Western Indian Ocean J. Mar. Sci. Vol. 1, No. 2, pp. 107–116, 2002

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Biogenic Assemblage and Hydrodynamic Settings of the Tidally Dominated Reef Platform Sediments of the Zanzibar Channel

Yohanna W. Shaghude[1], Kjell O. Wannäs[2] and Shigalla B. Mahongo[3]
[1]*Institute of Marine Sciences, University of Dar es Salaam, P.O. Box 668, Zanzibar, Tanzania;*
[2]*Department of Geology and Geochemistry, Stockholm University, S-106 91 Stockholm, Sweden;*
[3]*Tanzania Fisheries Research Institute, P.O. Box 9750, Dar es Salaam, Tanzania*

Key words: biogenic assemblage, hydrodynamics, carbonate sediments, reef platforms, Zanzibar channel, flood currents, ebb currents

***Abstract*—**The biogenic assemblage and hydrodynamic settings of the tidally dominated reef platform sediments (TDRPS) east of the Zanzibar channel were investigated in order to characterise the carbonate sediments. Benthic foraminifera were found to be the most important group, both in terms of average abundance (> 60 % by weight) and also in terms of spatial distribution, with common occurrence in all sediments samples. Pelecypods, with an average abundance of 8 % were slightly less widely distributed. The remaining groups occurred at lower average abundance and less frequently in the sediments. Current measurements indicated that the maximum current speed is higher during spring than during neap tides. The direction is phase-dependent with flood tidal current flowing from the northern and southern tips of the island towards Zanzibar town. The ebb current flows in the opposite direction. The geomorphological setting of the carbonate platforms together with the present investigation of the currents and biogenic assemblage of the clastic sediments permits us to subdivide the reef platform area in the Zanzibar Channel into two sub-provinces: the northern and the southern. The northern sub-province contains significantly higher proportion of lithogenic particles, pelecypods, gastropod and ostracods than the southern sub-province. Some samples from the southern sub-province had significantly higher proportion of corals, than those from northern sub-province.

INTRODUCTION

Tides, waves, currents and occasional storms are all of major importance to the compositional abundance of various biogenic groups in shallow water carbonate depositional systems (Boothroyd, 1985; Jones & Hunter, 1992; Scoffin, 1993; Li et al., 1997; 1998). Shallow water carbonate sediments are mainly produced by two major groups of living organisms. First, the autotrophic primary producers, which can utilise light energy from the sun to make organic carbon. These include organisms such as the coralline algae, the aragonitic algae (*Halimeda* spp.) and many others. Second, the non-autotrophic benthic organisms, which use manufactured organic carbon for their survival. These include both the sessile and sedentary organisms. The sessile organisms include molluscs, foraminifera, echinoderms, sponges and ostracods. Reef building corals and bryozoans are among the well known sedentary organisms.

Different carbonate-producing organisms flourish well if specific oceanographic conditions are satisfied. Corals, for instance, thrive in shallow water characterised by high agitative environments, where there is minimum siltation

Corresponding author: YWS.
E-mail: shaghude@zims.udsm.ac.tz

of fine sediments (Muhando, 1997; Wagner, 1999). On the contrary, *Halimeda* spp., composed of perforated segments which disintegrate into fine particles after death (Harney et al., 2000), are often associated with lagoonal environments where energy is low. Thus, since most shallow-water carbonate sediments are of intrabasinal origin (Swinchart, 1965), the oceanographic conditions directly influence the biogenic assemblage of the bioclasts.

The compositional assemblage of sediments in shallow water carbonate depositional basins is rarely composed of 100 % bioclasts. This is because most of these basins occur near continental land masses where terrigenous materials may be introduced into the basins. On land, the terrigenous material (lithoclasts) is transported mainly by rivers, wind or glaciers. When it enters the coastal ocean, the material is subject to the influence of currents, waves and winds, which mix them with the bioclastic sediments. Grain size and proportion of the lithoclasts deposited in a particular location depend upon various factors, including the distance from the source, the energy of the depositing medium and the general current pattern. Thus, oceanographic processes influence the ratio of bioclastic: lithoclastic components in the sediments.

The present study focuses on characterisation of the carbonate sediments of the tidally dominated reef platform sediments (TDRPS) east of the Zanzibar channel.

MATERIALS AND METHODS

Study area

Zanzibar (Unguja) Island (Fig. 1a) is one of the major islands of Tanzania located along the eastern coast of Africa in the western Indian Ocean. The island is approximately north-south oriented, about 85 km long and 35 km wide, with an area of 1530 km^2. It is part of the inner shelf which was uplifted during Early to Mid Eocene (Kent et al., 1971).

Unguja Island is fairly flat with only minor relief on the northwestern side, where the Masingini Ridge rises about 100 metres above mean sea level (Kent et al., 1971). The ridge is composed of uplifted sandstone sequences, which are unique for the island and could be a source of siliciclastic sediments found on the beaches of the west coast of the island (Shaghude & Wannäs, 1998; 2000). The main part of the island consists of coralline limestone formations of Pleistocene age (Kent et al., 1971).

The tides around the island are semi-diurnal with spring tidal range of 3.2 m and neap tidal range of 0.9 m (Cederlöf et al., 1995). Thus, the area can be classified as mesotidal coast (Boothroyd, 1985). The most important current in the Zanzibar channel is the East African Coastal Current (EACC), which has a net northward flow. The speed of this current varies between 0.25 and 2 m/s, being fastest during the SE monsoon, and lowest during the NE monsoon (Newell, 1957).

A bathymetric study conducted in one third of the channel area (Fig. 1a) shows that the channel is generally shallow and consists of a 'central deep' of between 30 and 40 m depth (Shaghude & Wannäs, 1998). The topography east of the central deep is irregular as is dominated by Pleistocene raised coral platforms, with a network of 'internal' channels. In the charts (e.g. Crown, 1995) the internal channels are labelled as Passes (Fig. 1b). Sediment characteristics of the Zanzibar channel and the biogenic, and mineralogical composition of the sediments has been discussed by Shaghude & Wannäs (1998; 2000), where they proposed a division of the sediments into three bio-physiographic provinces: 1- the coastal zone, 2- the central channel zone and 3- the reef platform/ patch reef zone. The higher sampling density on the eastern side allows further characterisation of the sediments in relation to the energy regime in this area.

In this study current measurements taken from the reef platform system were used to relate the biogenic assemblages of the carbonate sediments off the western coast of Zanzibar to the energy regime.

Sample and data collection

The sediment data consisted of 27 samples (Fig. 1b). All the samples were wet-sieved into four class categories: very coarse sand (1.0 to 2.0 mm), coarse sand (1.0 to 0.5 mm), medium sand (0.5 to 0.25 mm) and the fine grade material (< 0.25 mm). The last class (< 0.25 mm) was not counted, as these

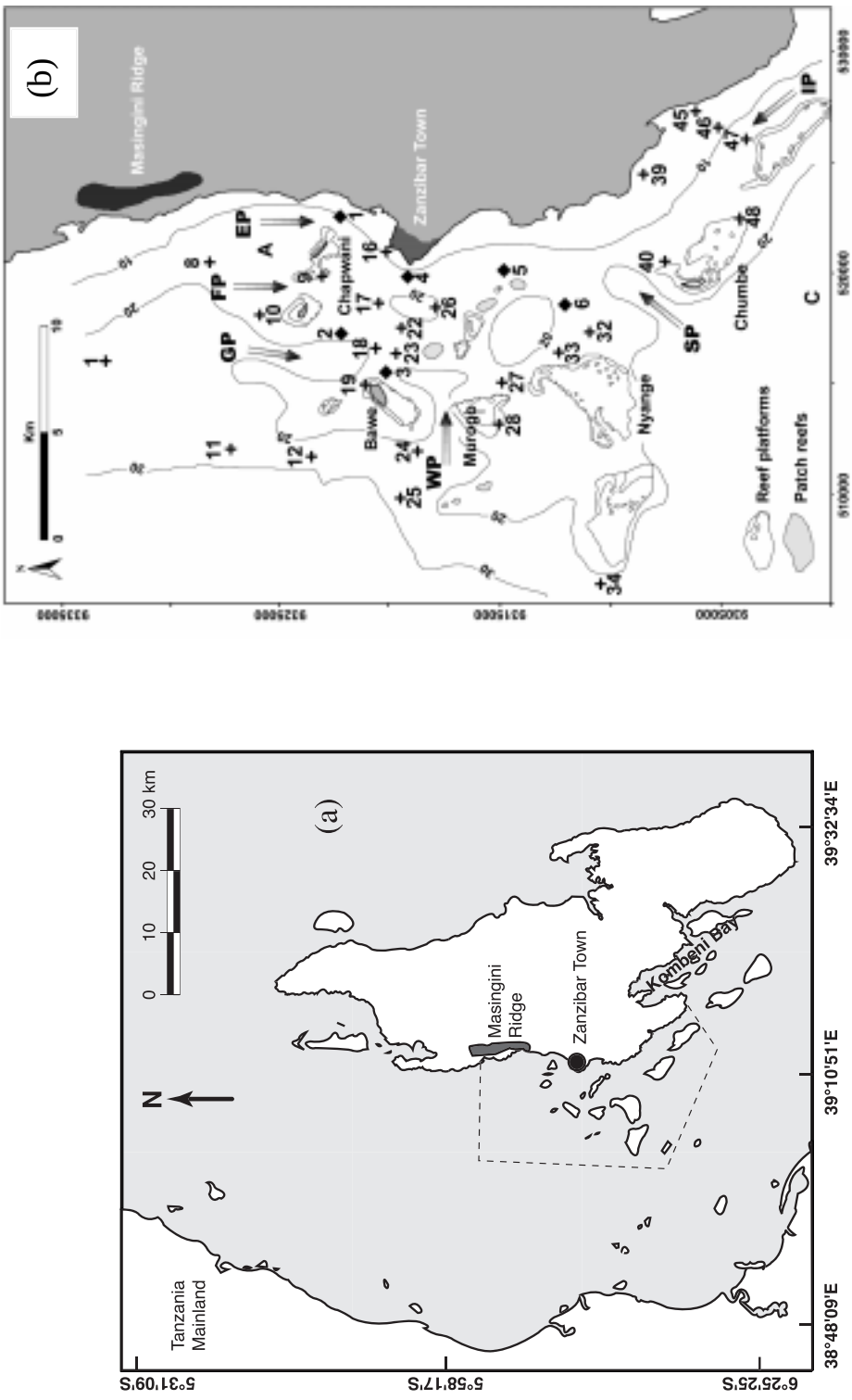


Fig. 1. The location map (Fig. 1a) showing the Unguja island and the approximate boundary of the study area. The location of the samples investigated (indicated by + sign) and the Self Recording Current meter (SRC) stations (indicated by ◆ symbol) are shown in Fig. 1b. The labelled passes (Fig. 1b) are: EP (English Pass), FP (French Pass), GP (Great Pass), WP (Western Pass), SP (Southern Pass) and IP (Inner Pass)

grains were difficult to identify under a binocular microscope. Using a binocular microscope, aliquots of approximately 300 grains of the other three classes were used to quantify different biogenic groups. Tidal currents were taken from 6 stations (Fig. 1b) using a self-recording current meter (RCM), Sensordata SD6000. In the present study, the six stations were located in the passes between the reef platforms. At each station, the RCM was deployed at a single depth, 5 m above the bottom for about 5–6 hours, during peak spring and peak neap tides.

RESULTS

Biogenic analysis of the sediments

The dominant biogenic groups found in the TDRPS samples are presented in Fig. 2. Of the six biogenic groups identified in the samples, the sponge spicules can be discarded as the average concentration in the three classes was negligible. Of the remaining 5 groups, benthic foraminifera were the most important. Other less important but common biogenic groups were pelecypods, corals and gastropods. Lithogenic particles were also common, particularly in the intertidal flat sediments.

The variation of the different groups in the three sand size classes was analysed by ANOVA statistical test at 10% level of significance, i.e α = 0.1 (Table 1). Foraminifera and corals did not show significant variation among the sand classes. However, pelecypods, gastropods, ostracods and lithogenic particles showed significant variation (P = 0.1), with decreasing concentrations of both pelecypods and gastropods for decreasing sand size class. Lithogenic particles on the other hand increases with decreasing sand size class. The ostracods dominated in the medium size class.

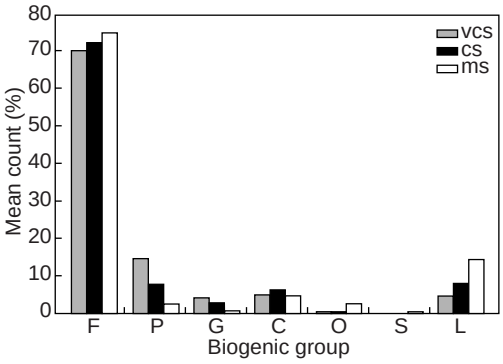


Fig. 2. Mean percentage counts of the biogenic groups (and the lithogenic particles) in the three wet sieved classes of the sediments. vcs, very coarse sand; cs, coarse sand; ms, medium sand; F, benthic foraminifera; P, pelecypods; G, gastropods; C, corals; O, ostracods; S, sponges; L, lithogenic particles

Table 1. Results of a significant test for comparing the concentration of the different groups in the three sand sized classes (P = associated P-value)

Group	P	Remarks
Foraminifera	0.89 (*)	No significant changes
Pelecypods	< 0.0001	Average decreases with decreasing size
Gastropods	0.1	Average decreases with decreasing size
Corals	0.96 (*)	No significant changes
Ostracods	< 0.0001	Dominant in medium sand
Lithogens	0.1	Average increases with decreasing size

*P-value greater than 0.1, not significant as the test was carried out at α = 0.1.

The total weight composition of the various groups mentioned above was also calculated and the spatial distribution of three groups with most common occurrence is presented in Fig. 3. Foraminifera (Fig. 3a) occurred in all samples, constituting more than 60 % by weight, except in those sediments which had very high proportions of molluscan shells (No. 1), lithogenic particles (No. 16) or coral fragments (No. 33 and 39).

Pelecypods (Fig. 3b) was the group with the next most common occurrence; occurring in 24 samples out of the 27 investigated. Gastropods (Fig. 3c), were less common than the foraminifera and pelecypods, but were common in the samples north of Chapwani reefs, central parts and the near shore samples in the southern parts. The spatial distribution of the remaining groups is generally narrow, and is not presented here. Ostracods and lithogenic particles had common occurrence mainly in the samples located in the central parts of the study area, with concentration varying from

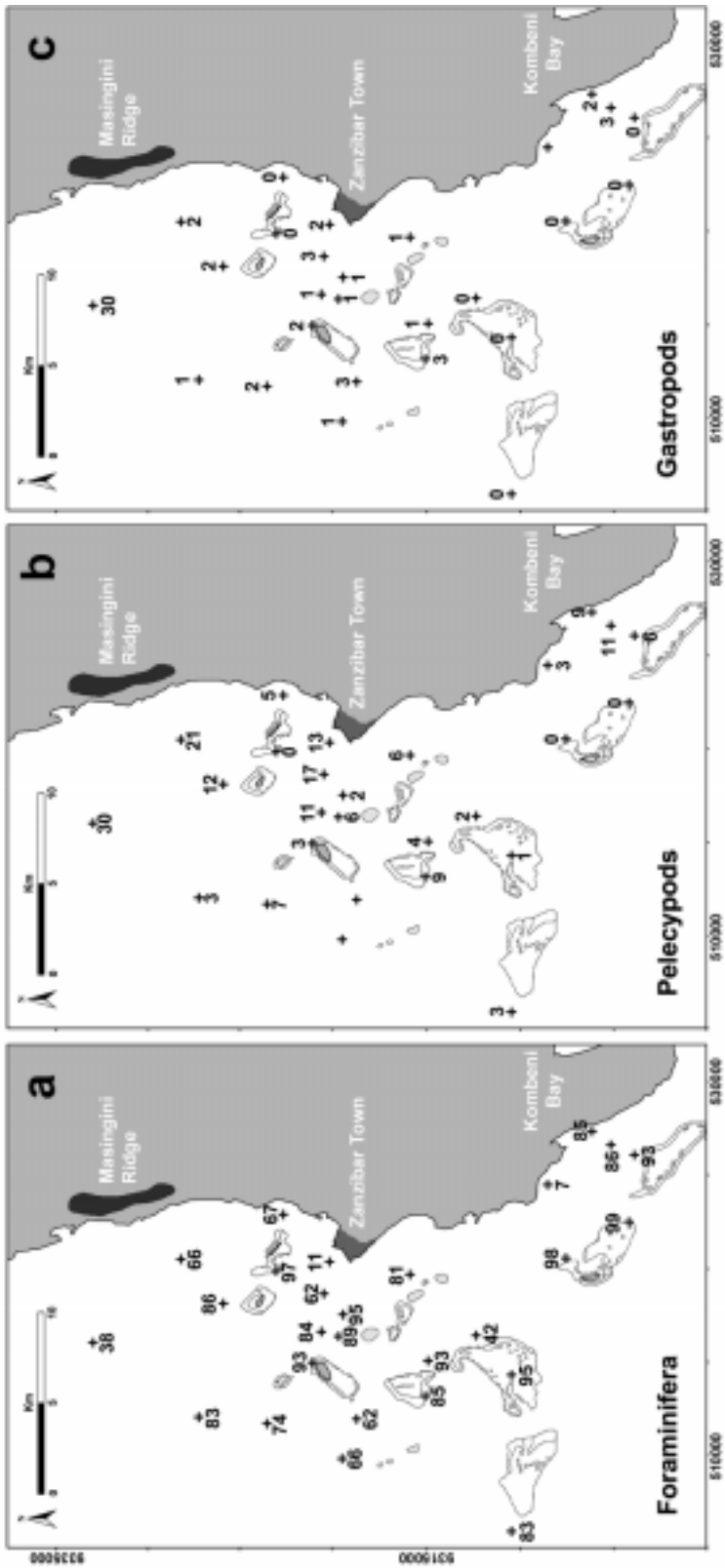


Fig. 3. Distribution of the three biogenic groups with the highest common occurrence. Numbers indicate weight % in the sum of the three grain size classes

1–3 % by weight (ostracods) and 3–20 % by weight (lithogenic particles). The distribution of coral fragments was patchy and mainly localised around some of the barrier reefs or reef platforms in the south. In these reef samples, the coral fragments in the sample averaged about 50 % by weight.

Current measurements

Current measurements (Fig. 4) showed that velocities in spring tides were generally higher than in neap tides. The highest velocities were experienced at stations 1, 3 and 6, with maximum speeds of 32, 25 and 34 cm/s, respectively during spring and 12, 15 and 10 cm/s during the neap. The lowest velocities were found at stations 4 and 5 with maximum of 10 and 9 cm/s, respectively, during spring and 5 cm/s (at both stations) during neap tide. The two stations seem to be located in relatively sheltered environments compared to other stations. At station 2 the current speed (14 cm/s during spring and 6 cm/s during neap) is slightly higher than at stations 4 and 5 but generally lower than at the other three stations (1, 3 and 6).

The current directions in the reef platform area show two different current systems, one north and the other south of Zanzibar Town (Fig. 5). The data, which represent current directions at six RCM stations during our study and two stations (A and C) documented from a sea chart (Crown, 1995)

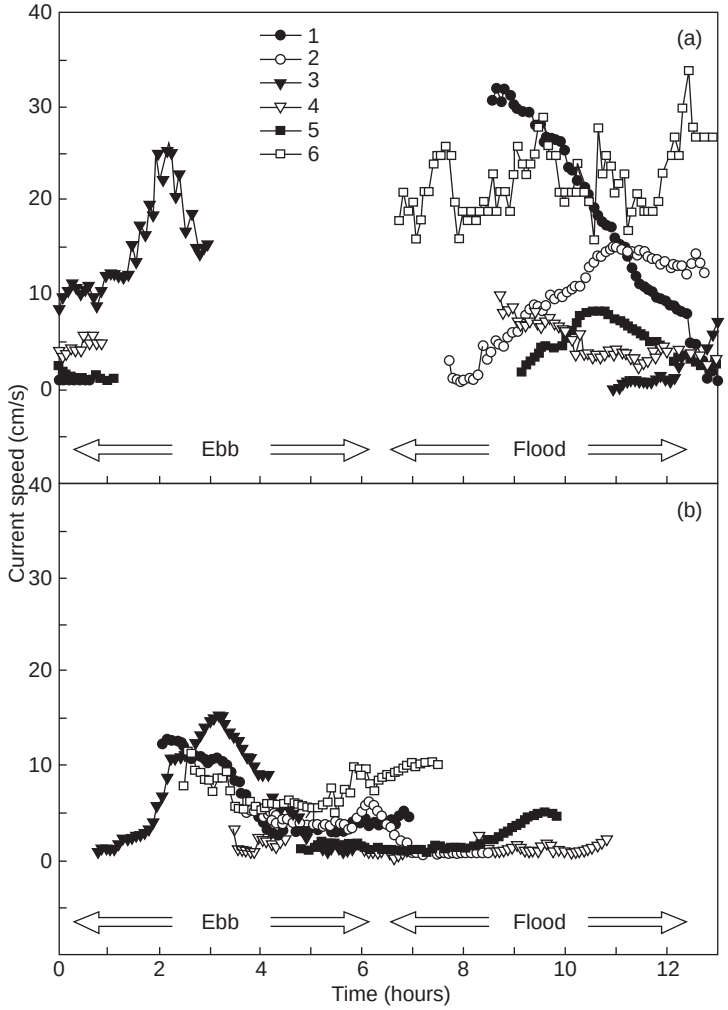


Fig. 4. Current speed at the six stations (1–6) during spring (a) and neap (b) tides. The ebb and spring tidal phases are each approximately 6 hours

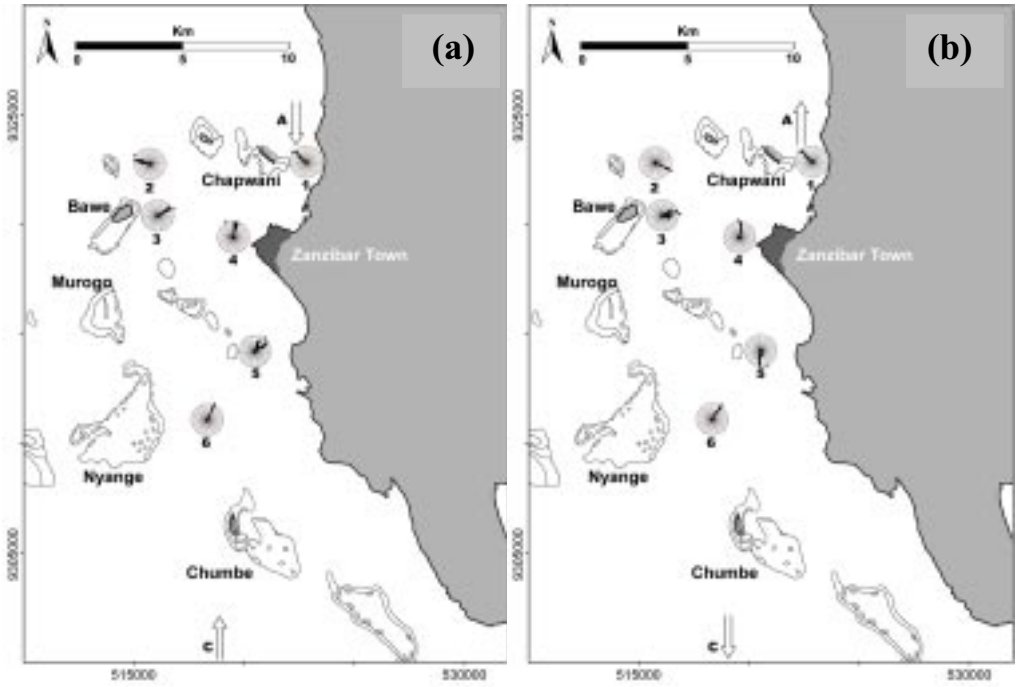


Fig. 5. Rose diagrams of the current direction at each of the six stations during the flood (a) and ebb (b) tides. Open arrows represent the current directions at the two tidal stations A and C

show that the two stations are out of phase. The data also show that during flood (Fig. 5a) the two current systems flow toward each other, meeting near Zanzibar Town. During the ebb phase (Fig. 5b) the two current systems flow in the opposite direction. The ebb tidal current direction at station 6 is the only exception, which is inconsistent with the expected general flow. The current directions shown by the remaining stations (including station 6 during flood) are all consistent with the directions shown by the two tidal stations A and C.

DISCUSSION AND CONCLUSION

The two current systems (one north of Zanzibar Town and the other south of Zanzibar Town) observed in this study are in agreement with the work of Mohammed et al. (1993). The two systems converge during flood tides and diverge during neap tides. Further examination of the current direction for the six stations revealed that the current directions are influenced by the ebb–flood tidal phases (Fig. 5), results which are partly consistent with the tidal information documented in the sea chart (Crown, 1995). In particular, the tidal influences are clearly seen in stations 2 and 5. In station 2, the flood current is predominantly western and the ebb current is eastern. In station 5, the flood current flows toward the northeast and during the ebb tide, it flows southwards. In stations 1, 3, 4 and 6, the current direction in each case is characterised by a single component. In the chart the direction of the tidal currents at two tidal diamond stations A and C (Fig. 1b) are as shown in Table 2. The direction of the tide at station A, located 4.5 km north of station 1, is generally southward during flood and northward during the ebb. The direction of the tide at station C, located 15 km south of station 5 and 6 is northward during the flood and southward during the ebb.

A standing wave (without any net through-flow) with its nodes at the northern end and southern end of the channel would result in flood and ebb tidal currents presented in Fig. 6. The generalised pattern of the current directions are consistent with the documented tidal currents at

Table 2. The direction of the tides at the tidal stations A (May, 1953) and C (November, 1954) located outside but close to the area of investigation (see also Fig. 2). Negative and positive times refer to time before and after high water respectively, Dir = current direction measured in degrees from true north. The current velocities are modified after Crown (1995)

Diamond station A				Diamond station C			
		Speed (knots)				Speed (knots)	
Time (Hours)	Dir	Spring	Neap	Time (Hours)	Dir	Spring	Neap
-6	258	0.2	0.1	-6	220	0.2	0.1
-5	164	0.2	0.1	-5	326	0.2	0.1
-4	152	0.3	0.1	-4	322	0.4	0.1
-3	155	0.4	0.1	-3	324	0.3	0.1
-2	150	0.3	0.1	-2	338	0.2	0.1
-1	152	0.2	0.1	-1	336	0.3	0.1
0	194	0.1	0.1	0	323	0.3	0.1
+1	272	0.2	0.1	+1	228	0.1	0.0
+2	338	0.3	0.1	+2	122	0.2	0.1
+3	007	0.4	0.1	+3	109	0.4	0.1
+4	006	0.3	0.1	+4	134	0.5	0.2
+5	326	0.3	0.1	+5	159	0.5	0.2
+6	287	0.2	0.1	+6	190	0.3	0.1

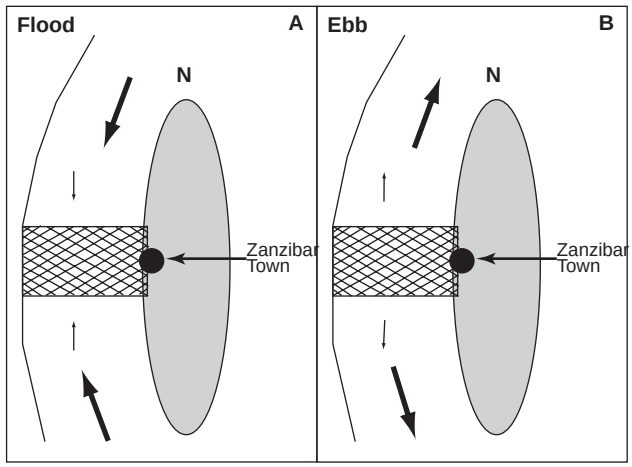


Fig. 6. The generalised pattern of tidal currents in the Zanzibar channel. Observe that the tidal currents are stronger at the node (N), located at the tips of the island than at the middle of the channel (crosshatched) which is also approximately near Zanzibar Town

stations A and C, where the tidal currents from north and south of the channel would meet at the middle of the island, which is roughly near Zanzibar Town (Fig. 6). This would imply that the tidal current speed near Zanzibar Town is generally low. Our present study shows local variability in the current velocity within the investigated area of the TDRPS.

It was not possible within the present study to investigate the net through-flow in the Zanzibar channel as related to the monsoon variability, and the authors are not aware of any study which has addressed this subject. However, another contemporary study (Shaghude et al., in prep.) investigating on the sediment dynamics on the western side of the channel, shows that the sediments entering the ocean via the River Ruvu are preferentially transported northwards. There are

Table 3. The calculated total average weights and standard deviation of the major groups in all samples and the two subdivisions. The table also shows the P-value of the significance test when the means of the groups in the two subdivisions are compared using ANOVA test at 10% level of significance

Group	Total (n = 27)	Northern (n = 15)	Southern (n = 12)	P-value
Foraminifera	Ave 74.1	71.5	78.9	0.7 (*)
	Std 24.8	23.3	27.4	
Pelecypods	Ave 7.5	9.8	4.6	0.04
	Std 7.0	8.1	3.6	
Gastropods	Ave 2.4	3.4	1.1	0.3 (*)
	Std 5.7	7.5	1.4	
Corals	Ave 4.0	0.6	8.4	0.1
	Std 13.4	1.0	19.6	
Ostracods	Ave 1.0	1.4	0.4	0.04
	Std 1.3	1.5	0.6	
Lithogens	Ave 7.8	11.1	2.1	0.1

* P-value greater than 0.1 not significant, as the test was carried out at $\alpha = 0.1$.

other studies conducted west of the Zanzibar channel, which noted preferential transport of sediments toward the north (e.g. Muzuka & Shaghude, 2000). Thus, in light of these studies, it seems that there is a net through-flow in the western side of the channel. Whether there is also a net through-flow on the eastern side of the channel, needs further investigation.

In the light of our study on the biogenic composition of the TDRPS and the current measurements obtained, we suggest two subdivisions of the sediments; the northern and southern TDRPS. The boundary separating the two subdivisions is assumed to be somewhere between Zanzibar Town and the Murogo reef platform (Fig. 1b).

The calculated total average weights (Ave) and the standard deviations (Std) of the major biogenic groups and the lithogenic particles and the P-value of the significant test carried to compare the two subdivisions are indicated in Table 3. The results show an overall higher mean of the pelecypods, ostracods and lithogenic particles in the northern subdivision than in the southern subdivision. It also indicates higher mean of the coral fragments in the southern subdivision than in the northern subdivision. As for the foraminifera and gastropods groups, the north–south differences are not significant.

Since Masingini Ridge is the major source of siliciclastic sediments on the eastern side of the Zanzibar channel (Shaghude & Wannäs, 1998; 2000), the current pattern discussed would lead to higher lithogenic material being found in the northern parts than in the southern parts, as the former are relatively closer to the source rock than the latter. This study confirms this hypothesis, with significantly higher lithogenic material being found in the northern parts of the TDRPS than the southern parts (Table 3). This observation might also explain the distribution of coral fragments, which is more patchy in the southern than the northern parts, most likely because of the higher siltation in the northern parts, leading to poor growth of coral polyps, which grow best in shallow and clear waters (Wagner, 1999).

Acknowledgements—We are very thankful for the financial support received from Sida/SAREC to conduct this research project. The authors also gratefully acknowledge Dr Eve Arnold (Stockholm University), Prof. Lars Rydberg and Dr Ulf Cederlöf (both from Göteborg University) and Dr Alfred Muzuka (IMS Zanzibar) for their constructive comments on the manuscript.

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