Grain size analysis and total organic matter and carbonate contents of sediments on Saya de Malha and Nazareth Banks

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Abstract

The Mascarene Plateau is one of the least studied regions of the Western Indian Ocean. The aim of this paper is to describe the qualitative grain size characteristics and the total organic matter and carbonate contents of sediments on the two underwater banks known as the Saya de Malha and Nazareth Banks. Sediment samples were collected during the R/V Dr Fridtjof Nansen expedition in 2018, using a Video-Assisted Multi-Sampler (VAMS). Sieving techniques and GRADISTAT software were used for granulometric analysis and grain size statistics, respectively. Total organic matter and carbonate contents were determined with the sequential weight loss on ignition method. Grain size parameters from 15 stations (depths ranging from 37 to 381 m) are reported in this study. The results showed that sand was the dominant grain size on both banks. Eleven of the 15 stations had a mean grain size of coarse sand, three stations had a mean size of medium sand and one station had fine sand. The average total organic matter and carbonate contents on the Banks ranged from 2.1 to 7.7 % and from 53.9 to 58.3 %, respectively. This study provides baseline information that will help to classify benthic habitats and better understand the ecosystem functioning and dynamics on of the Saya de Malha and Nazareth Banks.

Keywords: grain size analysis, total organic matter, carbonate content, Saya de Malha Bank, Nazareth Bank, Western Indian Ocean

Introduction

The Saya de Malha (SDM) Bank is situated in the Western Indian Ocean on the Mascarene Plateau and covers an area of about 40, 000 km^2. It is considered as the world's largest underwater Bank and is subdivided into a northern section, the North Bank or Ritchie Bank and a southern section known as the South Bank. South of the SDM Bank lies the smaller Nazareth Bank, covering an area of about 22, 000 km^2. Due to very few *in situ* studies conducted on the SDM and Nazareth Banks, their respective geological compositions are poorly described. A core of 3264 m deep drilled on the northwest area of the South Bank in 1975 revealed that the bottommost 832 m of sediment were composed of volcanic basalts, the intermediate section was limestone and the uppermost 1249 m were reported as "reef carbonates" (Meyerhoff and Kamen-Kaye, 1981). Another core of 1716 m was drilled from the Nazareth Bank indicating shallow bank limestones overlaid the bottom volcanic basalts (Meyerhoff and Kamen-Kaye, 1981).

The remoteness of the SDM Bank makes it one of the least studied shallow tropical marine ecosystems on earth. Based on a study on the Ritchie Bank, Hilbertz *et al.* (2002) put forward that sandy areas occupy less than 5 % of the seafloor, corals cover around 10-20 %, and seagrass meadows about 80-90 % of the SDM Bank. Two earlier studies investigating the sediment composition from different areas on the Bank reported the occurrence of stone-like pebbles, coral gravels, *Acropora* spp. fragments, silt (consisting of foraminifera shells, pteropods and calcium carbonate flakes), coral sand (comprising of calcareous algae fragments (10-15 %), sponge spicules and detritus) and mollusks and globigerina shells (Fedorov and Danilov, 1979; Ingole *et al*., 1992). On the Ritchie Bank, Hilbertz *et al*. (2002) found that the sediments

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consisted primarily of rhodoliths, described as spherical layered concretions from a few centimeters to decimeters in diameter that are formed by calcareous encrusting red algae growing around a nucleus. Rhodoliths were mostly found in areas predominantly affected by strong currents that prevent the accumulation of sand or fine-grained sediments (Hilbertz *et al.*, 2002).

The SDM Bank lies directly in the path of the South Equatorial Current (SEC) which is the dominant current in the western Indian Ocean. A large portion of the SEC is forced through the deep narrow channel (1100 m deep, 8-10 km wide) separating the SDM and Nazareth Banks (New *et al.*, 2005). The SEC also feeds the SDM Bank with waters high in nutrients through mixing and upwelling, which enhances the primary productivity over the area (New *et al.*, 2005). The prevailing bottom water currents are believed to have an influence on the physical properties of sediments on the seafloor and the benthic cover assemblages (Hilbertz *et al.*, 2002).

Grain size analysis is an important tool for categorizing different sedimentary environments (Anfuso and Gracia, 2005; Folk and Ward, 1957; Shepard, 1954). Granulometric distributions provide important information on sediment origin, transport dynamics and depositional conditions (Benavente *et al.*, 2005; Bui *et al.*, 1989; Folk and Ward, 1957). Grain size analysis has been commonly employed to statistically investigate spatial changes in sediment size properties. The common techniques employed in grain size analysis include direct measurement, dry and wet sieving, sedimentation, use of particle-size analysers, such as laser granulometers and Coulter particle counters (Blott and Pye, 2001). The classical sieving method is the most used technique in the case of sand and gravel (Blatt *et al.*, 1972).

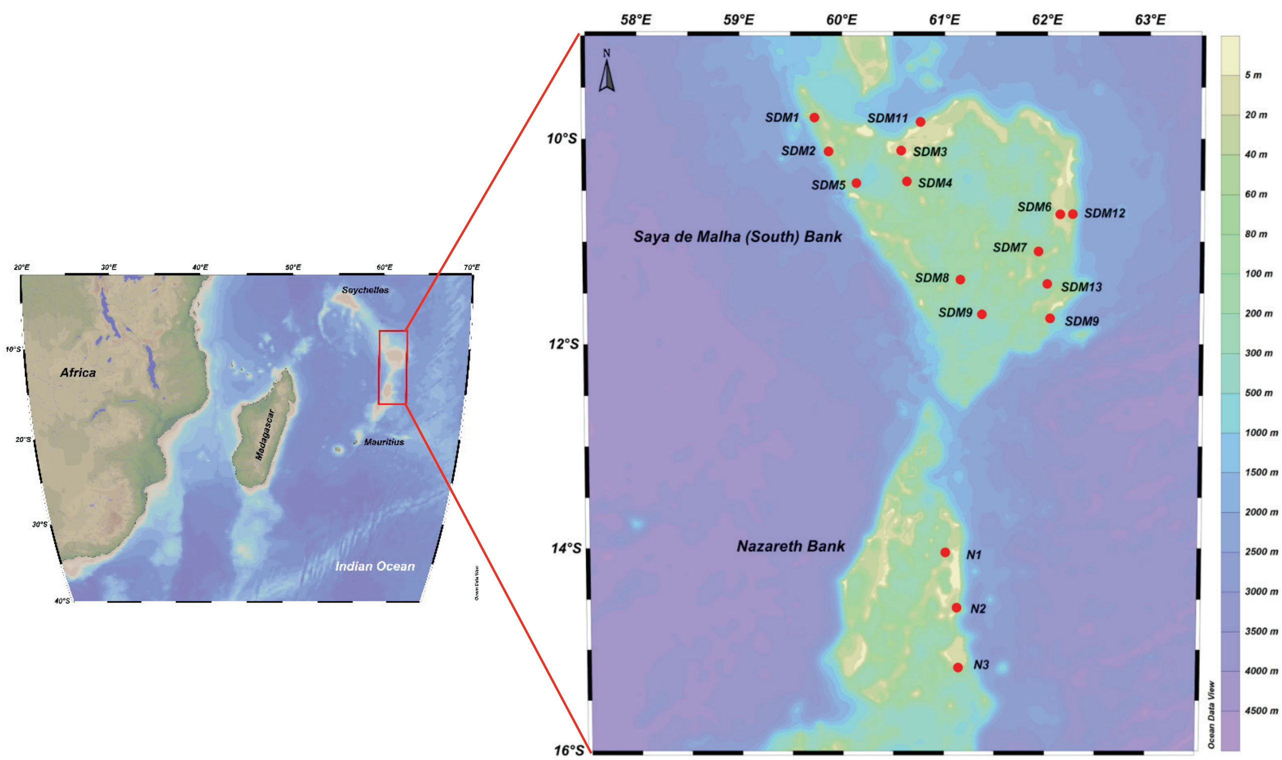

Figure 1. Sampling locations on Saya de Malha (South) and Nazareth Banks.

Sediment is also the major site for organic matter which is decomposed mainly by bacteria and thus mixing nutrients with overlying waters. The origin of organic matter content of sediments in the open ocean is mainly derived from the settling of biogenic material which originates from marine primary production. The quantity and nature of organic matter deposited in marine sediments are closely linked to the environmental conditions of deposition (Trask, 1955). The wet oxidation, sequential weight loss on ignition (WLOI) and gas chromatographic analysis are a few of the techniques employed to estimate organic carbon in sediments (Byers *et al.*, 1978). The sequential WLOI is a simple, cost-effective, commonly used method to determine the organic matter and carbonate content of sediments (Bengtsson and Enell, 1986; Dean, 1974; Heiri *et al.*, 2001; Wang *et al.*, 2011).

There are a very few publications (Fedorov and Danilov, 1979) that briefly described the sediment characteristics and composition on the SDM Bank. However, no investigations on the sediment grain-size distribution and organic matter and carbonate contents have been undertaken so far. This study aimed at qualitatively describing the sediment grain size characteristics on the SDM and the eastern part of the Nazareth Banks. Furthermore, the total organic matter (% TOM) and the carbonate content (% CC) of sediments were determined. This granulometric data could shed further light on the prevailing water current conditions and help better understand the ecosystem dynamics on the world's largest underwater bank.

Materials and methods

The present study is based on sediment samples collected by the Research Vessel Dr Fridjof Nansen from the 3rd May 2018 to the 3rd June 2018, with the scientific expedition entitled 'Leg 2.1: Characterizing ecosystems and morphology of the Saya de Malha and Nazareth Banks'. Sediment samples were collected on 16 selected stations at depths ranging from 37 to 381 m based on the pre-planned cruise track on the banks (Fig.1; Table 1). Due to insufficient amount of sediment collected at station N2, granulometric analysis was not undertaken and only the % TOM and % CC were measured.

Sediment samples were collected from different depths during the cruise using the five hydraulic-operated Van Veen grabs mounted on a Video Assisted Multi Sampler (VAMS) system. Depending on the amount of sediment sampled by the grabs, at least two sediment samples were collected per station and kept frozen until granulometric analysis and TOM and CC examination. Coral rubbles and rhodoliths greater than 5 cm in length, collected commonly from the shallow stations, were discarded as most of them were fouled by encrusting algae and were still being used by seagrasses and macroalgae as a medium to attach their roots (Fig. 7).

For the granulometric analysis, the sediment samples from 15 stations were washed, dried and sieved for 10 min (Román-Sierra *et al.*, 2013) through a sieve-shaker consisting of six different sieve mesh sizes of 2000,

Table 1. Sampling depths and coordinates of the 16 stations on the SDM and Nazareth Banks.

Station name	Sampling depth (m)	Coordinates	
		Latitude	Longitude
Saya de Malha Bank			
SDM1	132	-9.7917	59. 7317
SDM2	74	-10.1197	59.8680
SDM3	30	-10.1132	60.5752
SDM4	62	-10.4122	60.6322
SDM5	55	-10.4270	60.1397
SDM6	28	-10.7318	62.1298
SDM7	55	-11.0923	61.9195
SDM8	160	-11.3660	61.1555
SDM9	288	-11.7442	62.0352
SDM10	251	-11.7058	61.3673
SDM11	37	-9.8340	60.7648
SDM12	73	-10.7302	62.2540
SDM13	381	-11.4088	62.0077
Nazareth Bank			
N1	38	-14.0378	61.0128
N2*	58	-14.5803	61.1260
N3	133	-15.1732	61.1422

**Note: Due to limited availability of sediment, grain size analysis has not been carried out for station N2. Only TOM/CC results are available.*

1000, 500, 250, 125 and 63 µm. The weight of the sediment retained in each sieve was noted and the material passing through the 63 µm sieve was retained in the pan and recorded as silt. Grain size distributions were processed through the GRADISTAT Version 9.1 software package (Blott and Pye, 2001) to obtain grain size classifications according to Wentworth (1922) and grain size statistics [Median grain size (d_{50}), Mean grain size (Mz), Standard deviation (σI), Skewness (SK) and Kurtosis (KG)] according to Folk and Ward (1957). The grain-size parameters were expressed in terms of phi (ϕ) units with the formula: $\phi = -\log_2 d$, where d is the grain diameter in millimeters.

The median grain size (d_{50}) is the midpoint value of the sediment distribution, which means that half of the mass of the sediment grains are smaller than this value and the other half is higher. The mean grain size (Mz) refers to the average grain size of the sediment distribution and provides an indication of the dominant grain character. The mean size can also be employed to differentiate between areas influenced by high and low current velocities (Nordstrom, 1977). The standard deviation (σI) describes the variation of the grain sizes in sediment sample and the inclusive graphic standard deviation is used to evaluate the sorting of sediments (Folk and Ward, 1957). Skewness (SK) provides an indication of the symmetry of the grain size distribution. Skewness indicates the level of mixing of the different fractions within a sample and can also describe the energy conditions in a depositional area. The inclusive graphic skewness values are used to classify the sediment distribution (Folk and Ward, 1957). A symmetrical distribution has a skewness value of 0.00. A positively skewed curve has a fine-particle 'tail' whereas a negatively skewed curve has a coarse-particle 'tail'. Kurtosis (KG) measures the 'peakedness' in the grain size distribution curve and evaluates the ratio between sorting in the tail of the distribution and that in the central portion. A normal distribution with a kurtosis of 1.00 will have the sorting in the tails equal to the sorting in the central part. A curve is leptokurtic (excessively peaked) when better sorting is observed in the central part compared to the tails. If a curve shows better sorting in the tails than in the central part, then it is platykurtic (flat peaked). Kurtosis ranges from very platykurtic to leptokurtic with values from 0.51 to 1.30. The average value is 0.83 which indicates platykurtic conditions.

For the sequential WLOI method, sediment subsamples (5-10 g) were placed in crucibles and the weights were recorded. The weight loss was measured after oven-drying the sediment samples overnight at 105 °C and burned in a furnace at 550 °C for 4 h to oxidize organic matter to carbon dioxide and ash and then at 1000 °C for 2 hours to remove the carbonates, leaving oxide (Dean, 1974; Heiri *et al.*, 2001). The percentage of total organic matter (% TOM) and carbonate content (% CC) were estimated by loss on ignition (LOI) at 550 and 1000 °C using the following equations (weights are in grams) adapted from Dean (1974) and Heiri *et al*. (2001):

LOI_{550} = [pre-ignition weight (105 °C) - post-ignition weight (550 °C)] / pre-ignition weight (105 °C) * 100

LOI_{1000} = [post-ignition weight (550 °C) - weight after 1000 °C burn out] / pre-ignition weight (105 °C) * 100

The % TOM is equivalent to the % LOI_{550} and is twice the organic carbon content (Dean, 1974). The amount of carbonate content (% CC) in a sample is calculated as 1.36 x LOI_{1000}, with the assumption that ignition follows a stoichiometric relationship and the percentage total inorganic carbon (% TIC) is determined as 0.273 x LOI_{1000} (Dean, 1974; Heiri *et al.*, 2001).

Results and discussion

Granulometric analysis

The descriptive statistics of the different grain size parameters are represented in Table 2. The average sediment composition for each location is illustrated in Figure 2. Sand was found to be the dominant grain size representing an average of 98.12 % for the 15 locations on the two underwater Banks. Based on videos captured by the VAMS system and from sediment samples brought on board with the grabs (Bergstad *et al.*, 2018) and descriptions from previous studies (Hilbertz *et al.*, 2002), it was observed that the shallow banks provide habitats to a plethora of carbonate producers namely hermatypic corals such as *Porites* and *Acropora* spp., *Halimeda* spp., molluscs, large benthic foraminifera and sponges amongst others. Post-mortem, these organisms release their carbonate structures into the surrounding sediments which are broken down to smaller fragments and almost fully constitute the sand fraction in the range of -1 to 4 ϕ.

Bivariate relationships between grain size parameters

Bivariate plots provide important information that helps to differentiate between different depositional settings. This technique has been commonly

Table 2. Descriptive statistics of grain size parameters from 13 stations from SDM Bank and 2 stations from Nazareth Bank.

Station name	Mean size (Mz)	Mean Sand type	Standard deviation (σI)	Sorting type	Skewness (SK)	Skewness type	Kurtosis (KG)	Kurtosis type
Saya de Malha Bank								
SDM1	0.469±0.09	CS	1.00±0.02	PS	0.129±0.05	FS	0.977±0.08	MK
SDM2	1.62±0.15	MS	1.27±0.05	PS	-0.100±0.07	S	0.980±0.03	MK
SDM3	0.876±0.02	CS	1.35±0.03	PS	0.091±0.06	S	0.510±0.03	VP
SDM4	0.796±0.10	CS	1.14±0.02	PS	0.05±0.04	S	0.862±0.10	P
SDM5	0.322±0.14	CS	1.07±0.13	PS	0.370±0.21	VFS	0.605±0.01	VP
SDM6	0.993±0.01	CS	1.31±0.05	PS	-0.150±0.05	CS	0.550±0.12	VP
SDM7	0.165±0.34	CS	0.833±0.02	MS	0.244±0.13	FS	0.555±0.23	VP
SDM8	0.580±0.03	CS	1.02±0.02	PS	0.550±0.02	VFS	0.555±0.01	VP
SDM9	1.45±0.03	MS	0.885±0.04	MS	-0.012±0.02	S	1.16±0.05	L
SDM10	0.864±0.04	CS	0.986±0.01	MS	0.03±0.01	S	0.975±0.05	MK
SDM11	0.200±0.01	CS	1.13±0.02	PS	1.53±0.01	VFS	1.13±0.02	L
SDM12	1.50±0.21	MS	1.59±0.08	PS	-0.01±0.01	S	0.785±0.10	P
SDM13	2.13±0.02	FS	1.43±0.02	PS	-0.286±0.03	CS	1.30±0.01	L
Nazareth Bank								
N1	0.124±0.13	CS	0.870±0.11	MS	1.29±0.32	VFS	0.882±0.13	P
N3	0.888±0.24	CS	1.49±0.17	PS	0.349±0.02	VFS	0.622±0.05	VP

Mean sand type: CS= Coarse Sand, MS= Medium Sand, FS= Fine Sand. Sorting type: PS= Poorly Sorted, MS= Moderately sorted. Skewness type: FS= Fine Skewed, S= Symmetrical, VFS= Very Fine Skewed, CS=Coarse Skewed, FS= Fine Skewed. Kurtosis type: MK= Mesokurtic, VP= Very Platykurtic, P= Platykurtic, L= Leptokurtic.

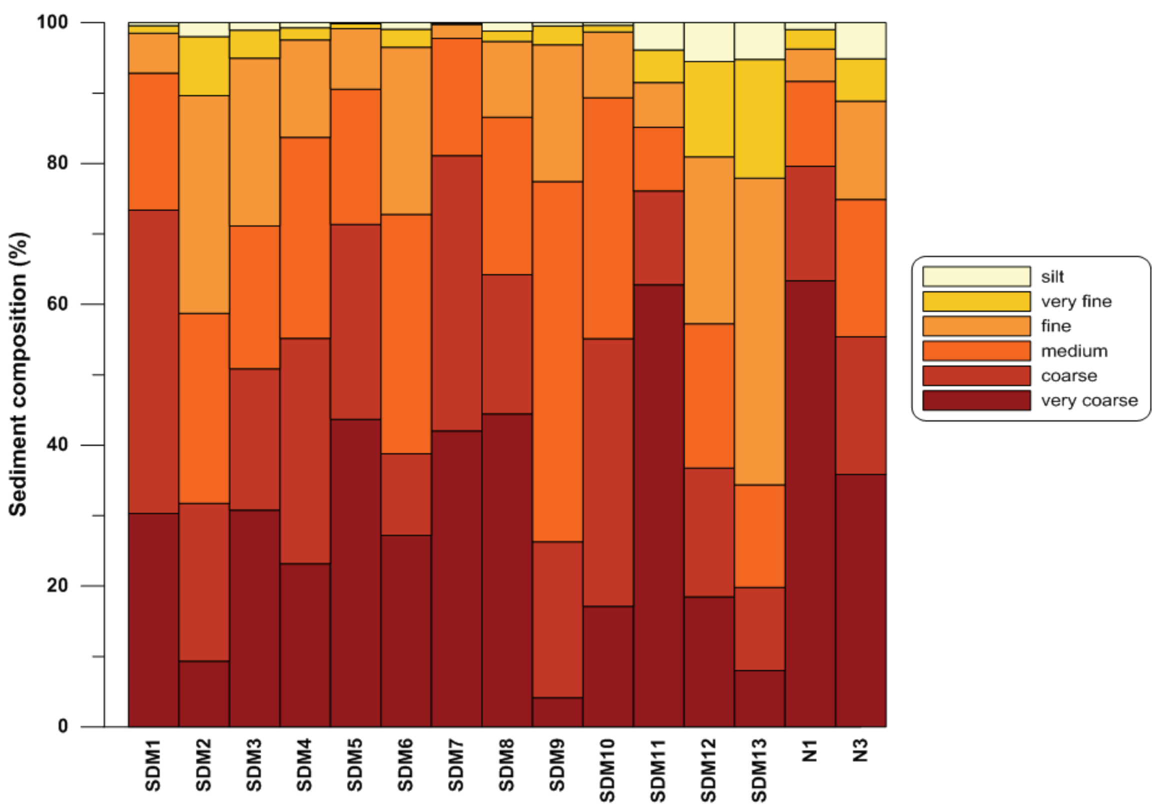

Figure 2. Percentage sediment composition of different grain sizes for 13 locations on SDM Bank and two locations on Nazareth Bank.

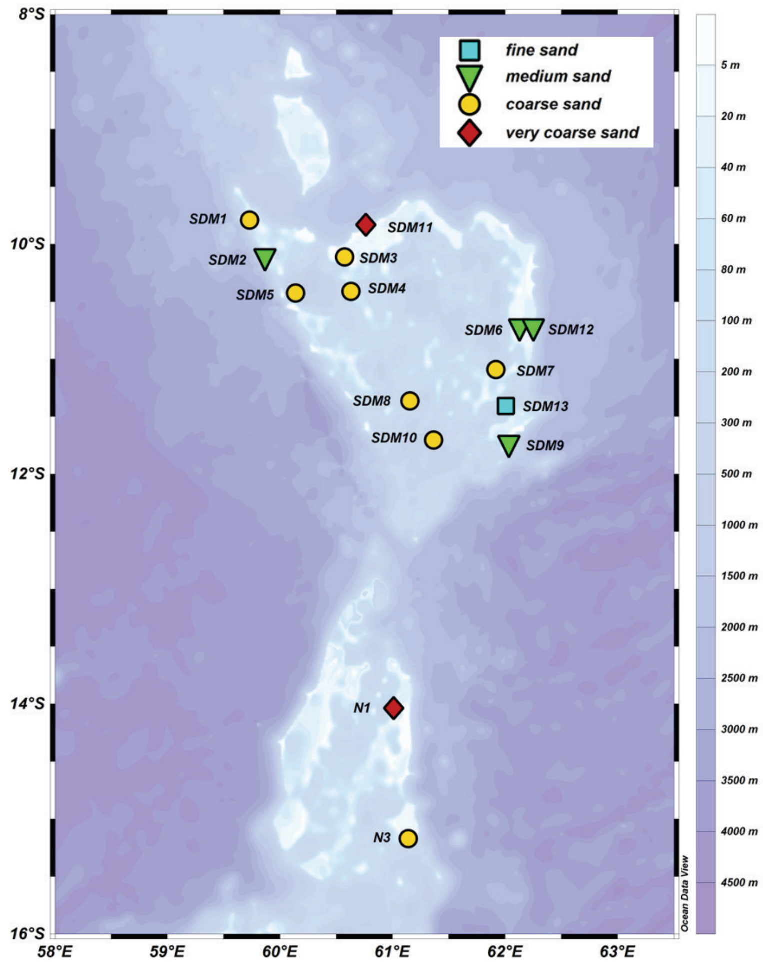

Figure 3. Median (d_{50}) values of sediment at different sampling locations.

employed to determine differences among beach sediment samples to elucidate transportation and deposition mechanisms and determine the governing energy conditions in these environments (Azidane *et al.*, 2020; Nordstrom, 1977; Rajganapathi *et al.*, 2013). To better understand the depositional environments prevailing at the different stations on the submerged banks, bivariate plots of mean versus standard deviation, mean versus skewness and mean versus kurtosis were computed.

Median grain size (d_{50})

The median size values of sediment samples from 13 locations on SDM Bank and 2 locations on Nazareth Bank are illustrated in Figure 3. The median size results revealed that 8 out of 15 stations had coarse grain-size and were mostly located in the inner and outer areas of the Banks. Medium grain-size sediment was found at four stations on the outer edge of the Saya de Malha Bank. The two shallowest stations (< 40 m) on the Banks had very coarse sediment grain-size. The deepest station of 381 m was located at the bottom of the 'Nansen sinkhole' (further described hereunder) on the Saya de Malha Bank and was characterized as fine grain-size sediment. A low positive relationship (y=64.142x+70.756, R^2 = 0.2749) was noted between median grain size and depth, where median sizes (ϕ) seemed to increase (towards finer grain size) with increasing depths. A Spearman's rank correlation coefficient demonstrated that the correlation was however, not significant (r' = 0.40, n = 15, α=0.05 and p > 0.05).

Mean grain size (Mz)

Eleven of the 15 stations had a mean size of coarse sand (0 -1 ϕ), three stations had medium sand (1 -2 ϕ) and one station (SDM13) had fine sand (2 -3 ϕ) (Table 2). The percentage composition of coarse sand varied from 11.5 to 43.1 % for the 11 stations with an average mean value of 0.57 ϕ. Medium sand ranged from 20.5 to 51.2 % for the three stations with an average mean value of 1.52 ϕ. The percentage composition of fine sand at SDM13 was 43.6 % with a mean size of 2.13 ϕ. It is suggested that the predominance of mean size in the coarse sand category may be due to the influence

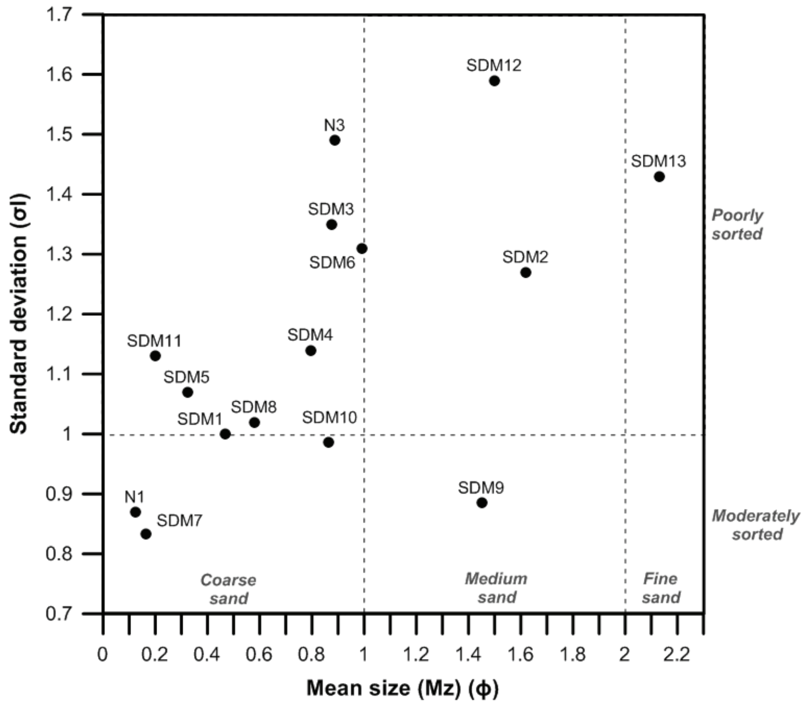

Figure 4. Bivariate relationship between mean size (Mz) and standard deviation (σI).

of the westward currents over the Banks that winnow away the smaller grain sizes, leaving behind higher proportions of coarser grains. At a depth of 50 m, a general strong westward current of 25 cm/s flows on the eastern side of the Banks, which then increases to 50 cm/s between the gap between the SDM and Nazareth Banks and which emerges again as a broad current with a speed of 30 cm/s (New *et al.*, 2005). Preliminary results from this cruise indicated the occurrence of westward currents of 10 and 30 cm/s on the Bank along latitude 10.5 °S and on the eastern slope along latitude of 11.5 °S, respectively (Bergstad *et al.*, 2018). The sudden changes in topography along the outer slopes and over the banks lead to changes in the zonal and meridional current velocities which further generated strong vertical shear over the top of the eastern slope (Bergstad *et al.*, 2018). The westward current of 10 cm/s measured over the bank along latitude 10.5 °S might be strong enough to cause erosion and movement of fine bottom sediments and possibly leaving behind the coarser fractions. This could explain why 11 of the 15 stations on the Banks had mean grain sizes in the coarse sand category.

Standard deviation (σI)

The values of the sediments varied between 0.83 and 1.59 ϕ (moderately sorted to poorly sorted) for the 15 stations. The average value is 1.16 ϕ which indicated poorly sorted grains. Eleven of the 15 stations had poorly sorted grains, while the remaining four stations exhibited moderately sorted grains (Table 2). The scatter graph of mean size versus standard deviation indicated that the sediment samples were mainly clustered in coarse sand size within the poorly sorted category (Fig. 4). Both mean size and standard deviation were influenced by hydrological conditions and the best-sorted sediments usually had the mean size of fine sand (Griffiths, 1967). None of the sediment samples in this study was in the 'very well sorted' range. The poorly sorted values observed at the majority of the stations may suggest the influence of high current velocities that could be constantly changing the sediment compositions with varying degrees of sediment influx to these sites over time. The predominance of mean size as coarse sand at eight stations exhibiting poorly sorted values could further indicate that high sorting values might be linked to occurrence of large grain sizes in the samples.

Skewness (SK)

Skewness values varied between -0.286 and 1.53 (coarsely skewed to very fine skewed), with an average value of 0.271 (fine skewed). Six stations with coarse sand as mean size showed symmetrical distribution, which indicates that coarse and fine sediments are distributed more or less equally. Five and two stations were very fine skewed and fine skewed, respectively. Only two stations were coarsely skewed (Table 2). Figure 5 illustrates the correlation between mean size and skewness. Most of the stations are clustered

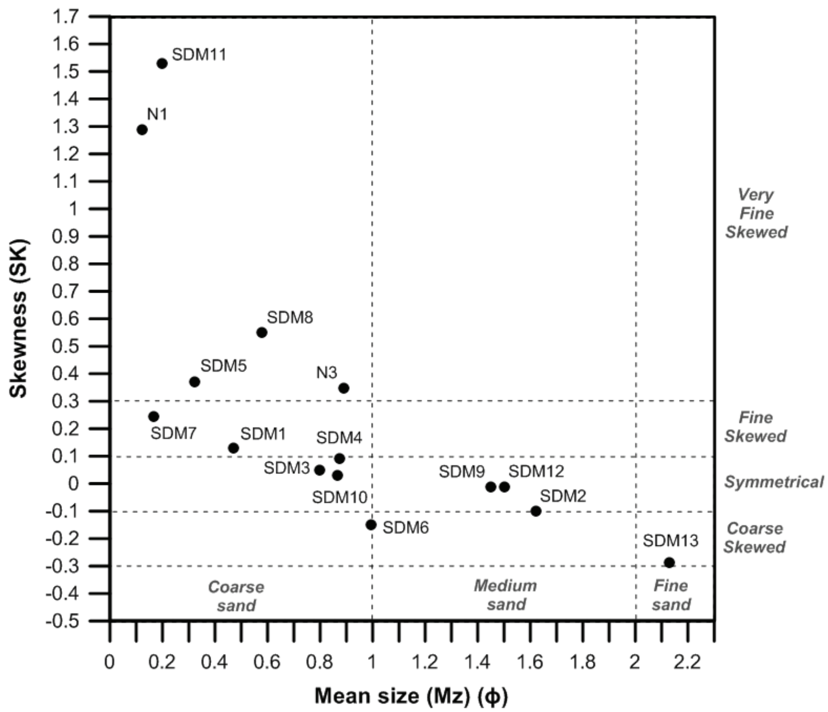

Figure 5. Bivariate relationship between mean size (Mz) and skewness (SK).

in the symmetrical to very fine skewed range. Only stations SDM13 and SDM6 with mean sizes in the fine and coarse sand categories respectively were coarsely skewed. An area affected by low current velocities is usually characterized with fine sediment grains which are poorly sorted and showed positive skewness. In contrast, an area influenced by high current velocities will have coarse sediment grains with good sorting and show either positive or negative skewness (Kim *et al.*, 2018). All the seven sites showing very fine to fine skewness (positively skewed) had mean size in the coarse sand category which indicate that they could be located in areas affected by strong currents.

Kurtosis (KG)

Six of the 15 stations were clustered in the very platykurtic category with mean size as coarse sand. Three stations exhibited platykurtic distribution, three stations showed sediment samples with mesokurtic distribution and three others indicated leptokurtic conditions (Fig. 6). Extreme values of kurtosis (leptokurtic to very leptokurtic) were usually observed when sediments are sorted in low or high energy environments (Folk and Ward, 1957). Two of the three stations exhibiting leptokurtic sediments are SDM11 (mean size=coarse sand, poorly sorted, depth=37 m) and SDM13 (mean size=fine sand, poorly sorted, depth=381 m). These results suggest that SDM11 might be influenced by high current velocities at shallower depth whereas SDM13 is located in a low energy environment. Platykurtic distribution usually occurs when a sediment distribution is poorly sorted and the three stations with platykurtic sediments were found to be moderately to poorly sorted. Skewness and Kurtosis values provide important clues of how closely a grain-size distribution fits a normal Gaussian probability curve. Pronounced skewness and kurtosis occur when the sediment distribution consists of different grain sizes, as observed for some sediment samples in this study.

Contribution of *Halimeda* spp. to sediments on the Banks

Sites SDM11 and N1 were comprised predominantly of very coarse sand (-1 to 0 ϕ) with compositions of 62.7 % and 63.3 %, respectively. Sites SDM11 and N1 were relatively shallow (< 40 m) and their sediment compositions consisted mostly of plates of the calcifying green macroalgae *Halimeda* spp. Video images from the VAMS indicated that *Halimeda* spp. plants thrived in high densities at these shallow depths. The plants consisted of several leaf-like calcareous segments and once dead, these calcified segments were shed into the surrounding sediments as individual plates. These calcified plates initially formed part of coarse sand to gravel size fractions and then with time disintegrated into mud-grade carbonate sediment as needles and nanograins (Ford and Kench, 2012; Neumann and Land, 1975). The contribution of

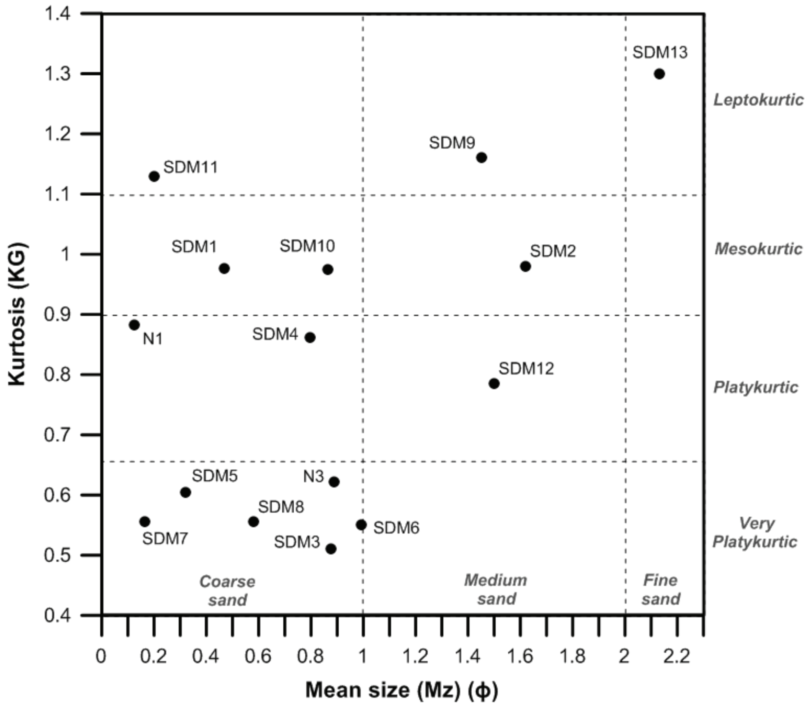

Figure 6. Bivariate relationship between mean size (Mz) and kurtosis (KG).

Halimeda spp. to the various sediment size fractions is considerably important in tropical shallow reef systems (Hewins and Perry, 2006) and further provides substrates and habitats (Jinendradasa and Ekaratne, 2002) for other reef communities. Rhodoliths were also observed on both Banks and were more abundant in areas influenced by strong currents, which prevented the accumulation of finer grain-size sediments. This general observation was also reported on the Ritchie Bank by Hilbertz *et al.* (2002), but the abundance or percentage composition of rhodoliths for the sampling stations on the SDM and Nazareth Banks were not assessed in this present study. At site N1 on the Nazareth Bank, rhodoliths were observed to occur in association with calcified plates of *Halimeda* spp. and coral rubbles (Fig. 7). Altogether, they provide substrate for seagrasses and other macroalgae to anchor their roots to the seafloor.

Figure 7. Intact grab sample for station N1.

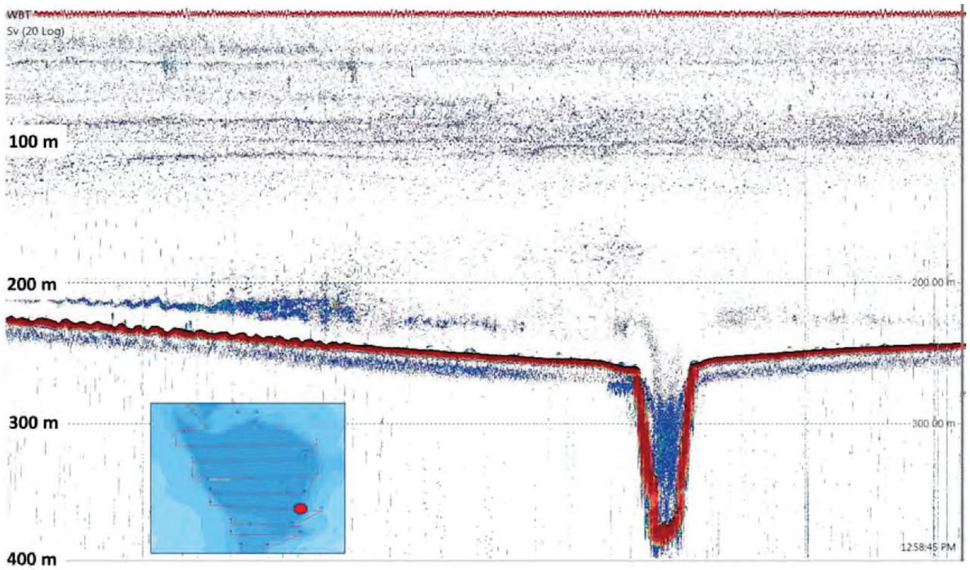

Figure 8. Station SDM13 known as the "Nansen Sinkhole". Depth profile from EK 80, 38 KHz. Picture taken from cruise report (Bergstad *et al.*, 2018).

Dominance of fine sediment at the bottom of 'Nansen Sinkhole'

Contrary to the shallow sites SDM11 and N1 where 62.7-63.3 % of the sediment composition fell in the very coarse range, the sediment collected from the deepest station SDM13 (381 m) was composed predominantly of finer grain size where 60.4 % of sediment was found in the range of fine to very fine sand (-3 to -1 ϕ). This station was provisionally called as the "Nansen Sinkhole" and was a prominent hole with a conical shape with more or less vertical walls on the sides (Bergstad *et al.,* 2018). The opening of the hole started at 260 m deep and the bottom depth reached approximately 385 m deep, which gave the cone a depth of 125 m (Fig. 8). The sediment accumulated at the bottom comprised of 43.5 % fine sand, 16.9 % very fine sand, 5.2 % silt, 14.5 % medium sand, 11.8 % coarse sand and 8.0 % very coarse sand. Little coral debris was observed at the bottom which was presumed to have fallen from the top edges of the hole and it was suggested that this debris be categorized as coarse to very coarse sand. The higher proportion of finer grain size accumulating at the bottom of the 'Nansen Sinkhole' can be explained by fine sediments in suspension and biogenic materials that have slowly settled to the bottom with time. The influence of currents was less pronounced inside the hole of 125 m deep, which could allow the settling and accumulation of fine sediments on the bottom.

Total organic matter and carbonate contents

The TOM of sediment samples on the SDM and Nazareth Banks varied from 2.09±0.40 to 7.70±0.03 %. The lowest TOM value of 2.09±0.40 % was reported at SDM9 at a depth of 288 m. The highest TOM values of 7.59±0.18 and 7.70±0.18 % were found at SDM7 and N2, respectively, at corresponding depths of 55 and 58 m (Fig. 9). A TOM of 3.17 % was recorded on the Kenyan shelf at a depth of 78 m (Mohamed *et al.*, 2018) and similar values in the range of 2.6±0.64-8.1±7.01 % were found in Mida Creek in Kenya (Wafula *et al*., 2020). The TOM measured on the SDM and Nazareth Banks are therefore in the same range as TOC values from coastal waters bordering land areas. A low negative relationship (y=-30.358x+237.54, R^2 = 0.201) existed between TOM and depth, where TOM values seemed to increase with decreasing depths. A significant Spearman's rank correlation was observed between TOM contents and depth (r' = 0.40, n = 16, α=0.05 and p < 0.05). This can further be explained by the fact that shallower areas have higher primary production compared to deeper zones. Remineralization of organic matter occurs in the water column as it sinks and this process can also explain the occurrence of low TOC values in the deeper zones.

The relationship between TOM and grain size was described to be positively correlated with the fine grain size category in comparison with coarser grain sizes (Mohamed *et al.*, 2018; Secrieru and Oaie, 2009). However, it was observed that SDM13 with mean size as fine sand had a low TOM value of 3.18±0.04 % and SDM7 with a mean size in the coarse sand range having a relatively high TOM value of 7.59±0.18 %. With the exception of SDM7, all sediment samples in the coarse sand range were clustered between TOM values of 2.67±0.04 and 4.82±0.40 %.

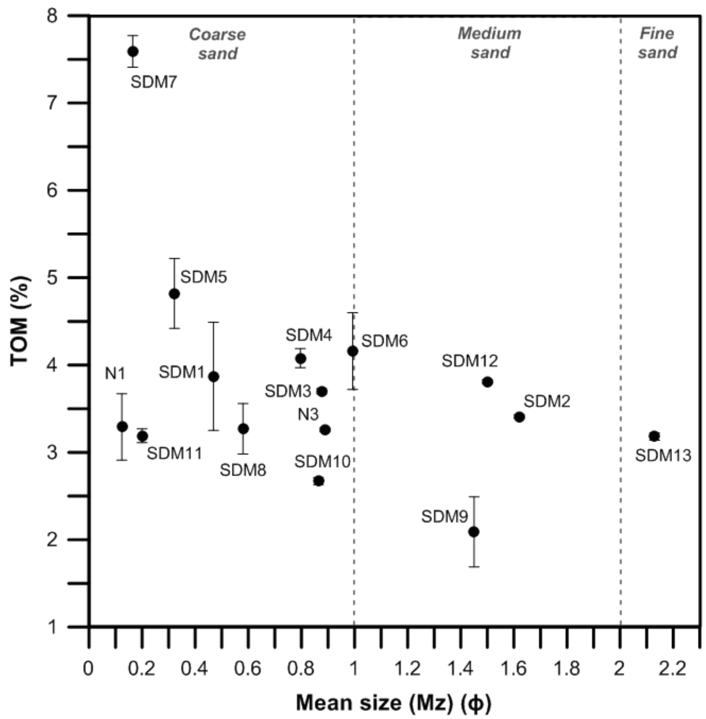

Figure 9. Scatter plot of mean size (Mz) versus Total Organic Matter (TOM (%)). Note: N2 is not shown in plot.

The high TOM content reported from SDM7 could be due to the presence of calcareous biogenic materials that can additionally contain organic carbon which could be released slowly into the nearby sediment. However, Krumgalz (1989) reported high concentrations of organic matter content in the medium and coarse sediment categories (> 2 ϕ) that have been formed from clusters of the smaller particles. This phenomenon can also potentially explain the anomalously high concentrations of TOC in the

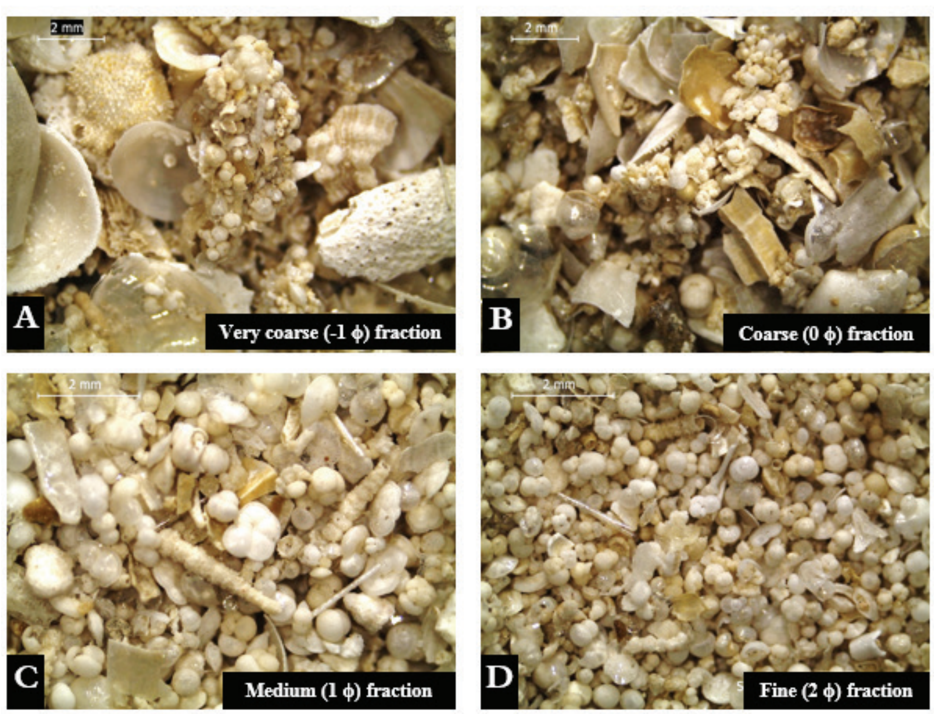

Figure 10. Micrographs of sediment fractions from SDM10. (A) very coarse (-1 ϕ), (B) coarse (0 ϕ), (C) medium (1 ϕ), and (D) fine (2 ϕ) fractions. Agglomerates are observed in (A) and (B).

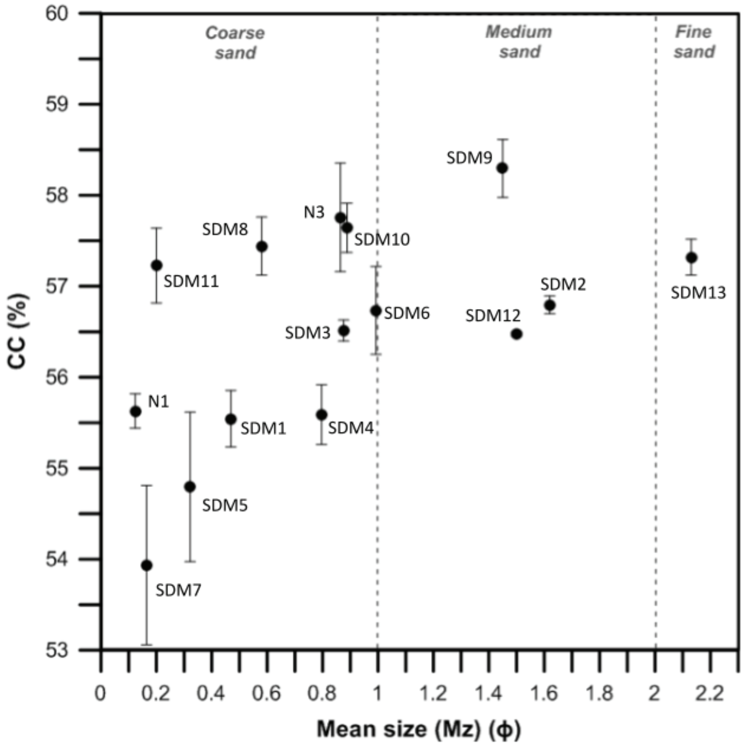

Figure 11. Scatter plot of mean size (Mz) versus Carbonate Content (CC (%))

coarser sand fractions on the Banks. The large agglomerates could be formed during the drying procedures without any prewashing step of the sediments. Therefore, during drying of unwashed sediment samples, sea salts or dissolved organic matter from calcareous biogenic materials present in the sediments cement the small sediment particles together to form these agglomerates and might affect the TOM measurements. It is suspected that the high TOM in the coarse sand category could be due to the presence of these agglomerates as confirmed by micrographs (Fig. 10) in the very coarse to coarse fractions (-1 to 0 ϕ) of sediment samples from SDM10, which had a relatively low TOM of 2.67 %. If such agglomerates were observed in a sediment sample with mean size of coarse sand with relatively low TOM, it is suggested that more such agglomerates should be present in SDM7 sample, which had a higher TOM value. The findings showed that standard mechanical sieving might be insufficient to break apart the agglomerates that had been developed. When designing standard methods for sediment analysis, the risk of large agglomerates forming from smaller particles should be taken into consideration.

Figure 11 illustrates the % CC in the sediment samples. CC values vary from 53.9 ±0.88 to 58.3 ±0.32 %. From the micrographs in Figure 10, it was observed that the sediments consisted mainly of remains of carbonate producers such as bivalve shells, coral rubble and foraminifera shells amongst others, which explain the moderate CC results. SDM9 with a mean size of medium sand had the highest CC with a value of 58.3±0.32 %. Siesser and Rogers (1971) reported that carbonate contents from 36 marine sediment samples varied from 40.2 to 98.0 % when employing a weight-loss method. This method however provides a rough approximation of the true carbonate value in marine sediments, but is widely employed due to its simplicity and cost-effectiveness (Siesser and Rogers, 1971).

Conclusion

This study has provided new information on the physical characteristics of sediments and their TOM and CC on the SDM and Nazareth Banks. It was revealed that sand was the dominant grain size with an average composition of 98.12 %. The majority of the stations (11 out of 15) had a mean grain size of coarse sand, three stations had medium sand range and only one station had fine sand.

The average TOM and CC on the Banks ranged from 2.1 to 7.7 % and from 53.9 to 58.3 %, respectively. The TOM estimated from sediments on the Banks falls in the same range of values as reported from the coastal waters of Kenya (Mohamed *et al.*, 2018; Wafula *et al.*, 2020). However, it is suspected that high TOM values > 7 % in the coarse sand range might be due to the formation of agglomerates during the drying procedures of sediments without any prewashing step.

Sediment grain size characteristics were found to be mostly influenced by the prevailing bottom water currents and possibly by the type of nearby living carbonate producers, which then integrate into the sediment composition. Rate of sand production seemed therefore to be high at shallow depths where the calcareous macroalgae *Halimeda* spp grows in high abundance. These newly generated data on the physical characteristics of sediments will provide baseline information that will help to classify benthic habitats in the different sedimentary environments and help to better understand the ecosystem functioning and dynamics on these two major underwater banks.

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