Variations of fluvial patterns and infilling history of a paleoincised valley system during Late Pleistocene to Holocene, Offshore Pahang River, Peninsular Malaysia

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Abstract

High-resolution 2D acoustic profiles, combined with time slices from a 3D data volume, were used to investigate the paleoincised valleys offshore of the present-day Pahang River, South China Sea. Paleovalleys were formed during the regressive phase of the last glacial cycle. They were submerged and possibly filled during valley formation and postglacial marine transgression. Interpretation of acoustic profiles illustrates that the valleys were incised and infilled during the regression and low stand followed by subsequent deglacial sea-level rise. They were overlain by a transgressive ravinement surface suggesting transitional deposits between fluvial-dominated filling and shallow-marine deposition. This ravinement surface is overlain by Holocene shallow marine deposits. A low-sinuosity low-stand valley system changed to a high-sinuosity meander belt and eventually evolved into a deltaic distributary channel system before the complete submergence of the area. The average Late Pleistocene surface lies between 53 and 64 m below present-day mean sea level in the study area with approximately 16–50 m of valley incision. The Holocene shallow marine cover thickness varies from 5 to 10 m.

Introduction

Paleofluvial systems are important features that provide insights on climate variability in the stratigraphic record, specifically in a shelfal region that was subaerially exposed during lower sea levels (Blum et al., 2013). Incised valleys are large fluvially eroded features that typically constitute a single-channel system (Boyd et al., 1994; Alqahtani et al., 2015). In general, the valley incises and plays an important role in transporting sediments to the shelf edge during lower sea level and glacial cycle low stand. It may contain a low-stand sequence boundary within eroded valleys as well as associated floodplains (Hanebuth and Stattegger, 2004). Valley infilling and fluvial morphology are also important components of the stratigraphic record through geologic time. These strata record sea-level change, climate-induced discharge rate change, and sediment supply changes (Blum et al., 2013; Alqahtani et al., 2015). Fluvial incision may be driven by one or more of the following factors: (1) a relative base level or sea-level fall driven by eustasy and/or tectonic uplift; (2) climate change, which may lead to increased rainfall resulting in greater fluvial discharge and incision; and (3) river capture, which can result in increased discharge in composite fluvial systems (Posamentier, 2001; Alqahtani et al., 2015). Late Quaternary sea-level and climate change in the Sunda Shelf have been studied using several approaches, e.g., a chronostratigraphic approach (Kamaludin, 2002), biomaterial (such as plant debris and coral reefs) dating coupled with high-resolution seismic profiles (Hanebuth et al., 2000, 2009; Puchala et al., 2011), seismic onlap and offlap markers (Zhong et al., 2004), sedimentation rate, organic δ¹³C and foraminiferal δ¹⁸O proxy records (Bird et al., 2010), and modern satellite bathymetry (Voris, 2000; Sathiamurthy and Voris, 2006).

Paleovalleys existed on the Sunda Shelf when it was exposed during the regressive phase and subsequent low-stand condition. The sea level on the Sunda Shelf fluctuated throughout the last glacial cycle. The smaller transgressive phases prevailed during the last regressive cycle (115–26 ka BP), and smaller regressive phases also occurred during the post-last glacial maximum transgressive system until the early Holocene (Biswas, 1973; Geyh et al., 1979; Islam and Tooley, 1999; Ta et al., 2002; Yulianto et al., 2005; Hanebuth et al., 2006; Tanabe et al., 2006). The LGM sea-level high stand is marked by 123 ± 3 m lower than present-day mean sea level (MSL), and the Holocene high stand is denoted as being an average +5 m higher at 5 ka BP (Hanebuth et al., 2009, 2011; Bui et al., 2013, 2014). However, the penultimate sea-level high stand prevailed approximately 120 ka

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BP with a similar high stand as the Holocene (Nakada and Lambeck, 1987; Chappell et al., 1996; Intasen et al., 1999; Hanebuth and Stattegger, 2004; Kitazawa et al., 2006; Hanebuth et al., 2011; Bui et al., 2014). The exposure of the shelf allowed development of extensive drainage systems that could be detected in acoustic sediment profiles (Stattegger et al., 1997; Posamentier, 2001; Sharma, 2002). After the LGM, marine transgression inundated the exposed shelf and shorelines retreated landward, causing submergence and development of a transgressive system tract above the drainage network of the low stand (Hanebuth et al., 2003; Hanebuth and Stattegger, 2004; Sathiamurthy and Voris, 2006).

This study investigates the Late Pleistocene-Holocene-incised valleys and their infilling as a response to the deglacial sea-level rise in the Penyu Basin, offshore Pahang, east coast of Peninsular Malaysia (Figure 1). The trunk valley system investigated from the 3D seismic data in this study could be the paleo-Pahang River system. The present-day Pahang River drainage basin covers an area of approximately 29,300 km². The river channel is on average approximately 330 m wide, 10 m deep, and 435 km long. In the middle-lower reaches, the meander belt is approximately 3.7 km in width. The average discharge rate of the river system is approximately 1712 m³/s. The river bed slope is approximately 0.016% (Ghani et al., 2012). The study area is located 720 km westward from the LGM shoreline. Hence, marine transgression took several thousand years to advance westward before reaching the Penyu Basin area (Sathiamurthy and Voris, 2006).

This paper illustrated changes in river morphology corresponding to sea-level rise during the Late Pleistocene using acoustic sediment profiles coupled with 3D seismic time slices to examine the changes.

**Geologic setting and paleoenvironment of the study area**

The Sunda Shelf is a geologically complex region (Figures 1 and 2). It has evolved through various phases of continental accretion, mountain building, and rifting between lithospheric plates (i.e., the Pacific, the Indo-Australian, and Eurasian plates) since the Triassic (Madon, 1995). The Penyu Basin is located in the shelfal region to the east of Peninsular Malaysia, separated from the Malay Basin by the Tenggol Arch (Figures 1–3) to the northwest, and structurally contiguous with the West Natuna Basin of Indonesia to the north.
east. To the west and southwest, the basin is bounded by the Pahang Platform and the Johor Platform, respectively (Figures 1 and 2). The sediments of the Penyu Basin are typically siliciclastic, consisting of interbedded shale, siltstone, and sandstone (Madon, 1995). The sedimentary succession is categorized into synrift and postrift sequences. The synrift sequence represents the Late Eocene to Oligocene sediments deposited during the extensional phase of the basin development as evidenced by half-graben fills, whereas the postrift sequence represents the Miocene to recent sediments infilling the basin after the extensional faulting. The Penyu Basin is located near the equator and West Pacific Warm Pool. This proximity suggests the likelihood of a Pleistocene climate comparable with a modern-day tropical climate (Sun et al., 2000; Morley, 2002). Monsoonal rainfall during the last glacial low stand was slightly lower than in the Holocene, which may have affected the vegetation pattern on the exposed Sunda Shelf such as the existence of savannah-like corridors (Sun and Li, 1999; Wang et al., 1999; Sun et al., 2000; Bird et al., 2005). The extent of the South China Sea during the last glacial low stand was smaller than in the present day (Figure 3) and appeared as a semienclosed marginal sea with a “blind gulf”-type configuration (Sathiamurthy and Voris, 2006). The continental shelf of the South China Sea was well-developed around the basin margins. Climate and eustatic sea-level changes are likely major factors that triggered episodic submergence and exposure of continental shelves during glacial and interglacial phases compared with tectonics because as the Sunda Shelf was tectonically stable during the Plio-Pleistocene period (Madon and Watts, 1998). These variability of forcings caused multiple phases of fluvial incision, valley infilling, and preservation of fluvial records (Zhuo et al., 2015).

**Methodology**

In total, 748 line km of 2D high-resolution subbottom compressed high intensity radar pulse (CHIRP) profiles collected in October 2009 were used in this study. A single EdgeTech SB-0512i CHIRP subbottom profiler was used for acoustic profiling. The instrument can

![Figure 3](image3.jpg)

Figure 3. Shaded interpolated present-day seafloor showing the transgressive phases of the shoreline retreating contour using the ETOPO 1 arc minute bathymetric data set.

![Figure 4](image4.jpg)

Figure 4. Time slices at (a) −122 ms and (b) −84 ms, (c and d) as well as their corresponding interpretational line drawings. (a and c) Note the southwest–northeast-extending Late Pleistocene trunk-incised valley and the pre-LGM meander channel belt at the −122 ms time slice, and (b and d) the lower reach fluvial and deltaic distributary channel at the −122 ms time slice. (e and f) Three-dimensional perspective views showing the relief of the Late Pleistocene trunk valley system and the lower-reach fluvial and deltaic distributary channel systems using the interpreted horizon data.
penetrate 20 m (coarse calcareous sand) to 200 m (clay) of subseabed with 8–20 cm vertical resolution. The frequency range used was 7–12 kHz. Acoustic trace data and geographical positions were recorded concurrently. An onboard global positioning system (GPS) was synchronized with the data logging software (EdgeTech Discover), and it was used to ensure the accuracy of data positions. The average velocity of seawater and near-surface sediments was set at 1600 m/s for the purpose of two-way travelt ime (TWT) to depth conversion (EdgeTech, 2014); hence, 1 ms is approximately equal to 0.8 m.

The original 2D JavaServer Faces (EdgeTech data format) format data were converted to standard Seg-Y format using EdgeTech Discover software. ProMax software was used to process the 2D standard Seg-Y data. Data noise above the edge line of the seafloor was removed. An automatic gain control (AGC) option was used to enhance the image quality. AGC automatically differentiates the gain in trace samples as a function of sample amplitude within a sliding vertical time window. The color scaling was modified for further enhancement of the subbottom profiles and exported as graphic files using KOGEO Seismic Toolkit software.

Figure 5. Late Pleistocene-incised valley system and valley filling (divergent pattern). The Late Pleistocene boundary is marked as a bold line. A continuous ravinement surface is denoted by a dashed line. The scoured seabed surface indicated by truncation termination is also evident.
Adobe Illustrator was used for manual interpretation of subbottom profiles. Processed subbottom images were graphically enhanced to make subtle differences more visible for the purpose of stratigraphic delineation. Seismic stratigraphic methods were used as the basis for data interpretation in which different seismic units were delineated based on reflection parameters including configuration, continuity, amplitude, and frequency. The paleochannels were traced up to a depth of 200 m below the seabed to identify the Late Pleistocene and Holocene valley systems and to analyze the morphological variation of the paleovalleys from Late Pleistocene to Holocene until they were completely submerged. ETOPO 1 arc minute (1.86 km) grid data were used to represent sea-floor morphology. The data were downloaded from the National Oceanic and Atmospheric Administration (NOAA) website (Amante and Eakins, 2009). A downloaded “xyz” file was interpolated with a hillshade effect (Figures 1 and 3) using ArcGIS 9.3 to create a seafloor bathymetric surface. Time slices from a 3D seismic data set covering approximately 980 km² (used with permission of PETRONAS, Malay-

Figure 6. Phases of Late Pleistocene valley incision and filling.
sia) were extracted from the near-seafloor interval to investigate the distribution and evolution of the Late Pleistocene-incised valleys. Petrel 2012 was used to generate the time slices and for manual interpretation of inline sections (one in every five inlines) to make 3D horizon surfaces from the base of Late Pleistocene-incised valley unconformity up to the seafloor. Horizons interpreted from inline sections were interpolated using the “inverse distance weighted” method in the Petrel 2012 software. The time slices were imported into ArcGIS 9.3 as georeferenced images for 2D interpretation.

Results

**Interpretation of 3D seismic data**

Time slices and inline/crossline-based interpretation of the 3D data provide a plan view and expose the evolution of the paleofluvial patterns within the LGM-

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**Figure 7.** V-shaped (very steep gradient), incised valley system (bold line). The dashed line denotes the ravinement surface that is overlain by the shallow-marine cover.
incised valley system (Figure 4). A major or "trunk"-incised valley can be identified in the 122 ms time slice that could have possibly existed during last glacial cycle (Figure 4a). The valley exhibits a low-sinuosity character and an inferred flow direction from southwest to northeast (Figure 4a and 4c). Its structure lies between approximately 110 and 144 ms (Figure 4e). The trunk valley extends at least 27 km and has an average erosional maximum width of approximately 2.7 km, an incision depth up to 27 m, and probably represents the paleo-Pahang river system.

Relative to the trunk valley, smaller post-LGM channels, characterized by high-sinuosity postfill meander belts, are found outside of the incised valley fill (IVF) (Figure 4a and 4c). They imply that the incised valley system changed from a straighter valley that existed during Late Pleistocene to a meandering river system above the base of the IVF when the sea level rose.

Figure 8. Phases of Late Pleistocene-incised valley and infilling. Vertical channel stacking of channel filling is evident. Well-demarcated ravinement surface (dashed line) overlain by a thin shallow-marine cover.
Stratigraphically higher, the fluvial system was transformed into a moderately sinuous deltaic distributary fluvial system as imaged by the 84 ms time slice (Figure 4b, 4d, and 4f). This distributive fluvial system flowed from west to east and extends for approximately 32 km in the data block. The average channel width is approximately 1.7 km with an average depth of approximately 14 m. This may represent that the latest incised valley system before the area was completely submerged during the Holocene highstand.

**Interpretation of 2D CHIRP profiles**

The high-resolution CHIRP profiles illustrate the cross-sectional morphology and high-resolution details of the IVF of the incised valley systems (Figures 5, 6, 7, and 8). The initiation of the Late-Pleistocene valley fill started during the low stand and early phase of sea-level transgression. The CHIRP acoustic profiles show several stages of incision and filling since the initiation of the LGM low stand (Figures 6–8). Stages 1 through 4 indicate their transition from older to more recent fluvial sequences that may form during the last regressive cycle (approximately 105–20 ka BP). These provide clear evidence of sea-level fluctuations during post-LGM transgression implying that the deglacial sea-level rise was not steady. It is likely that the sea level remained at the same level for quite some time, or even dropped. Our results suggest that the valley system has shifted vertically and laterally (Figures 7 and 8). Discordant parallel-bedded intervals suggest vertical channel stacking. We noted that the infilled V-shaped, incised valley system was underlain by a wider and shallower incised valley system (Figure 8). In contrast, a U-shaped, infilled Late-Pleistocene valley system was incised by a narrower, V-shaped Holocene channel. Late-Pleistocene valley incision depths range from 16 to 50 m. The confluence of the tributaries with the valley is clearly observable (Figure 5).

Infilling of these incised valleys possibly occurred during regressive, low-stand, and transgressive phases of the Late Pleistocene to the early Holocene (Paola and Mohrig, 1996; Blum and Törnqvist, 2000; Paola, 2000; Blum et al., 2013). A well-developed divergent filling pattern of the incised valley which is characterized by a wedge-shaped unit was observed in the acoustic profiles (Figures 5–8). The valleys were filled and subsequently overlain by a horizontal stratified layer of nearly uniform thickness of 5 m. A ravinement surface separates this shallow-marine sediment cover from the fluvial–dominated, IVF below. A clear ravinement surface (dashed line) could be found in all transects except in Figure 6. In that area, the seabed scouring may have dislodged the ravinement surface and shallow-marine cover exposing the valley in the seafloor. No evidence

![Figure 9](https://example.com/figure9.png)

**Figure 9.** (a) Present-day bathymetric surface, (b) CHIRP acoustic profile cruise track, (c) Isopach topography of last glacial cycle based on the interpretation and interpolation of the 2D acoustic profile data, and (d) Isopach map of postglacial sediment thickness.
of any fluvial system is found in the shallow-marine cover because the shelf was already submerged. The depth of our Late-Pleistocene surface from the studied acoustic profiles ranges from 53 to 64 m below present-day MSL, whereas the seafloor surface lies between 38 and 55 m below present-day MSL (Figures 5–8). The gradient of the Late Pleistocene-incised valley walls has steep to moderate side walls (35°–70°) related to a horizontal plain. The over bank gradient and the valley width decreased as the valley filled. The interpreted possible low-stand sequence boundary surface and the isopach map of possible deglacial sediment thickness were used to relate with the present-day seafloor bathymetry (Figure 9). The boundary depicts a basinward gradual slope corresponding to the horizontal horizon. The isopach map of deglacial-infilled sediments shows a distinct basinward increment of sediment thickness.

Discussion

The valley incision occurred during the Late Pleistocene low stand, whereas infilling started during the following transgression. As the transgression progressed, the incised valleys were filled and incised through several phases. Fluvial lag deposits could not be detected in the acoustic profiles, implying that the early transgressive systems tract might be limited within the incised valley systems similar to what was detected by Bui et al. (2013) on the Vietnam Shelf. The shoreline retreated and eventually reached the studied valley system and flooded it completely. The ravinement surface on the top of the valley fill sediments is an indication of the complete drowning of the shelf and records the transition from fluvial dominated to shallow-marine conditions (Bui et al., 2013; Tjallingii et al., 2014). The incision and filling occurred in several phases and might indicate that the sea-level rise was fluctuating rather than following a constant incremental curve, implying that the general sea-level rise trend was punctuated by periods of sea-level fall (Zhong et al., 2004). These incision phases took place probably due to either an anomaly in sea-level rise within the last transgressive cycle, hydrologic and sediment supply variation, or a combination of both. The wetter climate indicated by the increasing rainfall abundance index trend from 19 to 5 ka BP suggests larger fluvial and sediment discharge coinciding with sea-level rise (Partin et al., 2007; Shah et al., 2013). Several small cycles probably appeared during the last transgression (Islam and Tooley, 1999; Bird et al., 2007). This fluctuated transgression triggered the V-shaped, incised channels, even during the transgressive period or Holocene (Figure 6). The relationship between the transgressive surface and the sea level at the moment of marine inundation is given by the maximum possible water depth in the valley. The Sunda Shelf sea-level curve (Figure 10) shows that the sea level was approximately 76 m lower than present-day MSL at approximately 13.5 kaBP (Hanebuth et al., 2011). The shorelines took approximately 7.5 ka to reach the study area, i.e., 21–13.5 ka BP. (Figure 3). The channel adjusted to the westward retreat of the shoreline as the post-LGM transgression advanced as evidenced by the valley pattern evolving from an incised valley with a braided channel to a deltaic distributary channel system (Figure 4). The modern seafloor and the Late Pleistocene-exposed shelf topography as well as the valley morphology suggest that the channel took a general flow direction from west to east. The upper to middle-reach valley system is capped by lower reach deltaic distributaries (Figure 4a and 4e). After complete submergence of the area, the valley system was gradually buried by the Holocene shallow-marine sediments.

![Figure 10](http://library.seg.org/)

Figure 10. (a) Sea-level curve model more than 130 kyr depicting marine isotope stages and last glacial, interglacial, and deglacial period from Bui et al. (2014), interpolated from Hanebuth and Stattegger (2004) and Chappell et al. (1996). (b) Postglacial sea-level curve of the Sunda Shelf showing key time points (modified from Hanebuth et al., 2011 [deep blue]; Bui et al., 2013; Stattegger et al., 2013 [light blue]). Key time points including 21 ka BP as LGM when the sea level was −123 m below the present-day MSL demarked by maximum shelf exposure, 14.3 ka BP as meltwater pulse 1A when the outer shelf was submerged, 12.7 ka BP as Younger Dryas (−60 m) when the central shelf region was inundated, 10.8 ka BP indicating the start of the inner shelf inundation, and 4.2 ka BP as the mid-Holocene Highstand (+5 m) followed by slight sea-level fall and delta progradation.
Conclusion

Interpretation of 3D seismic data indicated that a low-sinuosity, incised valley system possibly existed during the Late Pleistocene. The valley began to evolve in response to deglacial sea-level rise and eventually filled during transgression. Smaller channels with moderate sinuosities developed on valley fill sediments. Furthermore, the fluvial system evolved to a highly sinuous meandering channel belt that eventually transformed to deltaic distributary channels just before complete submergence of the study area. Late Pleistocene to Holocene-incised valley morphology and sequence boundaries of regressive and transgressive depositional sequences were investigated. As marine transgression progressed in the last glacial cycle, the coastline retreated landward and eventually inundated the complete Sunda Shelf. Consequently, the Late Pleistocene-incised valley was filled with low-sinuosity to early transgressive fluvial sediments. Analysis of combined 3D data and 2D acoustic profiles depicted the valley incision and filling morphology. The transgressive system tract sediment-filled valley was overlain by Holocene shallow-marine deposits. A clear ravinement surface demarcates the boundary between fluvial-dominated valley filling deposits and the shallow-marine cover. Valley morphology changed significantly in response to sea-level changes during the transgression. Several phases of incision and filling during transgression are evident possibly due to unstable sea-level rise. Lateral and vertical shifting of the incised valley system is observed in the acoustic profiles.

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Biographies and photographs of the authors are not available.