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Ichnofossil of Nanggulan Deltaic System: Case Study of Watupuru Cross Section in Kulon Progo, Central Java, Indonesia

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Abstract - The Nanggulan Formation in Kulon Progo, Yogyakarta, Indonesia, is rich in ichnofossils as observed in a cross-section of the Watupuru River. This research aims to explore the relationship between ichnogenera, their behaviours and patterns during the deposition of the Nanggulan Formation in the Middle to Upper Eocene period. The study involved analyzing measured sections along the Watupuru River, paleocurrent measurements, and palynology. Seventeen ichnogenera were identified and linked to seven depositional facies within the Nanggulan Formation, i.e. Nummulites bank, prodelta, strand plain, delta front, delta plain, sandflat, and fluvial sand, categorized into autochthonous and allochthonous rock units. Allochthonous rocks, like tempestite and turbidite, were discovered within the autochthonous Nanggulan Formation with ichnogenera present in both types of rocks. Ichnofossils associated with the prodelta facies in autochthonous rocks included into *Bergaueria*, *Siphonichnus*, *Phycodes*, *Trypanites*, *Treptichnus*, *Teredolites*, *Chondrites*, and *Thalassinoides*, tend to indicate a muddy suspension environment. In contrast, the delta plain facies (FDP) indicating a calm oxidizing environment with ichnogenera contents like *Teredolithes*, *Bergaueria*, *Scoyenia*, *Aulichnitus*, *Helminthopsis*, *Chondrites*, *Gastrochaelites*, *Ophiomorpha*, and *Siphonichnus* were recognized. Factors influencing ichnofossil diversity include lighting, behaviour or adaptation to the environment, sedimentation rate, current control, and burrow infilling. The diversity of ichnofossils in allochthonous tempestite layers was influenced by post-catastrophic storm events. Barren ichnogenera at the base of tempestite layers indicated early storm surges, while the upper layers contained diverse ichnogenera such as *Gastrochaelites*, *Psilonichnus*, *Bergaueria*, and *Planolites* in the delta front facies (FDF). Tempestite layers in the sandflat facies (FSF) containing ichnogenera such as *Thalassinoides*, *Bergaueria*, *Rhizocoralleum*, *Planolites*, *Cylindrichnus*, and *Siphonichnus*, tend to show a favorable environment for organism post-storm.

Keywords: Nanggulan Formation, ichnofossil, autochthonous, allochthonous, ichnogenera diversity

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Introduction

The diversity of trace fossils in the Nanggulan Formation, Kulon Progo (7°63'22.75"- 7°78'00.47" S and 110°15'78.24" - 110°24'07.38" E: WGS 84) has not been extensively discussed by experts (Figure 1). This formation is not commonly studied in ichnology due to its limited exposure and challenges in documentation caused by weathering processes or other constraints. However, ichnofossils are widespread in the rocks of this formation. The Nanggulan Formation, deposited during the Middle to Late Eocene (Saputra and Akmaludin, 2015) (Figure 2), is characterized by transitional (Lelono, 2007; Polhaupessy, 2009; Amijaya *et al*., 2016; and

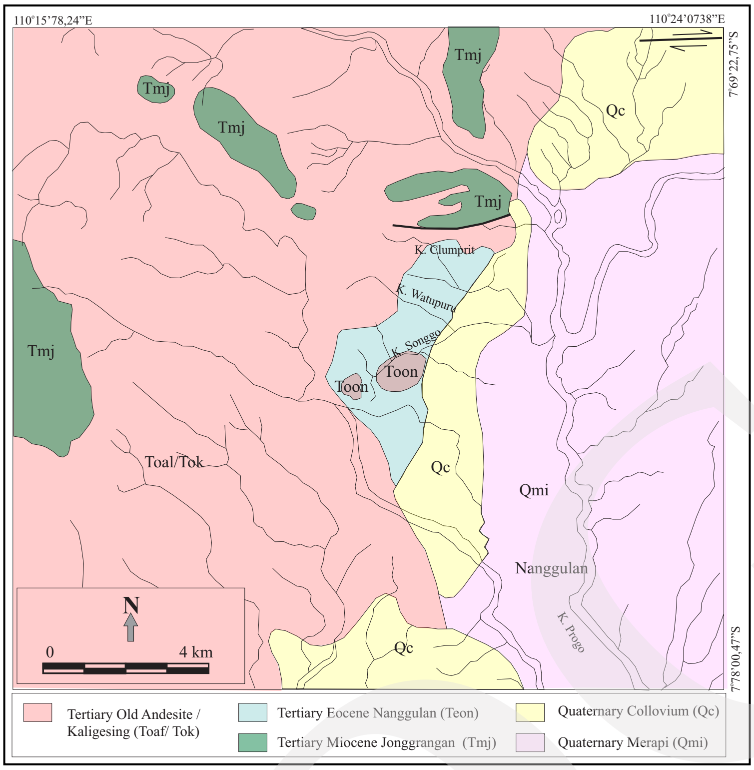

Figure 1. Geological map of studied area (modified from Rahardjo *et al*., 1996).

Nuraini and Hakim, 2021) to marginal marine environments (Coxall *et al*., 2016; Hartono and Sudradjat, 2017). Previous studies have reported evidence of rocks resulting from catastrophic events, such as turbidite deposits (Lelono, 2007 and 2000). Allochthonous rocks, like tempestites caused by catastrophic storms, are also found in the Nanggulan Formation, such as in the Watupuru River (Nuraini and Hakim, 2021). Both autochthonous and allochthonous rocks of the Nanggulan Formation rocks provide sufficient ichnofossil data for the study.

Tempestite, defined as a fining-upward succession rock resulting from a storm event (Einsele, 2000; Myrow *et al*., 2004) (Figure 3), typically exhibits a high abundance of ichnofacies at the top of the tempestite section, especially if it contains calcareous substances (Baziany, 2016), and can also be observed in hummocky-swaley sandstone units (Long, 2007; Pomar *et al*., 2019). Various ichnology studies have been conducted in brackish environments controlled by tidal currents (Buatois *et al*., 2005; Lima and Netto, 2012; Mikulas *et al*., 2013) as well as studies on the variability of ichnofossil behaviour in tempestite packages (Carmona *et al*., 2008; Desjardins *et al*., 2012; MacEachern *et al*., 2012; Leonowicz, 2016).

This research aims to investigate the patterns, behaviour, and diversity of ichnofossils in both autochthonous and allochthonous Nanggulan Formation, specifically in relation to current flow after catastrophic storms.

Geological Setting

The Nanggulan Formation has been the subject of various studies and interpretations regarding its depositional environment. Some researchers have suggested that it was formed in open sea sediments associated with volcanoes (Coxall *et al*., 2021), while others have proposed a more closed shallow sea setting (Hartono and Sudradjat, 2017). Some authors have concluded that it is a product of deltaic (Nuraini and Hakim, 2021) and estuaries (Amijaya *et al*., 2016) to shallow marine

(Ansori and Amijaya, 2014), while others view it is as a sublittoral (Polhaupessy, 2009) or

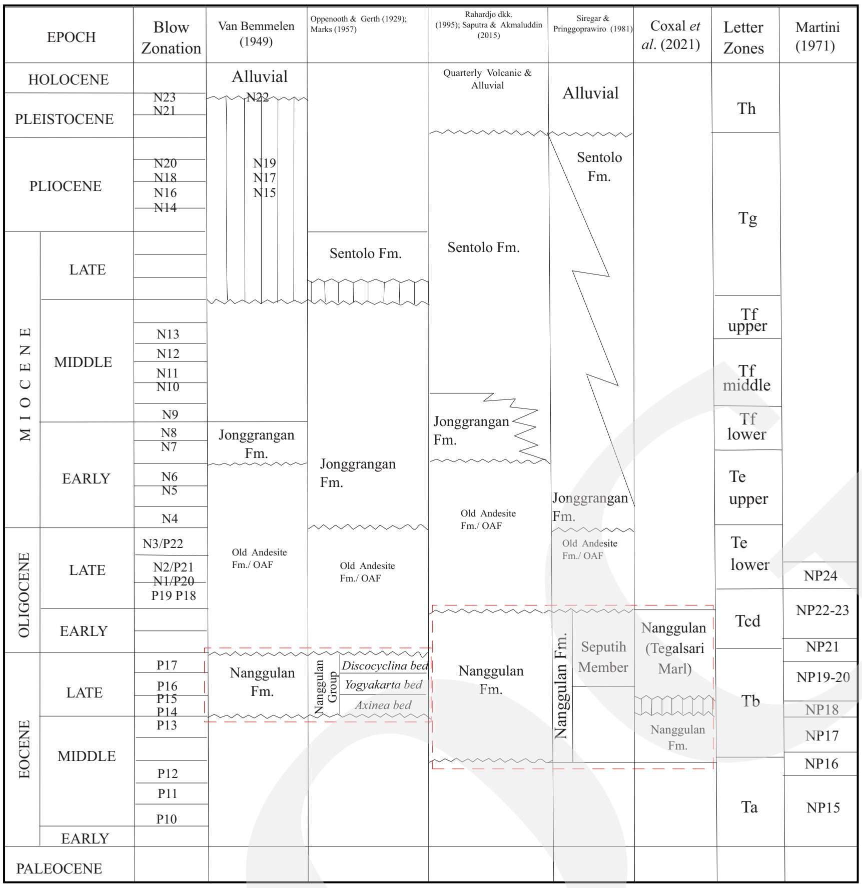

Figure 2. Regional stratigraphy of the Nanggulan Formation (based on previous researchers).

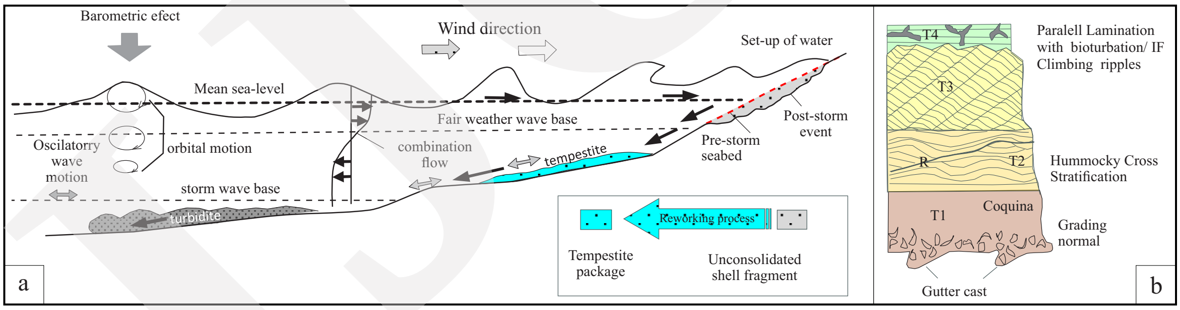

Figure 3. a). Basic concept of tempestite stated that it is triggered by the storm hitting the unconsolidated shore materials such as shell fragments, with sand and silt grains. They are transported and deposited in the zone between fair weather- and storm wave base as tempestite deposits (modified from Ensele, 2000). b). A sequence of tempestite with reactivated surfaces (R) present along the T2 Unit.

transitional - brackish to shallow sea (Lelono, 2007). Lelono (2000 and 2007) is among the limited number of authors proposing that gravity flow deposits could exist as allochthonous rock in the upper section of the Nanggulan Formation.

The coarsening-upward sequence of Nanggulan stratification in Watupuru section suggests a deltaic deposition (Nuraini and Hakim, 2021). Additionally, various sedimentary structures found, such as heterolithic structures such as lenticular, flaser, mud drape, double mud layer, trough-cross, wavy lamination, and mud/sand clasts indicate that tidal currents continued to influence the deposition of the Nanggulan Formation. Due to researchs on ichnofossils in Indonesia are limited, recent publications (Arifullah *et al*., 2015; Arifullah and Zaim, 2021) have contributed to enhancing our knowledge of ichnology in deltaic deposits, particularly in Nanggulan rocks.

Materials and Methods

The method used was measured stratigraphic sections (MS) crossing Watupuru River trending southeast to the northwest. Paleocurrent measurements were conducted to the tempestite - turbidite packages, and other cross-bedding features. In general, all depositional trends show E to SE directions, except for the bipolar feature relates to SE–NW, and vice versa, and turbidite packages in the bottom unit indicate SE to SW trends. The measured section method will be used to describe the texture and sedimentary structure, vertical stacking patterns, bedding geometry, trail pattern of trace fossil, etc. Identification of patterns and behaviour of ichnofossils and their depositional environments based on Pemberton *et al*. (2004), Buatois *et al*. (2005), Knaust (2015 and 2018), and Ekdale and Harding (2015) were carried out.

Results and Discussion

Stratigraphy, Lithology, and Palynology

Based on a stratigraphic section in Watupuru River, the Nanggulan Formation is divided into seven depositional facies sequentially from bottom to top, those are Nummulites bank (FNB), prodelta (FPD), strand plain (FSP), delta front (FDF), delta plain (FDP), sandflat (FSF), and fluvial sand (FFS) (Figure 4). That formation studied in Watupuru River displays a lithological sequence, transitioning from fine-grained sediments (FPD) at the base to coarse-grained clastic material (FDF) at the top. It then shifts to a nonmarine type with coal bed (FDP) before transforming into transgression sand flat facies (FSF), ultimately ending with fluvial sand facies (FFS). This sequence indicates a deltaic deposition pattern (Bhattacharya and Walker, 1992).

The strand plain lithological facies feature is medium- to coarse-grained sand, occasionally gravelly, in rapidly eroded areas with a high iron oxidation content, arranged in nearly horizontal layers. Strand plains are often categorized as tidal flats or sand ridges, both of which have straight or sometimes irregular coastlines, obtaining material either from onshore or longshore transport (Boyd *et al*., 1992). The presence of numerous of erosion and iron-rich layers in Nanggulan (Figure 4) suggests that the coastal plains are currently being exposed to the surface or updrift phase (Bhattacharya and Giosan, 2003) like Nanggulan strand plain (FSP). Furthermore, a predominance of heterolithic lithology in Nanggulan Formation indicates imperfect development of the delta body, likely due to river flow diversions and a frequent flooding from the sea. In other words, the delta is controlled by waves with a deflection pattern.

Within the Nanggulan Formation, there are at least two sets of tempestite packages (Tp 1 and Tp 2). The initial tempestite (Tp 1) was created in conjunction with the concluding stage of delta front (FDF) facies regression. In contrast, the subsequent tempestite (Tp 2) developed during the transgressive phase, marked by the presence of sand flat facies (FSF) (Figure 4).

Palynological investigations performed on the carbonaceous siltstone of delta plain facies (FDP) tend to indicate Middle Eocene palynomorphs, *i.e. Proxapertites* sp., *Spinizonocolpites echinatus*, and *Palmaepollenites kutchensis* (Lelono, 2000). Structural and stratigraphic constraints are related to anticlinal folds (Heriyadi and Tania, 2018; Widagdo *et al*., 2020) and normal faults (Hartono and Sudradjat, 2017). On the other hand, stratigraphic constraints are related to bedding orientation. Therefore, it may be grouped into two categories, flat bedding with a dip angle below 10o and inclined bedding (dip between 30-45^{o}).

Ichnofossil in Autochthonous Rocks

In the Nanggulan Formation, two types of rock are present, *i.e.* autochthonous and allochthonous. Autochthonous rocks are formed through regular, undisturbed depositional processes,

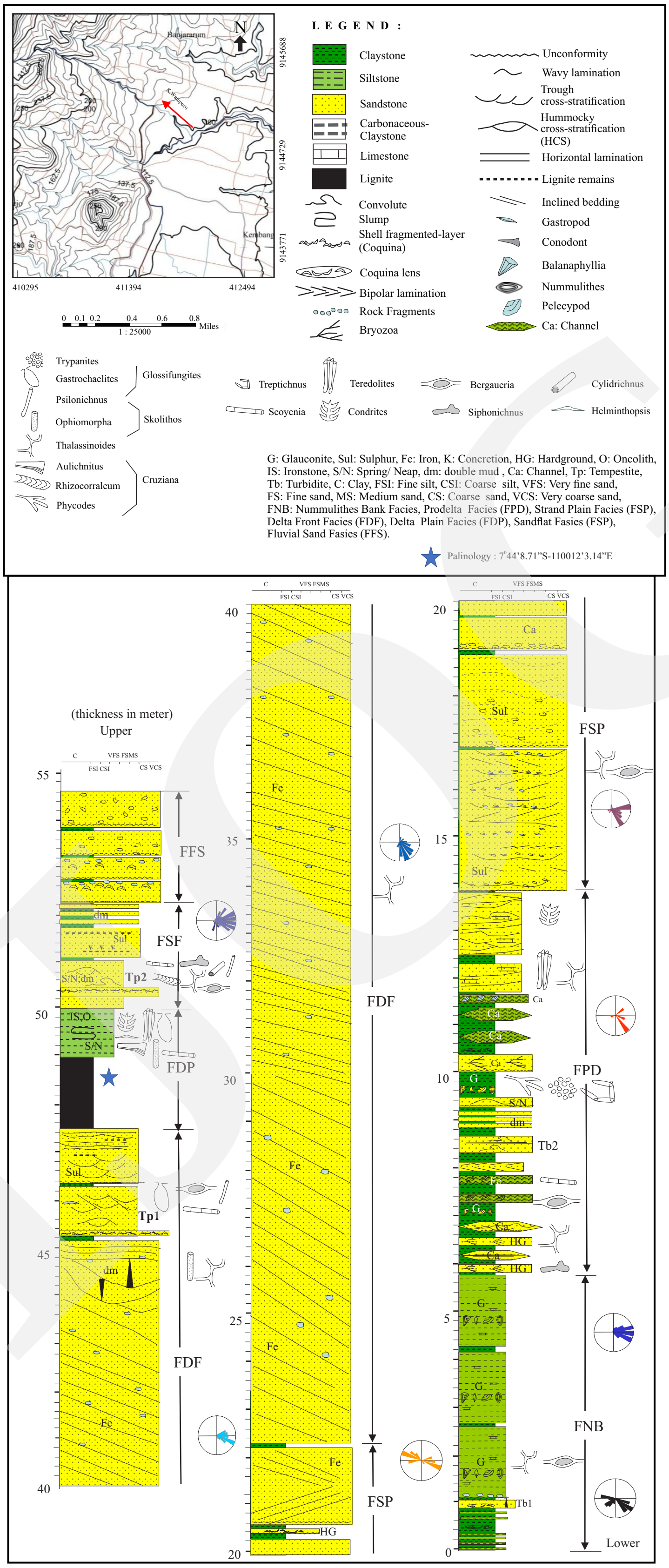

Figure 4. Locality map and columnar stratigraphic measured section of seven depositional facies of the Nanggulan Formation, sequentially from bottom to top in Watupuru River: Nummulites bank (FNB), prodelta (FPD), strand plain (FSP), delta front (FDF), delta plain (FDP), sandflat (FSF), and fluvial sand (FFS). Thickness in meters.

while allochthonous rocks are the result of sudden, catastrophic events such as gravity flows, and storms. Deposits resulting from catastrophic events such as gravity flows produce turbidite rock deposits, while storm events produce tempestite rock deposits. Turbidite deposits are found at the bottom of the Nanggulan Formation layers in the Nummulites facies (FNB) and prodelta (FPD). Tempestite was observed at the upper part of the first coarsening-upward of delta front facies (FDF) and the lower part of the second coarsening-upward of sandflat (FSF) (Figure 4).

This allochthonous rock tempestite package is less than 1 m thick (50-70 cm) comprising a coquina layer composed of shell fragments (mollusks: gastropod, oysters, bivalves, etc.), solitary corals, rock fragments in a clay matrix, cemented by calcite (Figure 5). Tempestite is formed through marine reworking processes during storms along the coastline, redepositing material between the zone of fair weather and storm wave base (Einsele, 2000; Myrow *et al.*, 2004) (Figure 3a). As a product of catastrophic storm events, the reworking rocks like this tempestite are allochthonous rocks that are interbedded within the overall autochthonous rocks of the Nanggulan Formation.

Above this layer, there are hummocky-swalley beds of fine, well-sorted sandstone, occasionally interrupted by reactivation surfaces (R) with rich iron oxidation (Figure 5a). The top layer is characterized by current laminations of very fine sandstone with occasional traces of fossils/IF (Figures 5a and 5b). Although previous researchers (Lelono, 2000; 2007) have mentioned the presence of gravity flow products at the top of Nanggulan Formation, the sedimentary structures point towards tempestite deposits.

The distribution of ichnofossil in Nanggulan Formation occurs in both autochthonous and allochthonous rocks. The diversity of ichnofossils in autochthonous rocks is associated with prodelta (FPD), delta front (FDP), and delta plain (FDP) facies, while in allochthonous rocks they are present in tempestite 1 (Tp 1) and 2 (Tp 2) rocks.

Ichnofossil of Prodelta Facies (FPD)

The lithology of prodelta facies is mainly characterized by dark grey claystone with occasional choncoidal cleavage. The presence of other minor lithologies such as fossiliferous and glauconitic greenish siltstone, with interbedding thin layers of clay and sand (neap/spring lamination), light grey, well sorted of fine to very fine sandstone, and coquina layers, all are present in the prodelta facies (FPD).

Associations of ichnogenera are characterized by the presence of *Bergaueria* (Ber) occurring in grey clay suspension lithology filled with light grey fine sands. A minor fault has cut through this full relief of *Bergaueria* (Figure 6a). The horizontal pattern of *Siphonichnus* (Sip) is built into light grey fine sandstone intercalation that is subsequently

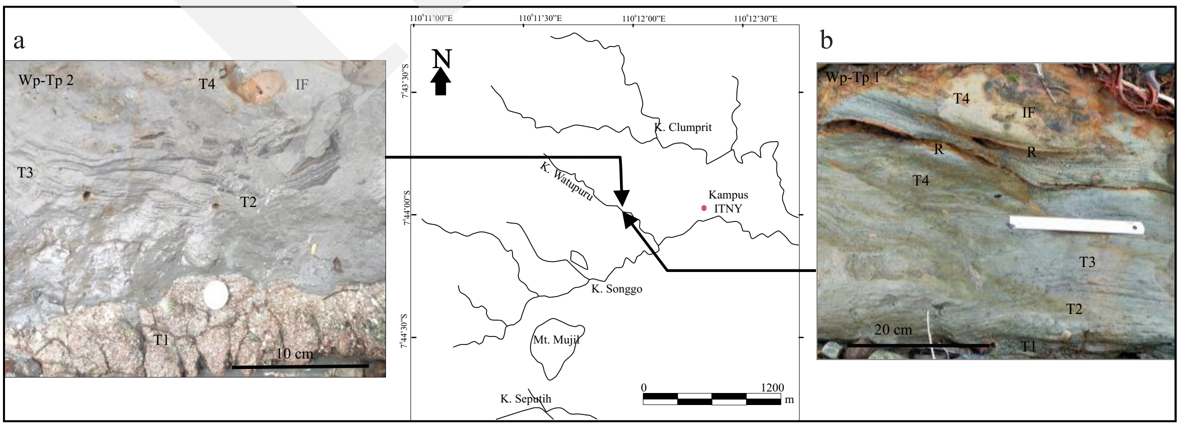

Figure 5. Tempestite in Kali Watupuru (a and b) composed of tempestite 1 (Tp 1) appearing in delta front facies (FDF) with several reactivated surfaces (R) and tempestite 2 (Tp 2) in sand flat facies FSF).

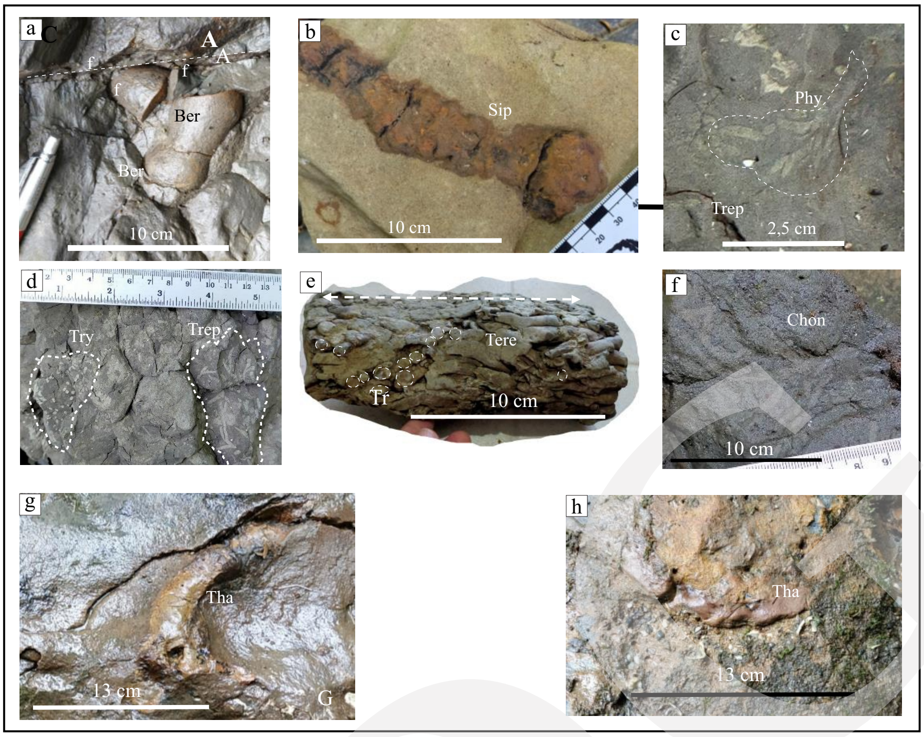

Figure 6. Ichnofossil diversity in prodelta facies (FPD) consist of: a). Full relief of *Bergaueria* occurring in a dark grey clay suspension, having been cut by micro-faults (f). b). Horizontal traces of *Siphonichnus* on light grey medium sandstone; the trace filling material has been strongly oxidized. c). A broom-like excavation pattern is represented by *Phycodes*. d). A vertical excavation type of *Trypanites* filled with calcareous substances, and *Treptichnus* reflected horizontal excavation. e). *Teredolites* clusters show the same direction, but some intersect each other (dash circles), formed in the grey mudstone of the prodelta facies. f). *Chondrites* showing a negative relief resembling leaf with veins. g). *Thalassinoides* trace developing horizontally to the upper layer of fine- and h). coarse-grained sandstone.

filled by iron rich lithology (Figure 6b). *Phycodes* (Phy) resemble-traces distribution collected in one groove at the tip like a broom (Figure 6c).

Ichnogenera with horizontal excavation patterns such as *Phycodes* (Phy), *Treptichnus* (Trep), and *Chondrites* (Chon) experience filling with calcareous substances (Figures 6 c, d, e). While the *Chondrites* (Chon) pattern characterizes branches/leaf veins (Figure 6f and Table 1). The vertical pattern of Trypanites (Try) tubes is filled with calcareous substances in a group. Clearly, the horizontal pattern of *Treptichnus* (Trep) forms coils that have been filled with calcareous substances in the prodelta mudstone of host rock (Figure 6d). *Teredolites* (Tere) reflect a group of massive trace patterns stacked on top of each other predominantly horizontally in one direction (dashed line). However, a small number of excavated tubes were present intersecting/ dashed circle (Figure 6e). The horizontal pattern of *Thalassinoides* forms at the top of medium sand layer (Figure 6g) and also the top of coarse sandstone, which are subsequently filled with brownish grey mudstone (Figure 6h).

<u>Ichnofossil of Delta Front Facies (FDF)</u>

The delta front facies (FDF) consist of medium- to very coarse-grained sandstone with poorly grain sorting, open fabric intercalated with light grey fine siltstone, medium sorted, closed fabric, strong sulphur odor. Trough cross stratification, parallel, horizontal, wavy lamination, bioturbated and normal graded bedding, double mud layer, mud drape and mud clast presents in the upper unit. Some igneous rocks such as andesite, basalt, and jasper, as well as metamorphic rock like quartzite, quartz, and zircon fragments ranging in size from sand to pebbles, are also found within the unit. The delta front of the rock layer is inclined parallel to the southeast.

Table 1. Ichnofossil Distribution within Nanggulan Formation Rocks

Facies	Sub-facies	Lithology	Sedimentary Structure	Flow Indicator	Ichnogenera
Nummulites Bank (FNB)	FNB	-Soft, fine siltstone, fossilifer ous, glauconitic -Siltstone, hard, calcareous	Parallel, horizontal bedding, basal erosional surface, imbricated fossil test	High energy	*Thalassinoides* *Bergaueria*
	FNB-Tb1	-Conglomeratic sandstone, fossil cast as fragments with medium sand matrix, cemented by ferroan oxidation.	Normal graded bedding, imbrication at the base, parallel, horizontal – wavy lamination	Turbidite	-
Prodelta (FPD)	FPD-mud	-Dark grey claystone, conchoidal fractures.	Massive, bioturbated	Quiet/calm energy	*Bergaueria* *Phycodes* *Trypanites* *Treptichnus* *Teredolites* *Chondrites*
	FPD-het	-Light grey, fine to very fine sandstone, well sorted. -Dark grey, claystone, conchoidal fractures.	Lenticular, flaser, wavy, parallel, erosional surface, cut & fill, bioturbated	Tide	*Siphonichnus* *Thalassinoides*
	FPD-Tb2	-Light grey, very fine sandstone, good sorted. -Dark grey claystone, firm, in places fractures.	Normal graded bedding, parallel, convolute, "water escape"	Turbidite	-
	FPD-spring/ neap	Intercalation between light grey to brown of very fine sandstone and black to dark grey claystone.	Parallel lamination, double mud layer	Tide	-
	FPD- fos	Greenish grey siltstone, firm, fossiliferous, glauconitic.	Imbrication	Quiet/calm energy	-
	FPD-coq	Shell fragments layer (coquina) consist of pelecypod, gastropod, oyster-mollusca	Lenses (discontinuity)	Turbidite	-
	FPD-chan	-Calcilutite (light yellow), hard, compacted. -Dark grey, coarse sandstone, horizontal bedding, compacted.	Lenses (discontinuity), massive, parallel horizontal, discordance, channel fill	Traction (fluvial)	-
	FPD-hg	Hardground layer (cemented by iron oxidation and calcite)	Reverse graded bedding, erosional surface, bioturbated	Paleoshoreline	*Trypanites* *Planolithes* *Thalassinoides*
Strand Plain (FSP)	FSP –loose	Brownish grey, conglomeratic coarse sandstone, poor sorted, open fabric, loose, thin iron oxidation layer	Cut and fill	Winnowed energy	*Thalassinoides*
	FSP-lam	-Light grey, fine sandstone, well sorted, loose, normal graded bedding, sulphur odour. -Carbonaceous claystone, firm	Parallel lamination, erosional surface, bioturbated	Quiet/calm energy	*Thalassinoides* *Bergaueria*
Delta front (FDF)	FDF-cong	Grey conglomeratic sandstone, fragments (andesite, basalt, quartzite, jasper, quartz, zircon *etc.*) in coarse sand matrix, poorly sorted.	Inclined bedding, bioturbated	Traction energy (fluvial)	*Ophiomorpha* *Thalassinoides*
	FDF-Tp1	-Basal layer consist of shell fragments cemented by iron oxidation, poorly sorted, closed fabric (coquina layer). -Greenish grey medium sandstone, closed fabric, well sorted, lignite remains. -Greenish grey fine sandstone, well sorted,	-Erosional surface, imbrication -Hummocky- swalley, climbing ripple, erosional surface, double mud layer -Massive, bioturbated	Storm	*Gastrochaelites* *Psilonichnus* *Bergaueria* *Planolites* *Thalassinoides*

Table 1. Continue

Facies	Sub-facies	Lithology	Sedimentary Structure	Flow Indicator	Ichnogenera
	FDF-het	-Light grey fine siltstone, medium sorted, closed fabric, strong sulphur odour. -Brownish grey coarse sandstone, medium to poorly sorted, open fabric	-Trough cross stratification, parallel, horizontal, wavy lamination, bioturbated -Normal graded bedding, double mud layer, mud drape, mud clast	Tide	*Psilonichnus*
Delta Plain	FDP	-Brownish grey fine sandstone, well sorted, lignite remains, -Carbonaceous claystone, lignite intercalation	Parallel to horizontal lamination, bioturbated	Quiet/calm energy	*Teredolites* *Bergaueria* *Scoyenia* *Aulichnitus* *Helminthopsis* *Chondrites* *Gastrochaelites* *Ophiomorpha* *Siphonichnus*
Sand Flat	FSF-Tp2	-Shell fragment layer (coquina), cemented by iron oxidation, closed fabric -Grey fine sandstone, medium to well sorted, closed fabric, lignite remains -Dark grey claystone	-Erosional base, imbrication -Hummocky- swalley, climbing ripple, erosional surface, double mud layer, mud drape, bioturbated	Storm	*Psilonichnus* *Siphonichnus* *Thalassinoides* *Rhizocoralleum* *Planolites* *Cylindrichnus* *Bergaueria*
	FSF-spring/ neap	Intercalation between fine sandstone and carbonaceous materials, claystone, highly iron oxidation	Parallel, horizontal, lenticular, flaser, wavy, double mud layer, erosional surface, bioturbated	Tide	*Bergaueria* *Psilonichnus* *Thalassinoides* *Siphonichnus*
Fluvial Sand	FFS	Light brown fine sandstone, well sorted, loose, few nodules present (jasper, concretion)	Reverse graded bedding, parallel	Traction (Fluvial channel)	-

The ichnogenera variations are not very diverse, only including *Ophiomorpha* and *Thalassinoides*. *Ophiomorpha* creates vertical burrows in trough cross-bedded sandstone, with walls filled with pellets (Figure 7a and Table 1). On the other hand, *Thalassinoides* forms tunnels with various orientations (inclined, vertical, and horizontal) and sometimes branching. Some of the holes left behind undergo erosion, are becoming empty cavities (Figure 7b). The fillings of *Thalassinoides* burrows are different from the original rock, mainly consisting of finer lithology rich in iron oxidation (Figures 7c and d).

Ichnofossil of Delta plain Facies (FDP)

The lithology of FDP facies consists of mudstone to siltstone, dark to brownish grey, partly containing carbon and interspersed with coal layers 1.4 m thick. In FDP facies, the diversity of ichnogenera is related to a calm environment with an adequate oxygen supply. Ichnogenera *Teredolites* (Tere) occur in carbon-rich siltstones or woody substances. Furthermore, they are able to form in small cracks underneath, indicating hypo-relief pattern (Figure 8a and Table 1). Several horizontal patterns such as *Scoyenia* (Sc) and *Aulichnites* (Au) developed in the iron-rich lithology (Figures 8b, c, d, f, and g).

The trace characteristics of *Scoyenia* (Sc) follow the bedding plane with streaks/ meniscate on the tube wall (Figure 8b). The *Aulichnites* (Au) pattern indicates epirelief in greenish-grey fine sandstone with thin iron-rich layers (Figures 8c and g). Meanwhile, small-sized ichnogenera *Helminthopsis* (Hel) unearth earlier cast of *Aulichnitus* (Figure 8c). The excavation shows a straight, elongated tube narrowing at the end filled with the lithology that was almost the same as the parent rock (Figure 8c). A convex form of *Chondrites* (Chon) developed above thin iron rich of medium sandstone, displaying a symmetric leaf-like pattern (*Figure 8d*). *Gastrochaelites* (Gas) form an enlarged chamber at the base with a small

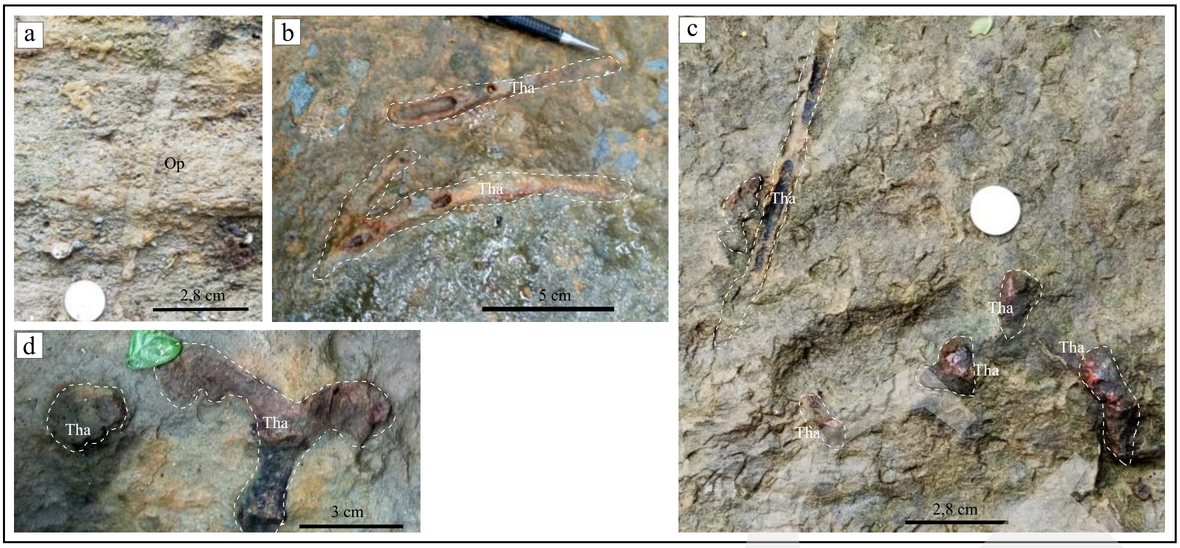

Figure 7. Photographs showing ichnofossils in the delta front (FDF) facies characterized by: a). *Ophiomopha* burrows vertically in a medium to coarse sandstone with tube walls coated in grains. b). Excavation pattern of *Thalassinoides* tubes with eroded filled tubes. c) and d). *Thalassinoides* trace filling comprises material rich-in iron oxides, distinct from the original rock.

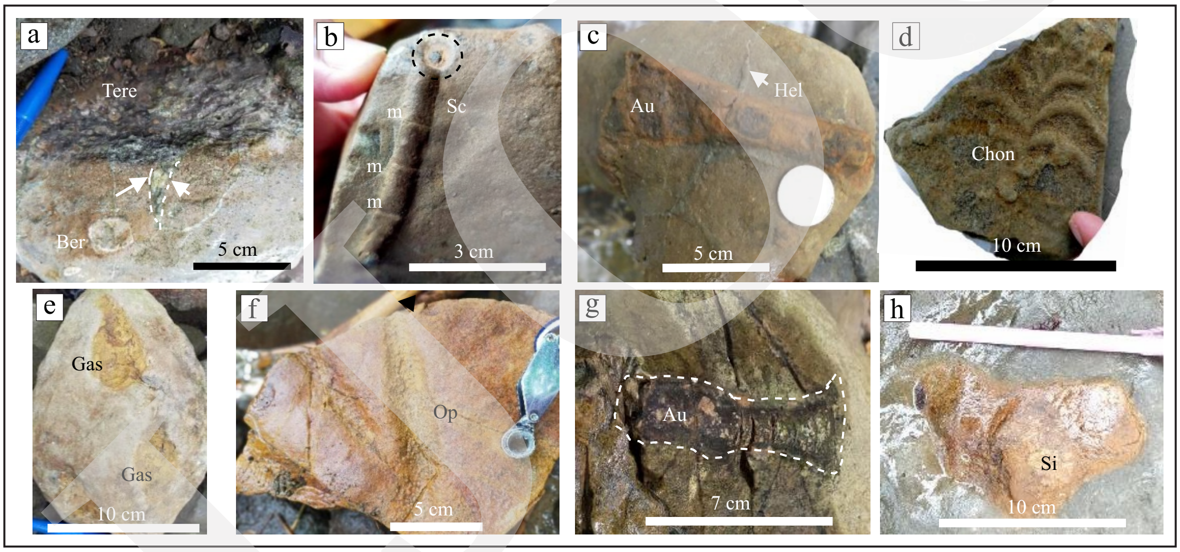

Figure 8. Ichnofossil diversity in delta plain facies, consisting of: a). *Teredolithes* penetrates massively carbonaceous siltstone including a small crack underneath, with *Bergaueria* (Ber) preserved as well. b). Horizontal trail of *Scoyenia* developing with meniscate (m) along the tube wall, while the edges of the hole are covered in oxidation-rich material (dashed circle). c). *Aulichnitus* (*Cruziana*) developed within the greenish grey fine sand showing a positive relief, filled by highly iron oxidation of very fine sand. Meanwhile, the *Helminthopsis* (Hel) cuts above it. d). A horizontal trace of *Chondrites* developed above a medium sand layer. e). *Gastrochaelites* exhibits a smaller aperture on the top of body. f). *Ophiomorpha* showing a tube covered by pellets. g). *Aulichnitus* (*Cruziana*) indicates a positive relief. h). A highly iron oxidation of *Siphonichnus* trail penetrated the light grey fine sands.

aperture at the top (Figure 8e). *Ophiomorpha* (Op) forms epirelief in brownish yellow, medium sandstone with tube walls covered with pellets and having streaks/meniscate. The trace has branches following the main tube (Figure 8f). The ichnogenera *Siphonichnus* (Si) appears within greenish-grey fine sandstone, then later filled by iron-rich fine sandstone (Figure 8h).

Ichnofossil in Allochtochthonous Rocks

In Watupuru allochthonous unit, only tempestite package containing trace fossil, but none in turbidite package. At least two tempestite packages occur within Nanggulan Formation that are tempestite of delta front fasies/FDF (Tp 1) and tempestite of sand flat facies/FSF (Tp 2). Firstly, the storm surged from SE (N120^o E) direction hit the paleoshore during regression phase ended resulting tempestite 1 in facies of delta front (Figure 5c). Secondly, the storm was returning to hit the paleoshore from SE (N150-165^o E) during the second regression phase, generating tempestite 2 in sand flat facies (Figure 5d).

The presence of trace fossil begins in the hummocky-swalley layer (T2) continuing upward layers (T3-T4), but it does not appear at the base (T1) of tempestite package. T1 clarifies fragmented shell layers (coquina) cemented by iron oxides with reddish to brownish clay matrix, poorly sorted, and closed fabric. None-marine fauna activities (ichnofossil) attributes T1layer. Above T1 layer develops well-sorted, greenish grey, fine-grained sandstone of hummocky-swalley cross lamination indicating T2 layer (Figures 9a and b, and Table 1). Among those layers, ichnofossil activities developed quite intensively, including *Planoites, Thalasinoides, Cylindrichnus, Psilonichnus, Gastrochaenolites, Siphonichnus,* and *Rhizocorallium.*

In general, they tend to be bulk, irregular, and sometimes show stacked pattern between one another (Figure 9b). The bore filling looks similar to host rock (Figure 9b) or performed calcareous content (Figure 9a) or even iron oxidation (Figures 9a and b). In places, thin clay layers cover a whole tube body as well. T2 layer of tempestite FSF (Tp 2) is characterized by greenish grey, well-sorted, fine to very fine sandstone, with lignite remains. The sedimentary structures such as double mud layer, mud drape, alternating thin muddy, and sandy layers also occur (Figures 9a and b). Ichnogenera *Rhizocoralleum* with spreiten structure created an oblique orientation pattern to thin laminae of hummocky-swalley cross stratification/ T2 (Figure 9b).

Ichnofossil Diversity of The Nanggulan Formation

Factors influencing ichnofossil diversity in the Nanggulan Formation are as follows:

Illumination

The distribution of ichnofacies in the deltaic Nanggulan Formation is concentrated in the prodelta (FPD), delta plain (FDP), sand flat (FSF),

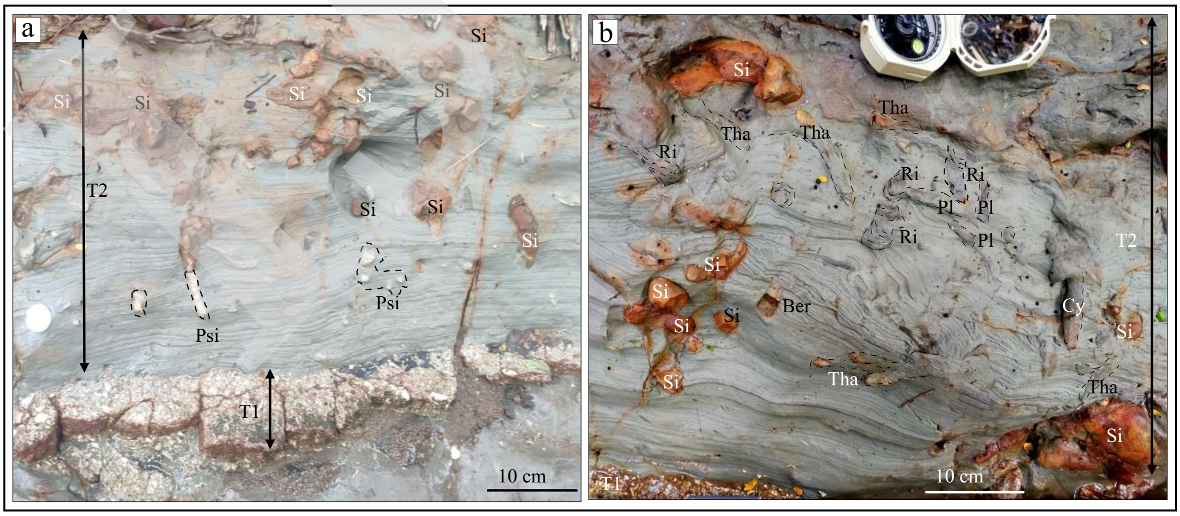

Figure 9. Photographs of diversity of trace fossils in allochthonous rocks of Nanggulan Formation. Massive trace fossil develops in layer of T2 from tempestite sand flat facies (FSF), however none in T1 (coquina layer). a). Vertical cylinder of *Psilonichnus* (Psi) filled by calcareous substances, while *Siphonichnus* (Si) filled by highly iron oxide claystone. b). Bird view-diversity of ichnogenera comprising *Thalassinoides* (Tha), *Rizocorraleum* (Ri), *Planolites* (Pl), *Cylindrichnus* (Cy), *Bergaueria* (Ber), *Siphonichnus* (Si), appearing in hummocky of T2 layer (T2) associated with double mud layer as the character of tidal current.

Table 2. Ichnofossil Diversity within Depositional Facies of Nanggulan Formation

No.	Facies	Depositional Environment	Major Depositional Environment	Salinity	Allochthonous Product	Pattern (horizontal/ vertical)	Ichnogenera
7	Fluvial Sand (upper)	River mouth			-	-	-
6	Sandflat	Tidal sandflat			Tempestite 2 (Tp2)	H>V	*Thalassinoides* *Bergaueria* *Rhizocoralleum* *Planolites* *Cylindrichnus* *Siphonichnus* *Psilonichnus*
5	Delta Plain	Mangrove/ Delta plain	D E L T A I C	Brackish water (0,05-3%)	-	H>V	*Teredolites* *Bergaueria* *Scoyenia* *Aulichnitus* *Helminthopsis* *Chondrites* *Gastrochaelites* *Ophiomorpha* *Siphonichnus*
4	Delta Front	Delta front			Tempestite 1 (Tp1)	V~H	*Gastrochaelites* *Psilonichnus* *Bergaueria isp* *Planolites* *Thalassinoides* *Ophiomorpha*
3	Strand Plain	Shoreline			-	V~H	*Thalassinoides* *Bergaueria*
2	Prodelta	Marginal marine			-	H >V	*Bergaueria* *Siphonichnus* *Phycodes Trypanites* *Treptichnus Tere-dolites* *Chondrites*
1	*Nummu-lithes* Bank (lower)	Marginal marine	Middle shore face	Saline water (3–5%)	-	H=V	-

and delta front facies (FDF). Dark grey, muddy substrate of prodelta facies (FPD) may provide a good habitat in particular for horizontal burrowing such as *Pycodes, Chondrites, Treptichnus,* and *Teredolites,* and also for a vertical trace such as *Trypinates* (Table 2). Even though light penetration or illumination was preferred by marine fauna, but some ichnogenera are proven to be available in reduction environments.

An environment that frequently receives direct sunlight leading to high oxidation levels, has been shown to support a wide variety of ichnogenera, such as those found in the Nanggulan delta plain facies (*Teredolithes, Bergaueria, Scoyenia, Aulichnitus, Helminthopsis, Chondrites, Gastrochaelites, Ophiomorpha,* and *Siphonichnus*) (Figure 8 and Table 1).

Behaviour

Teredolites is present in both reducing environments (prodelta) and oxidizing environments (delta plain). It commonly occurs in carbon-rich rocks of the delta plain (FDP) and also in prodelta mudstones (FPD). This may be related to excavation by bivalve fauna (Donovan and Isted, 2014) (Figure 6g and Table 1). The horizontal pattern of *Scoyenia* with some meniscus following bedding orientation (Figure 6h), may interpret to be food distributor route (fodinichnia) by arthropod or worm-like fauna (Kim *et al.*, 2005). The *Chondrite* pattern itself is believed to be the activity of bivalve fauna in cultivating food using chemical symbiosis methods (Baucon *et al.*, 2020). Furthermore, *Chondrites* exhibit branches of nearly equal size within each tube. This ichnofossil is known to be more adaptable to low oxygen conditions (Mork and Bromley, 2008), as seen in the Nanggulan prodelta facies (Figure 6f).

The ichnogenera of *Aulichnites* exhibits a horizontal orientation which implies dwellings (domichnia) and food routes (fodinichnia) (Knaust, 2018). Ichnogenera *Gastrochaelites* indicates a vertical hole which is interpreted to be crustacean fauna activities such as shrimp, bivalve, crab, and lobster, near the shoreline (Kleemann, 2009). The presence of *Trypanites* clusters is only found in the prodelta muddy lithology, which is interpreted as a filter-feeding for collecting food from the suspension (Wilson and Palmer, 2006) by polychaete worms (Taylor and Wilson, 2003).

Ophiomorpha was strongly influenced by surface oxidation like delta plain facies (FDP) and delta front (FDF) (Figure 6l). It has also been interpreted by previous researchers as being able to develop in a sandy beach with a low energy environment (Shamsuddin *et al.,* 2022). In the Nanggulan Formation, *Ophiomorpha* is also recognized in a high energy of cross-bedded medium sandstone (Figure 7a). Furthermore, ichnogenera *Siphonichnus* may come from bivalve-mollusk activity (Knaust, 2015), believed to be an adaptable activity against salinity shifts in deltaic environments like Nanggulan Formation (Table 2).

Thalassinoides tends to dig obliquely or horizontally sandy substrate with a solitary or branched tunnel such as in delta front facies (FDF). The tube is mostly covered by iron oxides on the outside and the erosion-filled tube left an empty space in the next period (Figure 7b). This pattern describes a dwelling type (domichnia) of decapod fauna (crustacean order) such as lobsters, crabs, and shrimp (Yanin and Baraboshkin, 2013).

Some authors also stated that horizontal patterns were associated with feeding behaviour, while vertical patterns are considered a way to capture nutrients from suspension (Bromley and Uchman, 2003).

Sedimentation Rate

The lack of ichnogenera variation in the delta front facies (FDF) is very likely due to the high rate of sedimentation during the sea level regression (Figures 3 and 7). However, other authors attribute it to a decrease in the salinity of coastal areas (Bromley and Uchman, 2003). Only two ichnogenera have been discovered, namely *Ophiomorpha* and *Thallasinoides* within delta front (FDF). In contrast to delta front which experience a higher sediment input, the calmer environments with lower sediment influx in prodelta (FPD) and delta plain (FDP) setting support a diverse range of ichnogenera. Additionally, the dominant horizontal pattern is observed in both autochthonous (prodelta and delta plain facies) and allochthonous rock, those are tempestite 1 in delta front facies and tempestite 2 in sandflat facies, likely indicating a quiet/calm habitat or less disturbed environment due to the low sediment influx (Table 2).

Current Control

The existence of ichnogenera in the allochthonous rocks of Nanggulan Formation was controlled after the cessation of the catastrophic storm. In tempestite packages, ichnofossil diversity is only associated with the second layer (T2) of tempestite. Major storm energy itself derived from the southeast towards the northwest direction. The initial storm surge hit paleoshore causing an avalanche of unconsolidated shoreline materials (shells, sand, silt, *etc*.) transferred to the deeper parts (below fairweather wave base) by the first incoming storm surge, resulting T1 layer (Figure 4a). This layer indicates a barren ichnogenera environment. Previous authors attributed it to environmental changes due to physical and chemical stress (Arifullah *et al.,* 2015).

The following wave behind the major storm caused the movement of radial oscillatory wave toward the top, then becoming an elliptical wave approaching the seafloor known as internal wave (Pomar *et al.,* 2012) (Figure 4a). These oscillatory waves or inernal wave controlled the deposition of hummocky and swalley cross stratification (T2) (Figure 4b). Another researcher said that internal waves were responsible for moving sediment deposits, especially carrying nutrients in the distribution of plankton and larvae (Pomar *et al.,* 2012).

Heterolithic sedimentary structures such as double mud layer, mud drape, alternating thin muddy and sandy layer also occur in T2, suggesting an indicator of tidal current. Tidal current is worthy for sorting out the grain size to be uniform, neutralizing salinity, and increasing photosynthesize to produce abundant nutrients. Therefore, the behaviour of ichofossil suggests for searching food (fodinichnia) and placing them (domichnia) after the storm quits. For example *Rhizocoralleum* formed a stacked curve pattern in T2 layer showing an oblique route that follows the hummocky structure (Figure 9b and 10). This pattern could be interpreted to be an indicator trail of food searching in good nutrient concentrations (Rodriquez-Tovar and Perez-Valera, 2008). Other researchers have concluded that the ichnogenera *Rhizocoralleum* are indicative of an environment with low sedimentation or erosion, typically following

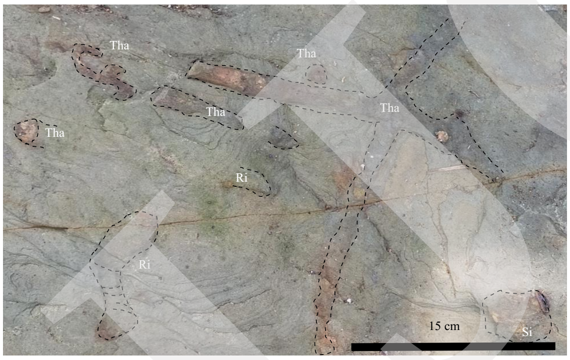

Figure 10. Photomicrograph of bird view-tube branching of *Thalassinoides* (Tha) and *Rhizocorraleum* (Ri) dig obliquely through the T2 layer. *Siphonichnus* (Si) is also present in the bottom right corner.

the formation of tempestite deposits (Chrzastek, 2013). Moreover, a pair of ichnogenera: *Rhizocoralleum* and *Planolites* in sandy substrate of tempestite deposit, usually shows horizontal patterns (Baziany, 2016).

Some reasons, the tubular cylindrical with two holes (in front and behind) of *Cylindrichnus* (Figure 9b) is interpreted to be filtering and capturing food activities horizontally by its tentacles (Ekdale and Harding, 2015). Tidal environments often leave large areas of muddy substrates, particularly in intertidal zones. This area is a favourite spot for animals to search for food, like *Helminthopsis* (Buatois and Mángano, 2012) (Figure 8c). *Helminthopsis* shows a simple horizontal pattern that aligns with its feeding behaviour of extracting nutrients from the muddy substrate (Lima and Netto, 2012), especially during a high tide in the Nanggulan delta plain.

Horizontal branching of ichnofossil *Thalassinoides* reaches 15 cm in length above T2 layer of Tempestite 2 (Tp 2) (Figure 10). It suggests a period of a short transgressive event between the second regresion phase of the Upper Nanggulan Formation (Figures 3 and 10). Basically, the tube structure of *Thalassinoides* in Tp 2 reflects a massive activity as vertical shaft to maintain a connection to the sediment-water interface and horizontal network for deposit feeding (Bromley and Uchman, 2003). This happens during brief transgression periods of sand flat facies (FSF), rather than during extended transgression periods as suggested by previous researchers (Pervesler *et al.,* 2011).

Infilling Material

Traces of ichnogenera left behind are typically filled with a different lithology compared to the host rock. The filling of the holes left by the organism traces is clearly derived from a suspension rich-in oxidized iron. The empty space left behind by *Thalassinoides* undergoes a passive backfilling by the sediment above it or also by the host rock in prodelta and delta front facies (Figures 7g and h; 7c and d). It is very common *Thalassinoides* present in silty or muddy lithology of shallow marine sands (Yanin and Baraboshkin, 2013).

Similarly, ichnofossils such as *Scoyenia, Aulichnitus,* and *Gastrochaelites* are found in a delta plain facies. Deep burrowing organisms can provide insights into seasonal surface conditions by revealing surface sediments (Wetzel, 2010). In tidal-influenced environments, the filling of trail burrows can indicate substrate conditions during the high or low tide. In coastal marine regions with tropical climates, these traces are often filled with firm or hardground substrates (Long, 2007). Figures 6g and h show an example of trace fossil filling by the hard ground layer in low tide conditions.

In the prodelta facies (FPD), traces formed in clay suspension lithology are often filled with calcareous substances such as *Phycodes, Treptichnus, Chondrites,* and *Trypanites*. On the other hand, a vertical tunnel*, Psilonichnus,* in tempestite rock still preserves calcareous/carbonate substances within their cylindrical body (Figure 9a). It may imply dissolving preliminary aragonite shells by surface water infiltration during lithification, then replacing them to be calcite cement. This is typically caused by chemical effect in calcite seawater, which commonly occurs in shallow tropical seas (Taylor and Wilson 2003).

Periods of filling abandoned tubes may be caused by organism activity and erosion from overlying rock (Arifullah and Zaim, 2021). This may take some time of regression phase of the areas ensued, and it is still controlled by tidal currents carrying Fe-rich suspension clay. Hence, the previous author called a discontinuity stratigraphic event following the storm ceased (Leonowicz, 2016).

Conclusions

The diversity of ichnofossils in the delta depositional system of Nanggulan Formation is observed in the Watupuru River cross section. Seven depositional facies have been identified, arranged from bottom to top as follows: Nummulites bank, prodelta, strand plain, delta front, delta plain, sandflat, and fluvial sand. The presence of ichnofossils is closely linked to the lithology type in which they are found, distinguishing between autochthonous and allochthonous rocks. Ichnofossil diversity is prominent in autochthonous prodelta, delta front, and delta plain rocks. While in allochthonous rocks, it is primarily found in storm deposits (tempestites). The growth of The Nanggulan Delta is often disrupted by frequent floods, so that the main river is diverted, or in other words controlled by waves.

Ichnogenera such as *Bergaueria, Siphonichnus, Phycodes, Trypanites, Treptichnus, Teredolites, Chondrites,* and *Thalassinoides* are associated with muddy suspension in the prodelta. On the other hand, the delta plain facies (FDP) offer a tranquil and well-oxygenated environment, hosting ichnogenera like *Teredolithes, Bergaueria, Scoyenia, Aulichnitus, Helminthopsis, Chondrites, Gastrochaelites, Ophiomorpha,* and *Siphonichnus*.

Catastrophic storm events can result in the cessation of organism activity, requiring time for the ecosystem to recover and stabilize. Subsequently, there is a resurgence of organism activity on the sandy substrate, with organisms burrowing into the hummocky layer (T2) and progressing upwards (T3-T4). Internal waves following the initial storm surge are believed to sustain the nutrient content in tempestite 1, hosting ichnogenera like *Gastrochaelites, Psilonichnus, Bergaueria, Planolites* and in tempestite 2 containing *Thalassinoides, Bergaueria, Rhizocoralleum, Planolites, Cylindrichnus,* and *Siphonichnus*. Various factors influencing ichnofossil diversity in both autochthonous and allochthonous settings include light availability, behavioural adaptations to the environment, sedimentation rates, current dynamics, and burrow infilling.

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