Sedimentological characterisation of sea bottom samples collected offshore Muara and Tutong, Brunei Darussalam

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Abstract: The study aims to get some additional knowledge on the modern seafloor composition offshore Brunei Darussalam by looking at the recent stratigraphic succession of the deposited sediments and their distribution patterns. For this reason, 10 shallow cores (22 to 46 cm thick) have been collected by scuba diving along two depth transects spanning from water depth of 20 to 60 m. One of the transects has been sampled north-northwest of the Muara village, just in front of the Brunei Bay and the other one off the coast near Tutong town, away from major sedimentary inputs. The results obtained portray two different sea bottom compositions and two different depth-related sediment distributions. The Muara transect is highly rich in mud and yielded abundant biogenic component at all investigated depths. The Tutong transect has a higher sand content but display constant changes along with depth. The sediment is mostly composed by biogenic grains such as rests of sponges, foraminifera, molluscs and echinoderms; the not biogenic grains are for the vast majority made of quartz. The sandy fractions of both transects have been tested for cyclicity and all cores can be described by functions with comparable periods, thus indicating that an oscillatory environmental event such as the alternation of the monsoon seasons, has similar influence on the seafloor of both transects.

Keywords: Sedimentology, biogenic component, depth distribution, offshore Brunei, marine environment

Abstrak: Kajian ini bertujuan untuk menambah ilmu pengetahuan mengenai komposisi dasar laut perairan Brunei Darussalam dengan melihat urutan stratigrafik sedimen dan pola taburannya. Oleh itu, sebanyak 10 batang teras cetek (22 hingga 46 sm) telah berjaya diambil oleh sekumpulan penyelam skuba sepanjang dua transek berkedalaman dari 20 hingga 60 meter. Salah satu persampelan transek telah diambil pada utara-barat laut daripada perkampungan Muara, di hadapan Teluk Brunei dan transek yang kedua diekstrak di hadapan Pekan Tutong, jauh dari sumber-sumber utama sedimen. Hasil yang diperolehi menunjukkan dua komposisi dasar laut yang berbeza dan dua taburan sedimen berlainan berikut kedalaman yang berbeza. Transek Muara didapati mengandungi jumlah lumpur yang sangat tinggi dan kaya dengan komponen biogenik pada semua kedalaman yang dikaji. Manakala Transek Tutong mempunyai kandungan pasir yang lebih tinggi tetapi terdapat perubahan di sepanjang kedalaman yang disiasat. Peratusan pasir pada kedua transek diuji bagi kitaran (cyclicity) dan didapati kesemua teras yang dikaji dapat dihuraikan oleh gelombang sinus (function) dengan tempoh-tempoh (periods) yang sebanding, di mana ianya menunjukkan bahawa osilasi peristiwa persekitaran seperti musim monsun yang bersilih ganti mempunyai pengaruh sama terhadap lantai laut pada kadua transek.

Kata kunci: Sedimentologi, komponen biogenik, pembahagian corak, luar pesisir Brunei, persekitaran laut

INTRODUCTION

The Sultanate of Brunei Darussalam is one of the richest countries in the world due to its extensive hydrocarbon reservoirs (e.g., Curiale *et al.*, 2000). Most of the drilling platforms are located in the immediate offshore regions that drill into thick mostly Miocene to recent sedimentary successions (Crevello *et al.*, 1997; Morley *et al.*, 2003).

The seafloor sediments have been accumulated over the past 20 to 30 million years as the results of complex deltaic dynamics, which have been deeply investigated since the sixties both on- and offshore (Wilford, 1961; Hodgetts *et al.*, 2000; Back *et al.*, 2001; Hall & Nichols, 2002; Hutchison, 2005). One of the most complex aspects of shoreface deposits in the region is to assess precisely their sedimentary provenance and genesis (Lambiase *et al.*, 2002). Specifically, the possibility to discriminate all those sediments, which have been deposited under the influence of tide, wave or river inputs (Lambiase *et al.*, 2003). Such inputs are commonly mixed in the final deposit and a clear differentiation of the different sources is very difficult in the field (Morley, 1991; Fiah & Lambiase, 2014; Collins *et al.*, 2018; Roslim *et al.*, 2019). The differentiation and the classification between wave and tide dominated sediments has been long debated on the Neogene deposits of Brunei

and the surrounding regions because their clear separation has been proven useful in correlating onshore outcrops and offshore wells (Lambiase *et al.*, 2003; Ovinda & Lambiase, 2017). In recent years, a number of studies have pointed out the importance of modern analogues as an additional tool to better interpret shoreface deposits in the region (e.g., Lambiase & Tulot, 2013). Using these helped consistently field geologists in giving better interpretations of sedimentary successions (Riadi & Lambiase, 2015; Liu *et al.*, 2016) and perhaps, petroleum geologists in their difficult task to tackle down reservoir properties, but confidentiality issues often do not allow sharing their experience.

The modern seafloor offshore Brunei has been intensively studied in the past 15 years as a valid modern analogue to further highlight the Neogene sedimentary succession cropping out onshore (Lambiase *et al.*, 2002; Lambiase & Tulot, 2013).

One of the most interesting results obtained from those studies is the fact that most of the offshore seafloor surface can be assumed to be relict sediment deposited by deltaic activity during the last transgression phase and, consequently, the consideration that no modern sediment is currently deposited offshore Brunei. This interpretation is worth investigating because it would definitely increase our understanding of the stacked parasequences reported from many localities in NW Borneo (Hassan *et al.*, 2013).

The way deltas can generate such unique type of sedimentary record has been recently discussed and interpreted by some studies (Liu *et al.*, 2016; Collins *et al.*, 2018), which justify the capability to accumulate large quantity of sediment in relatively short time with a model characterised by the so called "source-to-sink" effect. The delta simply works as a bypass zone, which delivers all sediment collected in an instant situation of heavy load that is immediately transported and deposited in the offshore region. In high tropical regions such as the one studied here, these phenomena are relatively common and can be seen in modern scenarios after heavy rains or after prolonged rainy seasons. The rivers can carry heavy loads, which are immediately transported through the deltas into the offshore region where they are finally deposited.

Previous studies have highlighted the fact that muddier versus sandier seafloors have the capability of driving biodiversity patterns (Forderer & Langer, 2018; Renema, 2018). Such effect has been observed also offshore Brunei (Goeting *et al.*, 2018) and additional data point to a rather complex sediment distribution with large sandy patches, extended muddy surfaces and some slow growing trophic and oligophotic reefs (Zaini *et al.*, 2017). These reefs are distributed along the coast of Brunei Darussalam and cover a total of 45 km² of seafloor (Chua *et al.*, 1987). Very minor in extension but extremely important for biodiversity are the more than 30 sunken wrecks that are lying on the seafloor, which are considered major points of enhanced marine biodiversity (Goeting *et al.*, 2018). Therefore, checking the modern sedimentary history of Brunei seafloor could not only be interesting to observe recent deltaic activity but could also shed light on biodiversity changes and environmental variations.

To obtain more data on the sediment composition of the modern Brunei seafloor and to check whether differences in sedimentation are truly visible along an environmental gradient, two depth transects have been sampled by scuba diving. The study of the sediment composition of such cores could shed additional light on the modern sedimentation offshore Brunei and possibly help understanding with higher resolution how the sediments are transported and deposited offshore. Additionally, this approach can check whether or not, are there some constant patterns in the sediment profiles, which are common among different environments.

MATERIALS AND METHODS

For this study, ten shallow cores have been collected along two depth transects offshore Brunei (Figure 1). Since the Brunei Bay is a major contributor of sediment into the eastern part of Brunei waters due to the estuaries of Brunei, Temburong and Trusan rivers (Yong, 2010), one transect was collected starting just at the opening of the bay toward north-west. This transect has been labelled "Muara Transect" because it has been collected offshore the village of Muara in Brunei Darussalam.

The second transect was collected at the middle distance between the Brunei Bay and the other major sediment discharge of the Baram Delta (Chua *et al.*, 1987), to avoid as much as possible contamination from major sedimentary inputs. This transect has been labelled "Tutong transect" as it is laid offshore of the Tutong town (Figure 1), almost 70 km off from the other transect.

While the Muara transect follows a rather straight line toward the deepest regions, the Tutong transect gently turns westward toward the deepest points. The reason to this shifting is to reach the deepest locations avoiding crossing two major carbonate productions zones (patchy reefs) known as Ampa (to the West) and Victoria (to the East) Patches.

For each transect, five cores have been collected at 20, 30, 40, 50 and 60 m water depth, or as close as possible to such depths depending on the dive site. The cores were labelled with the initial of the nearby village/town (i.e., "M" for Muara cores and "T" for Tutong cores) and are followed by the depth of collection (i.e., T20 is the core collected along the Tutong transect around the depth of 20 m). All data regarding sampling points, core recovery and depth are reported in Table 1.

Each core has been taken by scuba diving so that a rapid visual survey could be undertaken before inserting the core into the sediment. The visual survey permits to avoid collecting cores at obvious reworked sites such as ripple fields, bioturbation holes, or mounds. For this reason, once at the sea bottom the diver spent several minutes to spot the best site for the core penetration.
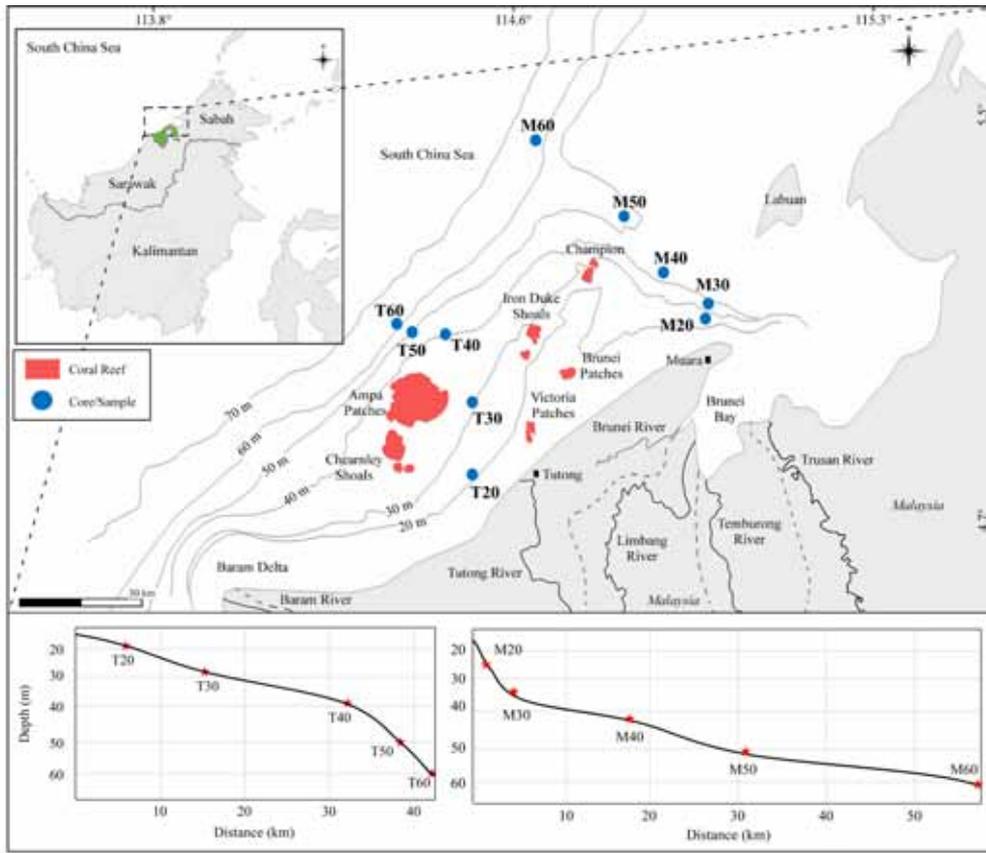
Figure 1: Geographical positions of the study area in Brunei Darussalam (top) and the sea bottom topography of each transect locations (bottom).

Table 1: Summary information on the sampling sites with core recovery and average mud fraction.

Sample	Date of collection (d/m/y)	Water depth (m)	Latitude	Longitude	Core Recovery (cm)*	<63 μm (%)
Muara-20 (M20)	30/05/16	25.9	5°5'49.98"N	115°2'30.00"E	32	84.6
Muara-30 (M30)	30/05/16	35	5°7'30.00"N	115°2'60.00"E	24	97.9
Muara-40 (M40)	30/05/16	42	5°10'50.00"N	114°57'0.00"E	38	84
Muara-50 (M50)	30/05/16	51	5°17'10.00"N	114°51'50.00"E	32	84.2
Muara-60 (M60)	30/05/16	63	5°25'35.70"N	114°40'4.70"E	30	55.4
Tutong-20 (T20)	31/05/16	20	4°48'30.00"N	114°31'30.00"E	38	29.7
Tutong-30 (T30)	31/05/16	30	4°56'30.00"N	114°31'30.00"E	46	33.8
Tutong-40 (T40)	31/05/16	40	5° 4'10.00"N	114°27'50.00"E	30	62.9
Tutong-50 (T50)	31/05/16	50	5° 4'20.00"N	114°23'30.00"E	22	79.4
Tutong-60 (T60)	31/05/16	60	5° 5'10.00"N	114°21'20.00"E	38	87.7

each core was sliced at 2 cm intervals, that resulted 165 samples.

The core itself was 60 cm long and the longest recovery was 46 cm. Most of the cores have an average of 30 cm recovery. After extraction, it was immediately transported to the surface and, on the vessel, it was sliced in 2 cm intervals. The first 4 cm (first 2 slices) were treated with a Bengal Rose – Ethanol solution to colour the living assemblages for future studies on the benthic fauna.

The core was 6 cm in diameter and to avoid contamination, the most external sediments were removed. This was done by using a 4.5 cm diameter ring, which allowed the collection of the internal part only of each slide. The amount of sediment used in these analyses was therefore, for each sample, a cylinder with 2 cm thickness and 4.5 cm diameter (ca. 31.8 cm^3). In this study altogether 165 samples have been retrieved

and used for both transects. All slices of the Tutong transect have been sieved using 250, 125 and 63 µm sieves; the slices for the Muara transect had much less sand portion and only the 125 and 63 µm sieved have been used. The < 63 µm fraction of all cores was not retained (see Table 1).

At 4 cm intervals a manual distinction between biogenic grains versus non-biogenic grains has been done on the 125 µm fraction to check whether the content of biogenic components are constant within each core or if they show any sort of variation trough the cores or along any environmental gradient. Due to the presence of a large variety of biogenic component, mostly but not exclusively calcareous, the sorting has been done manually and not by using an acid attack. This has been also done to preserve the sample content, which is currently used to study its faunal composition. The data are presented as percentages calculated on the relative weight of the biogenic grains respect to the total sample weight. The most common findings among the biogenic components are foraminiferal tests, ostracods and fragments of corals, molluscs, echinoids and sponges. Among the biogenic components (non-calcareous) are all agglutinated foraminifera, siliceous sponges and various chitinous remains (Figure 4-5). The layers in between the checked biogenic components have been averaged out. This is done by averaging the upper and the lower known biogenic percentage (i.e., Sum of biogenic weight of 6-8 cm and 10-12 cm divide by 2).

The proportion of the coarser fractions have been also used to check if periodical oscillations are visible in every core and whether some cycles are more recurrent than others. For the Muara transect, the > 125 µm and 63 µm fractions were used, whereas for the Tutong transect the sum of the > 250 µm and the 125 µm were used (i.e., Muara: 125 + 63 µm and Tutong: 125 + 250 µm). This has been done to make sure enough data are included into the calculation and giving the evidence that the Tutong transect is much sandier than the Muara transect, there has been no need to include also the very fine sandy fraction into the calculation. The obtained periods were taken and pooled from each core for each transects and later for both, then Mixture Analyses function of PAST 3.26 (Hammer *et al.*, 2001) were used to calculate re-occurring cycles, their probability and standard deviations (Table 2). Only the first significant cycles (Max 4) have been reported and used in this analysis.

RESULTS

The granulometric analyses made on all the retrieved cores as well as all the data on the biogenic components are shown in Figure 2 for Muara and Tutong transects. Both transects indicate a rather muddy sea floor with relatively low amount of sandy fractions. Even the Tutong transect, which contain more sand fraction than Muara, whose location was chosen as the sandiest one, is in fact still mostly composed of mud, especially in the deeper cores. The variation of the biogenic component throughout the cores is reported in Figure 2 and the mean percentage for each core is displayed in Figure 3.

None of the cores seem to show a fining or coarsening upward sorting of the material. Some of the cores seem to have abrupt changes at some depth intervals, from which the most distinctive is the sudden appearance of coarse fraction toward the bottom of the core T60.

All cores in both transects seem to show some vertical variations, which permitted the extraction of periodical cycles. Cycles with comparable periodicity (still measured in centimetres) are visible in all collected cores; they are listed in Table 2 and sorted by their significance. These recurring cycles have mean periods as 5.6, 14.4, 34.0 and 28.1 cm, where the last two are extremely low in significance.

Muara transect

The depth transect collected offshore Muara is characterised by a generalised increase in the sandier fractions (above 63 µm) with depth. The shallowest core (M20) seems however display the highest amount of coarsest sand (> 125 µm only) estimated at 8% despite being located at the opening of Brunei Bay; nonetheless, from M30 to M60 the sandy fraction increases constantly with M30 having the lowest amount of sandy fraction (both > 125 µm and 63 µm). However, the 125 µm fraction seems to remain rather constant from M30 to M50 and at the deepest site, there appear to be a clear increase (M60). There is also a clear increase of the 63 µm fraction from M20 to M60.

The average amount of biogenic particles in the shallowest depths is extremely abundant and they made up more than 90% of the entire fraction (Figure 2). This value gently decreases to almost 60% at M40 and then increases again to over 70% at M60. From Figure 5, suborder *Rotaliina* and pieces of

Table 2: Results from the sinusoidal functions observed in the cores with the average values of the most significant cycles (in cm) for both transects and their averages. Refer to figure in Appendix A and table in Appendix B for detailed data.

Cycles Muara			Cycles Tutong			All Cycles		
Probability	Mean	St.dev.	Probability	Mean	St.dev.	Probability	Mean	St.dev.
0.478	6.3	1.5	0.431	4.9	0.5	0.446	5.6	1.1
0.274	14.8	3.1	0.236	9.0	2.0	0.437	14.4	4.8
0.126	32.1	3.9	0.223	16.1	1.7	0.059	34.0	2.0
0.123	22.2	0.2	0.111	30.0	2.0	0.058	28.1	0.1
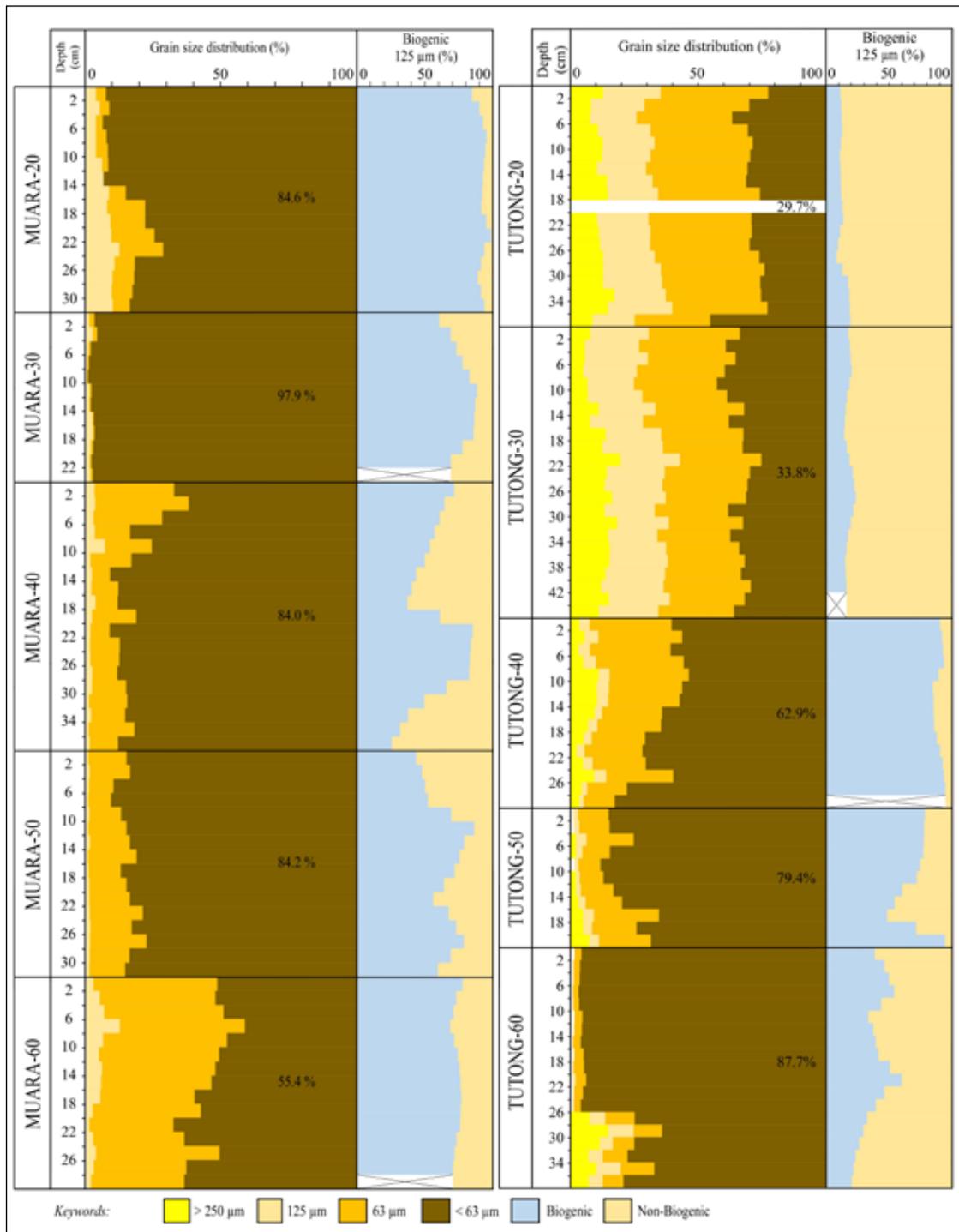
Figure 2: Granulometric analysis (left) and biogenic-grain percentage from the size fraction of 125 μm (right) of the Muara and Tutong transects. Note that the 63 μm of M20 (12-14 cm) and T20 (18-20 cm) were lost. Refer to tables in Appendix C and D for detailed granulometric data.

bivalve shells are constantly observed in the Muara transect from the shallowest (M20) to deepest site (M60).

The cores in this transect appear to show visible vertical variations and allowing periodic cycles to be identified. The most significant cycles for Muara transect have mean periods of 6.3, 14.8, 32.1 and 22.2 cm. Some cycles have quite broad standard deviations (Table 2).

Tutong transect

This transect shows a completely different depth trend than the one observed along the Muara transect. Here the sandy fraction decreases continuously and constantly from the shallowest toward the deepest sampling points. All intermediate sandy fractions also decrease with water depth. A major perturbation is clearly visible toward the
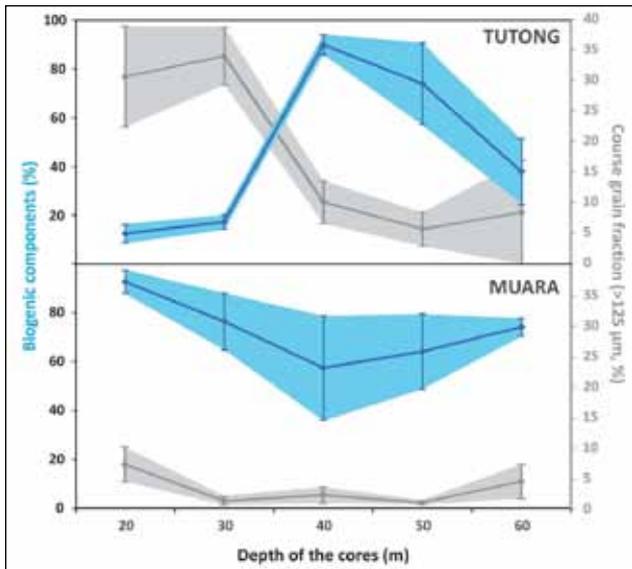
Figure 3: Core mean values of biogenic component from the size fraction of 125 μm (black) and averages of the courser grain size (125 μm) (grey) in each core for both transects.

bottom part of T60 core (26-38 cm) where a much sandier sediment takes over a very muddy one.

The biogenic components are very low in abundance at the shallowest locations but they do suddenly increase at T40 (90%) and then they decrease again down to almost 40% at T60 (Figure 2). Diversity and abundance data on faunal community of the top 2 cm shows very similar results (Goeting *et al.*, 2019). Similar to Muara transect, foraminifera and bivalves are also constantly observed in the different depth sites (Figure 4).

The obtained cycles for the cores along this transect are somewhat similar with those retrieved at Muara. The most significant cycles have mean periods at 4.9, 9.0, 16.1 and 30.0 cm. Both Muara and Tutong have mean periods as 5.6, 14.4, 34.0 and 28.1 cm, where the last two are extremely low in significance.

DISCUSSION

The distribution of the grain sizes for all the investigated cores gives several insights regarding the seafloor composition and its depositional pattern offshore Brunei Darussalam.

One of the most interesting results is that both transects show clearly different sand distribution along with the depth gradient. It was expected that an increase in mud should correspond to an increase in depth so that coarser sediments are deposited and preserved only at the shallowest depths due to hydrodynamics. This is only visible along the Tutong transect where indeed a decrease in the coarser fraction is visible along the depth gradient. In the Muara transect the data collected are quite different. The shallowest core shows the highest amount of the coarsest fraction (> 125 μm) but from M30 to M60 the trend is completely the

opposite. The greater the collection depth is, the coarser the sediment gets. One of the possible explanations considers the sedimentary load brought into the Brunei Bay by the three major rivers in the region (Brunei, Temburong and Trusan rivers), which can affect the distribution of the sand in the proximal offshore sectors. Such rivers are well known to be extremely efficient in transporting large amount of sediment (Chua *et al.*, 1987), whose composition is mostly very fine sand to silty mud. This fact could enhance the distribution of the sediments in the shallowest regions where most of its sandy load (> 125 μm) is deposited: the Brunei Bay itself and lastly the site (M20). The muddier fraction is transported for much further distances but, apparently, not too far as its abundance decreases from M40 to M60. The increase in sand in the deepest sampling points could be caused by two factors. One possibility, which has been partly proposed by Lambiase and Tulot (2013), is that modern sediment does not reach that far into the offshore, leaving therefore a relict blanket of material deposited during the previous sea level fluctuations. However, these authors indicate that such relict sand can be already visible few tens of metres offshore at a starting depth of 8 m. According to the data obtained here, it seems that the relict sand only starts at the M40 location, which is located 18 km off the Brunei coastline and more than 50 km from the Malaysian coast, where the rivers are distributing their sediment.

A second possibility is that seasonal monsoons could be capable of inducing a very weak seafloor turbulence by oscillatory waves, which could selectively remove finer particles and deprive the sediment of its siltier and muddier fractions. This "winnowing" effect could also explain the differences between M20-30 to M40-60 because these latter sites are much more exposed to the open sea than the shallowest sites, which are rather protected by Labuan Island and the outermost part of the Brunei Bay. Provenance studies as well as radiocarbon ages could shed more light into this issue and perhaps could give a confirmation to either theory.

Furthermore, both cores M40 and M60 seem to show a crude coarsening upward trend with exceptional abundance of benthic foraminifera in the first few centimetres (Saifulizan, 2018). Similar high abundance of foraminifera retrieved on surface samples in nearby location reached up to 35,000 individuals for comparable sediment volume (ca. 14 cm³) (Azmain, 2018). This could indicate condensed sedimentation which are autochthonous and continuously reproduce over time creating extraordinary accumulation of empty tests if not diluted by the continuous deposition of fine-grained sediment. The abundant and poorly preserved state of most of the biogenic component in the sample M40 to M60 also indicates intense reworking activity, which is indeed difficult to explain at such depths, but can commonly occur in all those conditions where sediment starvation leads to late burial of the shells that continuously accumulate as autochthonous material. Miocene outcrops
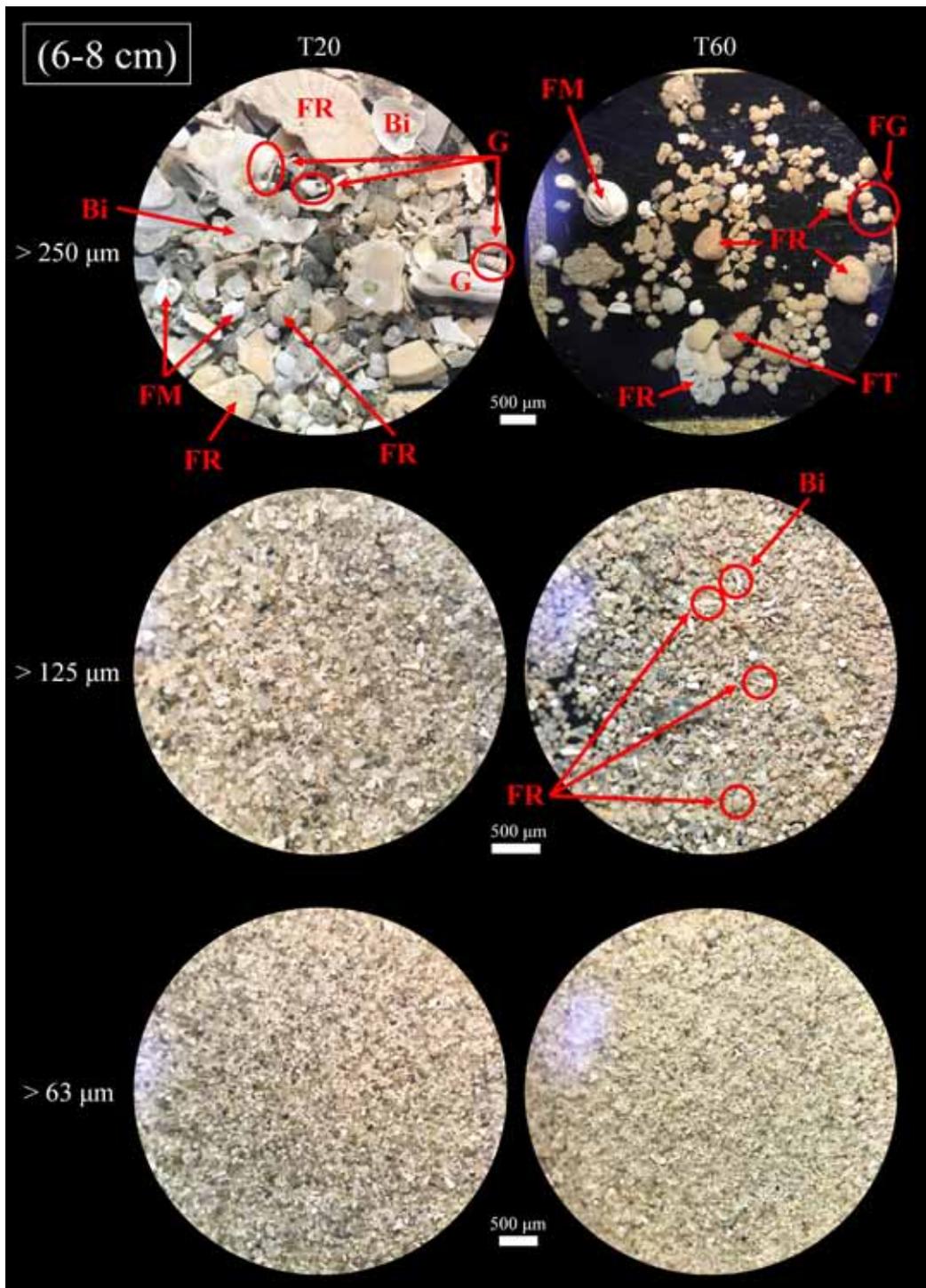
Figure 4: Biogenic components identified in the selected interval (6-8 cm) of the shallowest (T20) and deepest (T60) core samples at Tutong transect. Abbreviations: FR – Foraminiferida *(Rotaliina),* FM – Foraminiferida *(Miliolina),* FT – Foraminiferida *(Textulariina),* FG – Foraminiferida *(Globigerinina),* Bi – Bivalvia, G – Gastropoda.

in Brunei often show similar abundances of shelly remains, however some of these are rather resulted from storm-initiated reworking from somewhat shallower environment (Atkinson *et al*., 1986; Kocsis *et al*., 2018, 2019; Roslim *et al*., 2019, 2020).

The Tutong transect is sandier than the Muara Transect and clearly shows a decrease in all sandy fractions along with the depth gradient. It seems also that the nearby reefs do not affect the sand distributions, and this seems to be confirmed by preliminary data of Goeting *et al*. (2019). The
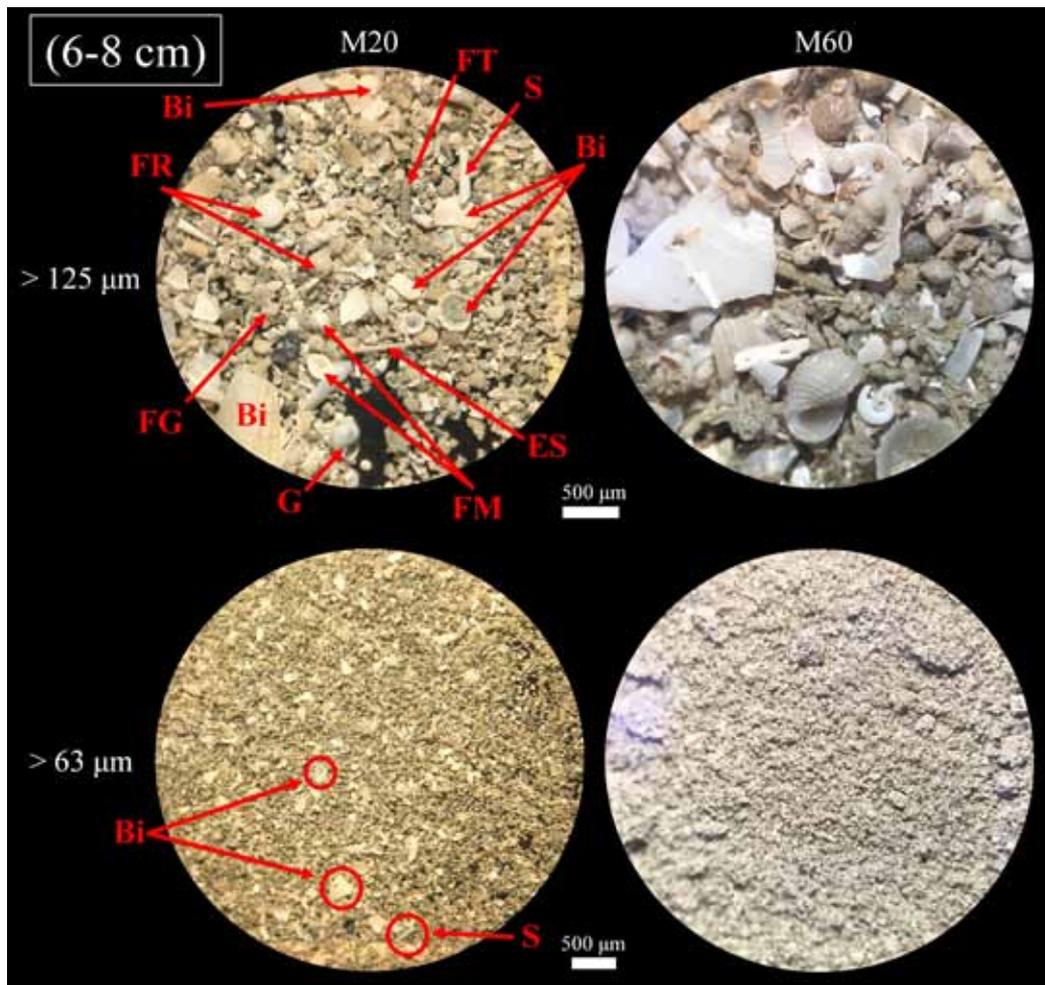
Figure 5: Biogenic components identified in the selected interval (6-8 cm) of the shallowest (M20) and deepest (M60) core samples at Muara transect. Abbreviations: FR – Foraminiferida *(Rotaliina),* S – Scaphopoda*,* ES – Echinoid spine, FM – Foraminiferida *(Miliolina),* FT – Foraminiferida *(Textulariina),* FG– Foraminiferida *(Globigerinina),* Bi – Bivalvia, G – Gastropoda.

rather small Tutong river, which ends nearby the beginning of the transect, does not seem to affect the grain distribution even in the shallowest site. The way the sand is distributed along the depth transect represent the most common way sand and finer fractions expected to be deposited and it can be used as a perfect analogue for all those Neogene outcrop where the river dominance can be only partially observed.

The distinction of the biogenic particles did not show any significant cycles or continuous variation throughout the investigated cores, therefore the data are simply averaged to a single value for each core (Figure 3). According to the data here presented, it seems that biogenic component is distributed in different ways in the transects and along the depth gradient. One of the key aspects to consider is that the count for biogenic material has been done on the 125 μm fraction only. In the Muara transect this fraction was the coarsest sieved whereas in the Tutong transect, also the 250 μm was used. The biogenic component that are separated by these two fractions are mainly larger foraminifera and molluscs. This obviously led to a reduction of the value of the biogenic data for the

Tutong transect. This is clearly visible by comparing Figure 4 and 5. In Figure 4, the 250 μm fraction for T20 is quite rich in biogenic grains but in fact only grains that refer to the groups of larger foraminifera and molluscs. These types of taxa are not abundant in the Muara transect and the 125 μm fraction retrieved (Figure 5) is in fact rich in smaller benthic foraminifera and planktonics that are all smaller than 250 μm. Similar evidence cannot be stated for the 125 μm fraction of the Tutong transect that lacks completely all the small benthic taxa. In the sandier substrate (i.e., Tutong transect) at shallower depths, the amount of biogenic within the 125 μm grain size is extremely low for a tropical coastal region (Figure 4) as the entire fauna is fully dominated by species of larger size such the symbiont bearing larger foraminifera or the large rotaliids (e.g., *Rotalidium* or *Cavarotalia*) that by kleptoplastidy manage to increase their size (Goeting *et al.,* 2019). The same dominance of larger foraminifera and molluscs continues down to 30 m water depth but the percentage of the biogenic components jump to very high values at 40 to 50 m, thus testifying the occurrence and the

abundance of smaller benthic organisms and the complete disappearance of the larger taxa that cannot find optimal light exposure at such depths (Briguglio *et al.*, 2017; Eder *et al.*, 2018). At Brunei coastline, the 30 m water depth might be considered as the depth where the benthic community switches from dominated by symbiont bearing authotrophic organisms to dominated by sediment feeders heterotrophic organisms. The deepest sampling points are already too deep and light penetration is probably too low to permit LBF communities to develop in diversity and abundance, and therefore their presence decreases constantly.

The drastic change in substrate between 30 and 40 m is in perfect agreement with the variation in benthic organisms and shall therefore not be interpreted as a drastic change in hydrodynamic conditions.

The Muara transect is richer in muddy sediments than the Tutong cores and the highest amount of biogenic component appears at its shallowest core reaching up to 90% (Figure 3). Muddy sediments represent a perfect habitat for smaller benthic foraminifera, which are mostly sediment feeders or suspension feeders. They are also well adapted to higher hydrodynamics as they have mostly infaunal lifestyle. The biogenic component is very abundant throughout the entire transect and does not show abrupt variations as those observed along the Tutong transect. Larger foraminifera are not reported from this transect, whilst smaller foraminifera are extremely abundant and diverse.

A more focused taxonomic approach in classifying all the biogenic grains is currently undergoing and will definitely shed more light into this issue. Nonetheless, it seems that both transects are characterised by a unique faunal composition and this interpretation is further supported by data partially published by Goeting *et al.* (2018) where the benthic community inhabiting a muddy seafloor was very different from the one inhabiting sandier conditions even if the sampling points were just few km away.

The extrapolation of cycles from continuous series of discrete data can reveal the presence of intrinsic variations in form of sinusoidal cycles or harmonic series. In this study, sinusoidal cycles have been extrapolated because the main goal is to look for periodic or semi periodic signals preserved in the sedimentary record caused by deep time oscillations. Cyclicity in seafloor granulometry is mostly due to sea level oscillation and fluctuations. The preservation of a pristine signal in the deposition of sediments on the seafloor is hampered by a number of factors, which can hide or completely erase any remain of the original signal. Especially in inner to middle shelf conditions, bioturbation plays a major role in hindering the preservation of a pristine signal. Burrowing organisms often modify the sedimentary layers and tend to mix their composition and therefore erasing all oscillatory signals if preserved. The scuba diving collecting method permits to a certain degree to avoid the collection of sediment on bioturbated surfaces if visible on the sea floor but certainly it is not possible to foresee any

sign of incipient ichnological activity underneath the surface. A possible evidence of bioturbated sediment could be the results obtained at T60 toward the bottom of the core (Figure 2). For this reason, the calculation of the cycles for T60 has been reduced to the undisturbed interval only and the cycles extrapolated are weak and not sufficiently significant.

To avoid these issues the most conservative way to interpret the oscillatory signals is to check only for significant cycles and to sum them up together with their probability value as reported in Table 2.

In this way, even small variations around a given value can be observed. Surprisingly for both transects it seems that constant periods are present. Not only within the same transect similar periods occur along the depth gradient but also some periods are comparable in both transects. This is the case for the values 5-6 and 14-16. These values, given in centimetres (cm), represent the period of two oscillatory functions as extrapolated from the analysis. They indicate that there is an oscillating signal that has a recurring period of 5-6 cm and another signal of 14-16 cm. In oscillatory waves and generally in wave theory, the period is a time dependent dimension. It is classically expressed in seconds. Here the metric parameter is also time dependent because the oscillatory signal runs through time along the collected core. Time is not recorded at the same pace in sedimentary environments: some layers can sediment in shorter times than a thin lamina; nonetheless in time series analyses, such as the one here proposed, the assumption that time is registered at constant pace is mandatory. In geology, the difference between the model and the reality is easily observed with the standard deviation of each single sinusoidal function, which we report for every single cycle. A continuous calibration with a chronological scale could only be possible if the sediment would be dated with geochronological methods that require profuse financial support here not available. However, the finding of such cycles is interesting, and it is more interesting that similar cycles can be recognized at both transects at all depths. It clearly indicates that the deposition of the sediments follows an oscillatory movement and is driven by sea level fluctuations and/or such as alternation of the monsoon seasons. It is realistic to indicate that the fluctuation observed are of fourth to fifth order sequences but having the possibility to use this method on longer cores will give the possibility to observe much longer cycles and therefore check for longer oscillations such as those described by Milankovitch (1948).

CONCLUSION

This study on the sediment pattern offshore Brunei Darussalam shows that Muara and Tutong transects are characterised by two different profiles possibly depending on the distance of both transects from the two major sediment sources. From the information obtained, Muara transect is much richer in mud as it is extremely closer to Brunei Bay, the supplier of the finest component to this transect.

The presence of relict sand can only be inferred for the deepest investigated depths where the mud decreases as the results of non-deposition or differential erosion. The Tutong transect is much more consistent with the classic theories of depositions where the coarser sediment is deposited at the shallowest depths and the finest toward the deepest. Further studies focusing on the geochronological calibration of the cores might enhance the timing of deposition and could solve the issue of the relict sand. The common periods of the sinusoidal functions calculated for all cores point to the evidence of long scale perturbation that will be more prominent if longer cores could be recovered. Both transects can be used as challenging analogues for river to wave dominated assemblages with very different sediment composition based on their distance from the sediment source. Sandier samples might be deeper than the muddier samples if the source of sediment is predominantly muddy. Similarly, far away from the sedimentary input the sand might decrease rapidly and having therefore at the same depth different sediment composition. The challenge to interpret the Neogene outcrops in the region is indeed a complex one because, as here demonstrated, there can be several physical parameters affecting the sedimentary composition of the seafloor and a conventional type of approach might be prove to be not accurate.

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APPENDIX A-D: Supplementary Materials

A - Example of fitting the sinusoidal function for M20 core. Compare values with the table in Appendix B below (see grey marked area).
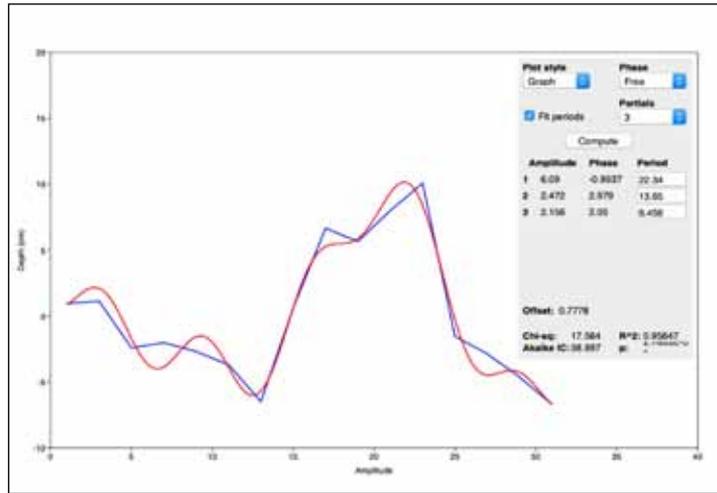
B - The obtained periods for the different cores and their combined re-occurrence in each transect and their sum. Grey marked areas are examples for the models (see figure above).

Core	Periods		Cycles Muara		
M20	22.34		Prob	Mean	Stdev
	13.65		0.478	6.3	1.5
	6.456		0.274	14.8	3.1
M30	16.92		0.126	32.1	3.9
	6.759		0.123	22.2	0.2
	36				
M40	7.791				
	5.148				
	21.98				
M50	12.01				
	6.159				
	3.797				
M60	28.22				
	18.42				
	5.951				
	9.267				

Core	Periods		Cycles Tutong		
T20	8.197		Prob	Mean	Stdev
	16.25		0.431	4.9	0.5
	11.63		0.236	9.0	2.0
	5.515		0.223	16.1	1.7
T30	31.93		0.111	30.0	2.0
	18.6				
	4.315				
	5.066				
T40	14.04				
	28				
	7.157				
	5.482				
T50	15.8				
	5.472				
	4.18				
T60	9.81				
	5.087				
	4.395				

Core	Periods		All Cycles		
ALL	22.34		Prob	Mean	Stdev
	13.65		0.446	5.6	1.1
	6.456		0.437	14.4	4.8
	16.92		0.059	34.0	2.0
	6.759		0.058	28.1	0.1
	36				
	7.791				
	5.148				
	21.98				
	12.01				
	6.159				
	3.797				
	28.22				
	18.42				
	5.951				
	9.267				
	8.197				
	16.25				
	11.63				
	5.515				
	31.93				
	18.6				
	4.315				
	5.066				
	14.04				
	28				
	7.157				
	5.482				
	15.8				
	5.472				
	4.18				
	9.81				
	5.087				
	4.395				

C - Granulometric and biogenic data from the Muara transect.

Core	Depth (cm)	Weight after Drying (g)	> 125 µm (g)	63 µm (g)	<63 µm (g)	Biogenic fraction on 125 µm (%)
Muara-20	0 – 2	11.966	0.425	0.441	11.100	84.8
	2 – 4	12.687	0.629	0.453	11.606	-
	4 – 6	15.396	0.541	0.396	14.459	-
	6 – 8	17.599	0.632	0.701	16.266	95.8
	8 – 10	18.646	0.659	0.833	17.154	-
	10 – 12	20.260	1.179	0.464	18.617	93.8
	12 – 14	23.237	1.490	0.000	21.747	-
	14 – 16	24.985	2.100	1.548	21.337	-
	16 – 18	20.304	1.572	2.844	15.888	91.9
	18 – 20	23.578	2.110	3.041	18.427	-
	20 – 22	25.313	2.339	4.065	18.909	99.1
	22 – 24	21.929	2.676	3.565	15.688	-
	24 – 26	20.225	2.108	1.524	16.593	-
	26 – 28	23.242	2.259	1.859	19.124	89.1
	28 – 30	25.463	2.386	1.958	21.119	-
	30 – 32	13.141	1.293	0.823	11.025	94.1
Muara-30	0 – 2	3.565	0.041	0.069	3.455	60.6
	2 – 4	2.572	0.061	0.043	2.469	-
	4 – 6	5.267	0.049	0.040	5.178	-
	6 – 8	5.808	0.028	0.028	5.752	77.8
	8 – 10	12.478	0.034	0.050	12.395	-
	10 – 12	9.712	0.118	0.065	9.529	88.5
	12 – 14	11.498	0.132	0.061	11.305	-
	14 – 16	11.082	0.252	0.054	10.776	-
	16 – 18	13.850	0.334	0.084	13.432	86.1
	18 – 20	13.057	0.210	0.129	12.718	-
	20 – 22	12.872	0.158	0.080	12.634	69.2
	22 – 24	9.289	0.140	0.080	9.069	-
Muara-40	0 – 2	4.790	0.145	1.416	3.229	71.7
	2 – 4	7.786	0.255	2.698	4.834	-
	4 – 6	9.682	0.253	2.468	6.961	-
	6 – 8	9.064	0.286	1.180	7.598	57.4
	8 – 10	8.704	0.600	1.504	6.600	-
	10 – 12	10.441	0.164	1.581	8.696	50.0
	12 – 14	8.977	0.191	0.601	8.185	-
	14 – 16	13.390	0.262	1.325	11.804	-
	16 – 18	11.727	0.398	0.969	10.360	37.3
	18 – 20	11.932	0.259	1.945	9.728	-
	20 – 22	12.383	0.191	0.888	11.304	85.4
	22 – 24	11.458	0.161	1.257	10.040	-
	24 – 26	10.191	0.155	1.096	8.941	-
	26 – 28	10.315	0.240	0.948	9.126	82.8
	28 – 30	12.815	0.276	1.613	10.926	-
	30 – 32	15.539	0.160	2.200	13.179	49.6
	32 – 34	14.082	0.258	1.779	12.045	-
	34 – 36	12.520	0.111	2.125	10.285	-
	36 – 38	13.282	0.163	1.396	11.723	25.6
Muara-50	0 – 2	4.000	0.028	0.568	3.404	43.8
	2 – 4	11.000	0.132	1.645	9.223	-
	4 – 6	8.309	0.079	0.760	7.470	-
	6 – 8	11.133	0.083	0.936	10.114	52.3
	8 – 10	9.956	0.117	1.168	8.671	-
	10 – 12	8.559	0.067	1.210	7.283	86.6
	12 – 14	9.903	0.140	1.453	8.310	-
	14 – 16	12.679	0.081	2.286	10.311	-
	16 – 18	9.712	0.086	1.154	8.472	72.0
	18 – 20	10.844	0.122	1.495	9.226	-
	20 – 22	12.688	0.143	1.903	10.642	56.3
	22 – 24	12.147	0.156	2.380	9.612	-
	24 – 26	12.823	0.186	1.980	10.657	-
	26 – 28	13.049	0.174	2.735	10.139	78.8
	28 – 30	11.998	0.156	1.759	10.083	-
	30 – 32	11.959	0.139	1.585	10.235	59.6
Muara-60	0 – 2	7.702	0.201	3.532	3.969	77.9
	2 – 4	12.804	0.628	5.489	6.687	-
	4 – 6	16.125	1.075	7.106	7.945	-
	6 – 8	11.368	1.407	5.264	4.697	68.9
	8 – 10	18.169	1.121	8.329	8.719	-
	10 – 12	16.461	0.778	7.302	8.381	74.3
	12 – 14	20.863	1.212	8.754	10.897	-
	14 – 16	20.031	1.086	8.197	10.748	-
	16 – 18	23.611	1.222	8.223	14.166	77.0
	18 – 20	18.793	0.440	7.510	10.843	-
	20 – 22	17.686	0.202	5.506	11.978	76.1
	22 – 24	19.644	0.500	6.620	12.524	-
	24 – 26	21.196	0.747	9.689	10.760	-
	26 – 28	18.603	0.520	6.362	11.721	70.8
	28 – 30	7.456	0.132	2.573	4.751	-

D - Granulometric and biogenic data from the Tutong transect.

Core	Depth (cm)	Weight after Drying (g)	> 250 µm (g)	125 µm (g)	63 µm (g)	<63 µm (g)	Biogenic fraction on 125 µm (%)
Tutong-20	0 – 2	22.037	2.784	4.982	9.309	4.962	10.9
	2 – 4	21.030	1.644	4.422	8.664	6.299	-
	4 – 6	22.598	1.728	4.109	8.486	8.274	-
	6 – 8	24.242	2.567	5.030	9.248	7.397	12.4
	8 – 10	27.664	3.464	5.617	10.657	7.926	-
	10 – 12	24.649	3.011	4.700	9.641	7.296	10.5
	12 – 14	30.188	3.111	5.818	11.995	9.264	-
	14 – 16	26.738	3.826	4.744	9.834	8.333	-
	16 – 18	30.000	4.339	5.933	11.994	7.736	11.7
	18 – 20	0.000	0.000	0.000	0.000	0.000	-
	20 – 22	30.177	3.103	6.081	12.198	8.795	13.3
	22 – 24	30.700	3.403	6.199	12.208	8.890	-
	24 – 26	26.659	3.049	5.265	10.367	7.978	-
	26 – 28	29.132	3.683	5.934	11.928	7.587	7.9
	28 – 30	29.129	3.692	6.612	11.831	6.994	-
	30 – 32	29.450	3.742	6.796	11.351	7.562	17.2
	32 – 34	27.797	4.729	5.623	10.381	7.064	-
	34 – 36	27.905	4.103	7.002	10.428	6.372	-
	36 – 38	49.778	4.234	8.230	14.743	22.571	19.0
Tutong-30	0 – 2	14.445	1.090	3.329	5.171	4.855	17.4
	2 – 4	12.219	0.675	2.587	4.174	4.783	-
	4 – 6	16.190	0.875	4.006	5.593	5.715	-
	6 – 8	14.752	0.732	3.089	5.093	5.839	19.9
	8 – 10	20.658	1.352	3.759	6.732	8.815	-
	10 – 12	22.464	1.491	4.830	7.451	8.692	16.5
	12 – 14	25.146	2.735	5.636	8.741	8.034	-
	14 – 16	24.466	1.822	5.130	8.223	9.292	-
	16 – 18	22.814	3.121	4.973	7.365	7.355	14.0
	18 – 20	25.565	3.160	6.071	8.005	8.329	-
	20 – 22	25.521	4.948	5.986	8.146	6.441	18.2
	22 – 24	24.878	3.533	5.631	8.320	7.393	-
	24 – 26	23.629	3.153	5.349	7.873	7.254	-
	26 – 28	23.258	3.772	4.885	7.350	7.250	23.3
	28 – 30	24.590	3.250	4.878	7.041	9.421	-
	30 – 32	25.552	4.676	5.155	7.444	8.277	19.4
	32 – 34	23.980	3.502	4.629	6.860	8.989	-
	34 – 36	24.840	3.809	5.493	7.140	8.397	-
	36 – 38	20.507	3.109	4.684	6.197	6.517	14.9
	38 – 40	24.815	3.372	5.796	7.403	8.246	-
	40 – 42	24.062	2.843	5.904	8.259	7.056	-
	42 – 44	23.799	3.560	5.702	6.985	7.552	15.8
	44 – 46	27.643	3.070	6.423	8.211	9.939	-
Tutong-40	0 – 2	13.184	0.440	0.524	4.242	7.979	90.6
	2 – 4	18.706	0.994	1.019	6.155	10.538	-
	4 – 6	23.576	0.736	1.039	7.436	14.365	-
	6 – 8	24.894	1.217	1.237	8.563	13.877	93.8
	8 – 10	24.269	2.661	1.035	7.539	13.034	-
	10 – 12	24.738	2.496	1.201	7.113	13.929	84.9
	12 – 14	22.443	2.311	0.987	6.286	12.859	-
	14 – 16	19.671	1.830	0.590	4.611	12.640	-
	16 – 18	21.776	1.488	0.765	5.445	14.077	85.7
	18 – 20	20.390	1.035	0.613	4.294	14.448	-
	20 – 22	19.150	0.427	0.602	4.345	13.777	90.6
	22 – 24	17.736	0.863	0.652	3.692	12.529	-
	24 – 26	15.955	1.438	0.773	4.202	9.542	-
	26 – 28	13.019	0.536	0.304	2.013	10.166	94.7
	28 – 30	10.091	0.331	0.175	1.229	8.355	-
Tutong-50	0 – 2	5.344	0.050	0.103	0.638	4.553	78.6
	2 – 4	6.322	0.080	0.130	0.747	5.364	-
	4 – 6	6.127	0.126	0.251	1.134	4.616	-
	6 – 8	11.979	0.233	0.308	1.290	10.149	77.3
	8 – 10	22.154	0.332	0.333	1.888	19.601	-
	10 – 12	14.133	0.292	0.201	1.323	12.317	72.0
	12 – 14	15.023	0.292	0.298	1.941	12.493	-
	14 – 16	16.854	0.516	0.454	2.423	13.461	-
	16 – 18	16.380	0.796	0.683	4.179	10.723	48.4
	18 – 20	12.091	0.595	0.412	2.119	8.966	-
	20 – 22	17.740	1.268	0.687	3.619	12.167	94.4
Tutong-60	0 – 2	3.154	0.010	0.037	0.084	3.023	38.5
	2 – 4	6.718	0.029	0.044	0.173	6.472	-
	4 – 6	8.095	0.018	0.066	0.202	7.809	-
	6 – 8	9.388	0.017	0.055	0.207	9.110	53.8
	8 – 10	10.870	0.011	0.096	0.237	10.526	-
	10 – 12	11.332	0.029	0.145	0.344	10.814	33.3
	12 – 14	10.394	0.057	0.085	0.307	9.946	-
	14 – 16	12.333	0.026	0.081	0.378	11.848	-
	16 – 18	10.714	0.048	0.101	0.399	10.167	41.2
	18 – 20	12.160	0.023	0.094	0.521	11.523	-
	20 – 22	14.056	0.117	0.145	0.578	13.216	60.0
	22 – 24	14.730	0.064	0.105	0.535	14.027	-
	24 – 26	20.863	0.058	0.163	0.599	20.044	-
	26 – 28	14.613	1.067	0.902	1.680	10.964	32.3
	28 – 30	15.922	2.323	1.599	1.773	10.227	-
	30 – 32	12.398	1.411	0.634	1.045	9.308	26.1
	32 – 34	12.900	0.895	0.728	1.243	10.034	-
	34 – 36	11.159	1.095	1.083	1.480	7.500	-
	36 – 38	9.281	0.651	0.513	0.753	7.365	20.0