

CHIRP acoustic characterization of paleo fluvial system of Late-Pleistocene to Holocene in Penyu Basin, Sunda Shelf

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Abstract: Architecture and morphology of the paleo-incised valleys in Penyu Basin, South China Sea (SCS) was investigated using high-resolution two-dimensional (2D) acoustic profiles. Acoustic surveys were conducted in 2009 using a CHIRP sub-bottom profiler. The paleo-valleys were formed during several phases of regression and subsequent Last Glacial Maximum (LGM) when the sea level was approximately 123 ± 2 m lower than present-day mean sea level (MSL). These valleys were filled during lowstand and subsequent postglacial marine transgression and subsequently submerged during last glacial cycle. Holocene shallow-marine cover healed the ravinement surface. Three distinct facies and two bounding surfaces are categorized in the CHIRP profiles. Lithified pre-glacial deposits (Unit-III) are characterized by possible previous highstand deposit and regressive shoreface deposits. The erosional surface is demarcated as lowstand sequence boundary that overlain by transgressive fluvial deposits. Several stages of the incision and infilling are identified, possibly caused by fluctuating sea level transgression. The average late-Pleistocene (LGM) surface lies between 53 to 64 m below present-day MSL in the study area with ~ 16 to 50 m of valley incision. The valley slope varies 35 to 85° correspondent with the horizontal horizon. The Holocene shallow-marine cover thickness varies from 3 to 10 m.

Keywords: CHIRP acoustic profile, paleo fluvial geomorphology, sea level change, sequence stratigraphy, Last Glacial Maximum

INTRODUCTION

The Penyu Basin is located at the inner section of the Sunda Shelf, offshore of the present-day Pahang River Basin (Figures 1 and 2). Paleo fluvial systems are considered as important geologic features in the stratigraphic record, particularly in shelf region that were subaerially exposed during lower sea level (Blum & Tornqvist, 2000; Blum *et al.*, 2013). However, incised valleys are large and fluvial erosive features that typically constitute a single channel system (Blum & Tornqvist, 2000; Posamentier, 2001; Darmandi, 2005; Darmandi *et al.*, 2007; Blum *et al.*, 2013; Alqahtani *et al.*, 2015). During the relative sea level fall, the drainage system incised into the valley and transported sediments to the shelf edge (Hanebuth & Statterger, 2004). Incised valleys are marked by a basal erosional surface which represents a sequence boundary in stratigraphic terminology. The internal stratal architecture of incised valleys fills are excellent record of depositional history in shelfal basins through geologic time. The incised valley fills record fluctuations of sea level, climate forcing induced river discharge and sediment supply (e.g., Blum *et al.*, 2013; Alqahtani *et al.*, 2015). Fluvial incision can be triggered by one or more of the following factors: (i) a relative base level or sea level fall driven by eustasy and/or tectonic uplift; (ii) climate change, which may lead to increased rainfall resulting in greater fluvial discharge and incision; and (iii) river capture, which can result in increased discharge in composite fluvial systems (Posamentier, 2001).

Paleo-valleys developed on the Sunda Shelf when it was exposed during regression and subsequent LGM at around 26-19 ka BP (Hanebuth *et al.*, 2011; Bui *et al.*, 2013). The sea level on the Sunda Shelf during LGM was 123 ± 3 m lower than present-day MSL (Hanebuth *et al.*, 2009; Hanebuth *et al.*, 2011; Bui *et al.*, 2013). Subaerial exposure of the shelf allowed development of extensive drainage

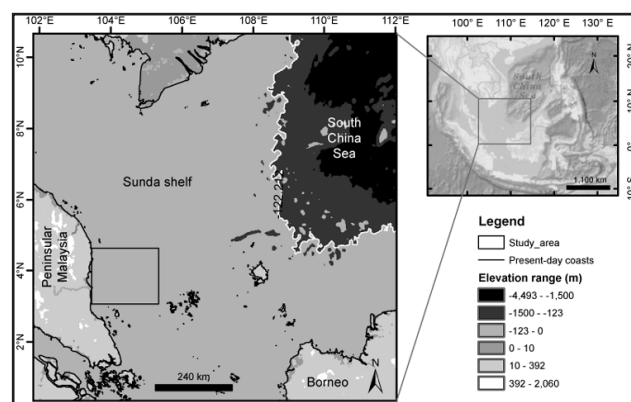


Figure 1: Location map of northern Sunda shelf based on ETOPO 1 arc minute data that combined satellite altimetry and bathymetry data. Bathymetry data is interpolated from National Oceanic and Atmospheric Administration (NOAA); shoreline data is adapted from GEODAS; Ocean base-map is modified from ESRI online resource contributed by ESRI, GEBCO, NOAA, HERE, Geonames.org, National Geographic and other contributors (Amante & Eakins, 2009).

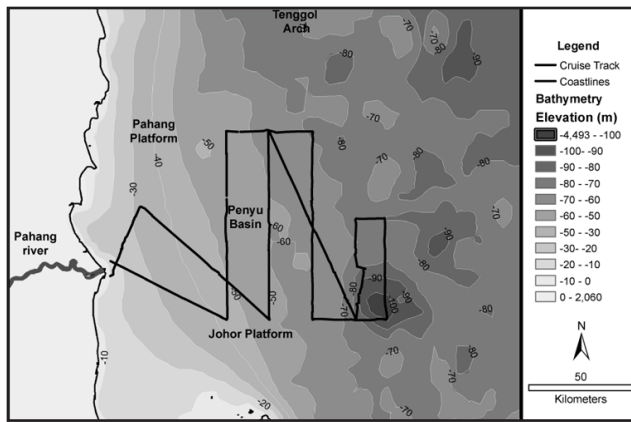


Figure 2: Bathymetric elevation and location of CHIRP acoustic profiles.

systems that could be detected in acoustic sediment profiles (Statteger *et al.*, 1997; Posamentier, 2001; Sharma, 2002). Deglacial marine transgression began after 19.6 ka BP to inundate the exposed shelf as shorelines retreated landward (Hanebuth *et al.*, 2011; Bui *et al.*, 2013). This submergence caused changes in the lowstand drainage systems (Hanebuth *et al.*, 2003; Hanebuth & Statteger, 2004; Sathiamurthy & Voris, 2006). As a result, fluvial morphology changed correspondent to sea level transgression during the last glacial cycle. This study investigates the stratal architecture of LGM incised valley and transgressive fluvial system and filling pattern caused by deglacial sea level transgression in the Penyu Basin area of the Sunda Shelf.

REGIONAL SETTINGS

The Sunda Shelf has been tectonically stable since the Plio-Pleistocene period (Maden & Watts, 1998). The Penyu Basin is located near the equator and West Pacific Warm Pool. This region has a non-seasonal climate with high temperature (24–28°C) and precipitation over 2000 mm (Sun *et al.*, 2000). The monsoonal rainfall during the LGM was lower than the Holocene and this condition may have affected the vegetation pattern on exposed Sunda Shelf (Wang *et al.*, 1999; Alqahtani *et al.*, 2015). The aerial coverage of SCS during last glacial lowstand conditions was smaller than the present-day (Figure 1). It formed semi-enclosed marginal sea with ‘blind gulf’ type morphology (Sathiamurthy & Voris, 2006). Tectonic activities, climate change, and sea level fluctuations triggered episodic submergence and exposure of the continental shelf during glacial and interglacial phases. These varieties of forcing caused multiple phases of fluvial incision, infilling and preservation (Zhuo *et al.*, 2015).

The Sunda Shelf is a geologically complex region that 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 age (Maden, 1999). Penyu Basin is located in the shelf region to the east of Peninsular Malaysia, separated from the Malay Basin by Tenggol Arch to the northwest, and structurally contiguous with the West

Natuna Basin of Indonesia to the northeast. To the west and southwest, the basin is bounded by the Pahang Platform and the Johor Platform, respectively (Maden, 1995; Madon, 1999, Figure 2). The basin probably initiated during the Late Eocene to Early Oligocene (~40–35 Ma) around the same period as the West Natuna Basin (Maden, 1995; Madon & Watts, 1998). The sediments of the Penyu Basin are typically siliciclastic, consisting of inter-bedded shale, siltstone and sandstone (Maden, 1995; Madon, 1999).

METHODOLOGY

High-resolution 748 line km of 2D sub-bottom CHIRP profiles were analyzed. The profiles were collected in October 2009. A single EdgeTech SB-0512i CHIRP sub-bottom profiler was used for acoustic profiling. It could penetrate 20 m (coarse calcareous sand) to 200 m (clay) of sub-seabed with 8–20 cm vertical resolution. The frequency range used was 7–12 kHz. An onboard global positioning system (GPS) synchronized with data acquisition. The average velocity of sea water and subsurface sediments was set at 1600 m/s for the purpose of two-way travel time (TWT) to depth conversion (EdgeTech, 2014). The original 2D JSF format data was converted to standard SegY format using EdgeTech Discover software. ProMax software was applied to process the 2D standard SegY data. First, we removed the data ‘noise’ found above the seabed. Automated Gain Control (AGC) option was applied to enhance the image quality. The color scaling was changed for further improvement of sub-bottom profiles using KOGEO Seismic Toolkit software. Adobe Illustrator was used for manual interpretation of sub-bottom profiles. Seismic stratigraphic methods were used as the basis for data interpretation, where different seismic units were delineated based on reflection parameters including configuration, continuity, amplitude, and frequency. We traced the paleochannels within the depth of 200 m below seabed to identify the LGM and Holocene valley systems and to analyze the morphological variation of the paleo-valleys from LGM to Holocene until the complete submergence. We used sequence stratigraphic concepts (*sensu* Blum & Tornqvist, 2000; Catuneanu *et al.*, 2009; Blum *et al.*, 2013; Tjallingii *et al.*, 2010; Bui *et al.*, 2013; Bui *et al.*, 2014; Tjallingii *et al.*, 2014) to delineate the facies distribution as well as stratal architecture.

RESULTS

High-resolution CHIRP profiles depict the cross-sectional morphology and internal configuration of the incised valley systems (Figure 3–6). Broadly, three basic units and two bounding surfaces have been identified within the studied transect lines.

Sequence boundary

The erosional unconformity with significant relief has been traced in all transect lines except some profiles, where it could not be delineated due to effects of shallow gas occurrence (Figure 3–6). The surface is characterized by high amplitude and continuity. This erosional surface, most

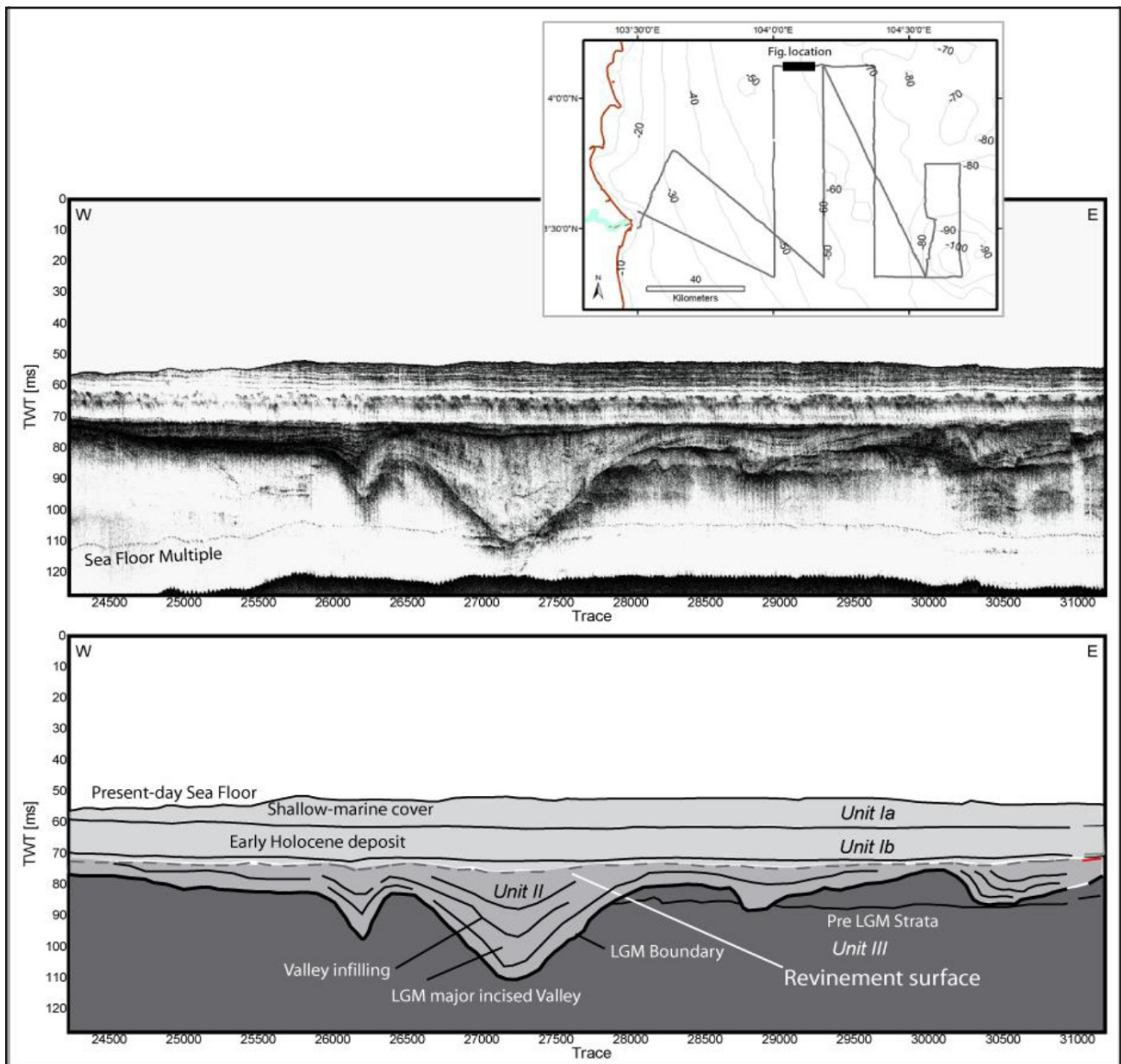


Figure 3: LGM Incised valley system and valley filling. Late-Pleistocene boundary is marked as bold line. A continuous ravinement surface is denoted by dashed line; scoured seabed surface indicated by truncation is also evident.

likely, represents the LGM lowstand sequence boundary. The sequence boundary is located 3 to 20 m below the present-day seafloor. This erosional surface incised into older, pre-glacial highstand strata or regressive alluvial deposits. The pre-glacial strata reflection is characterized by truncation with incised valley wall.

In addition, another bounding surface is identified as a ravinement surface in the CHIRP profiles, where it demarks a transitional depositional surface between fluvially dominated sediments and shallow marine deposits. This bounding surface overlying the incised valley fills (referred to unit II) (Figure 3-6) that are categorized by medium to low amplitude with higher continuous reflection. The surface is detected between 2 to 10 m below the modern-day bathymetric seafloor. The surface separates the transgressive

deposits from overlying marine sediments. The ravinement surface marks the eventual inundation of the fluvial system due to sea level rise.

Seismic Units

Three broad stratigraphic units have been identified within the studied interval, possibly representing different phases of pre-glacial to Holocene highstand depositions.

Unit-III

Unit-III is the lowermost and it is characterized by horizontally laminated strata and in some instances, slightly inclined strata that are interpreted as pre-glacial sediments deposited during the highstand, or regressive alluvial and shoreline deposits. The seismic character of this facies

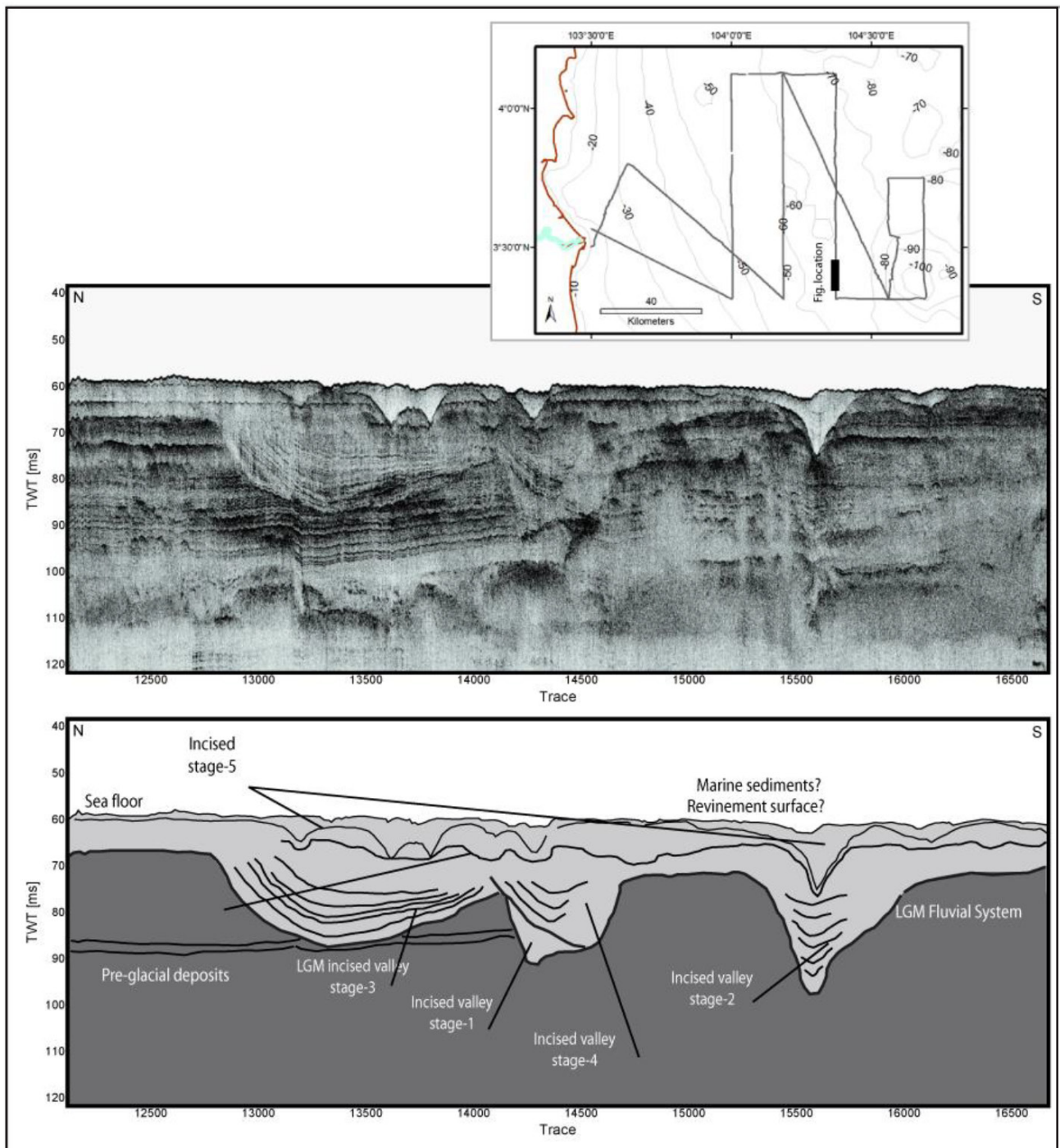


Figure 4: Phases of LGM valley incision and filling. The top Holocene marine sediments were possibly dislodged elsewhere as a result of seabed scouring.

is categorized by high amplitude and moderate to high continuous frequency. The top of the unit is bounded by the high amplitude, sharp erosional unconformity overlying the LGM sequence boundary. This unconformity forms the base of incised valleys and interflues which down cut the underlying Unit-III. The facies in Unit-III are not clearly visible or transparent in many profiles due to shallow gas occurrence (Figure 4 and 5). Hyperbolae echoes are also detected (Figure 5), possibly representing a basement high. The thickness of the unit generally reaches up to 50 m

or more. In some instances, the lower part could not be identified due to either it is not being imaged or transparent amplitude as shallow gas complex or acoustic reduction due to the higher reflectivity of overlying sediments or a combination of all the factors.

Unit II

Unit II is characterized by the incised valley systems with highly channelized features that overlie Unit-III. The lower boundary is marked by high amplitude and continuous

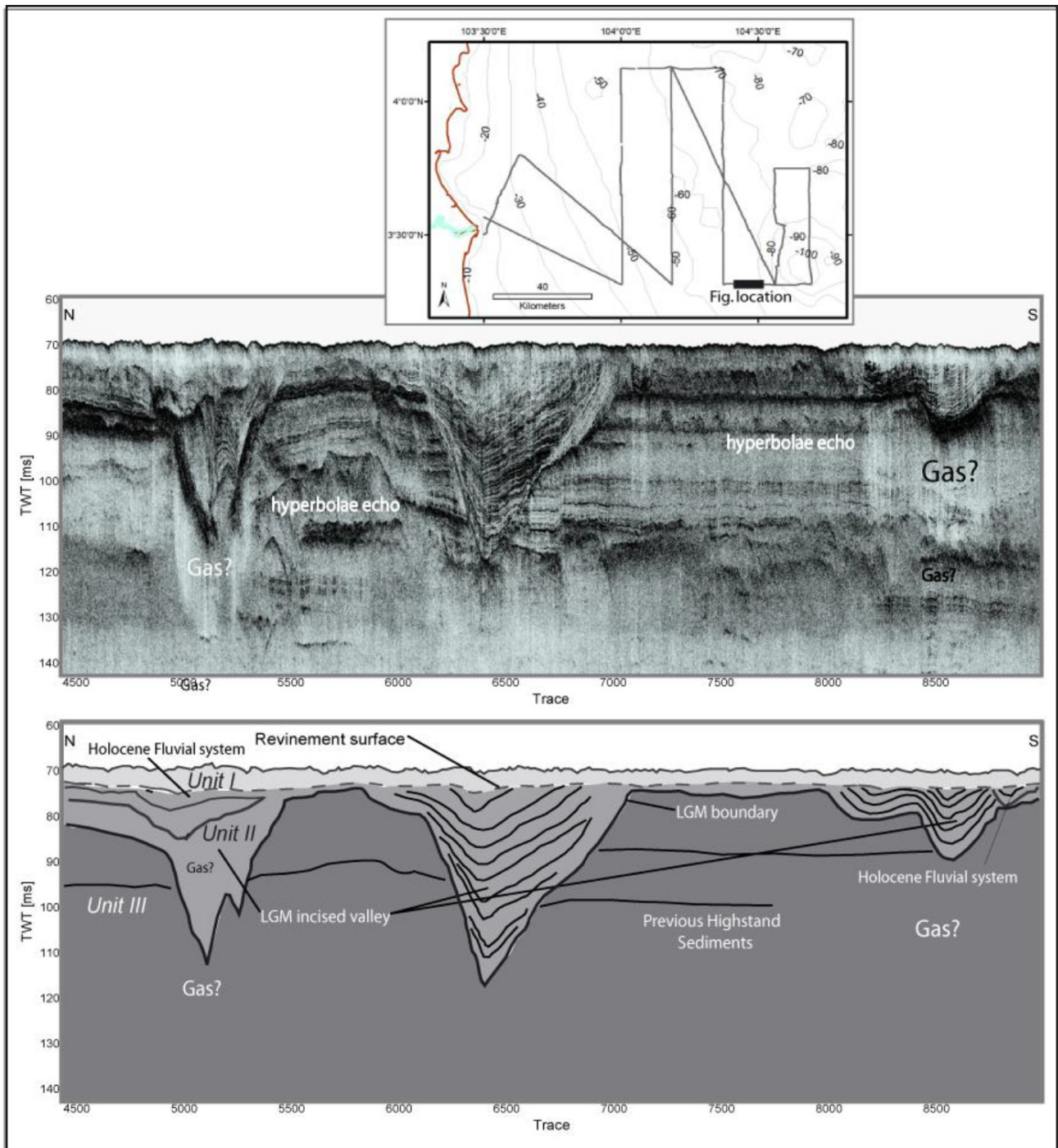


Figure 5: V-shaped (very steep gradient) incised valley system (bold line) that possibly existed during LGM. Post-LGM infilling and the incision are evident. Dashed line denotes the ravinement surface which is underlain by the shallow-marine cover.

reflector of the erosional unconformity/ sequence boundary. Top of the unit is bounded by a ravinement surface with higher amplitude and frequency. This unit is observed in all of the studied transects, and is characterized by seismic facies display of moderate to high amplitude and high to moderate frequency. Unit-II is divided into smaller sub-units bounded by higher frequency bounding surfaces due to vertical aggradation and avulsion of the incised valley systems during transgressive phase (Figure 4 and 5). The thickness of Unit-II ranges between 25 to 50 m in the incised

valley, while, in the interfluvial areas 5 to 15 m thick. The valley orientation is variable, but the most common trend E-W. The valleys are possibly filled with fluviially dominated sediments. Divergent valley filling has been recognized in most of the infilled valleys with the seismic facies characterized by medium to very high amplitude and medium to very high frequency. There is no evidence of fluvial lag deposits at the bottom of the incised valleys. The channels inside the incised valley show varied incision depths and widths. Generally, channels tend to decrease in width and

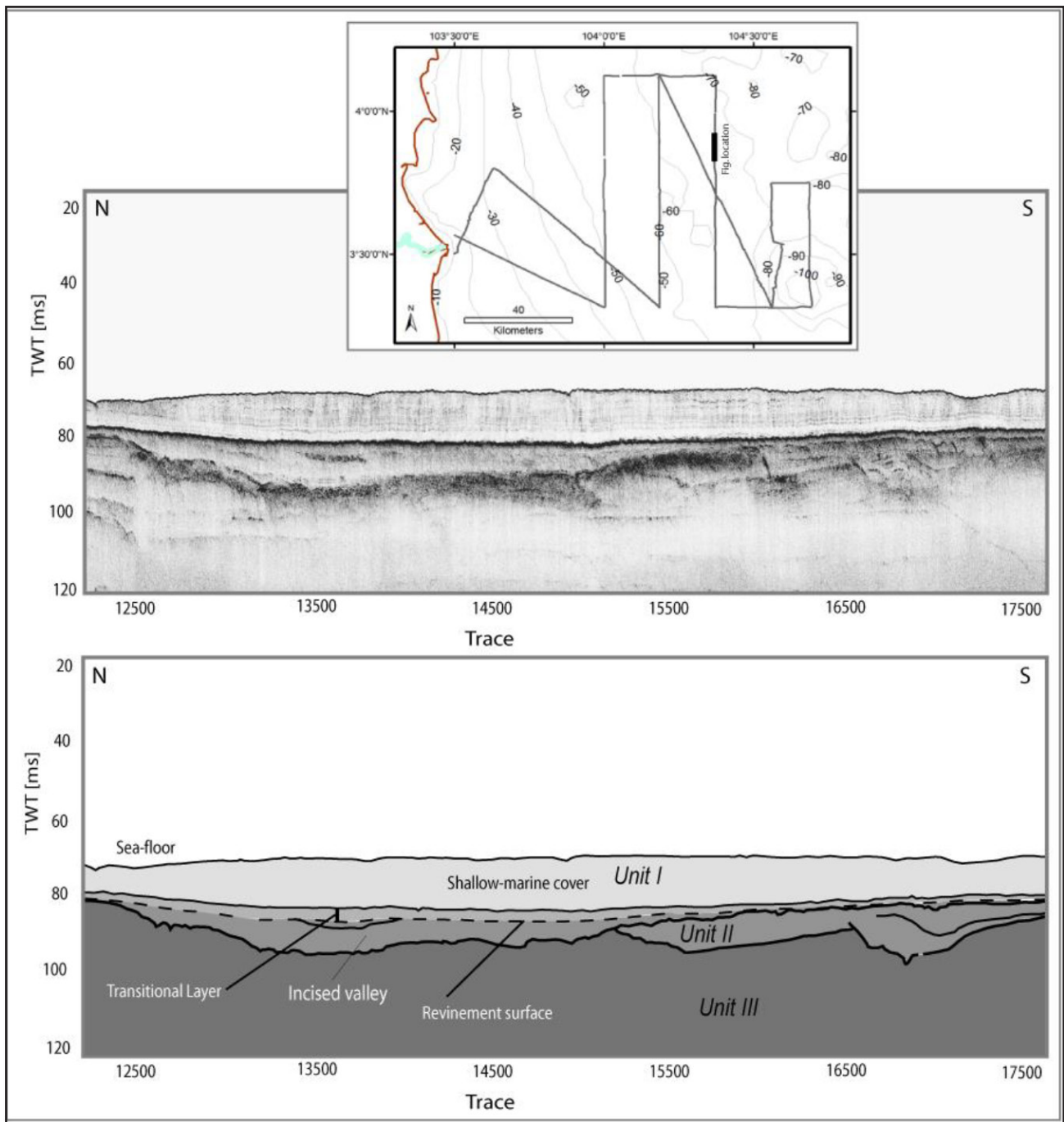


Figure 6: Shallow and wide channel system typically shows deltaic / estuarine fluvial system in last active channel before submergence. Well demarcated ravinement surface (dashed line) followed by a thin shallow-marine cover.

incision depth in the upper sequence. In some instance, the channels in the upper sequence appear as reduced depths with greater widths compare to lower channels.

Unit I

Unit I is the top most sedimentary package overlying Unit-II. This nearly horizontal stratified layer is characterized by high amplitude and high continuous frequency. It also appears as a transparent facies in some transects. The base of Unit-I is marked by the ravinement surface underlying Unit-II. Top of the unit is bounded by the modern-day

seafloor. The thickness of Unit-I ranges from 1 to 10 m. In some transects, Unit-I can be divided into sub-units: Unit Ia and Ib (Figure 3). Unit Ib is the lower, and thicker sedimentary layer, which is characterized by hyperbolae echoes. The strata of Unit-I represents deposition during early Holocene times, just after submergence of the area.

INTERPRETATION

The studied CHIRP acoustic profiles indicate the presence of significantly extensive Quaternary incised valley systems in the Penyu Basin. The profiles also depict

the infilling pattern of the incised valleys, which indicate transgressive aggradational strata. The vertical aggradation and laterally accreted fluvial incision and infilling is analyzed. Although there is no available core data to relate the age, we identified the sequence boundary based on the evidence of seismic characteristics (Figure 7). The valleys incised into underlying pre-glacial strata. In general, we identified 3 main sedimentary units in the seismic profiles. The pre-glacial substrata are denoted as Unit III, which underlying the incised valley system. The incision possibly took place during regression and subsequent glacial maxima. The shoreline at that particular point in time stayed furthest from the study area, and sea level reached ~ 123 m below present-day MSL (Hanebuth *et al.*, 2000; Hanebuth *et al.*, 2011; Bui *et al.*, 2013). Sea level started to rise during the deglacial period, which resulted in landward transgression of the shoreline. As the base level of the fluvial system started to rise, the valley system also started to fill. Lateral accretion as well as vertical aggradation developed in the valley filled sediments and the previous active floodplain. In general, the lowstand valleys in the studied transects show wider and higher incision depth and formed the V-shaped valley in the majority. However, V-shape valley system is also evident during the transgressive phase. The valley wall gradient with respect to horizontal horizon ranges from 35 to 85°. The younger phases of fluvial system, however, in general, on top of the valley filled sediment as well as previous active floodplain are characterized by lower incision depth and narrower to wider with U-shaped comparatively gentler channel wall slope. Very shallow and wide channel system of Unit-II can possibly be interpreted as deltaic distributary channel system (Figure 6). The distributary channel suggests a low energy depositional system in close proximity of the paleo-shoreline at that particular time. On top of this latest active deltaic channel system of Unit-II, the thin layer characterized by positive amplitude and underlying Unit-II interpreted as a ravinement surface. Basically, this bounding surface indicates the mixed condition of fluvial and marine-estuarine environmental condition that suggest the transgressive submergence of the fluvial system of the area. Further, there is a thin layer (~ 2 m to 12 m) of Holocene shallow marine sediment deposited on top of the ravinement surface. The channel responded through geological time possibly due to sea level transgression and/or climate-induced discharge and sediment supply variability.

DISCUSSION

CHIRP acoustic profiles of the Penyu Basin depict the incision and infilling history of a late Pleistocene to Holocene incised valley system offshore present-day Pahang River. As the transgression progressed, the incised valleys were filled. The shoreline retreated landward and reached until the studied valley system that eventually drowned. The transitional depositional surface typically known as ravinement surface on top of valley fill sediments is an indication of the complete drowning of the shelf. The ravinement surface is an indicator of deposition transforming

from fluvially dominated to shallow-marine conditions (Tjallingii *et al.*, 2010; Bui *et al.*, 2013; Tjallingii *et al.*, 2014). The incised valley system had been filled within a short period before complete submergence (Tjallingii *et al.*, 2010; Tjallingii *et al.*, 2014). However, the incision and filling occurring in several phases, possibly indicate that the sea level rise punctuated rather than a smooth transgressive curve (Islam & Tooley, 1999; Zhong *et al.*, 2004; Yulianto *et al.*, 2005). The different incision phases took place possibly due to either anomalies in sea level rise within the last transgressive cycle or other hydrological and sediment supply variation or a combination of both factors. Several small sea level (regression-transgression) cycles probably occurred during the last transgression. These fluctuations in sea level possibly triggered V-shape incised channel even during the post-LGM or Holocene period. The Sunda Shelf sea level curve (Hanebuth *et al.*, 2011; Bui *et al.*, 2013) shows that sea level was approximately 76 m lower than present-day MSL at around 13.5 ka BP. The shorelines took approximately 7.5 ka to reach the study area from 21 to 13.5 ka BP. The modern-day seafloor bathymetry and the valley morphology suggest that the overall flow direction of the channel was from west to east. After complete submergence of the area, the valley system was gradually buried by Holocene shallow-marine sediments.

CONCLUSION

High-resolution CHIRP acoustic profiles depict the incision and infilling pattern, internal channel morphology and their lateral shifting and vertical aggradations in the shallow subsurface in Penyu Basin. The studied transects indicate the presence of 3 distinct stratigraphic units. The lower unit (Unit-III) is represented as possible, previous Pleistocene highstand sediments. A prominent sequence boundary that is characterized by an erosional surface with high-amplitude reflector that related with sea level fall during last glacial cycle. Several incised valley systems with different scale and geomorphological architecture are identified. During the early transgressive phase, the valley system started to infill and also started to respond to sea level fluctuations by developing strata displaying vertical aggradation and lateral shifting, probably due to base-level fluctuations. Several deglacial phases of the incision and infilling appeared within the unit. In general, the channel size tends to decrease upward in depths and widths and channel bank gradients reduce upwards. Unit-II is thought to be a fluvial-dominated incised valley filled and associated floodplain sediment. The unit is bounded by a ravinement surface that is characterized by a high-amplitude reflector surface that represents the transitional facies between fluvially dominated sediment and tide dominated sediments. The ravinement surface marks the complete submergence of the fluvial system at that particular point and time. On top of this bounding surface, almost continuous stratified shallow marine cover has been identified. Most of the studied transects shows depression in the seabed that neither follows the lowstand incised valley/channel system nor the



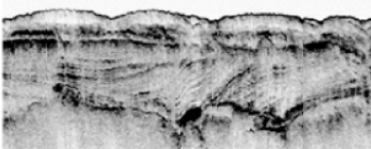
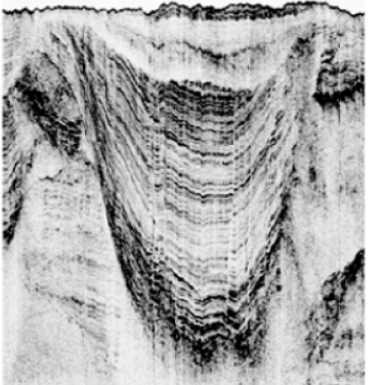
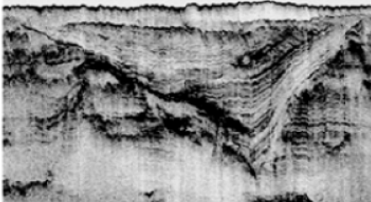
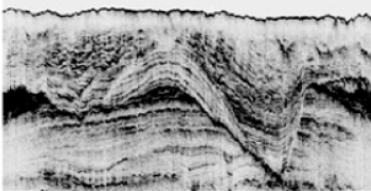

Incised valley image	Valley/ channel width	Incision depth	Gradient with horizon	Infilling pattern	Shape	Seismic character
	~120 m	~8 m	$\pm 45^\circ$	Chaotic	U shape channel	A- moderate F-Moderate C-low
	~850 m	~8 m	$\pm 25^\circ$	Aggradation	U shape channel (deltaic?)	A- moderate F-low C-low
	~460 m	~18 m	$\pm 35^\circ$	Divergent and Aggradation	Lateral channel shifting	A- moderate F-Moderate C-moderate
	~320 m	~52 m	$\pm 82^\circ$	Divergent	U shape channel	A-high F-high C-high
	~560 m	~38 m	$\pm 38^\circ$	Divergent	U shape vertical stacked channel	A-high F-high to moderate C-high
	~380 m	~31 m	$45-65^\circ$	Divergent	U shape channel	A-high to moderate F-high C-high to moderate
	~310 m	~31 m	$\pm 42^\circ$	Divergent	U shape vertical stacked channel	A- moderate F-moderate C-moderate

Figure 7: Physical and seismic characteristics of incised valley of the studied CHIRP transect (A-Amplitude, F-Frequency and C-Continuity).

last active channel trends (Figure 3, 5 and 6). Some profiles show some degree of incomplete filling, indicating that the seafloor surface was healed by the marine drape.

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