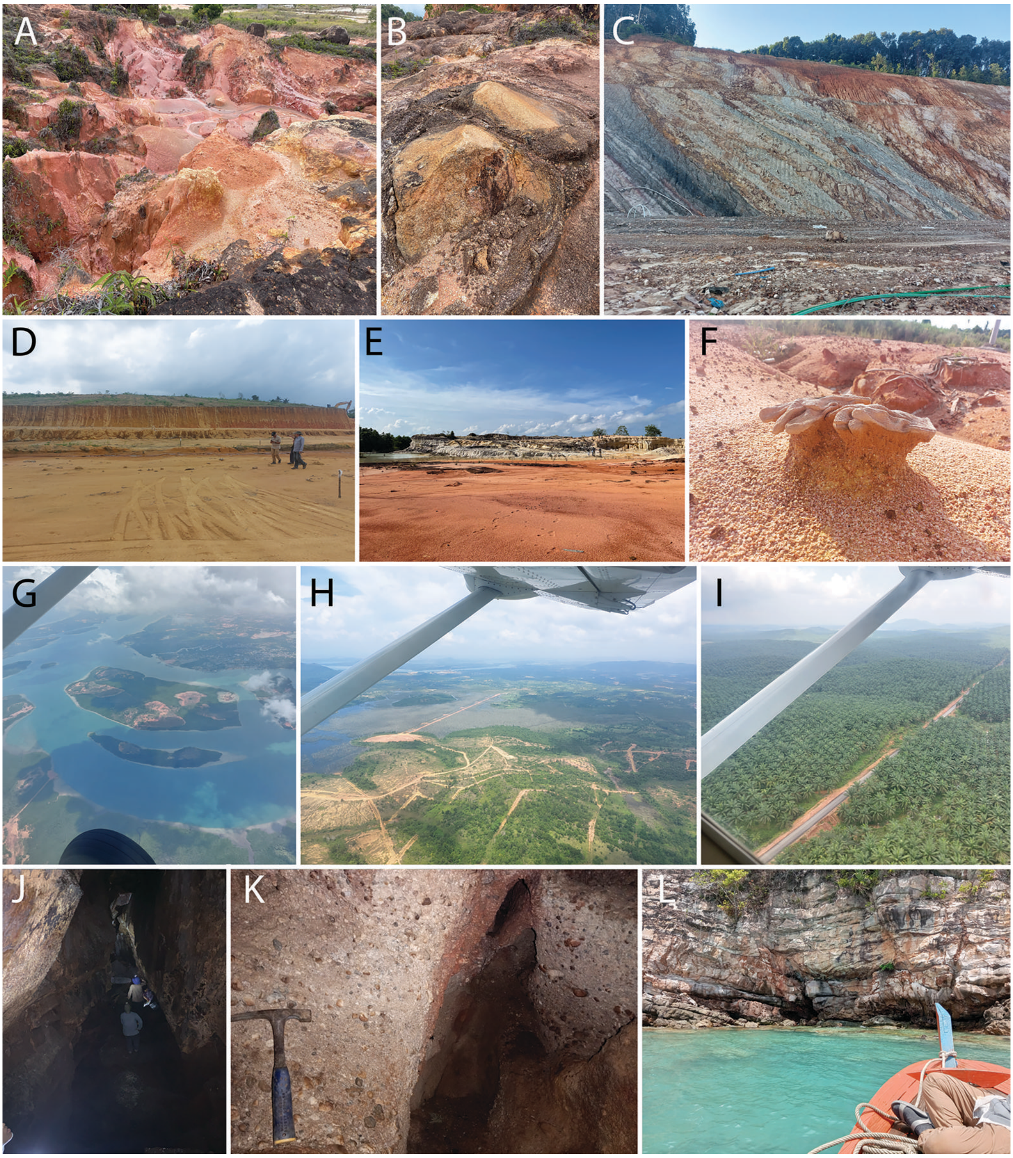

Figure 4. Outcrops and landforms. (A) Weathering of a granite outcrop in Karimunbesar. (B) Granodiorite xenolith weathering out of granite, Karimunbesar. (C) Highly tilted sedimentary beds likely predating the Triassic granites, Batam. (D) Cutting showing the lateralized soils of the peneplain, Karimunbesar. (E) Heavily weathered and actively eroding sands unconformably overlying clays, Bintan. (F) Gloves demonstrating the rapid erosional rates in the region, Bintan. (G, H, and I) Aerial views of the peneplains of Bintan. (J) Interior of Goa Kelelawar. (K) Interior of Goa Pegang. (L) Entrance of Goa Kukar.

granite outcrops. Some of the granite is undergoing heavy chemical weathering, producing the lateralized clays and quartz outcrops observed elsewhere on the island (Figure 4A). Granodiorite xenoliths formed within the granite (Figure 4B) are harder and weather out more completely, producing the only large cobbles observed. Chemical weathering of granites can produce soils with a complex mix of kaolinite, gibbsite, illite, quartz, vermiculite, feldspar, and amorphous material (Middelburg, van der Weijden, and Woittiez 1988).

More recent fluvial outcrops observed produced extensive unconsolidated sand deposits; these are likely young as evidenced by observations of vertical and unfossilized wooden stumps. The only archaeology observed on Karimunbesar is the well-known Pasir Panjang inscription, a Sanskrit lithograph first reported in the scientific literature in 1873 (Caldwell and Hazlewood 1994), as well as painted rock art nearby (Figure 5). The latter depicts a stylized skull and crossbones in white paint on top of a granite boulder. The skullcap appears to have been removed from the figure, and the clenched teeth hold what appears to be a pipe out of the left half of the mouth. This motif, the medium, and its placement on the top of what appears to be a recently displaced granite boulder indicates that this rock art is probably quite young. It differs notably from other anthropomorphic figures depicted in white paint from western Sumatra, for example the stick figures from Lida Ajer, tentatively attributed to relatively recent Islamic tariqh rituals (Arifin and Permana 2022), and a salamander-like anthropomorphic depiction in Ngalau Sirantai of unknown age but likely also relatively recent (Figure 2).

Kundur is comparatively flat (Germeraad 1941) although with similar geology to Karimunbesar. Five sediment samples from eroded granites and colluvium provided an average pH of 4.7 (Figure 1), much like the soil chemistry from Bintan. We observed a heavily metamorphosed outcrop at the northwestern tip of the island, consisting of slate, shale, and weathered clays, likely related to the Tapanuli Group. A very poorly sorted, highly angular colluvium sits unconformably on top of this group; similar colluvium was observed on top of some weathered granite outcrops. Our surveys revealed what appears to be a megalith or standing stone in the south of the island (Figure 6), identified as such due to its isolated and vertical appearance notably different from the

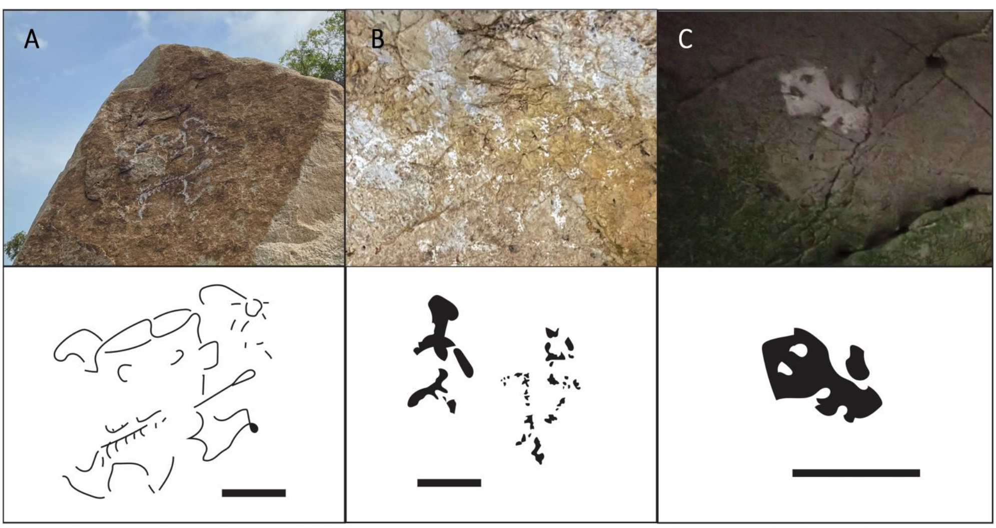

Figure 5. White rock art examples found in Riau–Lingga Archipelago and Sumatra. (A) Karimunbesar skull and bones motif. (B) Anthropomorphs in Lida Ajer, Padang Highlands. (C) Theriomorph in Ngalau Sirantai, Padang Highlands. Scale bar = 5 cm.

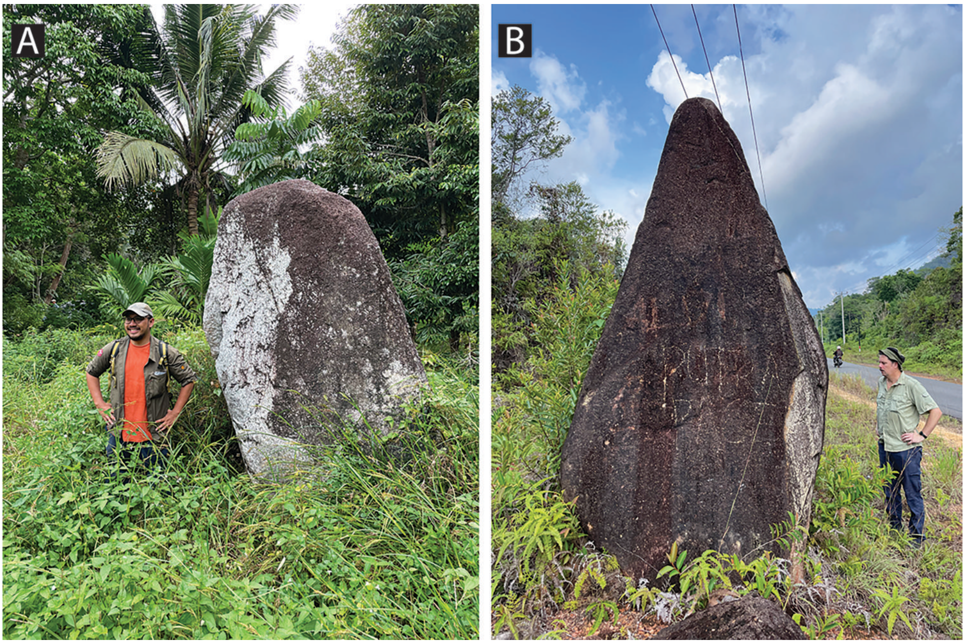

Figure 6. Possible standing stones in Riau–Lingga Archipelago, with authors for scale. (A) Kundur standing stone. (B) Singkep standing stone.

surrounding geography. Although megaliths have been widely reported from the central Sumatra highlands (Bonatz 2024), if verified, this standing stone would represent the first such record for the Riau–Lingga Archipelago. Potential engravings, in the form of triangles and vertical and horizontal lines were observed but difficult to confidently differentiate from natural erosional patterns. Excavations and further surveys for megaliths in the region are needed to establish if this is a genuine standing stone and if so, if these hold the same ritual/community significance as those from the highlands.

Palau Singkep and Palau Lingga

Unlike the northern islands surveyed above, Singkep and Lingga are more mountainous and densely vegetated, particularly Lingga. On Singkep, we observed outcrops with weathered metamorphic clays and abundant rhizoliths. Some fluvial sands were noted in outcrops close to the ocean, with rare bedding preserved. These sands do not preserve anything fossiliferous or archaeological.

Lithic scatter

Just outside the town of Dabo we observed a weathered clay outcrop with abundant copal eroding out of the sediments. At this outcrop, a surface scatter of 100 artifacts from what appears to be a single reduction event were recovered. The material was white with a light green tint when originally recovered (Figure 7), however it became a dark, smoky black when gamma irradiated (50.0 kGy minimum) for Australian quarantine purposes. This suggests the raw material is a quartz with aluminum impurities, as

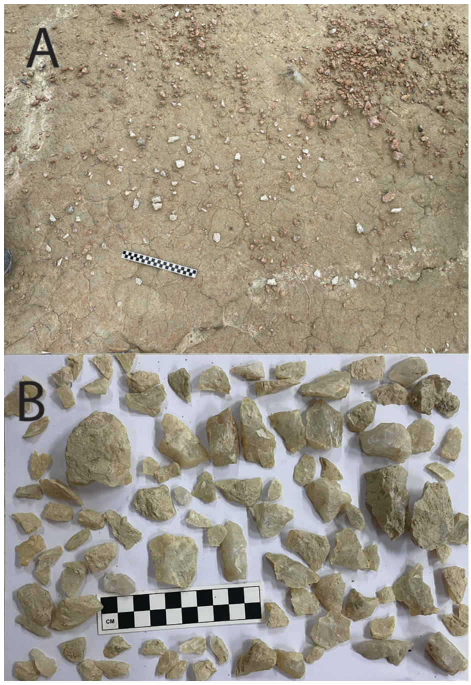

Figure 7. Dabo lithic scatter. (A) As observed *in situ* in the field. (B) Aggregated in the lab prior to irradiation.

irradiation can displace unpaired electrons associated with aluminum inclusions in the crystal lattice, thus changing the amount of absorption of the visible light spectrum and producing a smoky or "morion" quartz (e.g., Lameiras 2012; O'Brien 1955). The source of this quartz is likely the locally occurring quartz veins found in the Persing Complex but might also be quartzite from the more distant Bukit Duabelas units.

Unlike most raw materials favored for flintknapping, quartz has a crystalline structure that affects the fracture path making it difficult to identify deliberate breakage, with experiments showing up to 90–92% pieces in a flaked assemblage may lack features diagnostic of deliberate stone flaking (Moore 1997; Spry et al. 2022). Despite this, 64% of the Riau surface scatter ($n = 64$) could be classified as flakes, as well as one core, while the remaining 35% ($n = 35$) were unidentified pieces but assumed to be the results of deliberate stone-flaking given the context (Supplementary Table S1). The identifiable flakes have a recognizable platform and initiation features, including conchoidal as well as bending and wedging initiations (see Cotterell and Kamminga 1987), dorsal scars, acute exterior platform angle, and the flakes tended to target areas of high mass (after Moore 2010) (Figure 8A–D). Further, the artifacts lacked the extensive shearing one would expect to see if they had been formed by incidental crushing from heavy machinery or trampling (e.g., van der Walt and Bradfield 2018).

Two conjoin sets were identified, providing strong evidence that these are deliberately flaked hand-made stone artifacts (Figure 8E and F). Both conjoin sets, one of two flakes and one of three, show controlled blows placed sequentially behind and offset from the prior flake to target zones of high mass. Note that we use "conjoin" to refer to two pieces that were separated by flaking, while "refit" describes two pieces of a single

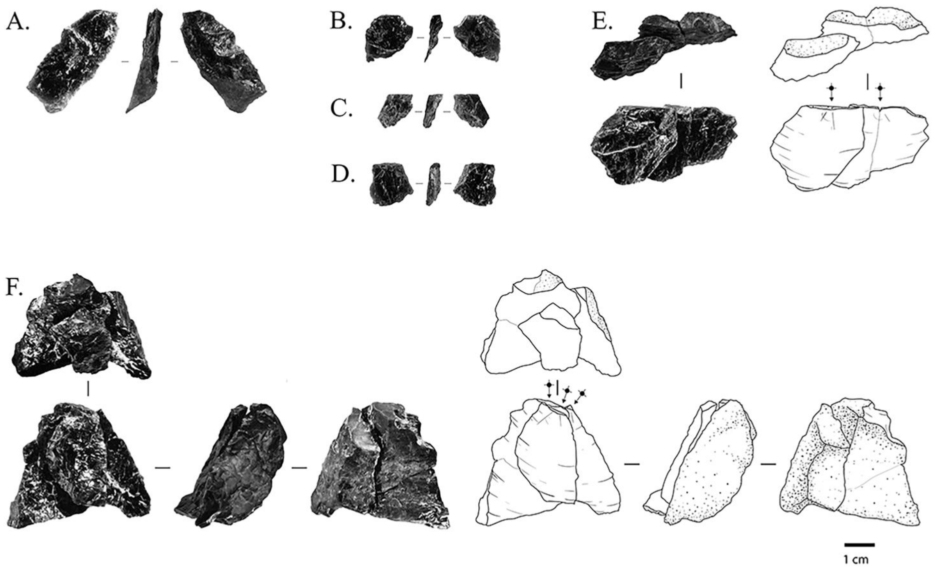

Figure 8. Dabo lithic assemblage. (A–D) Flakes, blackened by irradiation. (E and F) Conjoin sets (irradiated). Set E includes a flake broken by a siret fracture.

broken artifact that can be fitted back together. Two broken flakes could be refitted, including a flake within the smaller conjoin set that was broken by a siret fracture, a longitudinal break that forms during initiation often when the stone is struck with too much force (Inizan et al. 1999; Tsirk 2010). Eleven of the artifacts in this assemblage had siret fractures. Despite an extensive effort, these were the only conjoins and refits identified, suggesting that some artifacts are missing from the assemblage.

The artifact technology is straightforward, with flakes struck from single-facet and cortical platforms of an average depth of 3.38 ± 2.46 mm (mean ± SD), with no clear signs of platform preparation or bipolar reduction. It appears that at least one piece of water-rolled cobble with some natural flaw-line facets was reduced on-site. The unbroken flakes have an average size of 20.59 ± 7.62 mm long, 18.93 ± 7.48 mm wide, 6.75 ± 2.78 mm thick, and of the entire assemblage each piece had an average weight of 3.40 ± 5.80 grams. The core was bifacially flaked along a single platform edge; however, a single redirecting flake with prior scars at the distal end demonstrates that at some point during reduction a multiplatform core was flipped. It is impossible to estimate the age of this assemblage from the technology, though the flintknapper clearly had enough skill and experience to successfully reduce a difficult raw material to produce many sharp-edged artifacts.

Other archaeological finds

Near the artifact scatter and on top of the same geomorphic landscape, we also recovered six pottery sherds. These are kaolinite covered fired clay displaying even broken edges, with some red finish more pronounced in some pieces (Figure 9). The sherds are composed of sand-clay particles, including mica, feldspar, quartz contained in a black matrix suggesting a reducing environment during firing. The sherds had variable lengths

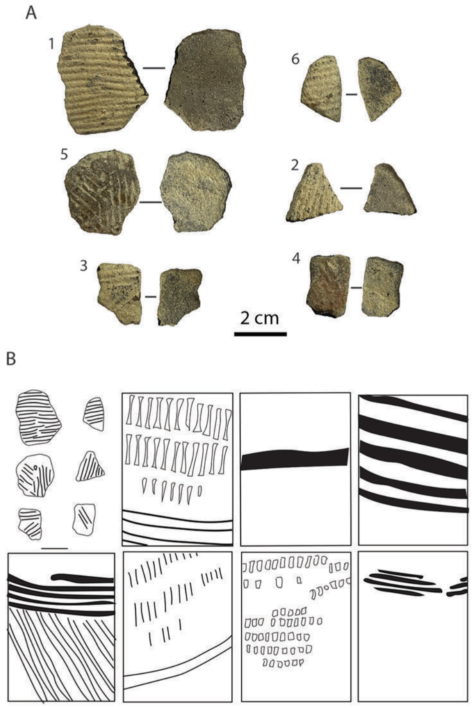

Figure 9. Pottery from Riau–Lingga Archipelago. (A) Six pottery sherds from Dabo, Singkep Island. (B) Pottery motifs from Dabo sherds (top left) and recent pottery housed in the Museum Linggam Cahaya.

Table 1. Riau pottery assemblage statistics.

No.	Length (mm)	Width (mm)	Thickness (mm)	Mass (g)
1	40.8	31.7	3.8	5.2
2	23.3	19.6	3.4	1.3
3	23.5	17.2	4.2	1.7
4	24.4	15.9	4.3	1.6
5	33.3	28.4	3.6	2.9
6	25.7	15.9	2.8	1.0
Average	28.5	21.5	3.7	2.3
Standard Deviation	7.1	6.9	0.5	1.6

and widths, 28.5 ± 7.1 mm (mean ± SD) and 21.4 ± 6.9, respectively, but a relatively uniform average thickness of 3.7 ± 0.5 mm (Table 1). They are simply decorated with linear parallel motifs like some observed in modern pottery housed in the Museum Linggam Cahaya (Figure 9) and are likely associated with the Bau-Malay pottery tradition which spread through the region from AD 700 onwards (Solheim 1990).

A second standing stone was observed in a road cutting in Batu Kacang (Figure 6B). However, its placement within the road cutting and adjacent to a major thoroughfare makes it seem unlikely that it remains in its original context.

On Lingga, river conglomerates were present, and especially abundant in riverbeds and banks, but we did not observe *in situ* archaeology. We were shown a stone adze owned by a local villager, but its exact provenance is unknown, and it resembles adzes

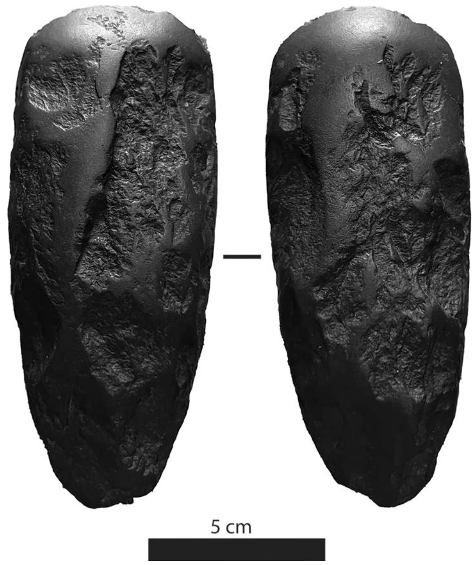

Figure 10. Adze owned by local villager in Lingga, provenance unknown.

found in the Pacific (Figure 10). Otherwise, outcrops were predominately composed of clays and weathered paraschists.

Lingga caves

Several caves on Lingga were identified as potential locums for faunal accumulation, including Goa Kelelawar, Goa Pegang Cave, Goa Kukar, and Goa Tanjung Kubang (Figures 3 and 4J–L). Goa Kelelawar is in the Daik Mountain region at an elevation of approximately 600 m above sea level. The cave was formed from the collapse of fault walls within metasedimentary rock debris (Figure 4J), primarily conglomerates. No sedimentary deposits or fossil evidence of past life were observed within the cave, except for accumulations of bat guano which is used by the local community as fertilizer. The absence of any vertebrate accumulation is presumed to be due to the cave's location in an area characterized by steep and rugged terrain, which reduces preservation potential due to high energy run off and thus erosional processes, as well as posing a challenge for access by medium to large-sized fauna (nor was there any evidence of small to medium-sized fauna [e.g., porcupines, rats, monkeys] in the surrounding area).

Goa Pegang is situated near the coastline; it is formed from the erosion of a fault scarp in a metasediment fluvial deposit (Figure 4F) and is inundated with seawater during high tide. Sedimentary layers within the cave are interpreted as coarse grained, poorly sorted coastal or fluvial deposits, with no evidence of fauna. Outside the cave and near the entrance, a conglomerate outcrop was observed, with a single enamel fragment identified in the field preserved (Figure 11). The enamel exhibits characteristics typical of the buccal side of a bovid upper molar, as indicated by its flat surface with a slight ridge. However, the specimen consists of only a single enamel fragment, which makes precise taxonomic and anatomical identification impossible, and unfortunately

Figure 11. Enamel fragment found outside Pegang Cave, Lingga, provisionally identified as bovid and indicated by red arrow; inset: enamel fragment, scale bar = 1 cm.

efforts to recover datable material for U-series and ESR dating methods (e.g., Duval et al. 2021; Louys et al. 2022) were unsuccessful.

Goa Kukar (Figure 4L) and Goa Tanjung Kubang are located along the shoreline and appear as elongated fissures formed by faulting in sandstone and paraschist bedrock, respectively. These caves were inaccessible due to submersion by seawater.

Discussion

At the global level, the distribution of fossil and archaeological deposits is not uniform through space or time due to biological, geological, and anthropological processes operating at different spatial and temporal scales. As a result, certain areas contain dense concentrations of sites, whilst others are entirely devoid of them (Plotnick 2017; Waters and Kuehn 1996). These processes produce fractal properties in site distribution patterns (Bailey and Smith 2005; Brown and Witschey 2003; Plotnick 2017) which also affect the preservation of extinct organisms' geographical ranges. At our regional level, this is what the current distribution and thus reconstructed former range of *H. erectus* looks like: while fossils have been relatively abundant at the northern and southern extremes of its distribution in Southeast Asia, evidence for this hominin between these extremes is scarce (Berghuis et al. 2025; Lee and Hudock 2021; Louys and Kealy 2024).

Least-cost pathway dispersal modeling suggested one area where a confluence existed between ease of movement for large-bodied mammals and emergent land that could be easily surveyed and might preserve evidence of *H. sapiens*, namely the Riau–Lingga Archipelago (Louys and Kealy 2024). Initial examination of geological maps and satellite imagery indicated several outcrops of the right age and sediment type for the preservation of fossils or archaeological material. However, our on the ground examination of the Riau–Lingga Archipelago revealed very little scope for the accumulation or the long-term preservation of such deposits. In our region of focus, the factors controlling

Figure 12. Gambier harvest, ca. 1880–1890. Album Or. 27.377, Geoffrey Allan Edwards Collection. Universiteit Leiden Digital Collections: Southeast Asian & Caribbean Images (KITLV).

accumulation and preservation of paleontological and archaeological material can be largely attributed to geological and geographical factors, although biological and anthropogenic influences likely also contributed. Furthermore, the identification of sites of potential archaeological and/or paleontological interest is currently complicated by the absence of independent age controls available, with very little data that could constrain the timing and duration of sediment deposition and potential associated fossil and lithic accumulations on the islands.

The Riau–Lingga Archipelago largely consists of granites and the weathering products of granites (Figure 4A, B, and D–F). Numerous granite outcrops were observed on Kundur, Karimunbesar, and Singkep. While granite has frequently been used for ground and pecked artifacts (such as Neolithic axes and maces), and has reportedly been used to produce knapped artifacts in some Acheulean assemblages (e.g., Sharon 2008), the coarse macro-crystalline structure and lack of a conchoidal fracture make it unsuitable for knapping as it does not produce controlled flake propagation or the formation of functionally sharp edges (e.g., Eren et al. 2011; Holdaway and Stern 2004). Further, the granite in the Riau–Lingga Archipelago was so friable that nodules or cobbles were rarely observed. The availability of suitable stone for toolmaking has been argued as a contributory factor in successful colonization of landscapes (Dennell 2007), and thus the dearth of suitable knapping stone in the Riau–Lingga Archipelago is noteworthy. Only on Lingga did we observe evidence of extensive river cobbles and suitable knapping stone. While a lack of suitable stone could be mitigated by a focus on perishable raw materials such as bamboo (Bar-Yosef et al. 2012; West and Louys 2007), the presence of a knapping floor and the production of lithics on Singkep indicates that suitable stone was sought after and used, and thus a likely limiting factor in dense or extensive hominin occupation of the region. Additional work is required to further constrain the age and taphonomy of this lithic assemblage, as well as the source of the quartz lithics on Singkep.

The weathering of the Triassic granites is also likely to have contributed to the unsuitability of preservation of archaeological or fossil material. Granite can weather both physically and chemically, with temperature and runoff best describing chemical weathering in granitic watersheds (Oliva, Viers, and Dupré 2003). The hot, wet tropical climate in the Riau–Lingga Archipelago combined with extensive peneplanation likely contributed to extensive chemical erosion of the granites. Studies of the erosion of granites from Bintan showed they form clays rich in quartz, illite, kaolinite, gibbsite, goethite, and hematite (Erawan et al. 2020). Resultant soils are acidic, with recorded pH averaging 4.5–4.7. Highly acidic soils are a destructive agent on bones (Andrews 1995), limiting long-term fossil preservation. While tropical forests are characterized in part by development on highly weathered soils with low soil pH, differences in plant communities can be attributed to different soil chemistry, in turn related to the geological history of a region (Fujii et al. 2018). Soils derived from I-type granites have higher fertility than soils derived from S-type granites (da Silva et al. 2017), such that lower biodiversity may have been present on Kundur and Singkep relative to Bintan and Batam and contributed to the dearth of preserved biological material on those islands.

Extensive peneplanation in the region (Figure 4G and H) is also associated with extensive physical weathering that has produced a variety of exogenic outcrops, but few fluvial sequences or floodplains. Alluvial processes have variable impacts on archaeological and paleontological site preservation, varying from poor (coarse channel deposits and colluvium), intermittent (illuvial and sandy traction deposits), to very good (suspension and paleosol deposits) (Seramur et al. 2007). The latter type in particular holds high potential for preserving cultural horizons as they represent a stable land surface (Seramur et al. 2007). However, extensive and active sheet erosion observed on many of the islands (e.g., Mulyono et al. 2021) does not promote either the formation of soil horizons (Lehmann 1993) or the long-term preservation of artifacts (Gouma, van Wijngaarden, and Soetens 2011).

A major reason for the high rates of erosion observed across the Riau Archipelago (e.g., Figure 4F) was the development of the gambier industry in the eighteenth and nineteenth century, as recounted in detail by Colombijn (1997). Gambier was produced from the boiled down leaves of the shrub *Uncaria gambir* and was used as a dye and tanning agent (Figure 12). These were initially tended by Chinese laborers brought to the Riau islands *en masse* in the 1700s. By the early 1800s, Chinese cultivators dominated the trade and the Chinese population of laborers had exceeded that of the traditional Malays. Production of gambier required vast amounts of fuel wood, and fields had to be abandoned after 10–12 years due to the loss of forest reserves. The result was massive waves of deforestation spreading across the Riau islands—somewhere between 3 and 5% of the islands' forest reserves were lost to gambier a year according to

Colombijn (1997). Once abandoned, little revegetation occurred, such that large swathes of the islands were subjected to erosion around former agricultural areas. Agricultural-associated sediment disturbance has been strongly and negatively associated with the preservation and visibility of archaeological finds (Krahtopoulou and Frederick 2008), and any archaeological remains that may have once been preserved on the landscape are likely to have been impacted by these processes. Past and current mining activities are also likely ongoing threats to archaeological preservation due to forest clearance, sediment removal, and loss of landscape function (Colombijn 1997; Naim et al. 2019).

Limited tectonic activity of the islands provides less opportunities for the development and subsequent exposure of sedimentary basins that could promote the accumulation and preservation of fossils. Extensive peneplanation of the region acted as a further control on the possible preservation of fossil and archaeological material. Most of the depositional environments recorded in the archipelago were near-shore, deltaic, or swamp. Active sedimentation today is largely confined to the latter, and while the former paleoenvironments are mapped as Plio-Pleistocene through most of the archipelago, age controls on these sedimentary units are very poorly resolved and many may be Triassic or older. The generally low topography and limited fluvial systems present in the archipelago do not aid the formation of sites, which are often related to distance from rapids and knickpoints in fluvial systems (Seramur et al. 2007). The limited tectonic activity in the region also means there has not been any reef building or extensive limestone build up, the necessary conditions for the development of caves and thus a major vector for the preservation of natural and archaeological deposits (Louys et al. 2017). The significant exception of the caves and large rivers in Lingga provides indications that, on that island at least, further archaeological or paleontological deposits may be found.

Conclusions

While hominin movement and occupation almost certainly took place through or near the Riau–Lingga Archipelago, little evidence of these traces is likely to be found. This is attributed to mostly geological and geographical factors, the latter driven by recent anthropogenic activities which had the effect of removing native vegetation and promoting large-scale soil erosion. Any archaeological remains that may have once been found in many of the islands have likely mostly weathered away. The extensive presence of granites and their weathering products has not been conducive to long-term preservation of biological material, and the landforms resultant from extensive peneplanation provide few opportunities for large-scale deposits of either paleontological or archaeological material. It is therefore likely that the search for early Pleistocene hominins and associated faunas will need to target regions currently underwater. Such finds are likely to be incidental and lacking in precise contextual information (e.g., Berghuis et al. 2025). Nevertheless, Lingga emerges as an island that could potentially yield more evidence of the original inhabitants of the Riau–Lingga Archipelago, and further survey efforts on this island are recommended based on the observations made through this research.

Supplemental Material

Supplemental S1. Riau quartz lithic assemblage description and statistics.

Acknowledgements

Ping Yang, National Library of Australia, is acknowledged for assistance in sourcing geological maps (COR-10837654), and Meg Walker, Griffith University, for drafting Figures 1–3. We thank two anonymous reviewers for their useful and constructive comments. While this manuscript was under review, our good friend, colleague, and co-author Agus Tri Hascaryo passed away. Agus was a key member of our project, a field researcher extraordinaire, and a kind mentor to students and the Western members of the team. His loss will be keenly felt in the years ahead.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

Permission for the research was granted by the Indonesian government—Surat Izin Penelitian (214/SIP/IV/FR/5/2023). This work was supported by the National Geographic Society [NGS-59859R-19] and the Australian Research Council [FT160100450, DP230101273]. Mathieu Duval's investigation is currently supported by the Spanish Ramón y Cajal Fellowship RYC2018-025221-I, which is funded by MCIN/AEI/10.13039/501100011033 and by "ESF Investing in your future."

References

Andrews, P. 1995. Experiments in taphonomy. *Journal of Archaeological Science* 22 (2):147–53. 10.1006/jasc.1995.0016

Arifin, K., and R. C. E. Permana. 2022. Recent rock art sites from West Sumatra, Indonesia. *Asian Perspectives* 61 (2):285–316. 10.1353/asi.2022.0027

Bailey, R. J., and D. G. Smith. 2005. Quantitative evidence for the fractal nature of the stratigraphic record: Results and implications. *Proceedings of the Geologists' Association* 116 (2):129–38. doi: 10.1016/S0016-7878(05)80004-5.

Bar-Yosef, O., M. I. Eren, J. Yuan, D. J. Cohen, and Y. Li. 2012. Were bamboo tools made in prehistoric Southeast Asia? An experimental view from South China. *Quaternary International* 269:9–21. 10.1016/j.quaint.2011.03.026

Batchelor, D. A. 1988. Dating of Malaysian fluvial tin placers. *Journal of Southeast Asian Earth Sciences* 2 (1):3–14. 10.1016/0743-9547(88)90016-5

Batchelor, D. A. F. 2015. Clarification of stratigraphic correlation and dating of Late Cainozoic alluvial units in Peninsular Malaysia. *Bulletin of the Geological Society of Malaysia* 61:75–84. 10.7186/bgsm61201508

Berghuis, H. W. K., Y. Kaifu, U. P. Wibowo, T. van Kolfschoten, I. Sutisna, S. Noerwidi, S. Adhityatama, G. van den Bergh, E. Pop, R. A. Suriyanto, et al. 2025. The late Middle Pleistocene *Homo erectus* of the Madura Strait, first hominin fossils from submerged Sundaland. *Quaternary Environments and Humans* 3 (2):100068. 10.1016/j.qeh.2025.100068

Bird, M. I., W. C. Pang, and K. Lambeck. 2006. The age and origin of the Straits of Singapore. *Palaeogeography, Palaeoclimatology, Palaeoecology* 241 (3–4):531–8. 10.1016/j.palaeo.2006.05.003

Bonatz, D. 2024. Across the highlands: Ethnicity, archaeology and monuments in the lands of the Rejang, Minangkabau and Batak. In *Quaternary palaeontology and archaeology of Sumatra*, ed. J. Louys, P. C. H. Albers, and A. A. E. van der Geer, 253–79. Canberra: Australian National University Press.

Bothé, A. C. D. 1925. Geologische verkenningen in den Riouw-Lingga Archipel en de eilandengroep der Poelau Toedjoeh (Anambas en Natoena eilanden) [Geological explorations in the Riau–Lingga Archipelago and the Palau Tudjuh Archipelago (Anambas and Natuna Islands)]. *Jaarboek van het mijnwezen in Nederlandsch Oost-Indië* 54:101–52.

Brown, C. T., and W. R. Witschey. 2003. The fractal geometry of ancient Maya settlement. *Journal of Archaeological Science* 30 (12):1619–32. 10.1016/S0305-4403(03)00063-3

Caldwell, I., and A. A. Hazlewood. 1994. "The holy footprints of the venerable Gautama": A new translation of the Pasir Panjang inscription. *Bijdragen tot de taal-, land- en volkenkunde/ Journal of the Humanities and Social Sciences of Southeast Asia* 150 (3):457–80. 10.1163/22134379-90003073

Cameron, N. R., S. A. Ghazali, and S. J. Thompson. 1982a. *Geologic map of the Siaksriindrapura & Tg. Pinang Quadrangles, Sumatra*. Bandung, Indonesia: Geological Research and Development Centre.

Cameron, N. R., S. A. Ghazali, and S. J. Thompson. 1982b. *Geologic map of the Bengkalis Quadrangle, Sumatra*. Bandung, Indonesia: Geological Research and Development Centre.

Cobbing, E. J. 2005. Chapter 5 Granites. *Geological Society, London, Memoirs* 31 (1):54–62. 10.1144/GSL.MEM.2005.031.01.05

Colombijn, F. 1997. The ecological sustainability of frontier societies in eastern Sumatra. In *Paper landscapes*, ed. P. Boomgaard, D. E. Henley, and F. Colombijn, 309–39. Leiden: KITLV Press.

Cotterell, B., and J. Kamminga. 1987. The formation of flakes. *American Antiquity* 52 (4):675–708. doi: 10.2307/281378.

da Silva, Y. J. A. B., C. W. A. do Nascimento, P. van Straaten, C. M. Biondi, V. S. de Souza Júnior, and Y. J. A. B. da Silva. 2017. Effect of I- and S-type granite parent material mineralogy and geochemistry on soil fertility: A multivariate statistical and GIS-based approach. *Catena* 149:64–72. 10.1016/j.catena.2016.09.001

Danardono, T., and S. Ridwan. 2024. Assessment of soil degradation for biomass production in Tanjungpinang, Indonesia. *IOP Conference Series: Earth and Environmental Science* 1291 (1): 012017. doi: 10.1088/1755-1315/1291/1/012017.

Dennell, R. 2007. "Resource-rich, stone-poor": Early hominin land use in large river systems of northern India and Pakistan. In *The evolution and history of human populations in South Asia: Inter-disciplinary studies in archaeology, biological anthropology, linguistics and genetics*, ed. M. D. Petraglia and B. Allchin, 41–68. Dordrecht: Springer Netherlands.

Duval, Mathieu, Kira Westaway, Jahdi Zaim, Yan Rizal, Mika Rizki Puspaningrum, Agus Trihascaryo, Paul C. H. Albers, Holly E. Smith, Gerrell M. Drawhorn, Gilbert J. Price, et al. 2021. New chronological constraints for the Late Pleistocene fossil assemblage and associated breccia from Ngalau Sampit, Sumatra. *Open Quaternary* 7:9. 10.5334/oq.96

Erawan, F., E. Sukiyah, J. Hutabarat, and A. Sudradjat. 2020. The permeability of granite weathering soil in Tanjungpinang, Bintan Island, Indonesia. *Journal of Geoscience, Engineering, Environment, and Technology* 5 (3):145–52. 10.25299/jgeet.2020.5.3.5285

Eren, M. I., S. J. Lycett, C. I. Roos, and C. G. Sampson. 2011. Toolstone constraints on knapping skill: Levallois reduction with two different raw materials. *Journal of Archaeological Science* 38 (10):2731–9. doi: 10.1016/j.jas.2011.06.011.

Fujii, K., M. Shibata, K. Kitajima, T. Ichie, K. Kitayama, and B. L. Turner. 2018. Plant–soil interactions maintain biodiversity and functions of tropical forest ecosystems. *Ecological Research* 33 (1):149–60. 10.1007/s11284-017-1511-y

GEBCO Bathymetric Compilation Group. 2024. The GEBCO_2024 Grid - a continuous terrain model of the global oceans and land. NERC EDS British Oceanographic Data Centre NOC. doi:10.5285/1c44ce99-0a0d-5f4f-e063-7086abc0ea0f

Germeraad, J. H. 1941. On the rocks of the isle of Koendoer, Riauw Archipelago, Netherlands East Indies. *Proceedings of the Section of Sciences, Koninklijke Nederlandse Akademie Van Wetenschappen te Amsterdam* 44:227–1233.

Gouma, M., G. J. van Wijngaarden, and S. Soetens. 2011. Assessing the effects of geomorphological processes on archaeological densities: A GIS case study on Zakynthos Island, Greece. *Journal of Archaeological Science* 38 (10):2714–25. 10.1016/j.jas.2011.06.009

Gupta, A., A. Rahman, W. P. Poh, and J. Pitts. 1987. The old alluvium of Singapore and the extinct drainage system to the South China Sea. *Earth Surface Processes and Landforms* 12 (3): 259–75. 10.1002/esp.3290120305

Hermes, J. J., and D. R. de Vletter. 1942. Contribution to the petrography of Bintan (Riouw-Lingga Archipelago). *Proceedings of the Section of Sciences, Koninklijke Nederlandse Akademie Van Wetenschappen te Amsterdam* 45:82–8.

Hernawan, U., N. Y. Geurhaneu, and M. Zulfikar. 2019. Characteristic of shallow subsurface Quaternary sediment in Nongsa Isle, part of Putri Islands, Batam, based on georadar data interpretation. *Bulletin of the Marine Geology* 34 (2):109–20. 10.32693/bomg.34.2.2019.624

Hijmans, R., and University of California, Berkeley, Museum of Vertebrate Zoology. 2015. Boundary, Indonesia, 2015. UC Berkeley, Museum of Vertebrate Zoology. http://purl.stanford.edu/py486tm4357.

Holdaway, S. J., and N. Stern. 2004. *A record in stone: The study of Australia's flaked stone artefacts*. Canberra: Aboriginal Studies Press.

Inizan, M.-L., M. Reduron-Ballinger, H. Roche, and J. Tixier. 1999. *Technology and terminology of knapped stone. Préhistoire de la pierre taillée*. Vol. 5. Paris: Cercle de recherches et d'études préhistoriques.

Jongmans, W. J. 1951. Fossil plants of the Island of Bintan (with a contribution by J.W.H. Adam). *Koninklij ke Nederlandse Akademie van Wetenschappen* B54:183–90.

Johnson, R. F. 1963. *Geology and bauxite deposits of the central Riau Islands, Indonesia*. Seri Geologi Ekonomi No. 6. Bandung: Direktorat Geologi.

Kamaludin, b. H., T. Nakamura, D. M. Price, C. D. Woodroffe, and S. Fujii. 1993. Radiocarbon and thermoluminescence dating of the Old Alluvium from a coastal site in Perak, Malaysia. *Sedimentary Geology* 83 (3–4):199–210. 10.1016/0037-0738(93)90013-U

Krahtopoulou, A., and C. Frederick. 2008. The stratigraphic implications of long-term terrace agriculture in dynamic landscapes: Polycyclic terracing from Kythera Island, Greece. *Geoarchaeology* 23 (4):550–85. 10.1002/gea.20231

Kusnama, K., T. C. Sutisna, S. Amin, K. Sukardi, and B. Hermanto. 1994. *Geological map of the Tanjungpinang Sheet, Sumatera*. Bandung: Geological Research and Development Centre.

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 United States of America* 111 (43):15296–303. 10.1073/pnas.1411762111

Lameiras, F. S. 2012. The relation of FTIR signature of natural colorless quartz to color development after irradiation and heating. In *Infrared radiation*, ed. V. Morozhenko, 41–56. Rijeka, Croatia: InTech.

Lee, S. H., and A. Hudock. 2021. Human evolution in Asia: Taking stock and looking forward. *Annual Review of Anthropology* 50 (1):145–66. doi: 10.1146/annurev-anthro-101819-110230.

Lehmann, R. 1993. Terrace degradation and soil erosion on Naxos Island, Greece. In *Farm land erosion: In temperate plains environment and hills*, ed. S. Wicherek, 429–50. Amsterdam: Elsevier.

Louys, J., and S. Kealy. 2024. How did *Homo erectus* reach Java? Least-cost pathway models and a consideration of possible Sumatran routes. In *Quaternary palaeontology and archaeology of Sumatra*, ed. J. Louys, P. C. H. Albers, and A. A. E. van der Geer, 199–218. Canberra: Australian National University Press.

Louys, J., M. Duval, G. J. Price, K. Westaway, Y. Zaim, Y. Rizal, M. Aswan, A. Puspaningrum, S. F. M. Trihascaryo, O. Breitenbach, et al. 2022. Speleological and environmental history of Lida Ajer cave, western Sumatra. *Philosophical Transactions of the Royal Society B* 377: 20200494.

Louys, J., S. Kealy, S. O'Connor, G. Price, S. Hawkins, K. Aplin, Y. Rizal, J. Zaim, D. Tanudirjo, W. D., Santoso, et al. 2017. Differential preservation of vertebrates in Southeast Asian caves. *International Journal of Speleology* 46 (3):379–408. 10.5038/1827-806X.46.3.2131

Louys, J., Y. Zaim, Y. Rizal, G. J. Price, A. Aswan, M. R. Puspaningrum, H. Smith, and A. T. Hascaryo. 2021. Palaeontological surveys in Central Sumatra and Bangka. *Berita Sedimentologi* 47 (3):50–6. 10.51835/bsed.2021.47.3.358

Metcalfe, I. 2013. Tectonic evolution of the Malay Peninsula. *Journal of Asian Earth Sciences* 76: 195–213. 10.1016/j.jseaes.2012.12.011

Metcalfe, I. 2017. Tectonic evolution of Sundaland. *Bulletin of the Geological Society of Malaysia* 63:27–60. 10.7186/bgsm63201702

Middelburg, J. J., C. H. van der Weijden, and J. R. W. Woittiez. 1988. Chemical processes affecting the mobility of major, minor and trace elements during weathering of granitic rocks. *Chemical Geology* 68 (3–4):253–73. 10.1016/0009-2541(88)90025-3

Miksic, J. N. 2021. Issues and approaches to studying Singapore before 1819. In *1819 & before: Singapore's pasts*, ed. K. C. Guan, 11–22. Singapore: ISEAS-Yusof Ishak Institute.

Moore, M. W. 1997. Appendix D: Milky quartz reduction experiments. In *Aboriginal archaeology of dry sclerophyll forest conservation reserves in eastern Tasmania*, ed. M. W. Moore, 268–86. Unpublished report for Forest Practices Board, Forestry Tasmania, Australia.

Moore, M. W. 2010. "Grammars of action" and stone flaking design space. In Stone tools and the evolution of human cognition, ed. A. Nowell and I. Davidson, 13–43. Boulder: University Press of Colorado.

Mulyono, A., M. R. Djuwansah, I. Narulita, R. D. Putra, and D. Surinati. 2021. Environmental impact of land-use changes and soil loss on coastal coral reef cover: Study case in the small tropical island, Indonesia. *Research Square*. 1–12. doi: 10.21203/rs.3.rs-148449/v1.

Naim, A., A. Saini, A. Shahbanu, K. B. H. Kusuma, M. Johansyah, M. Jamil, and T. Apriando. 2019. *Small islands of Indonesia, the land of mines: Report on the destruction of the entire bodies of small islands of Indonesia by mineral and coal Mines*. Jakarta: Jaringan Advokasi Tamabang.

O'Brien, M. C. 1955. The structure of the colour centres in smoky quartz. *Proceedings of the Royal Society of London. Series A. Mathematical and Physical Sciences* 231:404–14.

Oliva, P., J. Viers, and B. Dupré. 2003. Chemical weathering in granitic environments. *Chemical Geology* 202 (3–4):225–56. 10.1016/j.chemgeo.2002.08.001

Plotnick, R. E. 2017. Recurrent hierarchical patterns and the fractal distribution of fossil localities. *Geology* 45 (4):295–8. 10.1130/G38828.1

Raadshooven, B. v., and J. Swart. 1941. On rocks from Karimon Riouw Archipelago. *Proceedings of the Section of Sciences, Koninklijke Nederlandse Akademie Van Wetenschappen te Amsterdam* 45:89–96.

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 (1):240. 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 S. Susilohadi. 2019. Subsiding Sundaland. *Geology* 47 (2):119–22. 10.1130/G45629.1

Seramur, K. C., E. A. Cowan, L. Lautzenheiser, and J. M. Eastman. 2007. A model of distribution and preservation of archaeological sites along Piedmont streams: The Deep River, North Carolina. *Southeastern Archaeology* 26:32–46.

Sharon, G. 2008. The impact of raw material on Acheulian large flake production. *Journal of Archaeological Science* 35 (5):1329–44. 10.1016/j.jas.2007.09.004

Simatupang, D. E., D. Hidayati, N. Susilowati, and T. Setiawan. 2017. Ekskavasi dan kajian manajemen arkeologi situs Bukit Kerang Kawal Darat di Kabupaten Bintan, Prov. Kepulauan Riau [Excavation and study of archaeological management of the Bukit Kerang Kawal Darat site in Bintan Regency, Riau Islands Province]. *Berita Penelitian Arkeologi Nomor* 32:1–71.

Solheim, W. G., II. 1990. Earthenware pottery, the T'ai and the Malay. *Asian Perspectives* 29:25–36.

Spry, C., R. Kurpiel, E. Foley, and P. Penzo-Kajewski. 2022. Revisiting the "quartz problem" in lithic studies: A review and new, open-access, experimental dataset. *Lithic Technology* 47 (2): 171–81. doi: 10.1080/01977261.2021.1981655.

Sutisna, K., G. Burhan, and B. Hermanto. 1995. *Geology of the Dabo Quadrangle, Sumatera. Explanatory note and geological map*. Jakarta, Indonesia: Geological Research and Development Centre, Directorate General of Geology and Mineral Resources, Department of Mines and Energy.

Tsirk, A. 2010. Fracture markings from flake splitting. *Journal of Archaeological Science* 37 (8): 2061–5. doi: 10.1016/j.jas.2010.03.011.
Tweedie, M. W. F. 1953. The stone age in Malaya. *Journal of the Malayan Branch of the Royal Asiatic Society* 26:3–90.
Van Bemmelen, R. W. 1940. Bauxite in Nederlandsch Indië [Bauxite in the Dutch East Indies]. *Verslagen en Meded betreffende Indische Delfstoffen en hare toepassingen* 23:1–115.
Van Bemmelen, R. W. 1941. Origin and mining of bauxite in Netherlands India. *Economic Geology* 36 (6):630–40. 10.2113/gsecongeo.36.6.630
Van Bemmelen, R. W. 1949. *The Geology of Indonesia*, 1. The Hague: Government Printing Office.
Van der Bold, W. A., and J. P. Van der Sluys. 1942. On rocks from the isle of Batam (Riauw Archipelago). *Proceedings of the Section of Sciences, Koninklijke Nederlandse Akademie van Wetenschappen te Amsterdam* 45:1003–9.
van der Walt, J., and J. Bradfield. 2018. The effects of heavy-duty machinery on the formation of pseudo-knapping debitage in Stone Age cultural landscapes. *Antiquity* 92 (366):1429–44. doi: 10.15184/aqy.2018.170.
Van Wessem, A. 1941. On rocks from the islands of Soegi, Tjombol and Tjitlim, Riauw Archipelago, Netherlands East Indies. *Proceedings of the Section of Sciences, Koninklijke Nederlandse Akademie van Wetenschappen te Amsterdam* 44:1219–26.
Voris, H. K. 2000. Maps of Pleistocene sea levels in Southeast Asia: Shorelines, river systems and time durations. *Journal of Biogeography* 27 (5):1153–67. 10.1046/j.1365-2699.2000.00489.x
Wade-Murphy, J., and J. van Konijnenburg-van Cittert. 2008. A revision of the Late Triassic Bintan flora from the Riau Archipelago (Indonesia). *Scripta Geologica* 136:73–106.
Waters, M. R., and D. D. Kuehn. 1996. The geoarchaeology of place: The effect of geological processes on the preservation and interpretation of the archaeological record. *American Antiquity* 61 (3):483–97. 10.2307/281836
West, J. A., and J. Louys. 2007. Differentiating bamboo from stone tool cut marks in the zooarchaeological record, with a discussion on the use of bamboo knives. *Journal of Archaeological Science* 34 (4):512–8. doi: 10.1016/j.jas.2006.06.007.
Zeylmans van Emmichoven, C. P. A. 1938. Korte schets van de geologie van Centraal Borneo [Brief sketch of the geology of Central Borneo]. *De Ingeniellr in Nederlandsch Indie* 5:135–49.
Zwierzycki, J. 1930. Geologische overzichtskaartvan den Nederlandsch Oost Indischen Archipel, schaal 1: 1000,000- Toelichting bij blad VIII (Midden Sumatra, Bangka en de Riauw eilanden) [Geological overview map of the Dutch East Indian Archipelago, scale 1: 1000,000 - Explanation of sheet VIII (Central Sumatra, Bangka and the Riauw Islands)]. *Jaarboek Mijnwezen Nederlandsch Oost-Indie* 58:73–157.