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The Paleo-Lupar: Bathymetric and seismic evidence for a submerged Late Pleistocene river valley on the Sunda Shelf, off Sarawak

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Abstract: This article presents bathymetric and seismic evidence of a submerged Late Pleistocene river valley on the Sunda Shelf, off Sarawak. The submarine feature identified as the Paleo-Lupar is detectable in digital elevation models (DEM) at water depths of about 40 m near the Lupar river mouth to more than 100 m to the north nearer the shelf edge. Bathymetric profiles revealed an ~30 km-wide submarine valley, with individual channels that, in places, can be more than 80 m deeper than the surrounding seabed. The Paleo-Lupar is one of several major paleo-rivers that drained the Sunda Shelf when sea level was lowest during the Last Glacial Maximum (LGM) around 21 ka BP and were subsequently submerged due to the sea level rise that has since occurred.

Keywords: Paleo-Lupar, Sunda Shelf, bathymetry, submerged river valley, incised valley

INTRODUCTION

It is well established that a large part of the Sunda Shelf (Figure 1), the broad continental shelf surrounding Southeast Asia, had been subaerially exposed during glacial periods when sea level was low, the lowest during the Last Glacial Maximum (LGM), some 21,000 years BP (Hanebuth *et al*., 2003). Due to its low gradients, a drop in sea level in the order of tens of metres would have resulted in the exposure of vast areas of the shelf, in the order of millions of square kilometres (Sathiamurthy & Rahman, 2017). Maximum exposure of the shelf occurred during the LGM, when sea level was ca. 120-130 m below present level (BPL), while the shoreline laid further seaward, although not reaching the present-day shelf break at the 180-200 m isobath (Hanebuth & Stattegger, 2003; Hanebuth *et al*., 2009; Sarr *et al*., 2019). As a result of the exposure, the Sunda Shelf essentially became a landmass (called "Sundaland") across which a network of "paleo-river systems" are believed to have developed (Voris, 2000; Sathiamurthy & Voris, 2006; Figure 1).

The term "paleo-river" is used here to mean simply the supposed submerged continuation of a modern river which extended seaward from the present coastline to the paleo-shoreline near but not quite reaching the present shelf edge at around 180 to 200 m water depth. It is generally assumed that paleo-rivers are now submerged beneath the shallow seas as the result of the rapid sea level rise over the Sunda Shelf since the LGM (e.g., Hanebuth *et al*., 2000; 2011).

Various authors have used different morphological terms for the sea floor features that they interpreted as paleo-rivers. Molengraaff (1921, p.104) described them as "gullies" while Keunen (1950, p. 482) called them "channels". Although these terms have no size connotation, some of the v-shaped gullies are wide enough (10-50 km) to be called "valleys" instead of "rivers" *per se*. Later workers used the term "paleo-valleys", particularly when referring to the wider segment of the North Sunda River closer to the shelf edge (Steinke *et al*., 2003; Hanebuth & Stattegger, 2004). Strictly, these features were probably drowned river valleys because presumably rivers flowed along their axes. As pointed out by Voris (2000), the location of the paleo-rivers is largely hypothetical, based on their modern sea floor expression, as their exact location may have changed over time due to meandering and avulsion.

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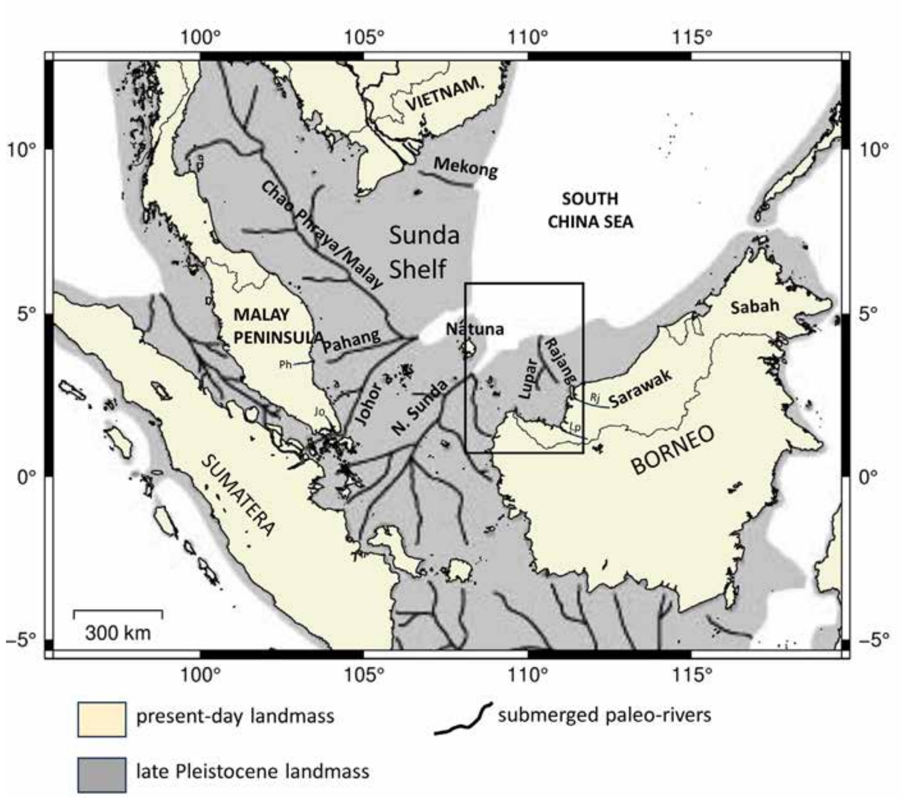

Figure 1: Map of Southeast Asia, modified from Voris (2000), depicting the approximate extent of the Late Pleistocene landmass (Sundaland) when sea level was 120 m BPL. As a result of the sea level drop, practically the entire Sunda Shelf was subaerially exposed and incised by major "paleo-river systems". The Paleo-Rajang-Lupar system (in the rectangle representing the present study area) is identified based on its proximity to the modern Rajang and Lupar rivers. Abbreviations: Ph – Pahang River, Jo – Johor River, Lp – Lupar River, Rj – Rajang River.

Whereas the positions of past shorelines may be inferred from present-day bathymetric contours based on digital elevation models (DEM) (e.g., Voris, 2000; Sathiamurthy & Voris, 2006), identifying submerged "paleo-rivers" or "paleo-valleys" is highly speculative without actual measured data, such as echo-sounding and shallow seismic. The advent of high-resolution 2D and 3D seismic reflection data has enabled more accurate and detailed geomorphological characterisation of paleo-rivers and their deposits. For example, in the Gulf of Thailand within 300 km south of the Chao Phraya river mouth, in water depths of about 70 m, these features were clearly discernible within the top 80 m of shelf sediments, including meandering channels up to 600 m wide in channel belts up to 10 km wide (Reijenstein *et al*., 2011). In the Malay Basin, about 500 km to the southeast, besides similar meandering and straight channel features (<3000 m wide), significantly wider (3.5–13 km) u-shaped features that are twice as deep (35-78 m) as the Thai ones have been observed within the top 300 ms (~200 m) of the seabed and have been interpreted as incised valleys that were formed during the LGM (Alqahtani *et al*., 2015, 2017).

These examples from the Gulf of Thailand and Malay Basin are part of what Voris (2000) called the "Siam" paleo-river system, which represents the submerged continuation of the Chao Phraya river into the Gulf of Thailand, Malay and West Natuna basins, and ultimately eastwards into the South China Sea basin (Figure 1). Unfortunately, Voris (2000) had been misquoted by Alqahtani *et al*. (2015, 2017) who mistakenly referred to the "Siam" paleo-river as the "Chao Phraya-Johore" river, while showing the "Siam" paleo-river as a separate east-flowing paleo-river originating from the present-day Pahang River (see Alqahtani *et al*., 2015, figure 12). On the contrary, Voris (2000) described the modern Johor River, which is a south-flowing river at the southern tip of the Malay Peninsula, as a tributary of the east-flowing Kampar paleo-river originating in Sumatra, which then joins with the "Siam" paleo-river at the triple junction between the Malay, Penyu and West Natuna basins (Figure 1). It would be more appropriate to call the Siam paleo-river the "Chao Phraya-Malay" paleo-river (Figure 1).

The North Sunda River (Figure 1), also known as the "Molengraaff River", is most well-known and has been studied in detail (Stattegger *et al*., 1997; Hanebuth *et al*., 2000, 2011; Hanebuth & Stattegger, 2003). Two other paleo-rivers on Voris's (2000) map were not mentioned in his text; these are identified in Figure 1 as the Paleo-Mekong on the Vietnam shelf and the Paleo-Rajang-Lupar on the Sarawak shelf. While the Paleo-Mekong has been relatively well-studied (Tjallingii *et al*., 2010; Ta *et al*., 2021), the Paleo-Rajang-Lupar on the opposite margin is practically unknown. This paper describes for the first time some aspects of this submerged paleo-river offshore Sarawak based on bathymetric and seismic evidence. It is hoped that this study will stimulate interest for further investigation.

IDENTIFICATION OF SUBMERGED PALEO-RIVERS

The realisation that drowned paleo-rivers existed on the Sunda Shelf can be traced back to the 1920s with the early work by Molengraaff (1921) and Molengraaff & Weber (1921). Based on sparse bathymetric data available then, Molengraaff (1921) suggested that the submarine "gullies" were the continuation of the major rivers that were incised into the shelf during glacial lowstands. Over the subsequent decades, surveying methods and technologies, ranging from echo-sounding to high-resolution shallow 2D seismic to multi-channel 2D and 3D seismic, improved significantly. As summarised by Sathiamurthy & Rahman (2017), research on the paleo-river systems of Sundaland had evolved rapidly in tandem with the technological advances.

In the late 1990s, the advent of satellite-derived bathymetric models provided researchers with full bathymetric data coverage of the oceans that complements ship-based measurements and, as a result, it became possible to map on a regional scale paleo-shorelines and paleo-rivers in more detail. This type of analysis assumes that Sundaland is tectonically stable since at least 17 ka BP, as some authors have suggested (e.g., Tjia, 1980; Tjia *et al*., 1984; Tjia & Liew, 1996), such that its general morphology was not significantly affected by subsidence or uplift that may have occurred since the LGM. Other factors such as tidal scouring and sediment accumulation are also assumed to have had no significant effect on the large-scale morphology of the shelf (Sathiamurthy & Rahman, 2017). Under these assumptions, the present-day water depth contours have been used as proxies for past sea levels and shorelines. Consequently, any morphological features such as channels, gullies or valleys on the sea floor that are found landward of the paleo-shoreline could potentially be interpreted as paleo-rivers.

Building upon the pioneering works carried out up to the early 1990s, Voris (2000) mapped the paleo-shorelines and associated paleo-rivers of Sundaland using the now deprecated ETOPO5[1] digital elevation/bathymetry model (with 5'x5' or ca. 10 km grid resolution) and GEBCO[2] gridded bathymetry available at the time. Many studies have since confirmed the presence of major Late Pleistocene paleo-rivers on the Sunda Shelf and have described in detail their sedimentation histories, particularly the North Sunda River system (Steinke *et al*., 2003; Hanebuth & Stattegger, 2003, 2004; Hanebuth *et al*., 2002, 2009, 2011). Subsequently, Sathiamurthy & Voris (2006) expanded on the work of Voris (2000) using ETOPO2 bathymetric grid which has a 2'x2' (3.5 km) resolution. With the higher resolution, the authors were able to identify "depressions" on the sea floor which were interpreted as "paleo-lakes" that developed on the exposed shelf (Sundaland) during the LGM.

The type of analysis described above is highly reliant on the quality and resolution of DEMs, which are dependent upon the availability of measured bathymetric data used in building the grid; the less superior satellite-derived bathymetry is normally used to fill gaps in the measured data. Even with the latest global DEMs, with a 15 arc-seconds (~450 m) resolution, smaller channel-like features may not be resolved, especially when ship-borne data are lacking for calibration.

There is now publicly available higher resolution gridded global DEMs, which combine satellite-derived bathymetry grids with ship-borne bathymetric measurements, where available. They are useful for a general analysis and the identification of seafloor features. Figure 2 compares a number of global bathymetric grids over the study area on the Sunda Shelf, off Sarawak. All the DEMs used were versions released in 2022. It is difficult to tell the models apart, as they are not significantly different; the ETOPO and GMRT are almost identical. There is a slight difference, however, between the GMRT and SRTM+ grids. Glaring artefacts occur in all models due to track lines of the input bathymetric data, especially between 3° and 4° latitudes. There is also a hint of a channel-like feature emanating from the modern Lupar river mouth at the apex of the Lupar estuary. This feature is more pronounced in the SRTM+ model. The artefacts from ship tracks were minimised by applying a low-pass gaussian filter, and after re-gridding, a distinct submarine valley is observed to emanate from the Lupar river mouth (Figure 3).

The existence of a submerged river valley on the Sunda Shelf, off west Sarawak, was noted by previous authors. Citing Haile (1969), Hanebuth & Stattegger (2004) referred to a "Proto-Lupar" valley that emanates from the Lupar River, and manifests itself as a series of landward indentations of the bathymetric contours on the

[1] ETOPO https://www.ncei.noaa.gov/products/etopo-global-relief-model

[2] Global Elevation and Bathymetric Chart of the Oceans https://www.gebco.net/

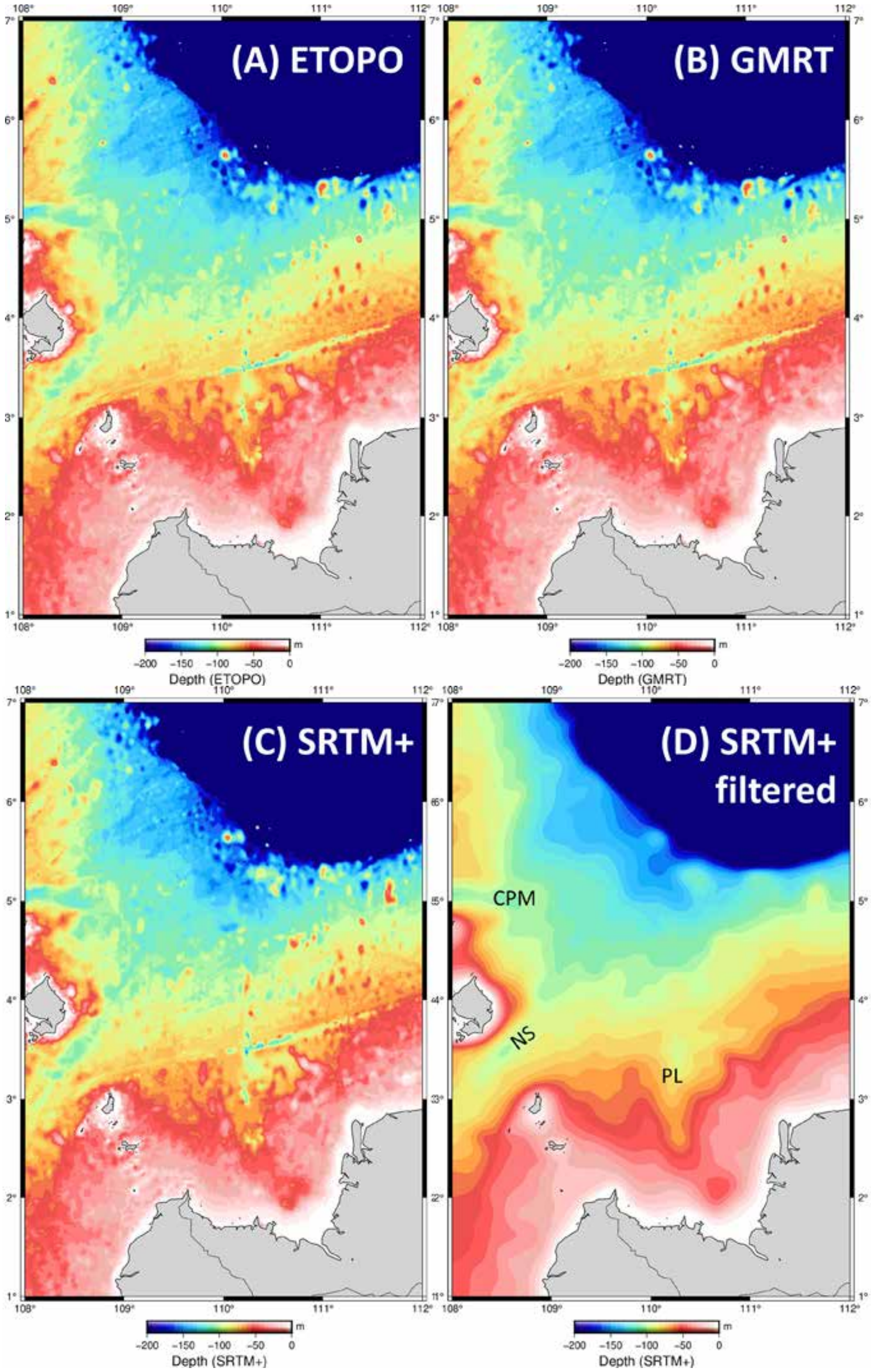

Figure 2: Bathymetric maps of the study area, offshore West Sarawak, based on various global digital elevation models (DEM). (A) ETOPO (NOAA, 2022a), 15 arc-seconds resolution. (B) GMRT v4.1 (2022) (Ryan *et al*., 2009), 7.5 arc-seconds resolution. (C) SRTM+ v2.5 (2022) (Tozer *et al*., 2019), 15 arc-seconds resolution. (D) filtered SRTM+, low-pass gaussian filter with 50 km search radius applied to remove ship-track artefacts. The submerged paleo-Lupar (PL) is more apparent, as are the North Sunda (NS) and Chao-Phraya/Malay (CPM) systems. Data processing (filtering) and mapping were done using GMT v.6 (Wessel *et al*., 2019).

shelf, off Sarawak. Independently, Sim & Jaeger (2004) interpreted this feature as the result of shelf incision during the latest low-stand phase in the Pleistocene, and called it the "Proto Rajang/Lupar River". This study will examine the bathymetric and complementary seismic evidence for this submerged paleo-river valley. Since the submerged river valley is only a bathymetric expression of the paleo-river, and probably represent a sediment bypass zone, seismic reflection data may provide insight into the associated river channel deposits in the subsurface.

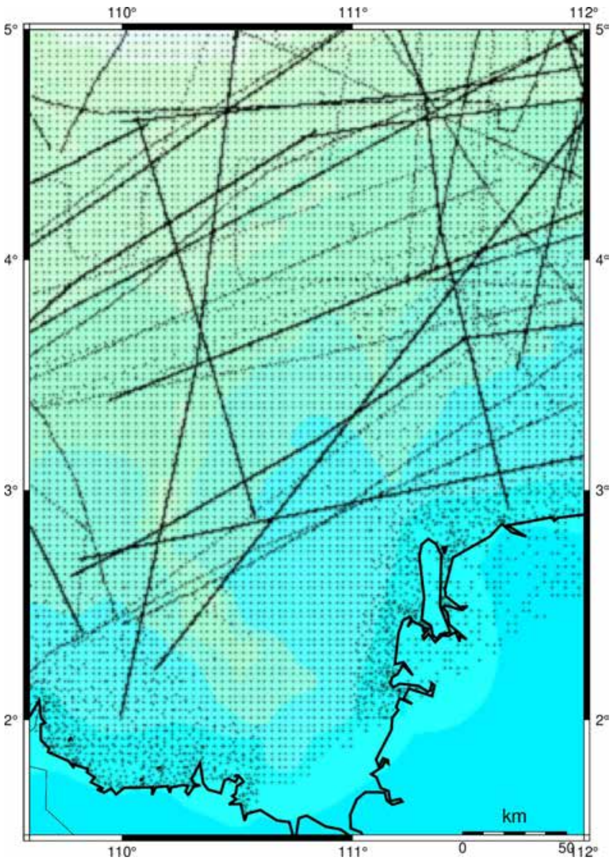

Figure 3: Map of the bathymetric data compiled in this study, comprising points, track-lines and grids described in the text.

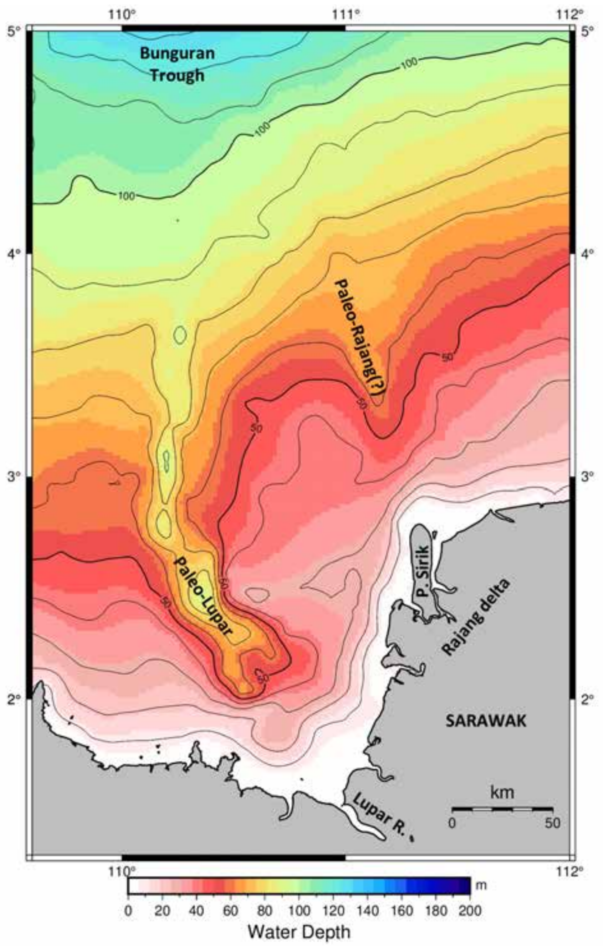

Figure 4: Bathymetric map generated from compiled data (Figure 3). Colour palette and 10 m contours are applied only for water depths less than 200 m. The prominent Paleo-Lupar river valley can be traced northwards directly into the region of Bunguran Trough. A similar but smaller feature could be related to the Paleo-Rajang river valley.

DATA AND METHOD

Besides the global DEMs mentioned above, additional bathymetric data were compiled from various sources for this study. As part of the Malaysian Continental Shelf Project (MCSP), bathymetric data based on multi-channel seismic reflection data were made available by PETRONAS (Hutchison & Vijayan, 2010; Vijayan *et al*., 2013). On seismic reflection profiles water depths were easily obtained from seabed reflections (in two-way time) converted to depth with an appropriate water velocity (1450 m/s) (Vijayan *et al*., 2013). Another source of bathymetric data is depth soundings from the nautical charts published by the Pusat Hidrografi Nasional (PHN). Last but not least, selected ship-borne bathymetric data were also downloaded from the NOAA website, traditionally referred to as “Geodas” (NOAA, 2022b). The full dataset compiled for this study is shown in Figure 3.

RESULTS

Figure 4 shows the bathymetric map generated from this compilation. The Paleo-Lupar river valley is easily identified as a sublinear trough (about 30 km wide measured at the 50 m water depth contour), starting with a NW-SE orientation, similar to that of the Lupar River, before striking N-S towards the shelf edge. Although some authors, such as Sim & Jaeger (2004), had assumed that this submerged river valley could be related to the Rajang River (“Paleo-Rajang”), the map clearly shows that it is directly on strike with the Lupar River. The modern Lupar River flows for 275 km on land and is the third longest river in Sarawak, after the Rajang and Baram. A sharp landward indentation of the isobaths north of Pulau Sirik, however, suggests the presence of a smaller submarine valley that could be related to the Rajang River. The map also indicates that the Rajang system may be feeding into some tributaries to the Paleo-Lupar (Figure 4). Both the Rajang and Lupar river systems most probably had provided the sediment supply to the Bunguran Trough, the main depocentre in West Luconia since the Late Miocene. The Paleo-Lupar may have persisted throughout the Pliocene to Holocene as a major sediment bypass route during sea level lowstands.

The geometry of the Paleo-Lupar valley was examined more closely in bathymetric profiles (Figure 5). These profiles cross the valley in an approximately ENE-WSE direction and therefore provide a cross-section image. The valley is wider and deeper nearer to the modern Lupar river mouth and becomes narrower and shallower further offshore. At the proximal end, the valley has an almost uniform width of about 30 km, with a maximum depth of about 80 m relative to the surrounding sea floor. The bathymetric profiles also suggest that in detail there may be several channels or distributaries forming a wider river valley that developed during lowstand periods. Towards the shelf edge to the north, the valley widens and becomes shallower and less distinct. A profile running approximately north-south, parallel to the paleo-depositional dip (Figure 5C) and also roughly parallel to the river valley appears to show two separate valleys in the same profile. However, this could be due to it being an oblique section along a bend in the paleo-valley.

Besides providing water depth profiles, multi-channel seismic reflection data show features that could be related to the sediment fill of the Paleo-Lupar river valley. Figure 6 shows segments of the seismic profiles from the SK2K survey and highlight some sedimentary features below the seabed. In SK2K-05 (Figure 6A), the main valley can be seen as a prominent unfilled depression, with the transport path perpendicular to the profile (to the north). Beneath the seabed there are indications of channelised

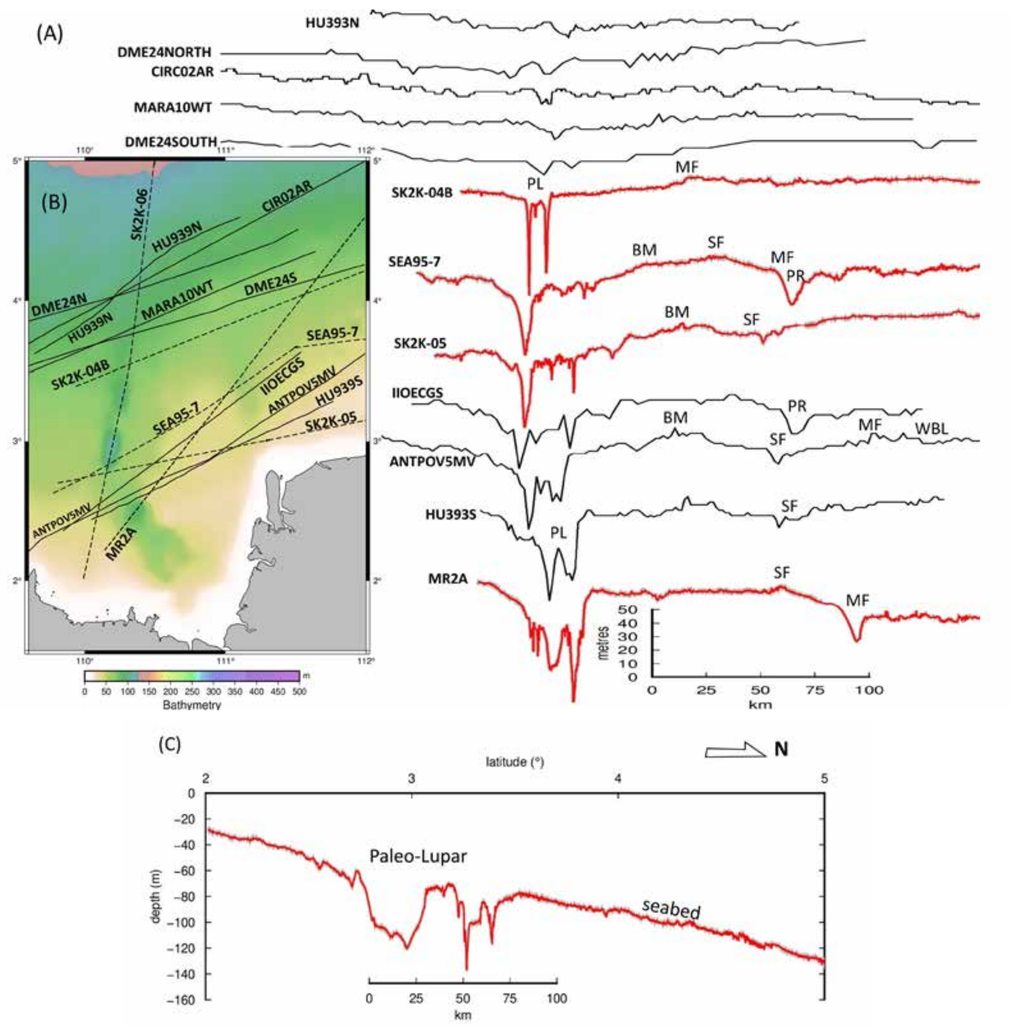

Figure 5: Bathymetric profiles across the study area on the western Sarawak Shelf. (A) Roughly E-W, shore-parallel seabed profiles along Geodas lines (black) and seismic lines (red), arranged from south (bottom) to north (top). (B) Location of profiles overlayed on bathymetric map generated from the compiled data. In (A), the Paleo-Lupar (PL) valley is clearly seen especially in the profiles across the southern half of the study area. Also identified on some lines are seabed features that coincide with major regional structural lineaments described by Madon & Jong (2022): Bukit Mersing Line (BM), Sirik Fault (SF), Mukah Fault (MF), West Balingian Line (WBL). The other major submarine valley is identified as Paleo-Rajang (PR) which seems to coincide with Mukah Fault along some profiles. (C) N-S profile between 2° and 5° latitudes, representing a roughly longitudinal section along the Paleo-Lupar valley.

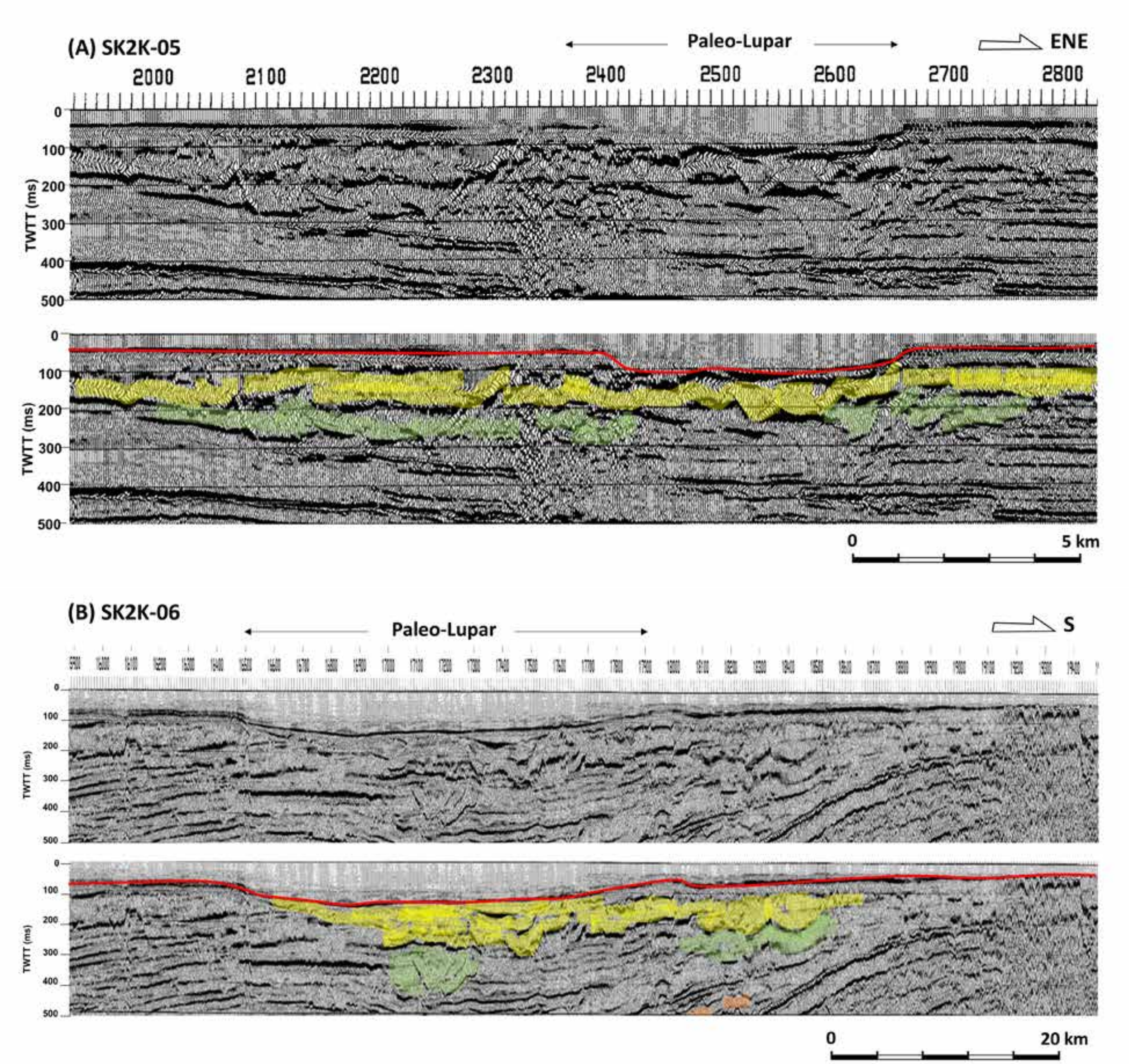

Figure 6: Examples of seismic section crossing the Paleo-Lupar valley and underlying deposits. (A) ENE-oriented SK2K-05 line (B) SK2K-06 line, oriented approximately N-S. The depression labelled "Paleo-Lupar" is the present-day seabed expression (red line) of the paleo-river system. In the lower panel of A and B, the interpreted seismic facies beneath the seabed, shaded yellow and green, probably represents Late Pleistocene deposits of the Paleo-Lupar river. Line locations shown in Figure 5. In the sediment column, 100 ms two-way travel time (TWTT) is approximately 75 m.

fluvial deposits down to about ~300 ms two-way time (ca. 150-180 m below seabed; Figure 6A) and ~450 ms beneath the seabed, suggesting that the course of the main river channels within a larger incised valley had changed over time. In SK2K-06 (Figure 6B), which is oriented sub-parallel to the main river valley, similar seismic facies indicate incised valley channel deposits down to ~450 ms (ca. 250 m below the seabed).

From Figure 6 we can identify two distinct packages of channelised fluvial deposits in the subsurface of the Paleo-Lupar valley; a younger, yellow-shaded unit underlain by an older, green-shaded unit. Both units extend laterally beyond the physical limits of the paleo-valley itself, which underlines the point made earlier that the paleo-valley only represents the most recent (modern) expression of a paleo-river, which is continuously changing its course over time. Since there are no core samples available, we may only speculate on the nature of these deposits based on similar studies elsewhere.

Paleo-rivers have also been documented in other parts of the Sunda Shelf using similar types of data, as reviewed by Sathiamurthy & Rahman (2017). One of the most extensive studies of Pleistocene incised valleys of the Sunda Shelf was during cruise SO-115 which focused on the North Sunda River (Stattegger *et al.*, 1997). Based on extensive core and seismic data, regressive and transgressive sediments filling the incised paleo-valleys were described in detail by Hanebuth & Stattegger (2003, 2004). Incised valleys 45–50 m deep relative to surrounding seabed have been described from the Vietnamese shelf (Dung *et al.*, 2013). Recent studies of the Paleo-Mekong river system also describe the evolution of the delta since ~13 ka through incised valley filling and delta progradation since the Late Pleistocene (Ta *et al.*, 2021).

A close analogue for these deposits would be the incised valley sequences of the North Sunda River, located 200 km to the northwest of the Paleo-Lupar. According to these studies, there are two main Quaternary sedimentary units: an older pre-LGM regressive deposit, separated from an overlying transgressive unit by an erosional surface attributed to the LGM. The two units in North Sunda River may be tentatively correlated with the two packages of channelised fluvial deposits beneath the Paleo-Lupar valley. The boundary between the two represents the erosive surface marking the LGM event (equivalent to S_{LGM} in Fig. 3 of Hanebuth & Stattegger, 2004).

DISCUSSION

While bathymetric data showed the presence of a submarine valley as the most recent seabed expression of Late Pleistocene paleo-river, multi-channel seismic reflection data provide subsurface evidence for prior incisions and subsequent infilling by regressive and transgressive deposits both before and after the LGM. Post-LGM transgressive fluvio-marine deposits filling the Paleo-Lupar incised valley were deposited during the rapid sea level rise after the LGM (Hanebuth *et al.*, 2000; Hanebuth & Stattegger, 2003) (Figure 7).

Detailed studies should be carried out in the future to further characterise the Paleo-Lupar. With more comprehensive seismic data, especially 3D seismic, and sediment cores, it is possible to work out the detailed erosional and depositional histories of this major river system, as was done in other parts of the South China Sea. In the Gulf of Tonkin, for example, point-bar migration and aggradational stacking of fluvial-estuarine sediments have been described from high-resolution seismic data (Wetzel *et al.*, 2021). Palynological and geochemical studies of cores from the subsurface sediments and associated paleo-channel deposits have provided useful insights into past climates and vegetation during the glacial and intervening periods since the LGM, preserved in the pollen and mineral contents of the sediments (e.g., Cheng *et al.*, 2023; Yu *et al.*, 2023).

Apart from their geological importance, there is increasing interest on the potential archaeological/anthropological significance in submerged paleo-river systems as records of past habitats and communities preserved in the paleo-landscapes over the last 1 million years. Considering the vast areal expanse of the Sunda Shelf, there is a high probability of finding ancient sites of pre-historic value, especially along major paleo-river systems, such as the Paleo-Lupar. Bailey (2004) has called for a systematic investigation of the submerged parts of the continental shelf for evidence of ancient coastal settlements that could be preserved underwater under the right conditions. Bicket & Tizzard (2015) reviewed the progress in research on Quaternary submerged prehistory of the British Isles. They reported that various materials have been recovered from the seabed at such sites around

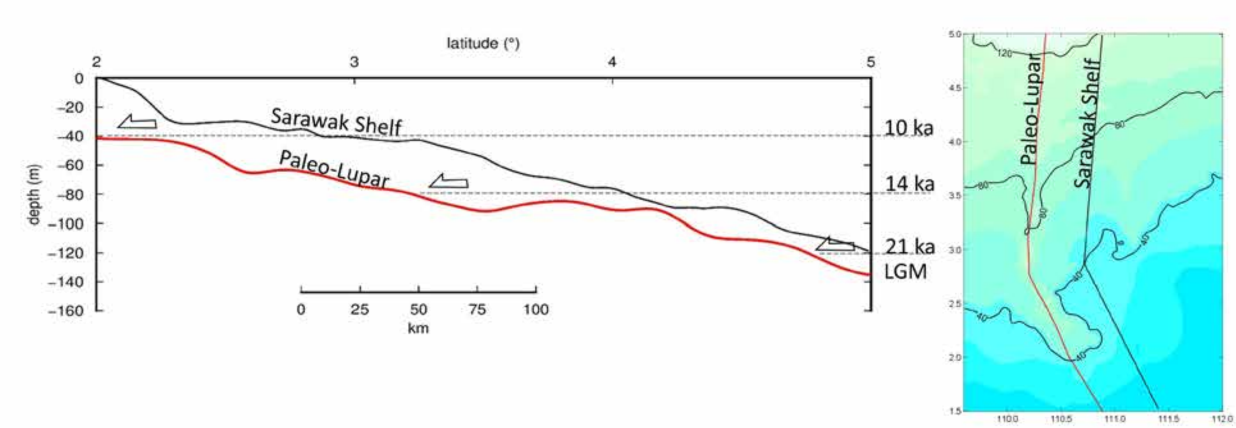

Figure 7: Synthetic longitudinal profile along the Paleo-Lupar (red) relative that of the adjacent seabed along a profile parallel to it to the east (black), showing the extent of vertical incision of the shelf due to sea level fall. The map to the right shows the location of the profiles in their corresponding colours. Horizontal dashed lines are approximate sea levels at 21, 14, and 10 ka during the sea level rise since the LGM, as estimated by Hanebuth & Stattegger (2003). Arrows indicate points of onlap of the sea level with the incised valley, representing the approximate paleo-shorelines at those times.

the British Isles, including bone and stone artefacts, extinct fauna, submerged forests and other relict landscapes. Submerged pre-history and landscapes are also actively being researched on other continental shelves of the world (Sturt *et al.*, 2018).

As one of the world's largest submerged paleo-landmasses, with financial support and the right tools, technologies, and expertise, Sunda Shelf has the potential for exciting discoveries in this area. From the Malaysian perspective, the Paleo-Lupar would be a good place to start. Detailed integrated studies using seismic, bathymetric and other data should be carried out to further characterise this and other submerged Pleistocene river valleys around Borneo and the Sunda Shelf, as they may hold critical information, not only with regard to paleoclimates and paleoenvironments but also on human paleohabitats.

CONCLUSIONS

Bathymetric and seismic data confirmed the presence of a submerged river valley that appears to continue from the modern Lupar River and extends for more than 350 km across the Sunda Shelf, off Sarawak. Together, the modern and Paleo-Lupar river stretch for more than 650 km and acted as a major sediment transport route from West Borneo to the Bunguran Trough.

The Paleo-Lupar is interpreted as the offshore extension of the modern Lupar River that was incised into the Sunda Shelf when large parts of it were subaerially exposed due to lowering of sea level to about 120 m BPL during the LGM about 21,000 years ago.

Multi-channel seismic data revealed the presence of channelised deposits beneath the Paleo-Lupar that probably represent the fluvial and transgressive deposits filling the incised river valley at the end of the LGM.

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CONFLICT OF INTEREST

I declare that I do not have any conflict of interest with regard to the contents of this paper.

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