

Channel Evolution in Southern Pattani Basin, Gulf of Thailand from Early Pleistocene to Present Day

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Abstract

Channel evolution in the southern Pattani Basin, Gulf of Thailand, was characterized across three stratigraphic intervals: the early Pleistocene (~3 Ma), late Pleistocene (~1.6 Ma), and present-day seabed. Root-Mean-Square (RMS) amplitude, variance attribute, geomorphic interpretation maps, seismic cross-sections, channel morphometric, azimuth analysis, and fault-throw profiles were integrated in Petrel 2017 to evaluate temporal changes in channel morphology and structural influence. A total of 41 channel segments were interpreted across the mapped intervals. The results indicate that relative sea-level fluctuation was the primary control on channel development. Highstand conditions favored sinuous to meandering channels with large channel belts, including a maximum sinuosity index of 2.2 and a maximum mapped channel channel belt width of approximately 12,120 m at the seabed interval. Lowstand conditions promoted straighter, more incised channels, with sinuosity approaching 1.0 and maximum apparent incision reaching 100.2 m in the early Pleistocene interval. Fault azimuth and throw analysis shows that Fault-1, Fault-3, and Fault-4 retain measurable displacement within the shallow stratigraphic succession, whereas Fault-2 and Fault-5 show no measurable late Pleistocene throw. These structural elements locally deflected drainage, especially in the late Pleistocene upper sector, but did not overprint the dominant sea-level control. The results improve understanding of Neogene-Recent channel evolution and sediment distribution in the Pattani Basin.

Keywords: seismic geomorphology; sinuosity index; sea-level fluctuation; structural inheritance.

1. Introduction

The Pattani Basin is major Cenozoic extensional basin in the Gulf of Thailand and forms part of the Sunda Shelf tectonic province (Bustin and Chonchawalit, 1997; Kornsawan and Morley, 2002). It lies located in the central and southern Gulf of Thailand, between approximately 7° N and 10° N latitude (Fig. 1). The basin is characterized by an NNW-SSE oriented graben system containing more than 8 km of sedimentary fill accumulated since the late Eocene. Basin formation was associated with regional crustal extension, related to Indochina extrusion, and strike-slip deformation along major fault systems in Southeast Asia (Kornsawan and Morley, 2002). Initial syn-rift development was followed by a post-rift phase dominated by thermal subsidence.

Sequence 5 (Pliocene-Recent, approximately 5-0 Ma), which forms the uppermost part of the basin fill and, records the combined effects of relative sea-level change, sediment supply, and differential subsidence during the progressive inundation of the Sunda Shelf (Niyomborwornwat, 2014). These processes influenced channel development, preservation and stratigraphic architecture. Although deeper hydrocarbon bearing intervals, have been studies extensively, the spatial distribution and temporal evolution of shallow channel systems within Sequence 5 remain incompletely documented (Abdelaziz, 2017).

This study investigates channel evolution in the southern Pattani Basin using high-resolution 3D seismic-reflection data. Root-Mean-Square (RMS) amplitude and variance attributes extracted around the seabed, late Pleistocene and early Pleistocene surfaces

were used to identify channel geometries and evaluate changes in planform morphology, sinuosity, and migration patterns through time (Ahmad et al., 2014; Niyomborwornwat, 2014; Hossain, 2020). The objectives are to reconstruct the mapped channel networks and to evaluate the relative roles of relative sea-level change, sediment supply and possible structural inheritance.

2. Materials and Methods

This study utilized a 3D seismic reflection dataset acquired from the southern Pattani Basin, Gulf of Thailand. Due to data confidentiality restrictions, exact survey coordinates and acquisition parameters cannot be disclosed; however, the survey covers an incline of 12.5m interval and a crossline of 25m interval, with a bin spacing of 4m. The migrated volume exhibits SEG reverse polarity, with the seafloor reflection expressed as a peak (positive amplitude). The data show dominant frequencies of 56Hz, 63Hz, and 48Hz at the seabed, late Pleistocene, and early Pleistocene, respectively. Using interval velocities of 1,670m/s (seabed, late Pleistocene, and early Pleistocene intervals), the estimated vertical resolution ($\lambda/4$) ranges from 7-7.5m for the shallower surfaces (seabed, late Pleistocene) to 9m for the deeper surface (early Pleistocene), while lateral resolution ($\lambda/2$) ranges from 13.5-15m for the shallower surfaces to 17.5m for the deeper surface in Table 1. This resolution is considered sufficient to resolve channel-scale geomorphic features in the shallower stratigraphic intervals. Horizon interpretation was carried out in Petrel 2017.

Three stratigraphic surfaces were mapped throughout the study area: (1) the present-day seabed (110-130 ms TWT); (2) a

late Pleistocene reflection within Sequence 5, interpreted as a regional lowstand surface, occurring (160-210ms TWT); and (3) the early Pleistocene surface at the base of Sequence 5, dated to 5.0 Ma (255-295 ms TWT). These age assignments follow the regional chronostratigraphic framework of the south Pattani Basin established by Jardine, 1997, (Fig. 4) in which Unit 5 spans from the Pliocene, late Pleistocene boundary (~1.6 Ma) down to approximately 5 Ma at its base. As independent well-tie or biostratigraphic control was not available within this study, the ages adopted here follow this established regional framework, and the associated age uncertainty should accordingly be interpreted in light of the confidence limits of the source publication. Horizon interpretation was guided by reflection continuity, amplitude character, and seismic geometry.

Table 1. Estimated seismic resolution at each mapped stratigraphic interval, based on dominant frequency and interval velocity.

	Seabed	Late Pleistocene	Early Pleistocene
Wavelength (m)	30	27	35
Vertical Resolution (m)	7.5	7	9
Lateral Resolution (m)	15	13.5	17.5

Channel systems were investigated using RMS amplitude and variance (edge method) attributes extracted around each interpreted horizon. Both attributes were calculated directly from the migrated seismic volume, without prior structural smoothing, trace AGC, or other conditioning. RMS amplitude was calculated over a symmetrical

window of ± 18 ms TWT (9 samples, at a 4ms sample interval) using Petrel 2017's default RMS amplitude algorithm, and no additional amplitude normalization was applied prior to extraction. The variance (edge method) attribute was computed using an inline range of 3 traces, a crossline range of 3 traces, and a vertical smoothing parameter of 15, without dip correction. The RMS attribute highlights acoustic-amplitude contrasts that may correspond to changes in lithology or bed geometry, while the variance attribute was used to enhance discontinuities and channel-margin lineaments. As no well, core, or log data were available within the study area, attribute anomalies are interpreted as indicative of potential lithological or geomorphic contrasts rather than confirmed sand-rich or fine-grained lithologies. Horizon slices were analyzed in plan view to delineate channel geometry, continuity, and spatial distribution.

Morphometric analysis was used to quantify channel width, sinuosity, orientation, lateral migration, mapped channel belt width, and apparent incision depth (Hossain, Junayed and Rahman, 2023; Harishidayat et al., 2024). Comparisons among the early Pleistocene, late Pleistocene and seabed intervals were then used to assess temporal changes in channel architecture and to evaluate possible controls related to accommodation space, sediment supply, paleoslope, and relative sea-level change. Rivers display a range of planform patterns that are commonly classified as straight, meandering, or braided. A widely used measure of channel form is the sinuosity index (SI), defined as the ratio of the length of the channel measured along its course (the thalweg) to the straight-line length of the valley. Straight channels have sinuosity values close to 1.0,

whereas meandering channels have higher values, conventionally above about 1.5 (Fig. 2). Other diagnostic parameters include channel width, the width of the channel belt (the zone across which a channel has migrated laterally through time), and the orientation, or azimuth, of the channel.

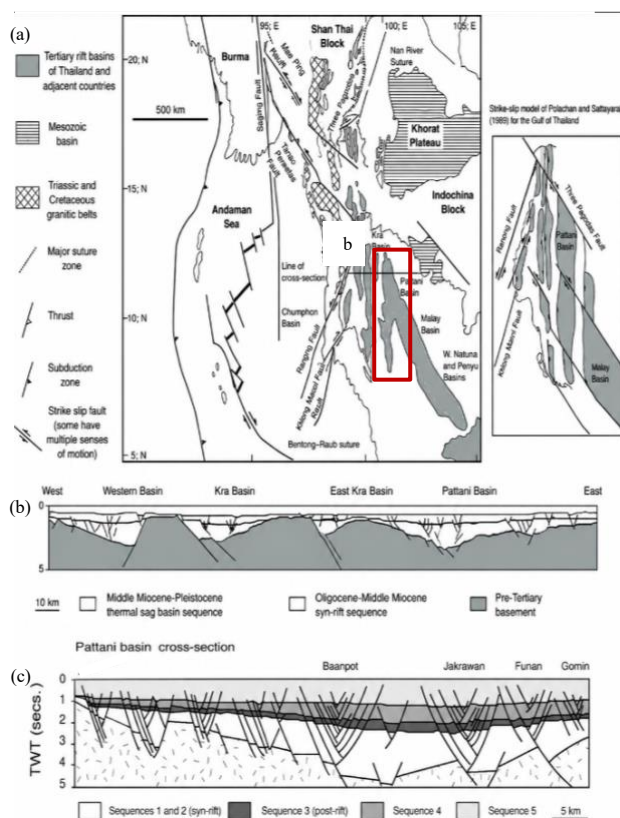


Figure 1. Tectonic setting of the Pattani Basin and adjacent Cenozoic basins in the Gulf of Thailand, (a) Regional map showing basin depocenters, major faults, the Three Pagodas Fault Zone, and the study area (red rectangle), modified from (Watcharanantakul and Morley, 2000), (b) Regional east-west cross-section across the central Gulf of Thailand, modified from (Bustin and Chonchawalit, 1997), and (c) Detailed cross-section through the southern Pattani Basin showing the principal seismic-

stratigraphic sequences (modified from Kornsawan and Morley, 2002).

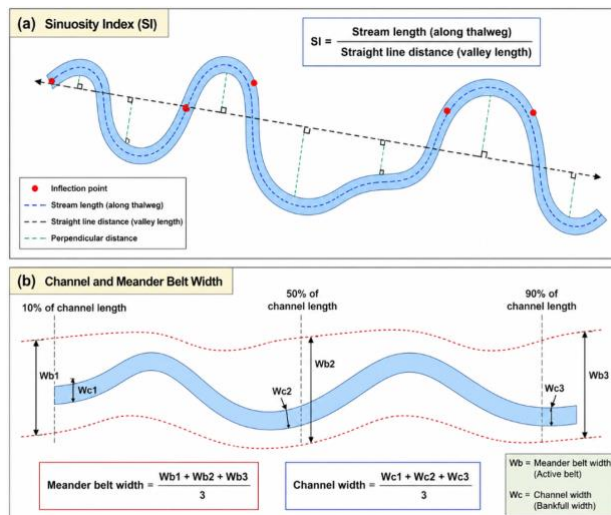


Figure 2. Schematic illustration of the measurement methods: (a) Sinuosity Index (SI), defined as channel thalweg length divided by valley length; and (b) channel width and meander channel belt width measurements from plan-view.

These planform patterns are not merely descriptive: they reflect the balance of physical controls acting on the river. Straight, low-sinuosity channels tend to form on steep gradients or where flow is confined, whereas high-sinuosity meandering channels develop on gentle gradients with stable banks and abundant fine sediment. The morphology preserved in the subsurface therefore carries information about the conditions under which the channel formed.

3. Geological Setting of the Pattani Basin

3.1. Regional Tectonic Framework

The Pattani Basin is one of the several NNW-SSE trending Cenozoic rift basins developed within the Gulf of Thailand basin province on the Sunda Shelf continental block. Basin formation is generally attributed to regional lithospheric extension associated with the India-Eurasia collision and subsequent extrusion of

the Indochina block during the Cenozoic. The Gulf of Thailand contains several structurally related basins, including the Western, Chumphon, Kra, Surat Thani, Pattani and Malay basins (Fig. 1a; Watcharanantakul and Morley, 2000), which share elements of a common tectonic history.

Regional deformation was strongly influenced by major NW-SE oriented strike-slip fault systems, particularly the Three Pagodas Fault Zone, which accommodated tectonic strain and influenced basin architecture. Continued extension produced N-S to NNW-SSE oriented normal fault systems, and a series of graben and half-graben depocenters that define the present-day structural configuration of the basin province (Fig. 1b).

The southern Pattani Basin contains one of the principal depocenters of the Pattani rift system and contains more than 8 km of Cenozoic sedimentary fill (Bustin and Chonchawalit, 1997). Basin architecture is dominated by antithetic and synthetic normal faults with planar to listric geometries that controlled subsidence patterns and sediment accommodation throughout basin evolution. Although structural inversion is limited relatively to some other Southeast Asian rift basins, localized fault reactivation modified the structural framework and contributed to hydrocarbon-trap developments in producing gas fields within the broader basin.

3.2 Basin Evolution and Tectono-stratigraphic Stages

The pre-Sequence 5 tectono-stratigraphic evolution of the Pattani Basin can be in four major stages, each recording changes in tectonic activity, subsidence style, and depositional setting (Fig. 3).

The initial rift phase began during the Late Eocene-Oligocene, when regional extension caused crustal thinning and formation of N-S oriented graben and half-graben structures. Sedimentation during Sequence 1, (35-23 Ma) was dominated by lacustrine mudstones, shales and coarse syn-rift clastic deposits that accumulated in rapidly subsiding, fault-controlled depocenters. Organic-rich lacustrine sediments deposited during this stage constitute the principal hydrocarbon source rocks of the basin.

The subsequent syn-rift stage (Sequence 2, 23-15 Ma) was characterized by continued fault activity and high rates of tectonic subsidence. Thick accumulations of fluvial, alluvial and lacustrine successions accumulated and form an important reservoir interval in the Pattani Basin. Sandstone bodies associated with braided and meandering fluvial systems may have favorable reservoir properties, while seismic profiles show wedge-shaped geometries that thicken toward major normal faults (Fig. 1c). During the Middle Miocene transitional stage (Sequence 3, 15-10 Ma) tectonic extension diminished and basin subsidence became increasingly controlled by thermal relaxation of the lithosphere. This interval records a gradual transition from continental fluvial environments to marginal marine conditions associated with regional marine inundation. Seismic reflections in Sequence 3 are generally more laterally continuous and less influenced by fault-controlled accommodation than those in the underlying syn-rift succession.

The post-rift stage (Sequence 4, 10-5 Ma) was dominated by thermal subsidence and widespread deposition of fluvial sediment across an extensive alluvial plain. Sand-rich channel systems prograded basinward and

formed laterally amalgamated sandstone bodies. This phase may reflect reduced accommodation space and relative sea-level fall during continued post-rift basin evolution, which enhanced fluvial sediment dispersal across the basin.

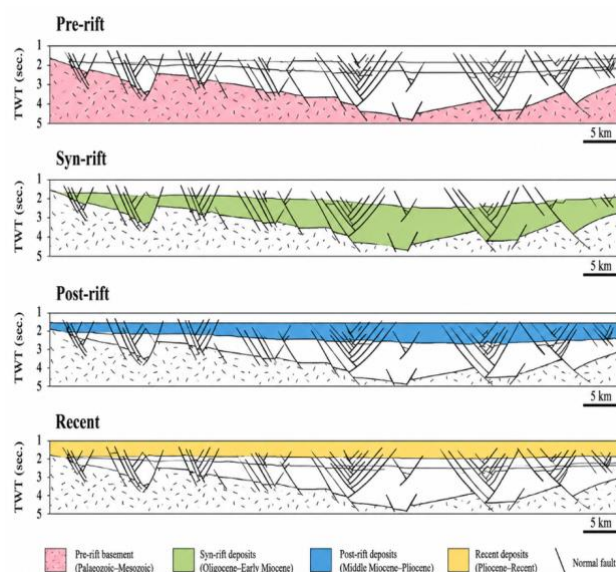


Figure 3. Schematic evolution of the Pattani Basin through four broad stages; pre-rift, syn-rift, post-rift, and recent, illustrating changes in basin geometry and fault activity (conceptual, not to scale; modified from Morley and Racey, 2011).

3.3 Pliocene-Recent Succession (Sequence 5)

Sequence 5 (5-0 Ma), which forms the primary focus of this study, is the uppermost stratigraphic unit in the Pattani Basin and records the response of the basin to Pliocene-Recent relative sea-level fluctuations and progressive marine inundation of the Sunda Shelf (Niyomborwornwat, 2014). A regionally extensive unconformity at approximately 5 Ma defines the lower boundary of the study interval. Sequence 5 includes interpreted incised valley fills, estuarine deposits, tidal channel deposits, and shallow marine successions (Fig. 4) Jardine,

1997. Its uppermost part of the sequence is dominated by marine clay deposits that directly beneath the modern seabed. Sequence ages and interpreted depositional environments, from Pliocene to recent, are summarized in Table 2.

Pleistocene deposition was strongly influenced by repeated glacio-eustatic sea-level oscillations. Lower sea level exposed parts of the Sunda Shelf and promoted fluvial incision, whereas subsequent transgression and highstand promoted estuarine and marine infilling of incised valleys (Posamentier and Kolla, 2003; Niyomborwornwat, 2014). The resulting succession may contain stacked valley fills bounded by regionally correlatable flooding surfaces in the 3D seismic volume.

Continued sea-level rise during the Late Pleistocene and Holocene established widespread shallow marine conditions across the Gulf of Thailand. This marine transgression connected the Pattani and Malay basins across the former Sunda Shelf lowland and contributed to the modern estuarine and shallow-marine depositional systems expressed at the seabed.

The southern Gulf of Thailand is a shallow epicontinental sea with water depths generally below 80 m. The modern seabed preserves a relict fluvial drainage network, superficially reworked by modern tidal and wave processes, forming shallow channels and sediment bars at the seabed. Comparison of these features with the buried Pliocene and Pleistocene channel systems provides a framework for discussing changes in channel morphology and sediment dispersal within the southern Pattani Basin, although modern surficial reworking should be considered when interpreting amplitude-based grain-size inferences at this level.

Table 2. Summary of the tectono-stratigraphic evolution of the Pattani Basin, including sequence ages and interpreted, depositional environments (modified after Morley & Racey 2011).

Sequence	Geological age	Interpreted environment
5	5-0 Ma	Transgressive to Shallow marine; Incised-valley fills
4	10-5 Ma	Regressive, fluvial
3	15-10 Ma	Marginal marine
2	23-15 Ma	Fluvial-dominated
1	35-23 Ma	Lacustrine, syn-rift

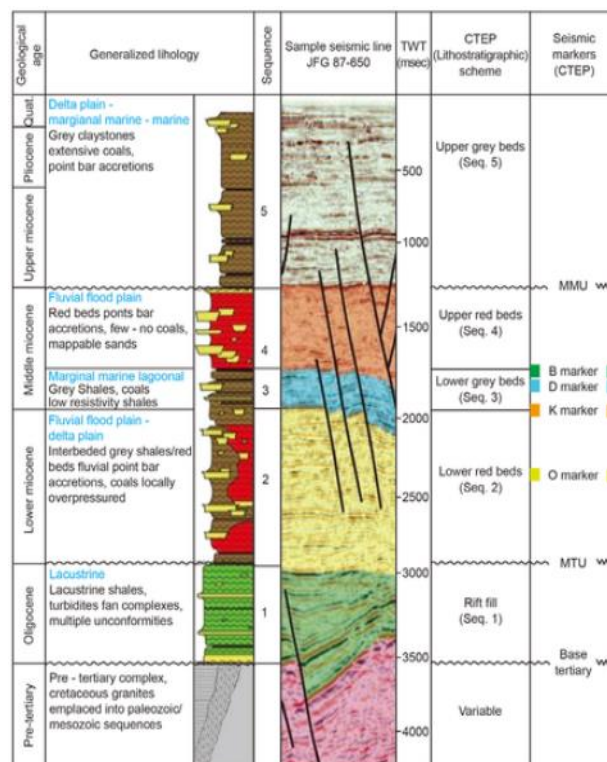


Figure 4. Generalized stratigraphic succession of Pattani Basin (by Jardine, 1997), showing Sequences 1-5, generalized lithology, interpreted depositional environments, and the regional markers (B, D, K, O) and unconformities (MTU, MMU).

4. Results and Interpretation

Three stratigraphic intervals were analyzed using RMS amplitude maps, variance attribute maps and geomorphic interpretation maps, seismic cross sections, fault throw analysis, and azimuth rose diagrams. The mapped surfaces are the seabed (110-130 ms TWT), late Pleistocene (160-210 ms TWT), and early Pleistocene (255-295 ms TWT). For descriptive purposes, each mapped interval, was divided into upper, middle, and lower sectors in Figures 5, 11, and 18. Sinuosity index (SI), channel width, channel channel belt width, azimuth and incision depth were, measured and compiled in Tables 3, 4, and 6.

Across the three intervals, the middle sectors generally contain the most sinuous channels and the largest mapped channel belt widths, whereas the lower sectors include several of the widest individual features. These map-position patterns are described below. Their possible relation to palaeoslope gradient, accommodation, confinement, and preservation is evaluated in the Discussion.

4.1 Seabed Channel Systems (110-130 ms TWT)

Eleven channel segments were mapped in the upper (Ch-1 to Ch-4), middle (Ch-1 to Ch-3) and lower (Ch-1 to Ch-4) sectors (Table 3). Upper-sector SI values range from 1.1 to 1.3, mapped widths. The variance map of seabed interval (Fig. 5b) delineates channel margins most clearly in the lower-sector where Lower Ch-2: has a mapped width of 1,478.7m. The east-west seismic cross section in Fig. 10 shows a gently dipping post-rift succession containing the seabed, and late Pleistocene reflections, above an early Pleistocene horizon and a deeper syn-rift section characterized by a series of asymmetric grabens bounded by prominent normal faults. The seabed interpretation shows a network of sinuous to meandering features (Fig. 5c).

The middle sector contains three channel segments and shows greater sinuosity than the upper sector (SI=1.3-2.2). Middle Ch-1 has the highest SI in the seabed interval (2.2), a mapped width of 5,867.6m, and the largest mapped channel belt width (12,119.7m), indicating substantial lateral displacement of the channel axis. Middle Ch-2 has SI=1.7, a mapped width of 1,688m, and a channel belt width of 3,790m. Middle Ch-3 has SI=1.3 and a channel belt width of 3,832m. Middle-sector

azimuths range from 15.9 degrees to 176.9 degrees, indicating a predominantly south-southeast trend (Fig. 9). Seismic cross-sections (Figs. 6-8) contain geometries interpreted as range from 502 to 5,868m, and apparent incision depths range from 27 to 94m when calculated using a sediment velocity of 1670m/s. The RMS amplitude map (Fig. 5a) shows moderate to high anomalies along several mapped channel axis; including local amplitude maxima near bends in the middle sector, Channel fills (CF) and possible lateral-accretion packages (LAP). Channel depth was estimated by converting the measured two-way travel time (TWT) to depth using as an average seismic velocity of 1.67 km/s. the conversion was calculated using the equation:

$$\text{Depth} = \frac{V \times \text{TWT}}{2}$$

Where V is the average seismic velocity (m/s) and TWT is the two-way travel time (s). The result is divided by two because the recorded travel time represents the seismic wave travelling from the source to the reflector and back to the receiver.

Table 3. Seabed channel morphometric parameters.

Channel	Sinuosity Index	Channel width (m)	Azimuth	Channel belt width (m)	Depth (m)
Upper					
Ch-1 (a)	1.3	646.7	97.4°	1,491	79.8
Ch-2	1.3	572.7	182.6°	1,706.3	94.13
Ch-3 (b)	1.1	808.3	170.2°	1,370.3	27.02
Ch-4	1.1	1,080	151°	2,863	60.51
Middle					

Ch-1 (a)	2.2	5,867.6	156.9°	12,119.7	50.1
Ch-2	1.7	1,688	157.3°	3,790	60.62
Ch-3 (b)	1.3	2,727	176.9°	3,832	30.31
Lower					
Ch-1	1.1	1,089.7	185.3°	2,141.7	44.9

Ch-2	1.6	1,478.7	140°	4,892	29.3
Ch-3	1.1	502.3	171.3°	1,055	73.8
Ch-4	1.2	515.3	110°	1,906.5	38.91

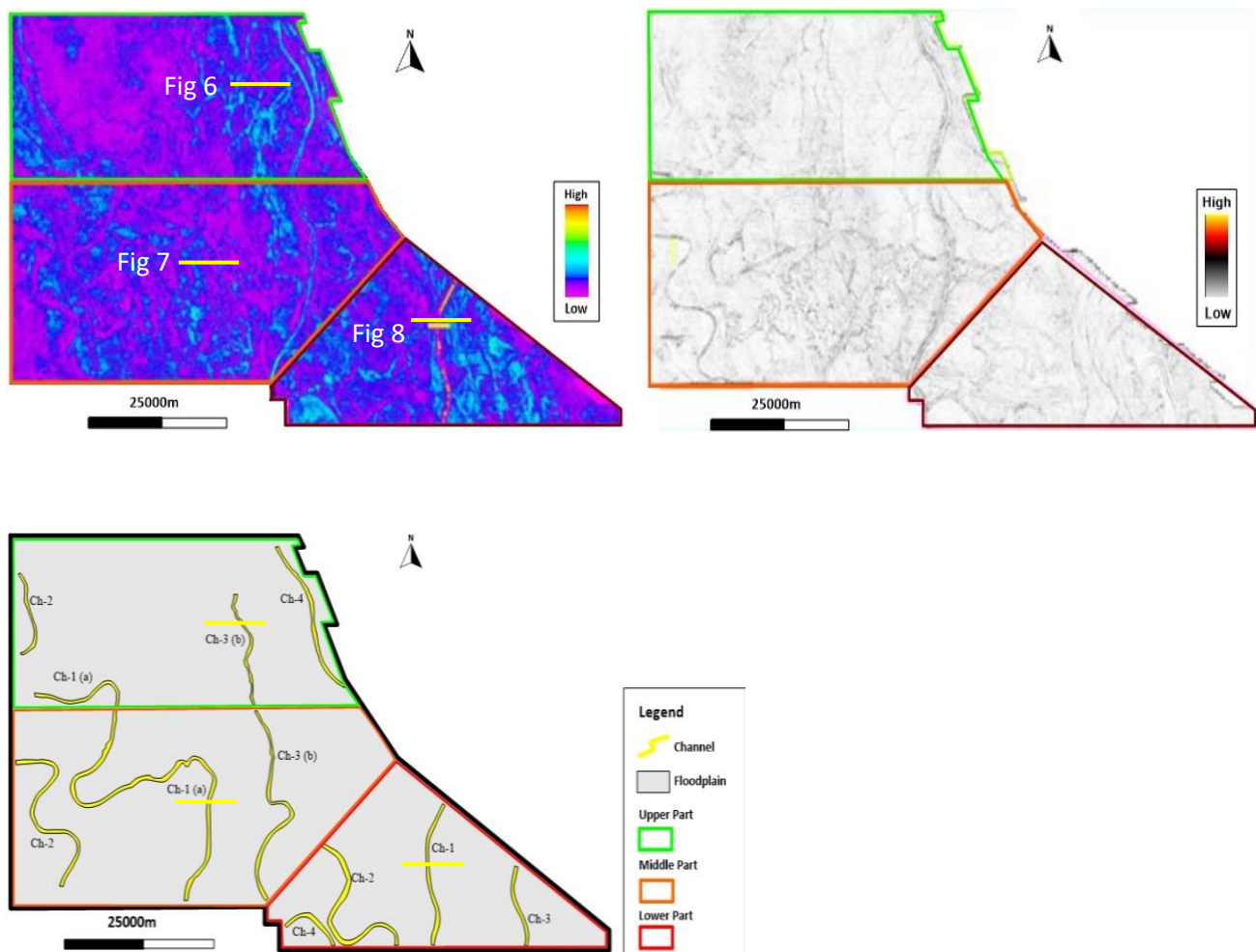


Figure 5. Combined seabed attribute and geomorphic interpretation panels: (a) RMS amplitude map, showing channel-related amplitude anomalies; (b) variance attribute map, showing interpreted channel margin lineaments; and (c) geomorphic interpretation map, showing mapped sinuous to meandering channels (yellow) and floodplain deposits (grey) in the upper (green boundary), middle (orange boundary), and lower (red boundary) sectors of the study area.

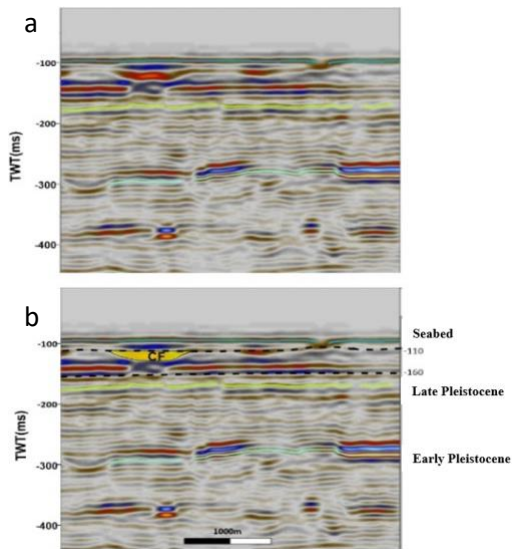


Figure 6. Seismic cross section through the upper sector of the seabed interval showing the uninterpreted (a) and interpreted (b) sections.

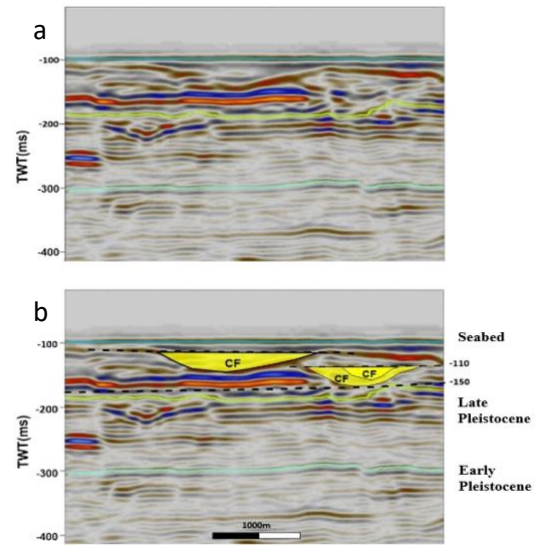


Figure 8. Seismic cross section through the lower sector of the seabed interval showing the uninterpreted (a) and interpreted (b) sections.

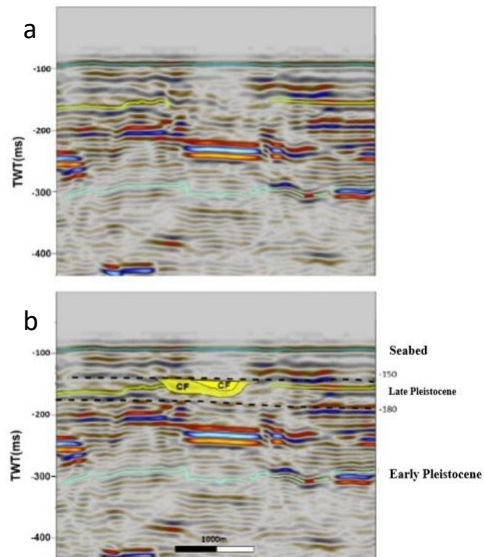


Figure 7. Seismic cross section through the middle sector of the seabed interval showing the uninterpreted (a) and interpreted (b) sections.

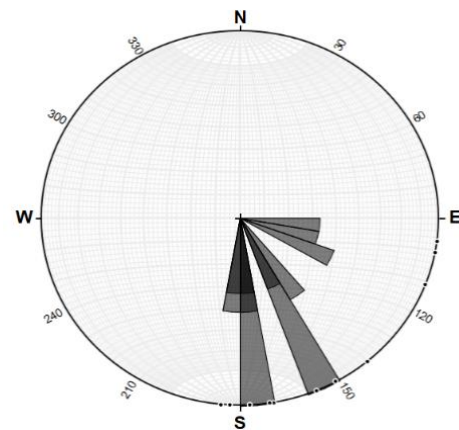


Figure 9. Azimuth rose diagram for the seabed channel segments. The distribution is near-unimodal and concentrated in the SSE-S sector (approximately 140-185 degrees), indicating a predominantly southward-trending network across the study area.

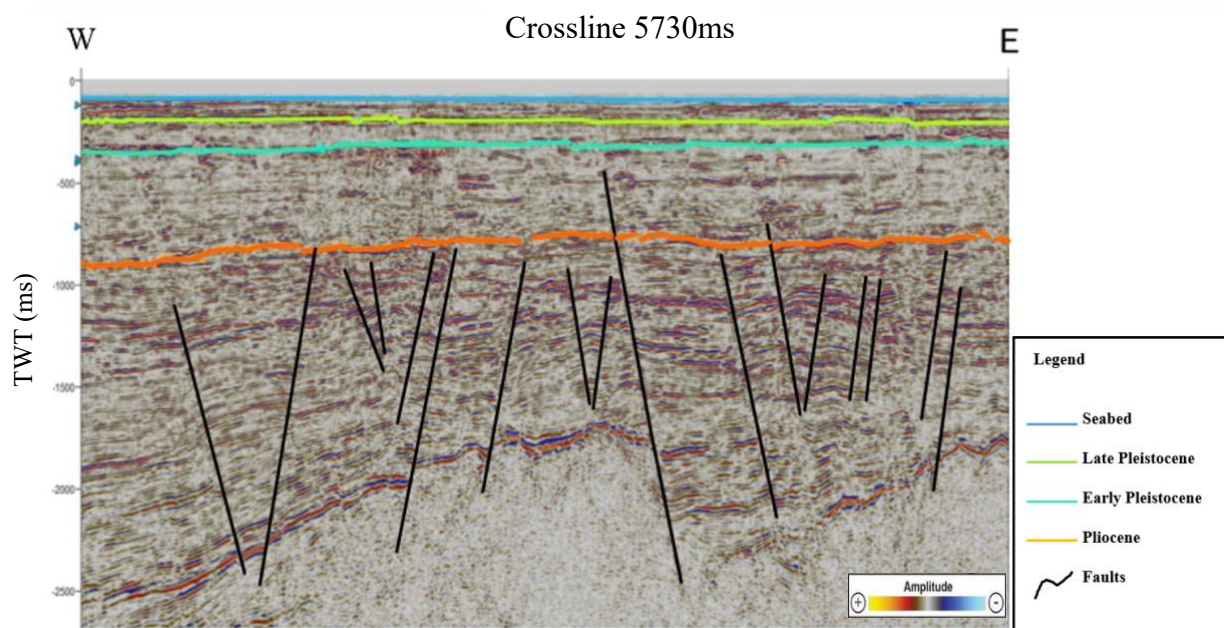


Figure 10. Regional seismic section through the study area, showing the seabed, Late Pleistocene, Early Pliocene, and Pliocene and interpreted faults.

4.2 Late Pleistocene Channel Systems (160-210 ms TWT)

Ten channels segments were identified: four in the upper sector, three in the middle sector, and three in the lower sector (Table 4). Mapped widths reach 3,922.6m (Upper Ch-1), and mapped channel belt widths reach 6,392m (Middle Ch-1), indicating either boarder composite features or substantial time-integrated lateral displacement. The RMS amplitude map (Fig. 11a) is more heterogeneous than at the seabed, consistent with episodic coarse grained delivery and the variance map (Fig. 11b) delineates broad belt-scale features, including an upper-sector channel belt width of 6,057.4m for Ch-1. The geomorphic interpretation in Figure. 11c.

The upper sector comprises four channels (Ch-1 to Ch-4). Upper Ch-1 is the most sinuous channel in this part (SI = 1.7,

meandering, with a width of 3,922.6m and the widest belt in the late Pleistocene interval 6,057m, indicating sustained lateral migration. Ch-2 is sinuous (SI=1.1, belt 1,541m). Ch-3 and Ch-4 are sinuous (SI=1.0-1.1) and anomalously directed WSW (252.1 and 253.5 degrees). Fault azimuth measurements show dominantly N-S to NNW-SSE structural trend (178 and 183 degrees; Table 5), oblique rather than parallel to channel azimuth. However, the channel orientations lie close to the direction perpendicular to these fault strikes (268 and 273 degrees, within 15-21 degrees of channel azimuth), consistent with drainage deflection down the dip-slope of tilted fault blocks rather than flow parallel to inherited basement structure. Fault throw analysis (Fig. 17) and seismic cross-sections (Fig. 16) confirm that Fault-1, Fault-3, and Fault-4 retain measurable displacement at the late Pleistocene level within

Sequence 5, supporting continued or residual fault activity during this interval. In contrast, Fault-2, Fault-3, and Fault-5 show negligible or no throw at this level and are not considered to have influenced late Pleistocene channel development. This spatial and vertical correspondence supports scarp-controlled deflection of drainage from N-S to NNW-SSE trending normal faults as the more likely mechanism for the anomalous WSW orientation of Ch-3 and Ch-4, rather than the previously stated parallel structural inheritance from NW-SE basement faults.

The middle sector contains three channel segments. Middle Ch-1 is the widest in this sector (SI=1.4, width = 6,597 m, channel belt width = 6,392 m) and trends, ESE at 123.1 degrees. Middle Ch-2 has SI = 1.1, an azimuth of 126.6 degrees, and a channel belt width of 1,968m. Middle Ch-3 trends approximately south (183.8 degrees) and has a channel belt width of 2,453m. The contrast between the WSW-trending upper features and ESE- to south-trending middle features produces the interval's bimodal azimuth distribution.

The lower sector contains three channel segments. Lower Ch-1 has SI=1.1, a mapped width of 5,037 m, and an azimuth of 102.7 degrees. Lower Ch-2 is the straightest mapped feature in the dataset (SI=1.0), with a width of 823m and a reported channel belt width of 895 m. Lower Ch-3 has SI=1.6, a channel belt width of 5,525 m, and an azimuth of 129.7 degrees. Seismic sections (Figs. 12-14) show broad channel-fill geometries and local features interpreted as lateral-accretion packages.

The most diagnostic characteristics of the late Pleistocene interval is its bimodal azimuth distribution (Fig. 15). Upper Ch-3 and Ch-4 trend WSW (252-254 degrees), whereas

most middle- and lower-sector features trend ESE-SE to south (103-184 degrees). This divergence could reflect structural inheritance or local palaeoslope variation, but the proposed relation to NW-SE oriented Paleogene fault should be tested by overlying the channel traces on mapped shallow fault or structural surfaces.

Table 4. Late Pleistocene channel morphometric parameters (a dash indicates a value that could not be measured).

Channel	Sinuosity Index	Channel width (m)	Azimuth	Channel belt width (m)	Depth (m)
Upper					
Ch-1 (a)	1.7	3,922.6	183.8°	6,057.4	37.88
Ch-2	1.1	930	151°	1,541	45.34
Ch-3	1.0	592.6	252.1°	1,291.2	-
Ch-4	1.1	938.6	253.5°	1,759.6	-
Middle					
Ch-1 (a)	1.4	1,439	123.1°	6,392	25.05
Ch-2	1.1	1,077.3	126.6°	1,968	39.25
Ch-3	1.2	992.3	183.8°	2,452.7	40.92
Lower					
Ch-1 (a)	1.1	1,196.7	102.7°	2,142	43.75
Ch-2	1.0	823	162°	895	20.04
Ch-3	1.6	3,726.3	129.7°	5,525.5	41.75

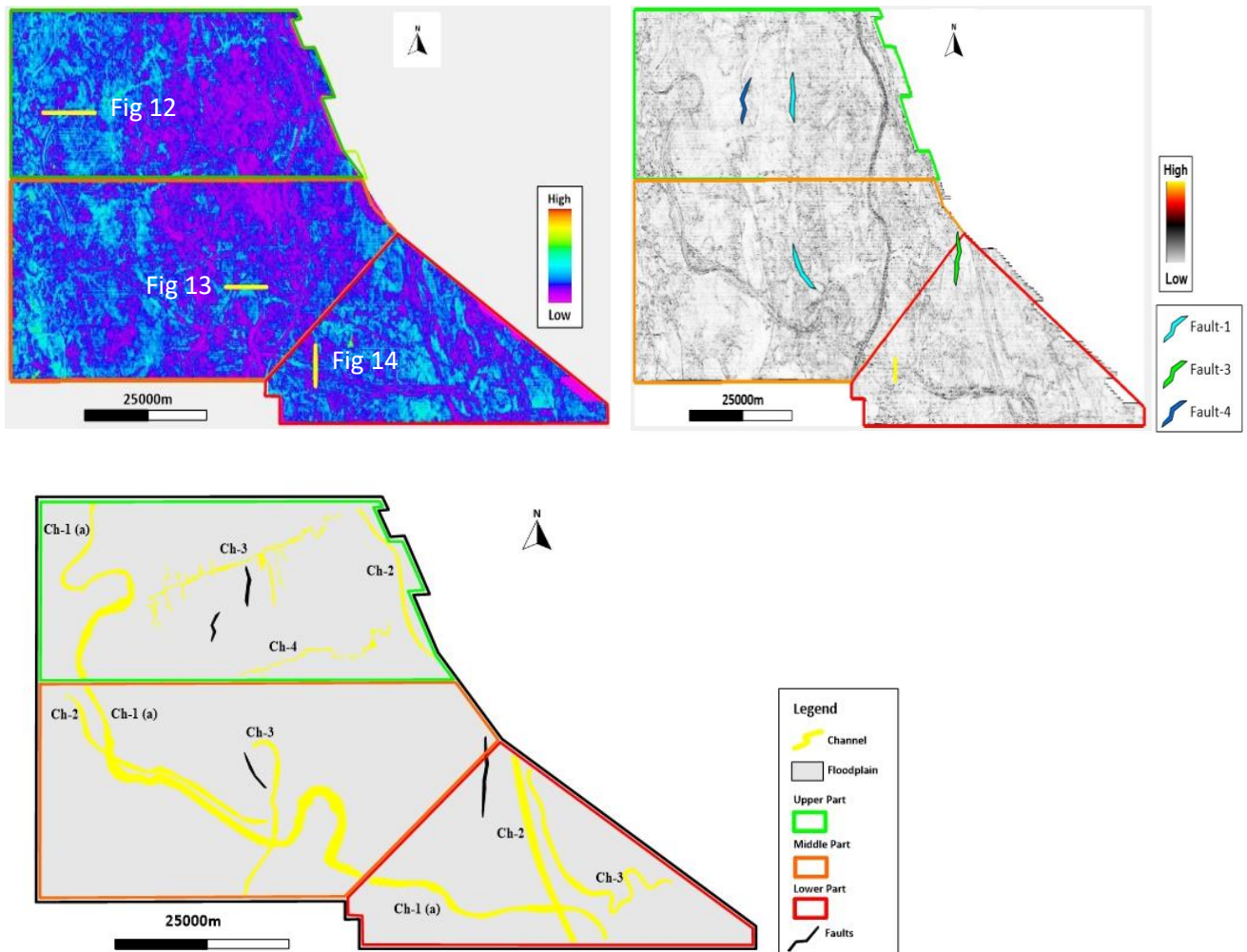


Figure 11. Combined late Pleistocene attribute and geomorphic interpretation panels: (a) RMS amplitude map, showing channel-related amplitude anomalies; (b) variance attribute map, showing interpreted channel margin lineaments; and (c) geomorphic interpretation map, showing mapped sinuous to meandering channels (yellow) and floodplain deposits (grey) in the upper (green boundary), middle (orange boundary), and lower (red boundary) sectors of the study area.

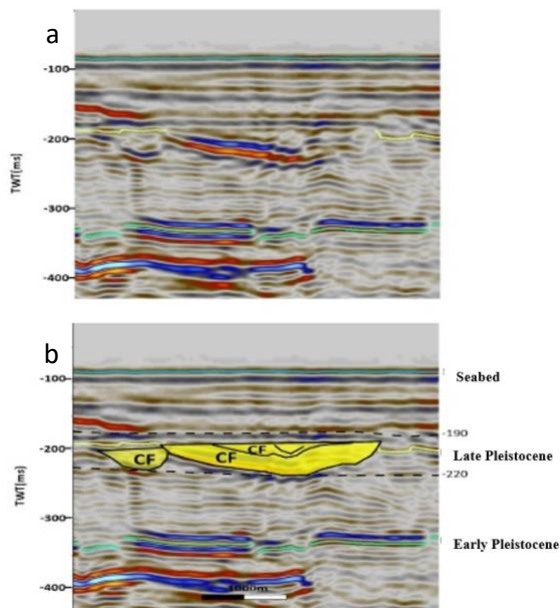


Figure 12. Seismic cross section through the upper sector of the late Pleistocene interval showing the uninterpreted (a) and interpreted (b) sections.

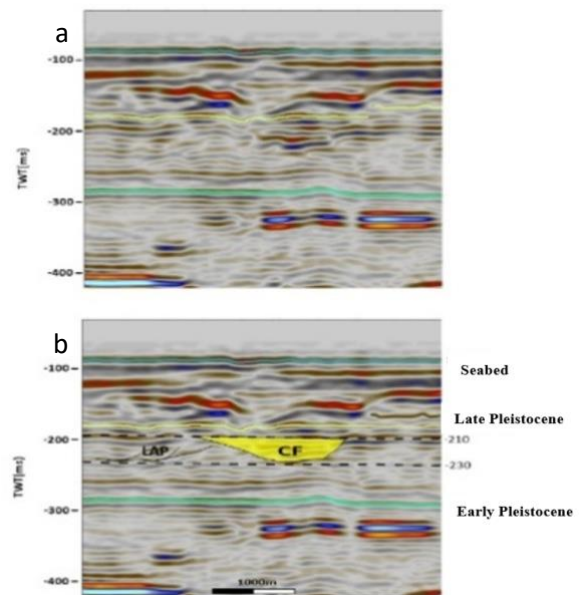


Figure 14. Seismic cross section through the lower sector of the late Pleistocene interval showing the uninterpreted (a) and interpreted (b) sections.

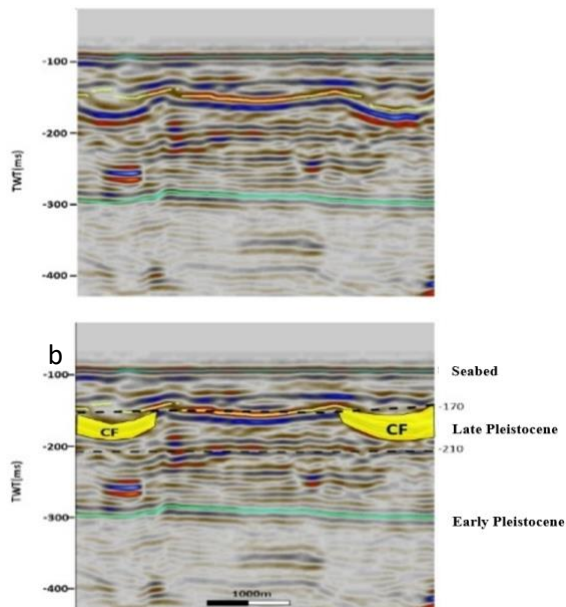


Figure 13. Seismic cross section through the middle sector of the late Pleistocene interval showing the uninterpreted (a) and interpreted (b) sections.

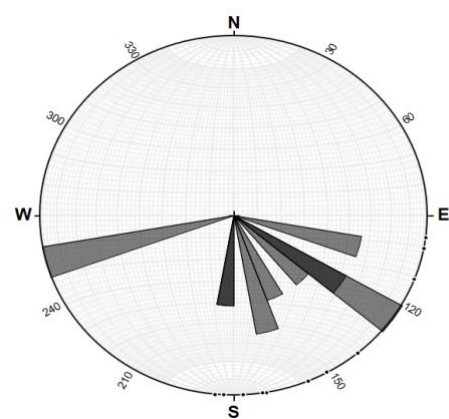


Figure 15. Azimuth rose diagram for the late Pleistocene channel segments (160-210 ms TWT) showing a bimodal distribution, with a dominant ESE-SE cluster (approximately 120-160 degrees) and a secondary cluster directed WSW (approximately 250-255 degrees) clusters, reflecting drainage divergence between the upper and middle, lower parts.

Table 5. Fault azimuth measurements interpreted from mapped fault traces.

Fault	Azimuth	Structural trend	Interpretation for late Pleistocene interval
Fault-1	178°	N-S	Measurable late Pleistocene throw
Fault-2	185°	N-S	No measurable late Pleistocene throw
Fault-3	188°	N-S to NNW-SSE	Measurable late Pleistocene throw
Fault-4	183°	N-S	Measurable late Pleistocene throw
Fault-5	170°	NNW-SSE	No measurable late Pleistocene throw

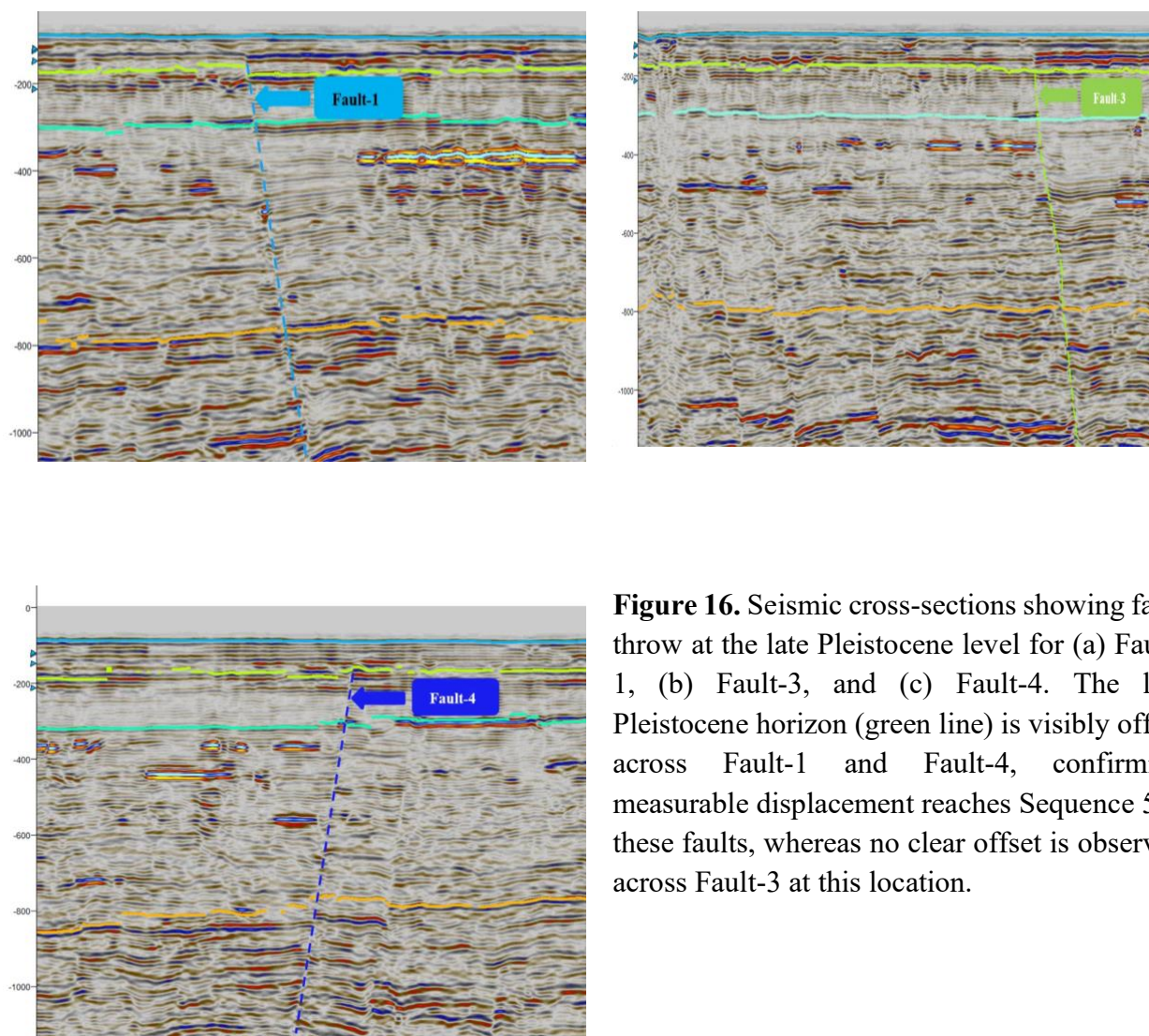


Figure 16. Seismic cross-sections showing fault throw at the late Pleistocene level for (a) Fault-1, (b) Fault-3, and (c) Fault-4. The late Pleistocene horizon (green line) is visibly offset across Fault-1 and Fault-4, confirming measurable displacement reaches Sequence 5 at these faults, whereas no clear offset is observed across Fault-3 at this location.

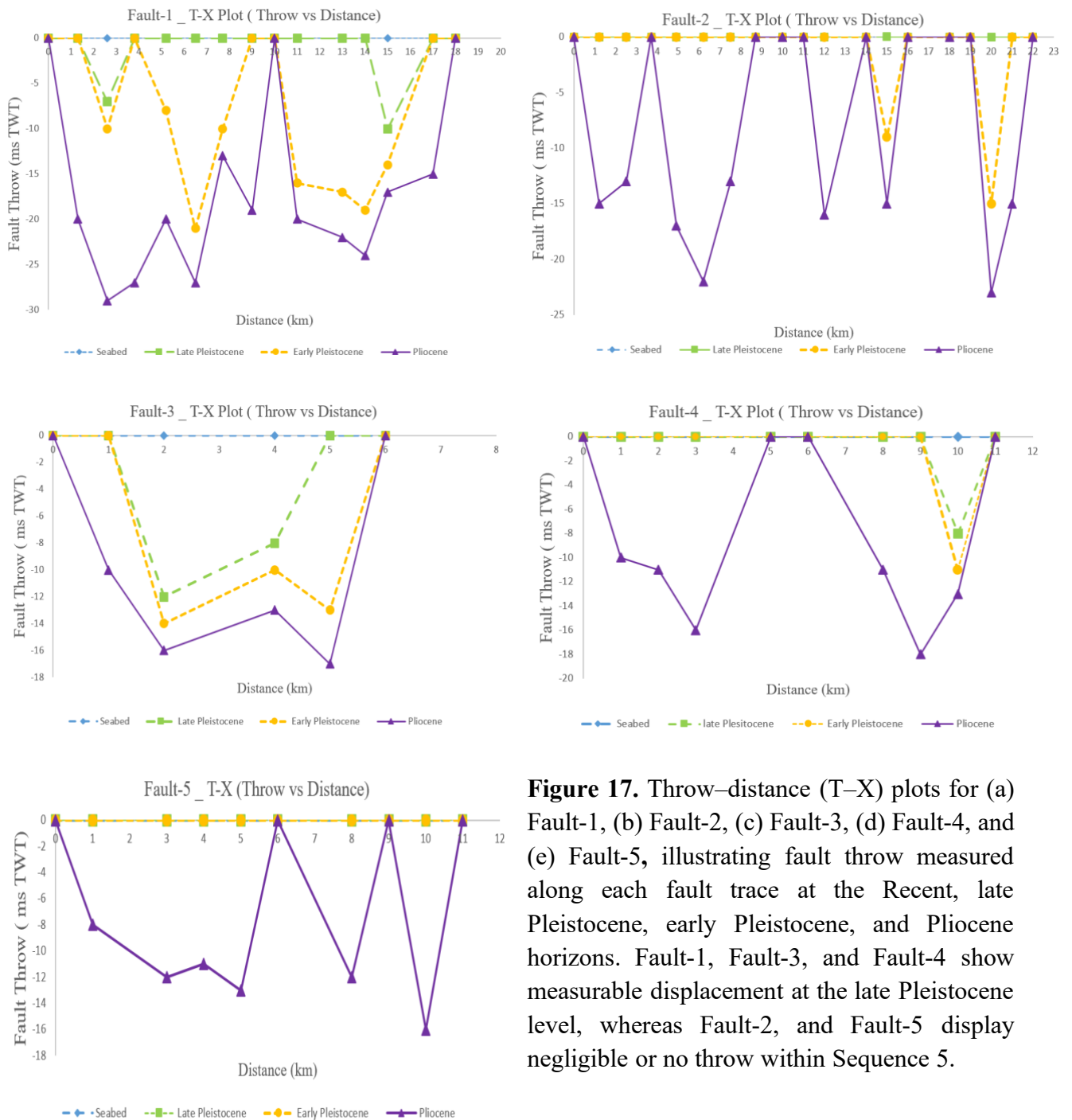


Figure 17. Throw–distance (T–X) plots for (a) Fault-1, (b) Fault-2, (c) Fault-3, (d) Fault-4, and (e) Fault-5, illustrating fault throw measured along each fault trace at the Recent, late Pleistocene, early Pleistocene, and Pliocene horizons. Fault-1, Fault-3, and Fault-4 show measurable displacement at the late Pleistocene level, whereas Fault-2, and Fault-5 display negligible or no throw within Sequence 5.

4.3 Early Pleistocene Channel Systems (255-295 ms TWT)

Twenty channels segments were identified, the highest count across all intervals: eight in the upper sector, seven in the middle sector, and five in the lower sector (Table 6). The RMS amplitude map (Fig. 18a) displays multiple intersecting high-amplitude bodies, consistent with episodic coarse-grained delivery; anomalously bright amplitudes occur near middle Ch-3 (apparent incision 77.65m; TWT=93 ms, converted using an interval velocity of 1,670 m/s), although the deepest apparent incision in the dataset is recorded by middle Ch-7 (100.2m; TWT=120 ms). The variance map (Fig. 18b) delineates broad belt-scale features, including a middle-sector channel belt width of 6,464m for Ch-2 and lower-sector channel belt width of 4,427m for Ch-3, and reveals fault traces absent in younger intervals. The early Pleistocene geomorphic interpretation map reveals a network of sinuous to meandering channels (Fig. 18c).

The upper sector comprises eight channels (Ch-1 to Ch-8) with SI values of 1.1-1.6. Two channels are classified as meandering: Ch-4 (SI=1.6, azimuth 129.5° SE, belt 3,936m) and Ch-6 (SI=1.5, azimuth 102.2° ESE, belt 2,542m). The remaining channels are sinuous, with azimuths ranging from 98.5° (E) to 180° (S), indicating a dispersed drainage pattern in this part. Seismic cross section (Fig. 19) reveals stacked channel-fill bodies recording repeated cut- and -fill cycles consistent with sea-level-driven incision and aggradation.

The middle sector contains seven channels (Ch-1 to Ch-7) with SI values of 1.1-1.6. Middle Ch-2 is the only meandering channel in this part (SI=1.6, azimuth 135.5° SE, belt 6,465 m) and records the widest belt in the

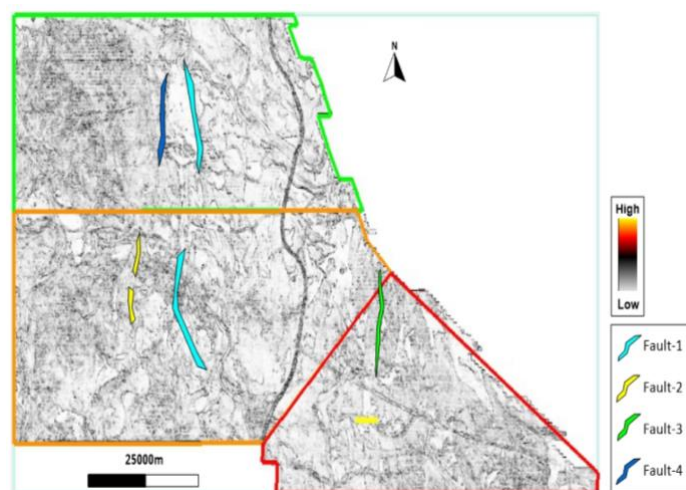
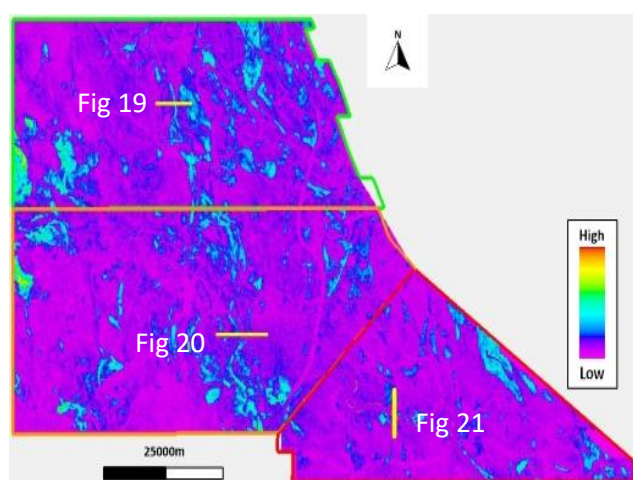
early Pleistocene dataset. Middle Ch-3 shows a notable apparent incision depth (77.65m; TWT=93 ms, azimuth 110.1° ESE) and anomalously high amplitudes on the RMS map; while this may reflect a relatively coarse-grained fill associated with lowstand incision, RMS amplitude alone cannot establish grain size or lithology in the absence of well, core, or log calibration, and this interpretation should be regarded as tentative. Middle Ch-7 records the deepest apparent incision in the dataset (100.2m; TWT=120 ms). Azimuths in the middle part range from 95.4° (E) to 253.4° (WSW), reflecting the structurally complex palaeoslope of this interval. Seismic cross-sections (Fig. 20) show broad channel-fill bodies and complex lateral stacking patterns.

The lower sector contains five channels (Ch-1 to Ch-5) with SI values of 1.1-2.1. Lower Ch-3 is the most sinuous channel in the entire early Pleistocene dataset (SI=2.1, meandering, azimuth 235.2° SW) and records the widest belt in this sector (4,427m), indicating sustained lateral migration. Channel azimuths span 90°-253° (E to WSW) with no dominant direction (Fig. 22), reflecting a dispersed, multi-thread drainage network on a structurally complex palaeoslope. Seismic cross-section (Fig. 21) reveals three closely spaced channel-fill bodies in a confined valley geometry, consistent with repeated lowstand incision controlled by pre-existing fault trends inherited from Paleogene rifting.

Table 6. Early Pleistocene channel morphometric parameters.

Channel	Sinuosity Index	Channel width (m)	Azimuth	Channel belt width (m)	Depth (m)
Upper					
Ch-1 (a)	1.2	660.3	180°	1,749.7	-
Ch-2 (b)	1.4	1,054.3	144.8°	3,190.7	45.93
Ch-3 (c)	1.2	525.0	111.5°	1,336.7	52.10
Ch-4	1.6	1,529.7	129.5°	3,935.7	53.29
Ch-5	1.4	1,149.0	129.0°	1,944.3	60.96
Ch-6	1.5	1,314.3	102.2°	2,542.3	53.44
Ch-7	1.1	764.0	98.5°	1,889.0	85.17
Ch-8	1.2	1,821.7	161.2°	2,186.7	-
Middle					
Ch-1 (a)	1.4	695.3	177.2°	3,330.3	36.74

Ch-2 (b)	1.6	2,292.3	135.5°	6,464.3	32.57
Ch-3 (c)	1.3	1,308.3	110.1°	1,699.3	77.65
Ch-4	1.3	673.3	95.4°	1,136.7	47.60
Ch-5	1.1	1,120.0	220.5°	1,623.0	52.61
Ch-6	1.1	421.7	253.4°	848.0	78.49
Ch-7	1.2	550.3	173.0°	1,115.7	100.20
Lower					
Ch-1 (a)	1.4	1,398.0	119.6°	3,669.0	38.41
Ch-2	1.2	848.7	191.1°	3,185.3	40.08
Ch-3	2.1	1,244.0	235.2°	4,427.0	42.00
Ch-4	1.1	986.7	90.0°	2,109.7	45.10
Ch-5	1.3	1,017.0	123.5°	1,981.3	40.10



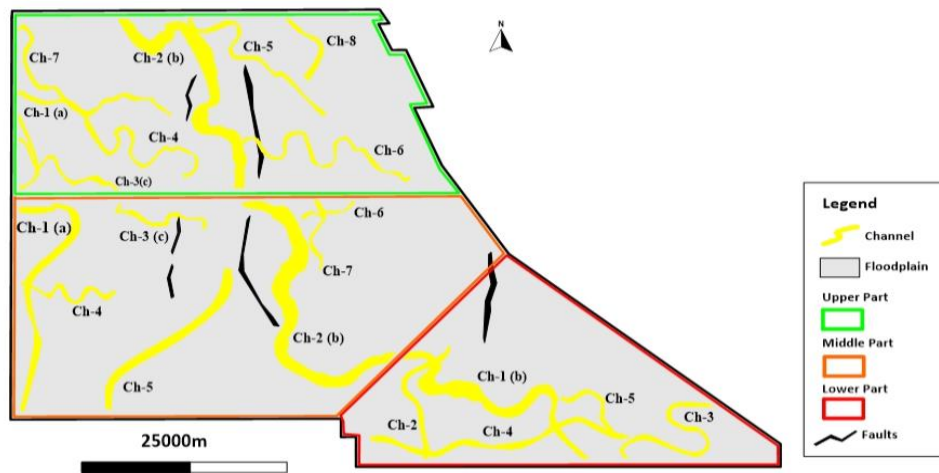


Figure 18. Combined early Pleistocene attribute and geomorphic interpretation panels: (a) RMS amplitude map, showing channel-related amplitude anomalies; (b) variance attribute map, showing interpreted channel margin lineaments; and (c) geomorphic interpretation map, showing mapped sinuous to meandering channels (yellow) and floodplain deposits (grey) in the upper (green boundary), middle (orange boundary), and lower (red boundary) sectors of the study area.

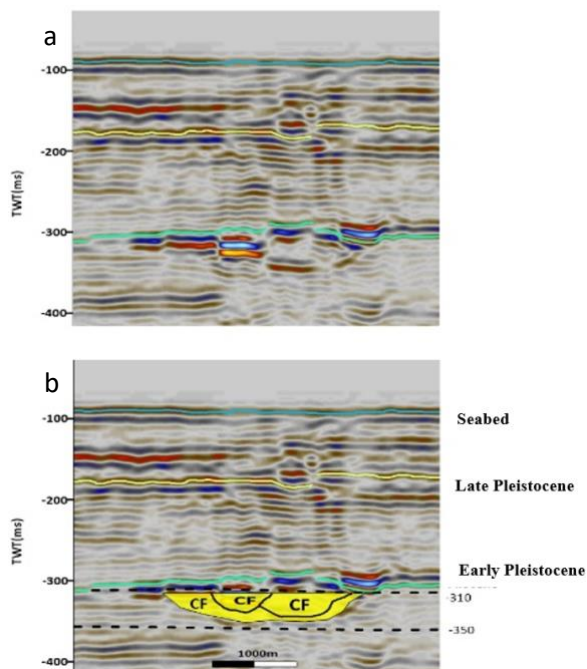


Figure 19. Seismic cross section through the upper sector of the early Pleistocene interval showing the uninterpreted (a) and interpreted (b) sections

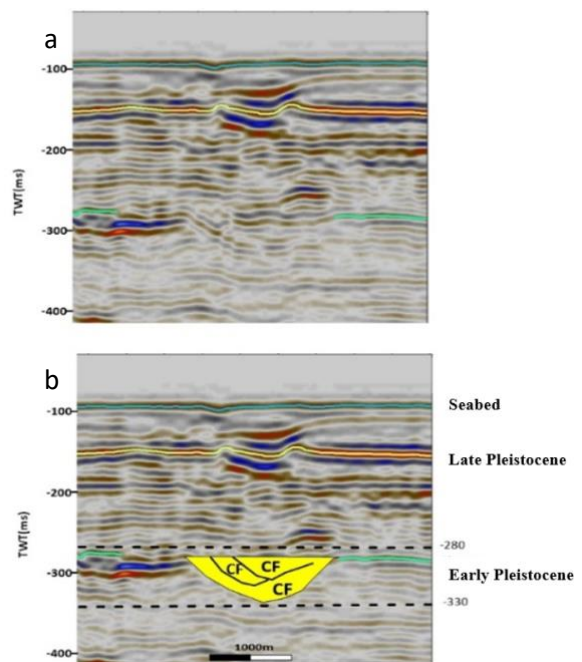


Figure 20. Seismic cross section through the middle sector of the early Pleistocene interval showing the uninterpreted (a) and interpreted (b) sections.

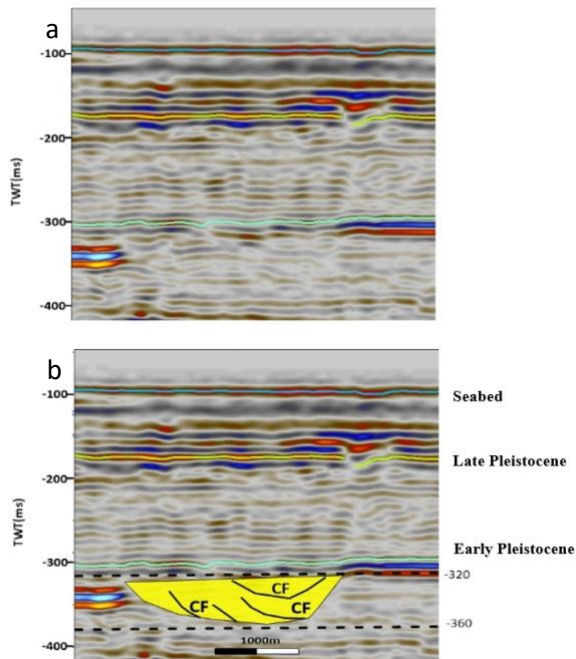


Figure 21. Seismic cross section through the lower sector of the early Pleistocene interval showing the uninterpreted (a) and interpreted (b) sections.

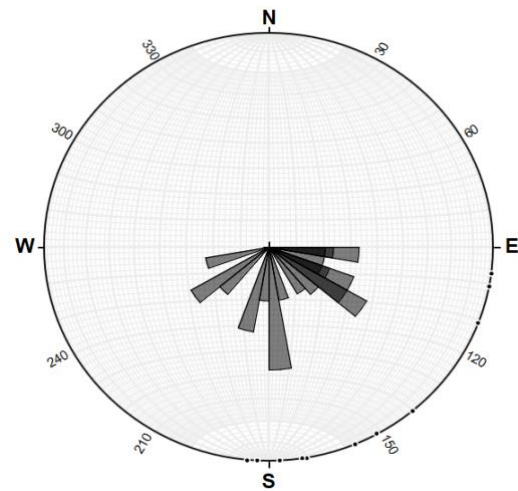


Figure 22. Azimuth rose diagram for the early Pleistocene channel segments, showing a dispersed distribution from approximately 90 degrees to 253 degrees and no single dominant orientation.

5. Discussion

5.1 Controls on Channel Development

This study identifies three seismic-stratigraphic surfaces in the southern Pattani Basin; the present-day seabed, a late Pleistocene lowstand-related surface, and the base of Sequence 5, defined independently on the basis of reflection terminations, onlap and downlap relationships, and erosional truncation (Section 3.3). These surfaces broadly coincide with systematic changes in channel sinuosity, incision depth, and channel belt width, a pattern consistent with the established sequence-stratigraphic framework in which glacio-eustatic sea-level oscillations during the early Pleistocene to Recent drove repeated cycles of base-level fall and rise across the shallow Sunda Shelf (Niyomborwornwat, 2014). However, relative sea-level is unlikely to be the sole control on the observed channel architecture. Palaeoslope gradient, sediment supply and discharge, bank and substrate erodibility, tectonic subsidence and fault-related accommodation, valley confinement, and tidal reworking may all have contributed, and in places appear to do so directly: fault throw analysis indicates that basement-involved faulting locally influenced late Pleistocene channel orientation (Section 4.2), and the modern seabed channel network shows evidence of tidal and wave reworking superimposed on an inherited fluvial drainage pattern

(Section 4.1). The following sections examine the patterns most consistent with sea-level control, while these alternative and potentially interacting controls are considered further in Section 5.1.4.

5.1.1 Highstand Interpretation: Sinuosity and Lateral Migration

Wide mapped belts, high SI values, and possible lateral-accretion packages are compatible with sustained lateral migration under low-gradient, accommodation-rich conditions. The clearest example is Seabed Middle Ch-1 (SI = 2.2; mapped channel belt width = 12,119.7m). However, these features are not uniquely diagnostic of highstand, and the mapped belt-width definition must be clarified before the values are used as a sequence-stratigraphic indicator. The interpreted lateral-accretion geometries in Figures. 7, 12, and 13 should also be demonstrated at a scale and resolution that allow their internal architecture to be assessed.

5.1.2 Lowstand Interpretation: Incision and Low-Sinuosity Channels

Relative base-level fall can promote shelf exposure and fluvial incision. In this dataset, early Pleistocene Middle Ch-3 has the largest reported apparent incision depth (approximately 77.65m), substantially greater than most other mapped values. This measurement should be verified

because it is an outliner and depends on the time-depth conversion and the definition of the channel top and base. The bright RMS amplitude near this feature indicates an acoustic contrast but, without well or core calibration, does not by itself demonstrate a coarse-grained lowstand fill. The closely spaced channel-fill bodies in Fig. 21 may record repeated incision and infill, although their sequence-stratigraphic timing remains to be established.

Lowstand-SI features such as late Pleistocene Lower Ch-2 (SI=1.0) and several early Pleistocene channels (SI=1.1) may be compatible with steeper, confined, or incision-dominated reaches. Nevertheless, low sinuosity is not uniquely diagnostic of lowstand, and the interpretation should be evaluated together with independent evidence for exposure surfaces, valley relief, facies, and regional correlation.

5.1.3 Chronostratigraphic Context and Sea-Level Events

The three mapped intervals are assigned broadly to the early Pleistocene, late Pleistocene, and present-day seabed. If these age assignments are supported by independent well, biostratigraphic, or regional seismic control, the stacked channel-fill bodies could be discussed in the context of repeated incision and infill during early Pleistocene-Recent relative

sea-level cycles. At present, however, the manuscript does not provide sufficient age control to correlate individual channel packages with specific glacial or interglacial events.

The late Pleistocene interval (2-0.1 Ma) reflects the more pronounced glacial-interglacial cycles of the Middle to Late Pleistocene, during which sea-level amplitudes reached 120-135 m. Sinuosity index (SI) values differ modestly among the three intervals but do not show a consistent progressive trend: early Pleistocene channels (n=20) have a mean SI of 1.33 (median 1.3, range 1.1-2.1, SD 0.24); late Pleistocene channels (n=10) have a mean SI of 1.23 (median 1.1, range 1.0-1.7, SD 0.25); and seabed channels (n=11) have a mean SI of 1.36 (median 1.3, range 1.1-2.2, SD 0.34), or 1.28 (median 1.25) with the single highest-sinuosity outlier channel excluded. The modest decrease in central tendency from the early Pleistocene to the late Pleistocene is broadly consistent with increasing sea-level amplitude and progressive drainage network integration, but seabed sinuosity does not continue this trend and instead returns to values comparable to, or slightly higher than, the early Pleistocene. This indicates that sinuosity is not solely or progressively controlled by increasing glacio-eustatic amplitude, and that other factors, including tidal and wave reworking of the modern seabed channel network (Section 4.1),

likely also contribute. The seabed interval represents the present highstand following the Last Glacial Maximum (LGM) sea-level lowstand (120 m below present), during which the entire Sunda shelf was exposed and incised; the modern seabed channels record reworking of this inherited drainage network during the Holocene transgression, rather than a simple continuation of a progressive early Pleistocene-to-late Pleistocene sinuosity trend.

5.1.4 Criteria for Recognizing Relative Sea-level Change

Four observations are potentially relevant to relative sea-level interpretation: (1) changes in SI; (2) mapped channel and belt dimensions; (3) internal seismic architecture, including channel-fill and possible lateral-accretion geometries; and (4) amplitude character. None of these observations is independently diagnostic. A stronger interpretation would combine them with mapped sequence boundaries, regional correlations, calibrated lithology, palaeoslope reconstruction, and uncertainty estimates. Thresholds such as SI greater than 1.5 for highstand and SI below 1.1 for lowstand should not be applied without justification and sensitivity testing.

6. Conclusions

This study maps 41 channel segments on early Pleistocene, late Pleistocene, and seabed surfaces in the southern Pattani Basin. SI values range from 1.0 to 2.2,

mapped widths range from hundreds of metres to several kilometers, and reported apparent incision depths range from approximately 20 to 77.65m. The early Pleistocene network has a dispersed orientation, the late Pleistocene network contains ESE-SE and WSW trends, and the seabed network is predominantly directed toward the south-southeast. These patterns suggest a combined influence of palaeoslope, accommodation, relative sea-level change, sediment routing, and possible structural inheritance. Independent age control, calibrated lithology, explicit measurement definitions, and quantified uncertainty are required before the mapped elements can be assigned confidently to specific highstand or lowstand phases.

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