Tiering Style and Its Interpretation: Ichnofabric Study in Balikpapan Formation, Kutai Basin, Indonesia

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Abstract. The determination of tiering style is an important task in ichnology. Tiering styles can be modeled by using ichnodiversity, the number of behaviors and number of tiers and their relationships. In this study, this approach was applied in the area of Samarinda, Kutai Basin, Indonesia. The values of ichnodiversity, number of behaviors, and number of tiers were identified. Ichnodiversity was strongly correlated with number of behaviors but weakly correlated with number of tiers. Accordingly, three tiering styles were identified. Typically, tiering styles A, B, and C demonstrated high ichnodiversity, number of behaviors and number of tiers. In general, the colonization window that coincides with the environmental conditions characteristic for deltaic settings is the factor that mostly regulates these tiering styles.

Keywords: *colonization window; environmental conditions; ichnodiversity; number of behaviors; number of tiers.*

1 Introduction

Tiering, the establishment of a community structure in which different organisms are distributed vertically in space, is a common biological method for resource partitioning [1] within a single habitat [2,3]. Multiple tiers that display distinct behaviors and have been constructed in one time can be found in a composite ichnofabric. The main features are: 1) a tier is equivalent to an ichnofabric unit; 2) a tiering is composed of one or more tiers; 3) each tier reflects any amount of ichnodiversity and any number of behaviors; 4) tiering is a biological solution; 5) a tiering is constructed in one time. This suggests that a high number of tiers is correlated with high ichnodiversity and a high number of behaviors. Tiering relates to palaeoecological factors that have been described implicitly in [4] and explicitly in [5]. The study of tiering style was initiated by [6] and extended by [7]. The eleven tiering styles of [7] can be simplified by using ichnodiversity, number of ethologies and number of tiers as the basic characteristics. The objective of this study was to determine ichnodiversity, the number of behaviors and the number of tiers and their relationships with tiering style, which is regulated by depositional setting.

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2 Geology of Research Area

The research area was located in Samarinda, Indonesia (Figure 1), which geologically comprises the Balikpapan Formation, deposited within the Kutai Basin. This basin borders on the Sangkulirang strike-slip fault to the north and the Paternoster strike-slip fault to the south to. To the west, the basin is bounded by highly deformed and uplifted Paleogene sediments and Cretaceous metasediments that make up the Central Kalimantan Mountains. The Kutai Basin is open to the Makassar Strait in the east. In addition, Samarinda was a depocenter during the Miocene [8], which is interpreted as a deltaic setting [9-11]. Ichnologically [11], ichnofacies of deltaic deposits are visible. High ichnodiversity and diverse bioturbation are displayed by wave-dominated deltas to a greater degree than by fluvial or tidal ones.

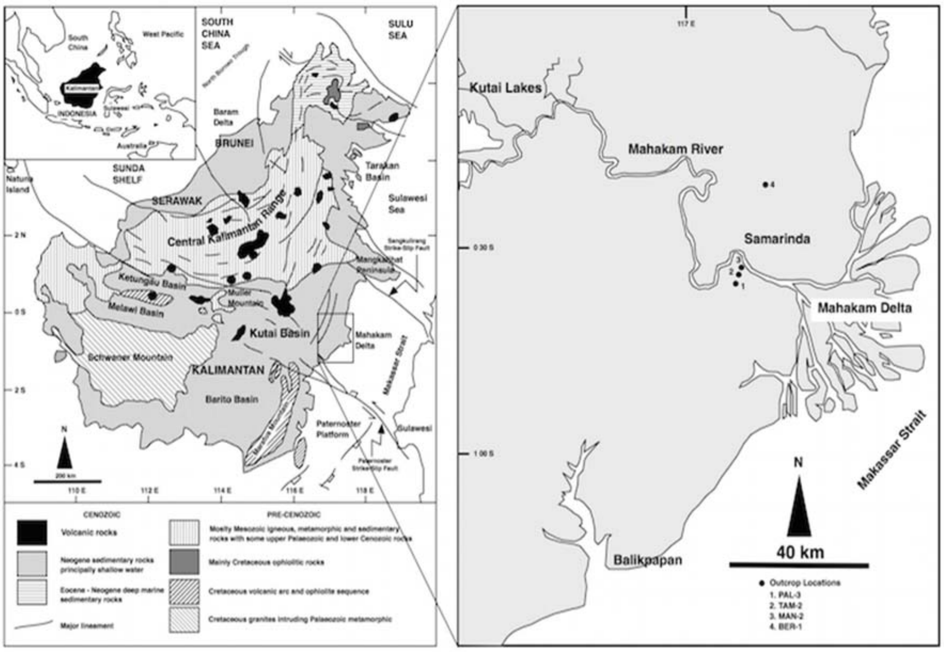


Figure 1 Geological map of Kalimantan [16,17] and the research location.

3 Materials and Methods

3.1 Ichnodiversity and Number of Behaviors

Data collection was conducted from January to February 2016. The true thickness of 100 m of the beddings of four outcrops was observed, of which 26.02 m was bioturbated and in which 232 ichnofabric units were identified.

The outcrops were located in Samarinda (Figure 1), which coincides with the Kutai Basin NE-SW structural trend. Ichnodiversity is the number of ichnogenera in a tier (ichnofabric unit). Ichnogenera are identified based on ichnosystematic classification with respect to general morphology, orientation to the bedding surface, branching, burrow lining, and burrow fills [12]. A three-dimensional view of the general morphology of the research area is provided by a cross-sectional view of cylindrical burrows cut tangentially at various angles [13] (Figures 2-3). It is useful to decode the flecks, dots, smudges, and smears that are usually left by ichnofossils. With respect to behavior, each ichnogenus is a typical sample of one behavior, referring to the classification in [14] and the updated one proposed by [15]. However, one behavior may be exemplified by several ichnogenera.

3.2 Tiering Determination

As pointed out by [1,2,5], three points should be considered in tiering determination. Firstly, confirm that the tiering is constructed in one time, no matter how many tiers are identified. This is done by examining the ichnofabric unit below the keybed or event bed, such as a coal seam, a coral reef, a nonbioturbated (barren) bed or a sharp base contact [7], working from top to bottom. Secondly, determine how many tiers there are and how shallow or deep they are, based on the criteria from [5]. Against highly weathered outcrops, burrow fill and lining cannot be easily distinguished from the surrounding sediment and the cross-cutting relationship is blurred. The solution for this problem is to carry out a close and thorough inspection of the burrow fill and lining and sketching the features. In the case of a vague cross-cutting relationship, the rule of thumb is that lined ichnofossils are cross-cut by unlined ones.

3.3 Statistical Analyses

Referring to the method described in the preceding paragraph, the ichnodiversity, the number of behaviors, and the number of tiers were organized and summarized. A boxplot and the quartiles describe the shape of the distribution of the variables. Furthermore, since multivariate data were used, principal component analysis (PCA) was applied in the next step. Before PCA could be applied, the original data had to be standardized (see Table 2, supplementary data) and processed to obtain factor scores per tiering (see Table 3, supplementary data). The goal of PCA is to reduce the dimensionality of a data set that consists of multiple variables. Only components that have an eigenvalue or cumulative percentage of total variance greater than 1 can be considered for determination. Revealing the correlation between the variables (i.e. ichnodiversity, number of behaviors and number of tiers) is critical. Refer to [18,19] for a detailed explanation of PCA. In this study, PAST-3 was applied for running PCA.

3.4 Supplemented Data

The four tables included in this paper comprise: (1) a list of ichnodiversity, number of behaviors, and number of tiers per tiering; (2) standardized data from Table 1 per tiering; (3) a list of factor scores for PC-1 and PC-2 per tiering; (4) a list of ichnofabrics and their ichnofossil content per tiering. Two figures are included: PC-1 loading and PC-2 loading.

4 Results

4.1 Descriptive Statistics

In total, 239 ichnofabric units were examined based on which 199 tierings were determined (Table 1, supplementary data). Descriptive statistics of the tierings are displayed as boxplots in Figure 2.

Table 1 Quartiles (first, second, third), including Minimum and Maximum Value of Ichnodiveristy (ID), Number of Behaviors (NB), and Number of Tiers for 199 Tierings (AT).

Parameters	ID	NB	AT
N	199	199	199
Min	1	1	1
Q1	1	1	1
Q2	2	1	1
Q3	3	2	1
Max	7	4	4

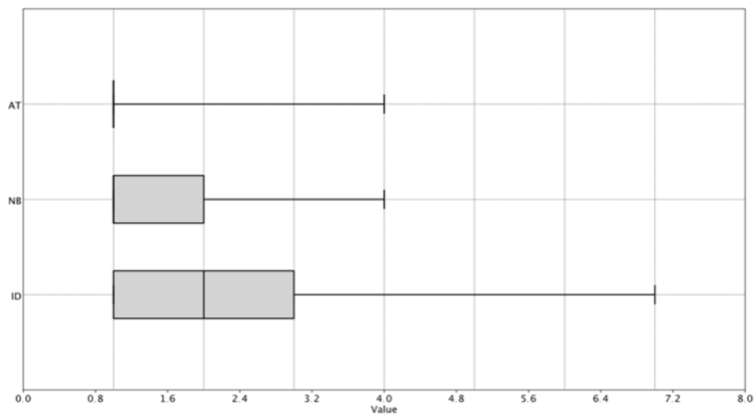


Figure 2 Box plot of ichnodiveristy (ID), number of behavior (NB), amount of tier (AT) (for detail see Supplementary Data: Table. 1).

The data distribution is skewed to the right. This causes the distance from the median to the minimum value in the dataset to be smaller than the distance from the median to the maximum value in the dataset. In addition, Figure 2 (based on Table 1) shows the quartiles, including the minimum value, first quartile (Q1), median (Q2), third quartile (Q3) and the maximum value for ichnodiversity, number of behaviors and number of tiers. It can be seen that the highest interpercentile was shown by ichnodiversity, followed by the number of behaviors and then the number of tiers

4.2 Relationships among Variables

Table 2 shows Component 1 (PC-1) and Component 2 (PC-2), which represent 90% of the total variation of the data. However, only Component 1 (PC-1) with eigenvalue greater than 1 was included in the criteria for determining significant relationships.

Table 2 Eigenvalues and percentage variance for each component.

Principal Component (PC)	Eigenvalue	% variance
1	2.3	74.29
2	0.53	16.97
3	0.27	8.73

According to Figure 3, ichnodiversity and number of behaviors are strongly correlated, which is demonstrated by the cosine of the small angle between both. Moreover, the cosine of the larger angle between ichnodiversity and number of behaviors on the one hand and number of tiers on the other hand indicates a weaker correlation. Generally, higher ichnodiversity is correletaed with a higher number of behaviors and occasionally by a higher number of tiers.

The clustering in Figure 3 shows that tiering style A is influenced strongly by ichnodiversity and number of behaviors. Furthermore, incorporation of more tiers and higher ichnodiversity and number of behaviors produced tiering style B. Finally, tiering style C illustrates that the increase of the number of tiers is the key variable that controls the tiering style, despite an increase of ichnodiversity or number of behaviors.

Moreover, a close relationship between the variables and the Component-1 axis is indicated by the smaller cosine angle between them. The Component-1 axis is contributed by all variables with different loading. In this case, the ichnodiversity and the number of behaviors contributed more than the number of tiers. However, the Component-1 axis is an artificial factor that regulates tiering style formation.

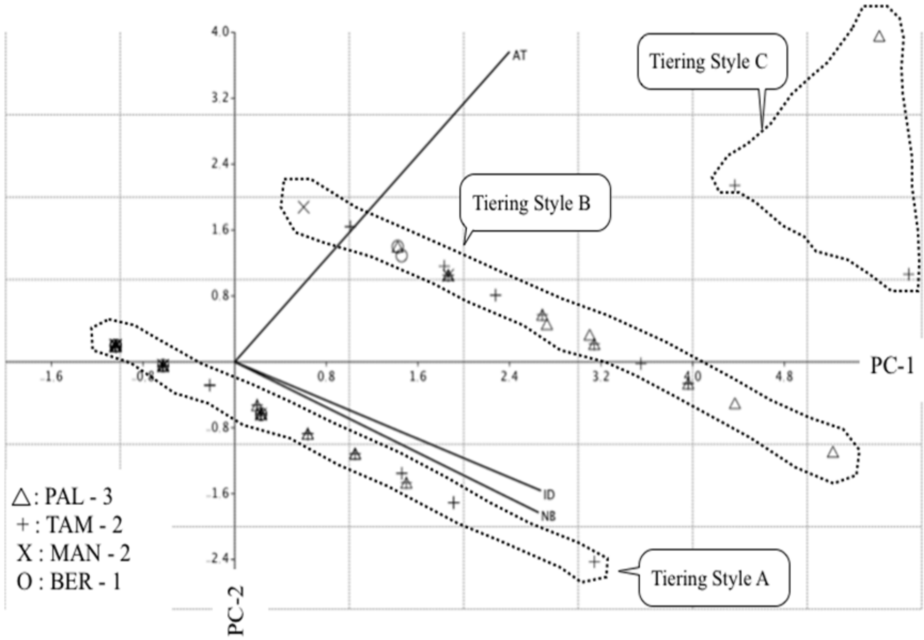
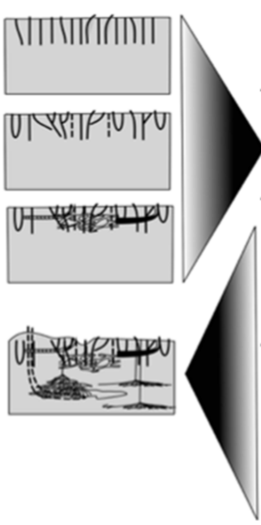


Figure 3 Projection of ichnodiversity (ID), number of behaviors (NB) and number of tiers (AT) in tierings in Component 1 (PC-1) and Component 2 (PC-2). Three groups can be seen that were promoted to tiering style. Component 1 was correlated with all variables, for which the coefficient correlation values were required (see Figures 1 and 2, supplementary data).

4.3 Tiering Style A

Tiering style A covered 85% of the total number of tierings that were determined. The main characteristics of this style are: a single tier, encompassing all ichnogenera and all behaviors (Table 3). Skolithos, Paleophycus, Planolites, Ophiomorpha, Thallasinoides and Chondrites are ichnogenera that constitute this style by single or multiple tiering with other ichnogenera. By combining ichnodiversity and number of behaviors, three substyles of style A can be distinguished: style A1 contains one single ichnogenus and one single behavior (Figure 4); style A2 contains multiple ichnogenera and one single behavior (Figure 5); style A3 contains multiple ichnogenera and multiple behaviors (Figure 6).



Tiering style		Variables			Ichnofossil
		Ichnodiversity	Number of behavior	Amount of tier	
A	A1	Single	Single	Single	*Skolithos, Paleophycus, Planolites, Ophiomorpha, Thallasinoides*
	A2	Multiple	Single		
	A3	Multiple	Multiple		
B		Multiple	Multiple	Double	**Shallow tier:** *Paleophycus, Skolithos, Ophiomorpha* **Deep tier:** *Chondrites*
C		Multiple	Multiple	Triple or quadruple	**Shallow tier:** *Paleophycus, Thallasinoides* **Deep tier:** *Ophiomorpha, Rhizocorallium, Zoophycos*

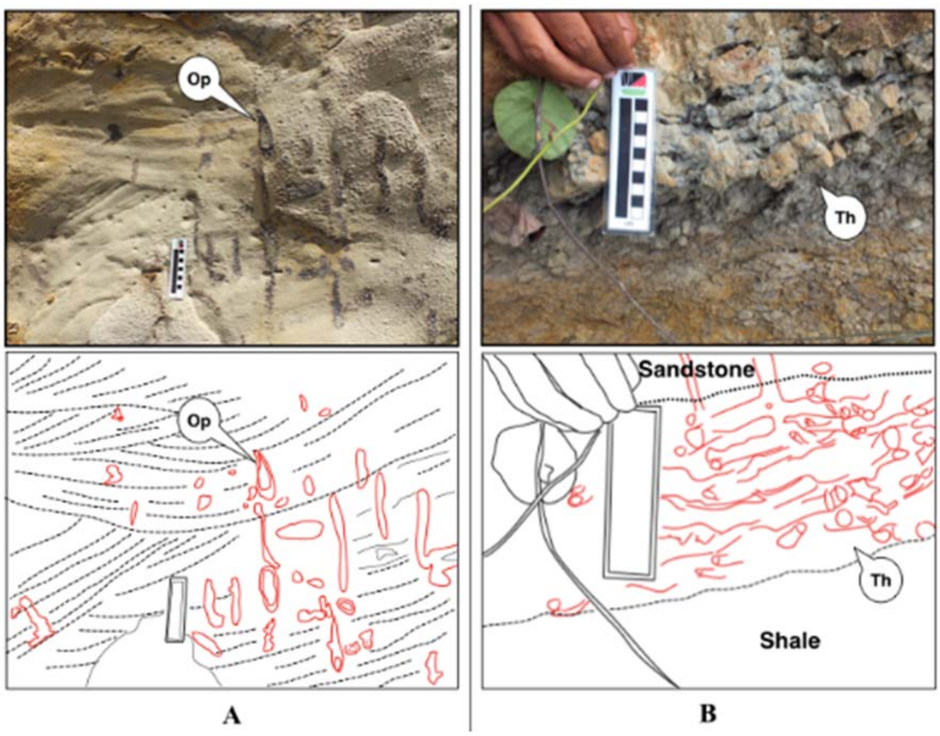


Figure 4 Example of tiering style and their variables, A1: (A) Ophiomorpha (Op) and (B) Thallasinoides (Th).

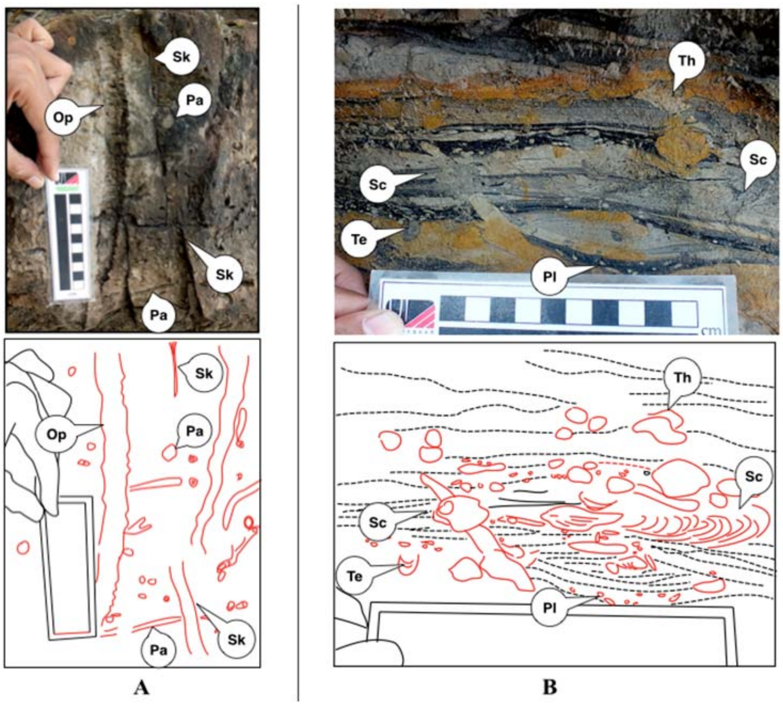


Figure 5 Example of tiering style A2: (A) Ophiomorpha (Op), Paleophycus (Pa), and Skolithos (Sk); (B) Thallasinoides (Th), Scolicia (Sc), Teichichnus (Te) and Planolites (Pl).

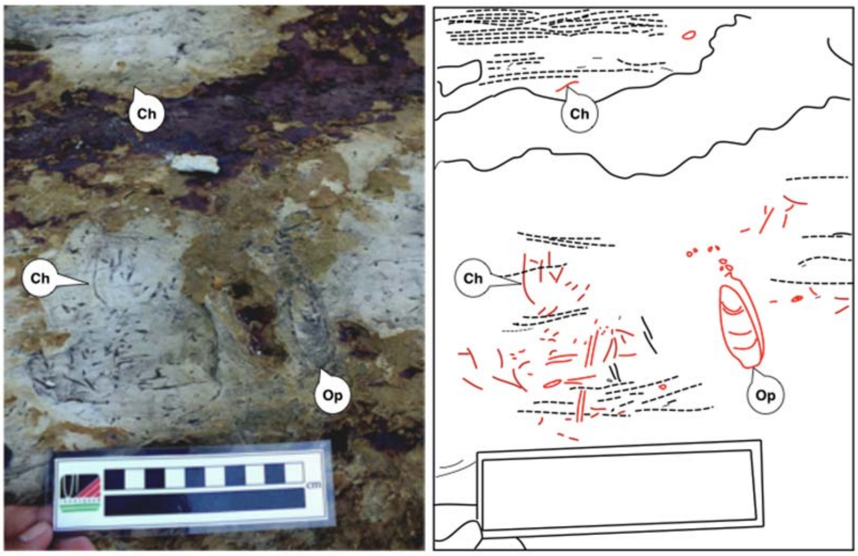


Figure 6 Example of tiering style A3 with Chondrites (Ch) and Ophiomorpha (Op).

4.4 Tiering Style B and C

Tiering style B covered 14% of the total number of tierings that were determined. The main characteristic of this style are: two tiers, a shallow and a deep one, containing multiple ichnogenera (Table 3). Shallow tiers are primarily colonized by Paleophycus and then by Skolithos and Ophiomorpha. Meanwhile, deeper tiers contain primarily Chondrites and then Ophiomorpha. Occasionally, Zoophycos was observed. Style C represents 2% of the total number of tierings. It has three or four tiers, followed by ichnodiversity and number of behaviors (Table 3). The shallow tier contains Paleophycus and Thallasionides, the middle tier contains Ophiomorpha, Rhizocorallium, and Zoophycus, and the lower tier contains Chondrites (Ch) (Figure 7).

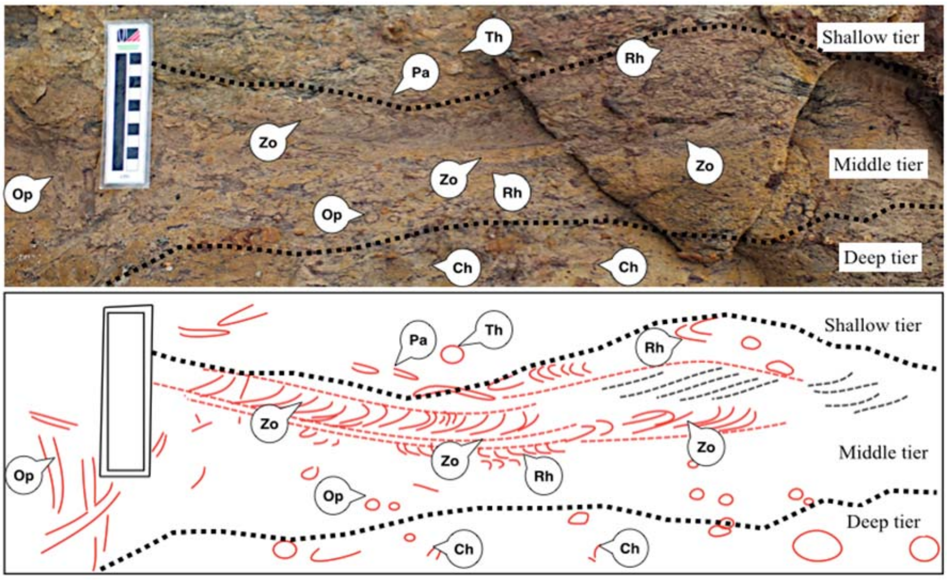


Figure 7 Example of tiering styles B and C. The uppermost tier is composed of Paleophycus (Pa) and Thallasinoides (Th). The middle tier contains Zoophycos (Zo), Rhizocorallium (Rh), and Ophiomorpha (Op). Chondrites (Ch) is settled in the lower tier.

5 Discussion

These findings show that: (1) the data distribution is skewed, and (2) that ichnodiversity is strongly correlated with the number of behaviors and weakly correlated with the number of tiers (Figure 3). Finally, all variables correlate to Component 1 (see Figure 3 and percentage variance of PC-1 in Table 2). The interpretation of Component 1 (PC-1) will be further discussed below.

Based on these findings, tiering style can be defined as a relic of an organized strategy of trace making for survival. Unexpectedly, this definition fits both [20] and [15], who define the behavior comprehensively. Implicitly, this behavior is represented by the tiering style's complexity. This inference is reinforced by the definition of complexity from [21,22,23] and is related to the definition of a colonization window from [24]. The composite tier from [3] is clearly comparable with tiering style B and tiering style C shows complexity.

The ichnofossil content, the ichnodiversity and the number of behaviors in tiering style A can be compared partially to e.g. [25]. This reference notes ichnofossils (i.e. Skolithos, Paleophycus, and Planolites) and low ichnodiversity and low number of behaviors as indicators of a brackish environment. However, there is an obvious difference between Skolithos, Paleophycus, Planolites on the one hand, which have a simple structure, and Ophiomorpha, Thallasinoides, and Chondrites on the other hand, which have a more complex structure. The finding of complex structures is interpreted as palaeoecological patchiness in a brackish or occasionally marine-influenced environment, which is common in deltaic settings.

In relation to substrate consistency, Ophiomorpha and Palaeophycus in tiering style A1 are typically found in loose sandy substrate [13,6]. Conversely, Planolites and Thallasinoides are commonly found in firmer substrate [13]. If one of these ichnofossils colonize a tiering exclusively (tiering style A1), it suggests a specific environmental condition, at least related to substrate consistency.

The combination of *Ophiomorpha* and *Skolithos* is an example of tiering style A2. According to [15] they are related to *domichnia*. The difference between them is related to their structural complexity. *Ophiomorpha* indicates longer occupation than *Skolithos* [23]. However, tiering style A is characterized by simple to complex ichnofossils from single to multiple ichnogenera, as well as a large number of behaviors.

Tiering style A3 is characterized by the combination of *Ophiomorpha* and Chondrites, with multiple ichnogenera and different behaviors. This style may be related to tier replacement [5] or suddenly deteriorating conditions [7]. The minor occurrence of this style may indicate a rare environmental event.

The development of tiering style B suggests increased space utilization and increased complexity. The shallow tier is colonized by Paleophycus, Skolithos, Ophiomorpha, and Thallasinoides, which resemble the ichnofossils in tiering style A. Moreover, the deep tier is colonized by Chondrites, which may be related to an anoxic environment [26]. Hence, tiering style B suggests the presence of *domichnia* in the shallow tier and *chemichnia* in the deep tier. Implicitly, the tiers in style B are probably associated with the oxygen gradient.

The triple or quadruple tiers observed in tiering style C can be compared to [3]. The sediment-water interface is open for a longer time span for colonization, which corresponds to nondeposition, depositional discontinuity or a slow sedimentation event. This time span is called the colonization window [24], either 'deliberate' or 'incidental' [21-23]. However, this time span should be supported by tolerated environmental conditions. Consequently, the colonization window has to be extended to the chemical colonization window [7] or an equivalent environmental term.

As identified in [27], some processes or environments are unique to a deltaic setting, which encourages the interplay of fluvial, tidal and wave processes on the one hand and fresh, brackish and saline water on the other hand. These intricate relationships regulate tiering style formation, where tiering style A is dominant, followed by tiering style B and more sporadically by tiering style C.

6 Conclusion

The complexity of a tiering style is exemplified by ichnodiversity, the number of behaviors and the number of tiers, which correlate with the colonization window. The dominance of tiering style A implies a small colonization window, caused by fluctuating and intricate environmental factors in a deltaic setting. However, these tiering styles should be compared to other ones in a more stable environment.

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Supplementary Data

Supplementary data related to this article can be found online at http://journals.itb.ac.id/index.php/jmfs/article/view/3638.