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Mineralogical and Biogenic Composition of the Zanzibar Channel Sediments, Tanzania

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Sediments from the Zanzibar Channel have been analysed for mineralogical and biogenic composition. The main objective of the study was to describe the depositional environment of the sediments based on these parameters. The study was also conducted to give an insight into sediment provenance of the sediments. Quartz, feldspar (both microcline and plagioclase) and hornblende are the main mineralogical components, while zircon, muscovite, biotite and augite occur as accessory minerals. The quartz grains are generally angular to sub-angular and highly strained, indicative of immature sediments, probably derived from highly metamorphosed rocks. The presence of hornblende also supports the conclusion that the sediments are immature. A possible source is the metamorphic rocks of the Mozambique belt, located about 25–50 km from the coastline. Benthic foraminifera are the dominant biogenic constituents. Other common biogenic constituents are molluscs (pelecypods and gastropods) and corals. Bryozoans and ostracods are relatively less common, while sea urchins are accessory biogenic components. The composition and abundance of these biogenic components and morphological, sedimentological and mineralogical data permit construction of a simple model which distinguishes between three bio-physiographic settings in the Zanzibar Channel using depth contours: (1) the coastal zone (0–10 m depth); (2) the reef platform/patch reefs zone (10–20 m depth) and (3) the central channel zone (>20 cm depth). In the coastal zone, the sediments are dominated by fine sand, sized with a very prominent fine sand mode. The proportion of benthic foraminifera is lower than in the other two zones (<45%) as is the biogenic:quartz ratio (<2), but the lithogenic concentration is highest (>25%). Two lithogenic mineral components (quartz and feldspar) occur in significant proportions. In the reef platform/patch reefs zone, the sediments are coarse to medium sand sized with no distinct mode. the proportion of benthic foraminifera is highest (80–85%) there, and so is the biogenic:quartz ratio (>10) but that of lithogenic components is lowest (<5%). In the central channel zone, the sediments are medium to fine sand sized and often bimodal, with a prominent fine mode and a less prominent coarse mode. The proportion of benthic foraminifera (70–75%) is also higher than in the coastal zone but slightly lower than in the reef zone. The proportion of lithogenic components (5–20%) is higher than in the reef zone but lower than in the coastal zone and the biogenic:quartz ratios is intermediate.
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Introduction

The Zanzibar Channel (Figure 1) separates the island of Zanzibar and the mainland of Tanzania. It is approximately north–south oriented and about 120 km long and 35 km wide. The morphology and major characteristics of the Zanzibar Channel sediments have been discussed by Shaghude and Wannäs (1998).

The central deep (30–40 m depth), is the most important elongated north–south feature in the channel. To the east and west of the central deep are Pleistocene coral platforms which are associated with elongate sand banks, coral islets and minor reef structures. Coral platforms similar to those found off the island of Zanzibar are also common along other areas of the Tanzania mainland, especially in areas where silt input from the rivers is relatively low, such as Msasani Bay, north of Dar es Salaam (Fay *et al.*, 1992). Coral platforms on the mainland side of the Zanzibar Channel are probably absent because of high silt input from the rivers. The silici-clastic sediments are thought to enter the sea through two major rivers: Ruvu and Wami. The morphology on the western side of the channel can be summarized as topographically smooth with a gentle gradient (Shaghude & Wannäs, 1998). On the Zanzibar (eastern) side of the channel, the erosional products from the island are of too little significance to cause any major morphological changes on the sea bottom topography. Consequently, most of the coral platforms are directly observable, which partly causes the topography to be relatively

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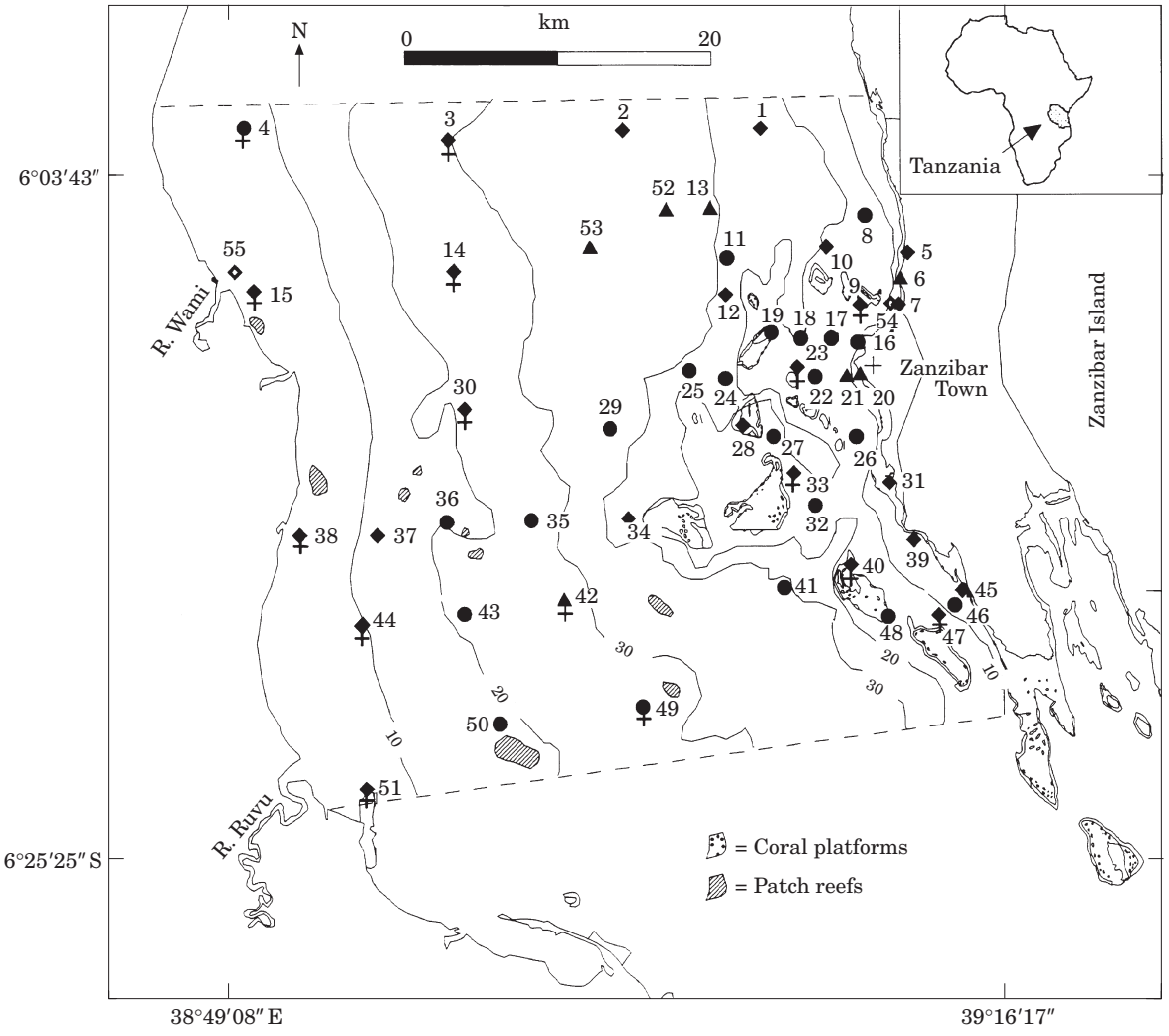


FIGURE 1. Index map of the Zanzibar Channel showing the approximate boundary of the area of investigation and the sample locations. The bathymetric isolines (m) are modified after Shaghude and Wannäs (1998). <10 m=Coastal (C) zone, 10–20 m=Reef platform/patch reefs (R) zone and >20 m=Central channel (CH) zone. Samples Nos. 54 and 55 were not analysed in this study but have been referred to in the test. Sample locations: ●: biological; ▲: mineralogical; ◆: mineralogical and biological; +: north–south profiles.

irregular and sharp. The morphological differences between the eastern and western flanks are, however, not entirely attributed to differences in the silici-clastic input, but are considered to be influenced by the tectonic development of the area.

The tectonic development of the Zanzibar Channel since the Tertiary has been discussed by Kent *et al.* (1971) and summarized by Shaghude and Wannäs (1998). The island of Zanzibar was probably uplifted during the Early to Mid Eocene. The uplifting of the island was accompanied by subsidence/down-warping of the area between the island and the mainland. Another uplift of the island followed during Oligocene, with sedimentation in the down-faulted Zanzibar Channel. During the Pleistocene, sea-level dropped to about 120 m below the present level, and the present channel was probably acting as a drainage system for the mainland (Fairbanks, 1989).

To a large extent, the silici-clastic input of sediments from the mainland through the rivers Ruvu and Wami controls the sediment distribution patterns on the sea bottom in the western part of the channel, a fact demonstrated by the distribution of carbonates as well as the sediment grain size (Shaghude & Wannäs, 1998). The carbonate content in most of the sea bottom is more than 30%. Silici-clastic sediments only dominate the sea floor adjacent to the mainland and beneath the sediment plume from the river Ruvu. On the Zanzibar side of the channel, the silici-clastic material dominates the near-shore sediments in the

area of investigation. The silici-clastic sediments are generally finer grained and better sorted than the carbonate sediments. In addition, the silici-clastic sediments adjacent to the mainland show a tendency toward decreasing skewness offshore.

Biological as well as other oceanographic phenomena in the channel are influenced by the monsoon currents (Lugomela & Semesi, 1996). The speeds of the currents are lowest (Newell, 1957) during the north-east monsoon winds (November to March) and highest during the south-east monsoon winds (May to September). The weather is warm and moist, with temperatures between 27 and 35 °C and the annual rainfall ranging between 1000 mm on the mainland coast (Mgaya *et al.*, 1999) and 1600 mm on Zanzibar Island (Mmochi & Mberek, 1998).

The focus of the present study is the investigation of the mineralogical and biogenic composition of the sediments in the channel. Although the study of Shaghude and Wannäs (1998) discusses the major characteristics of the Zanzibar Channel sediments, detailed information on the mineralogical composition of the sediments on the bottom of the channel which could give some insight into the possible sources of the sediments and their transport paths (Milliman, 1967; Naidu *et al.*, 1995; Ockay & Hubert, 1996; Petschick *et al.*, 1996; Ergin *et al.*, 1996; Graham *et al.*, 1997), is still lacking. Furthermore, since carbonate sediments occupy a large part of the Zanzibar Channel, the different biogenic groups which are the source of the carbonate sediments and their relative abundance in the sediments are of major importance. The biogenic composition and the relative species abundance in the sediments may shed some light on the physical environments under which these sediments were deposited (Ginsburg, 1956; Milliman, 1967; Nelson & Bornhold, 1983; Ramsay, 1994; Iryu *et al.*, 1995; Andruleit *et al.*, 1996).

Materials and methods

A map for the area of investigation (Figure 1) shows the sample location for petrographic and biogenic studies. These locations were also used for previous studies on the channel (Shaghude & Wannäs, 1998). Some of these samples were analysed for both mineralogical and biogenic composition. The samples used for this study are given in the Appendix.

Thirty-one samples from the channel were selected for petrographic analysis. Approximately 20 g of material was impregnated with epoxy resin and epoxy hardener. The impregnated samples were polished using 120, 400, 800 and 1200 grit abrasives to obtain standard thin sections (*c.* 3 μm). The thin sections were then analysed using a petrographic microscope to determine the mineralogical composition of the samples as well as other diagnostic features of the mineral grains.

Forty-seven samples were used for biogenic analysis in order to describe the different environments, with a denser coverage taken from the near shore area off Zanzibar Island which has a higher carbonate content than elsewhere. Preparation of the samples for biogenic analysis involved wet sieving, drying and splitting the samples into subsamples of approximately 300 grains, which is generally considered adequate for statistical accuracy (Milliman, 1967).

During wet sieving, the samples were sieved into four classes: >1·00 mm (<0Φ) diameter, 0·5–1·0 mm (0–1Φ) diameter, 0·25–0·5 mm (1–2Φ) diameter and <0·25 mm (>2Φ) diameter. Based on the Wentworth scale (Wentworth, 1922), the four classes may be regarded as very coarse sand, coarse sand, medium sand and fine sand classes, respectively. However, for practical purposes, a great number of grains less than 0·25 mm (fine sand class) were too small to identify under the binocular microscope, and were not counted. In the mineralogical analyses the lithogenic material was not divided into different classes as the material is totally dominated by the fine sand class. The biogenic analysis involved point-counting loose grains, separating the different biogenic components into seven groups and tallying the number of organisms of each group in the sample. More than 42 000 grains were so classified.

Results

Mineralogical analysis

The results of the mineralogical analyses are presented in Table 1. Quartz is by far the most abundant silici-clastic mineral. The beach samples (Nos. 5 and 31) taken from the Island of Zanzibar consist of at least 85% quartz. The four samples (Nos. 15, 38, 44 and 51) near the mainland coast have at least 50% quartz. The percentage of quartz by volume in the samples is generally highest near shore and decreases towards the reefs or patch reef areas. The quartz grains are often fine to medium sand size, angular to sub-angular, strained and fractured.

Feldspar (plagioclase and microcline) is the next most abundant mineral in the samples. With the exception of samples taken from the southern parts of Zanzibar and those from the extreme north of the study area, most of the samples analysed for mineralogical composition contain feldspar minerals at a concentration of 10–20% by volume. The last

TABLE 1. Mineralogical composition of samples in percentage by volume

Sample	Bio	Qz	Fd	Hn	Min
1	95	3	2	—	—
2	80	~20	—	—	Hn
3	70	~30	—	—	Hn
5	—	90	~10	—	Hn
6	60	30	10	—	—
7	50	45	5	—	—
9	95	4	~1	—	Zr
10	95	4	~1	—	—
12	90	10	—	—	—
13	20	60	~20	—	Zr
14	60	30	10	—	Hn
15	5	70	20	~5	Zr
20	40	50	10	—	Hn
21	60	30	10	—	Zr
23	95	~5	—	—	Zr
28	95	5	—	—	—
30	60	25	10	5	—
31	5	85	~10	—	Hn, Zr
33	95	5	—	—	—
34	85	~15	—	—	Hn
37	80	10	5	~5	Hn
38	5	80	10	~5	Zr
39	90	~10	—	—	Zr, Mv
40	95	~4	1	—	Hn, Zr
42	50	30	10	~10	Bt, Zr
44	40	50	~10	—	Hn, Zr
45	70	~30	—	—	Zr, Mv
47	95	4	1	—	—
51	10	80	~10	—	Hn, Zr
52	90	10	—	—	—
53	60	25	10	5	—

Bio=biogenic; Qz=quartz; Fd=feldspar; Hn=hornblende; Min=minor; MV=muscovite; Zr=zircon; Bt=biotite; Ag=augite.

important mineral in the sediments is hornblende which occurs as a primary as well as an accessory constituent. All occurrences of hornblende as a primary constituent (with a typical concentration of 5–10% by volume) are limited to the western side of the channel. The remaining minerals (zircon, muscovite, biotite and augite) generally occur as accessory components in the samples.

Biogenic components in the thin sections averaged *c.* 60% and usually were dominated by shells of various species of benthic foraminifera. The shells were in some cases filled with re-crystallized calcite. However, some thin sections, especially from the beach and intertidal area at Zanzibar, and others near the mainland shore had less than 50% biogenic components.

Biogenic analysis

The basic statistics obtained from the counts of the various biogenic components in the different sieved sub-samples are presented in Table 2. Sediments in the channel are composed of the following biogenic groups: foraminifera (benthic), molluscs (pelecypods and gastropods), corals, ostracods, bryozoans and sea urchins. Less than 1% of the biogenic grains were unidentified. These were combined together with the non-biogenic components and were classified as lithogens. Of the biogenic components, foraminifera is by far the dominant group. In order of decreasing abundance, the foraminifera are followed by molluscs, corals, bryozoans, ostracods and sea urchins. Pelecypods generally constitute more than 75% of the molluscs.

The distribution and abundance of benthic foraminifera are shown in Figure 2. The distribution maps generally show similar patterns, with only some minor variations in all three size classes; more than 70% of the samples consist of at least 50% foraminifera tests. Samples with the lowest proportion (<25%) of foraminifera normally include those collected near the mainland and the island coastlines. In general, all three maps reveal higher proportions (in

TABLE 2. Mean percentage counts for biogenic groups and lithogens for all wet sieved sub-samples analysed

Biogenic group	0·25–0·5 mm (medium sand)	0·5–1·0 mm (coarse sand)	>1·0 mm (very coarse sand)
Foraminifera	67·27	66·7	69·57
Pelecypods	2·5	7·2	12·8
Gastropods	0·2	2·1	3·7
Corals	3·2	4·77	3·62
Bryozoans	0·77	1·14	0·53
Ostracods	1·74	0·22	0·12
Sea urchins	0·44	0·26	0·16
Lithogens	23·16	17·34	9·12

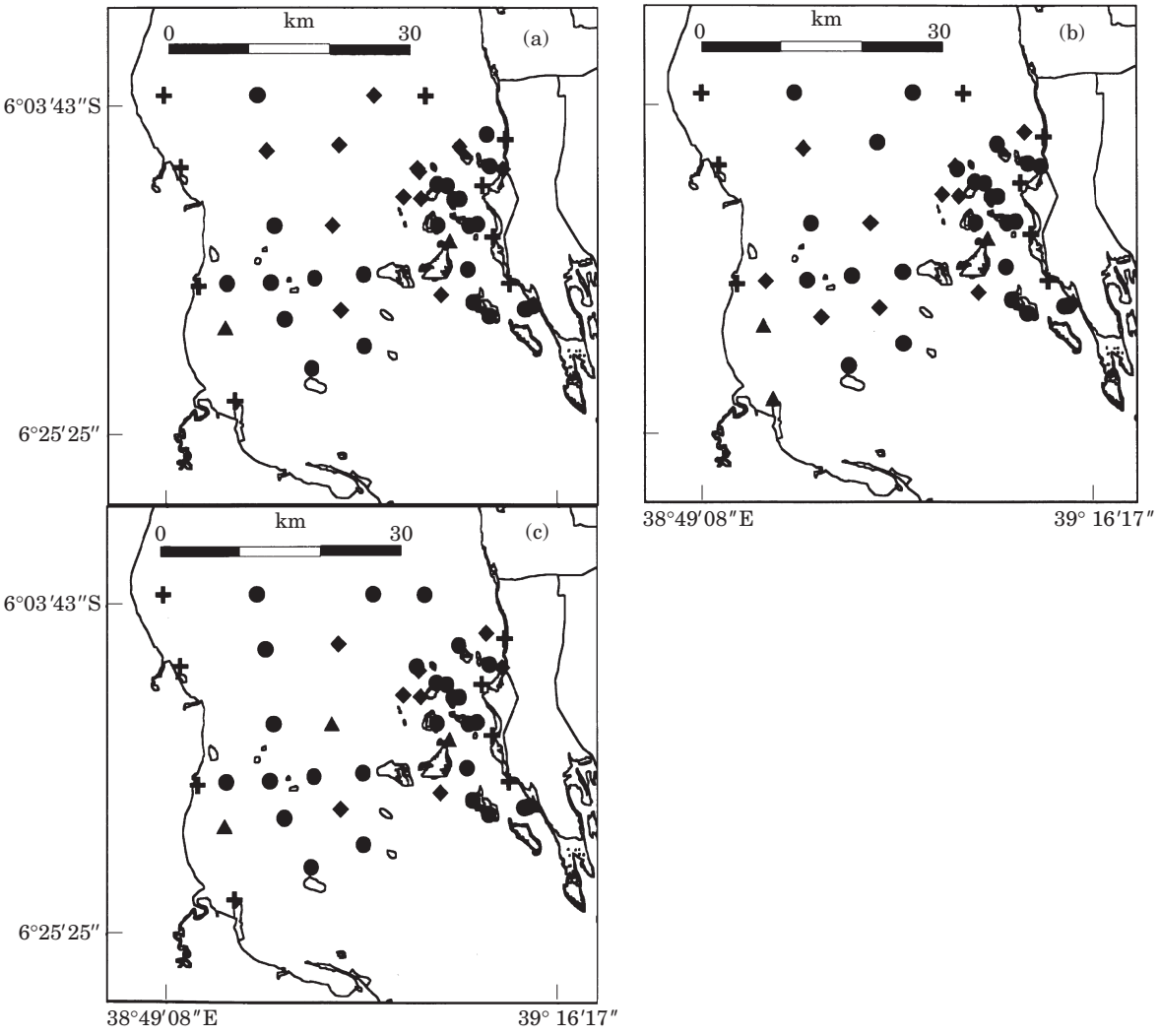


FIGURE 2. Distribution map for benthic foraminifera tests; (a)=very coarse sand size class, (b)=coarse sand size class and (c)=medium sand size class. The ranges 0–25 (crosses), 25–50 (triangles), 50–75 (diamonds) and 75–100 (circles) represent the percentage of benthic foraminifera from all grain counts at those sites.

excess of 50%) of foraminifera in areas with >30% carbonate content (Shaghude & Wannäs, 1998).

Discussion

The mineralogical analysis shows that most of the lithogenic components (particularly quartz), are angular to sub-angular. This suggests that the lithogenic sediments are texturally immature. Thus the sediments have probably been transported a short distance and have generally not been reworked after deposition. The presence of hornblende in the sediments is also evidence of chemical immaturity. The hornblende, like biotite, augite or fosterite which are high temperature metamorphic mineral facies, is generally chemically unstable at earth surface temperatures and pressures (Blatt *et al.*, 1972), and therefore less resistant to chemical weathering than the low temperature metamorphic mineral facies such as quartz.

In the present study, minerals such as hornblende, muscovite, zircon and other heavy minerals have been found along the beaches of Zanzibar Island and in the near shore sediments of the island. These minerals could be derived from a metamorphic or igneous rock, or from sedimentary formations. The bedrock geology of Zanzibar Island (Kent *et al.*, 1971) mainly consists of Pleistocene bedrock with one exception, the elevated Masingini Ridge, which represents feldspar rich sandstones.

The observed gradient of hornblende in the sediments (which decreases from west to east) has two

TABLE 3. Average (Ave) and standard deviation (SD) of the biogenic percentage counts and lithogens in the three sand sized classes (medium, coarse and very coarse sand) analysed, for each bio-physiographic zone

Biogenic group		Medium			Coarse			Very coarse		
		C	R	CH	C	R	CH	C	R	CH
Foram	Ave	35	88	75	39	83	74·8	47	83	72·4
	SD	39	14	15	38	17	16·6	36	13	16·2
Pelecypod	Ave	3·4	2·2	2·1	10	6·9	5·6	17	8	16·2
	SD	12	2·9	3·4	17	8·5	6·8	17	6	14·3
Gastropods	Ave	0·2	0·4	0·6	0·9	1	3·8	2·6	2·6	5·2
	SD	0·5	0·5	0·9	1·1	1	10·3	2·9	2·4	9·4
Corals	Ave	6·6	3·5	6·6	7·1	6·3	1·7	6·8	4·9	1·2
	SD	23	13	23	25	16	2·4	23	14	2·3
Bryozoans	Ave	0·1	0·9	1·3	0·1	1·2	1·9	—	0·5	0·9
	SD	0·2	2	2·5	0·3	2·6	3·3	—	1·5	1·4
Ostracods	Ave	1·1	2·2	1·8	0·2	0·3	0·2	0·1	0·1	0·1
	SD	2·1	3·9	2·1	0·7	0·9	0·3	0·02	0·4	0·4
Sea urchins	Ave	0·3	0·3	0·7	0·5	0·1	0·1	—	0·1	0·3
	SD	0·5	0·5	1·8	1·3	0·2	0·2	—	0·2	0·8
Lithogens	Ave	53	1·5	18	42	1·4	11·6	27	0·4	5·4
	SD	43	2	18	43	2·2	11·4	37	0·9	6·1

C=coastal zone; R=reef platform/patch reefs and CH=central channel.

possible explanations: (1) the hornblende on the eastern side of the channel has the same origin as that on the western side, and has been transported east of the channel by easterly moving currents, and (2) the hornblende on the western side of the channel derives from an un-reworked source rock from the mainland, while the hornblende on the eastern side of the channel might be erosional reworked material from Masingini Ridge sandstones. However, the dominant currents in the area are the East African Coastal Currents (EACC), which are influenced by the seasonal monsoon winds (north-east monsoon and south-east monsoon). Neither the north-east monsoon nor the south-east monsoon may transport the sediments across the channel. The tidal currents which may transport the silici-clastic sediments off-shore are only effective on the near shore areas. In view of this, the first possibility can be ruled out. Hence, the most likely explanation for the observed gradient of hornblende in the sediments is as explained by the second alternative discussed above.

The two rivers Wami and Ruvu, which act as the major transporting media for the silici-clastic sediments to the sea on the western side of the channel, both drain the metamorphic crystalline rocks of the Mozambique belt and then pass through the younger coastal sedimentary formations before reaching the sea. The metamorphic rocks are believed to have formed during the Pan African episode, about 550 ± 100 m.y. ago (Windley, 1977) and the sedimentary formations vary in age from Mesozoic to Recent (Kent *et al.*, 1971; Kapilima, 1984). In view of the present mineralogical analyses which shows that most of the quartz grains are highly strained, it seems that the source of the silici-clastic sediments on the western side of the channel is metamorphic rocks.

The present biogenic analysis and the previous study on the morphology and sediment characteristics of the channel (Shaghude & Wannäs, 1998) suggest a simple model to delineate the bio-physiographic settings of the study area. The model proposes three bio-physiographic zones in the investigated area as follows (1) the coastal zone which comprises the coastal strips on both sides of the channel above 10 m water depths; (2) the reef platforms/patch reefs zone which comprises the sea bottom between 10–20 m depth; and (3) the central channel zone which constitutes the sea bottom lying below 20 m. The contours defining the three proposed bio-physiographic zones are shown in Figure 1

Table 3 presents the mean and standard deviation for the different biogenic groups in each of the above bio-physiographic zones. The variation of the different biogenic groups in the three zones was compared using ANOVA statistical tests at 10% level of significance. The results (Table 4) show that there is a significant difference in the distribution of both benthic foraminifera and the lithogenic components in the sediments between the coastal zone and the reef platforms/patch reefs zone and also between the

TABLE 4. The results of the significant test showing the *P* (probability) values for benthic foraminifera and lithogens. The bio-physiographic zones C, CH and R are as defined in Table 3

	Benthic Foraminifera			Lithogens		
Zones	Medium	Coarse	Very coarse	Medium	Coarse	Very coarse
C, CH	$P<0{\cdot}0001$	$P=0{\cdot}0002$	$P=0{\cdot}0035$	$P=0{\cdot}0004$	$P=0{\cdot}0011$	$P=0{\cdot}0041$
C, R	$P<0{\cdot}0001$	$P<0{\cdot}0001$	$P<0{\cdot}0001$	$P<0{\cdot}0001$	$P<0{\cdot}0001$	$P=0{\cdot}0008$
CH, R	ns	ns	ns	$P=0{\cdot}0803$	ns	ns

ns=no significant difference.

TABLE 5. Average (Ave) percentage by volume and standard deviation of the main mineral groups in the sediments of the three bio-physiographic zones

	Biogenic		Quartz		Feldspar		Hornblende	
Zone	Ave	SD	Ave	SD	Ave	SD	Ave	SD
T	62·6	32·5	30·7	27·3	5·6	6	1·1	2·5
C	34·1	31·1	56·4	26·5	8·6	5·5	0·9	2
R	89·4	12·1	7·9	8·5	2·1	3·3	0·6	1·7
CH	69·1	22·2	23·6	15	5·5	6·9	1·8	3·4

T=calculated total average/standard deviation for all analysed samples in the three zones, C, R and CH refer to coastal, reef platform/patch reefs and channel zones respectively.

coastal zone and the central channel zone. There is also a significant difference in the distribution of the medium sized lithogens among all the three zones. However, there is no significant difference in the distribution of all three classes of benthic foraminifera and the other two classes of lithogens (coarse and very coarse sand sized) between the reef platforms/patch reefs zone and the central channel zone.

There was no significant difference in the distribution of the other biogenic groups between the different bio-physiographic zones. This is probably due to their general occurrence in very low proportions in the sediments. In order to ascertain their significant differences in the different zones, a larger number of samples and a higher number of grain counts would be needed.

Table 5 shows the mean and standard deviation for the main mineral groups and the biogenic content of the samples analysed in thin section. The same ANOVA statistical test was carried out on the mineralogical analysis as for biological counts. The results (Table 6) show that there is a significant difference in the distribution of both the biogenic and the quartz content in the sediments among all the three bio-physiographic zones. Also, there is a significant difference in the distribution of the biogenic:quartz ratios between the coastal and reef platforms/patch reef zones and between central channel and reef platforms/patch reef zones.

The distribution of the other two main minerals (feldspar and hornblende) among the three bio-physiographic zones show no significant differences. Again this might be because the proportion of these minerals in the sediments are lower than the proportion of quartz or the biogenic components, and so significant differences in their distribution among the three zones could not be ascertained given the number of samples analysed.

Very high (>10) biogenic:quartz ratios (Figure 3) characterize the samples in the reef platforms/patch reefs zone, reflecting the dominance of biogenic

TABLE 6. *P* values for quartz, biogenic content and biogenic: quartz (B–Q) ratio based on the significant test conducted on the data from Table 1

Zones	Quartz	Biogenic	B–Q ratio
C, CH	$P<0{\cdot}0003$	$P<0{\cdot}0001$	ns
C, R	$P<0{\cdot}0001$	$P<0{\cdot}0001$	$P<0{\cdot}0001$
CH, R	$P<0{\cdot}0001$	$P<0{\cdot}001$	$P=0{\cdot}0005$

The abbreviations C, CH, R, ns and P are as defined in Tables 3 and 4.

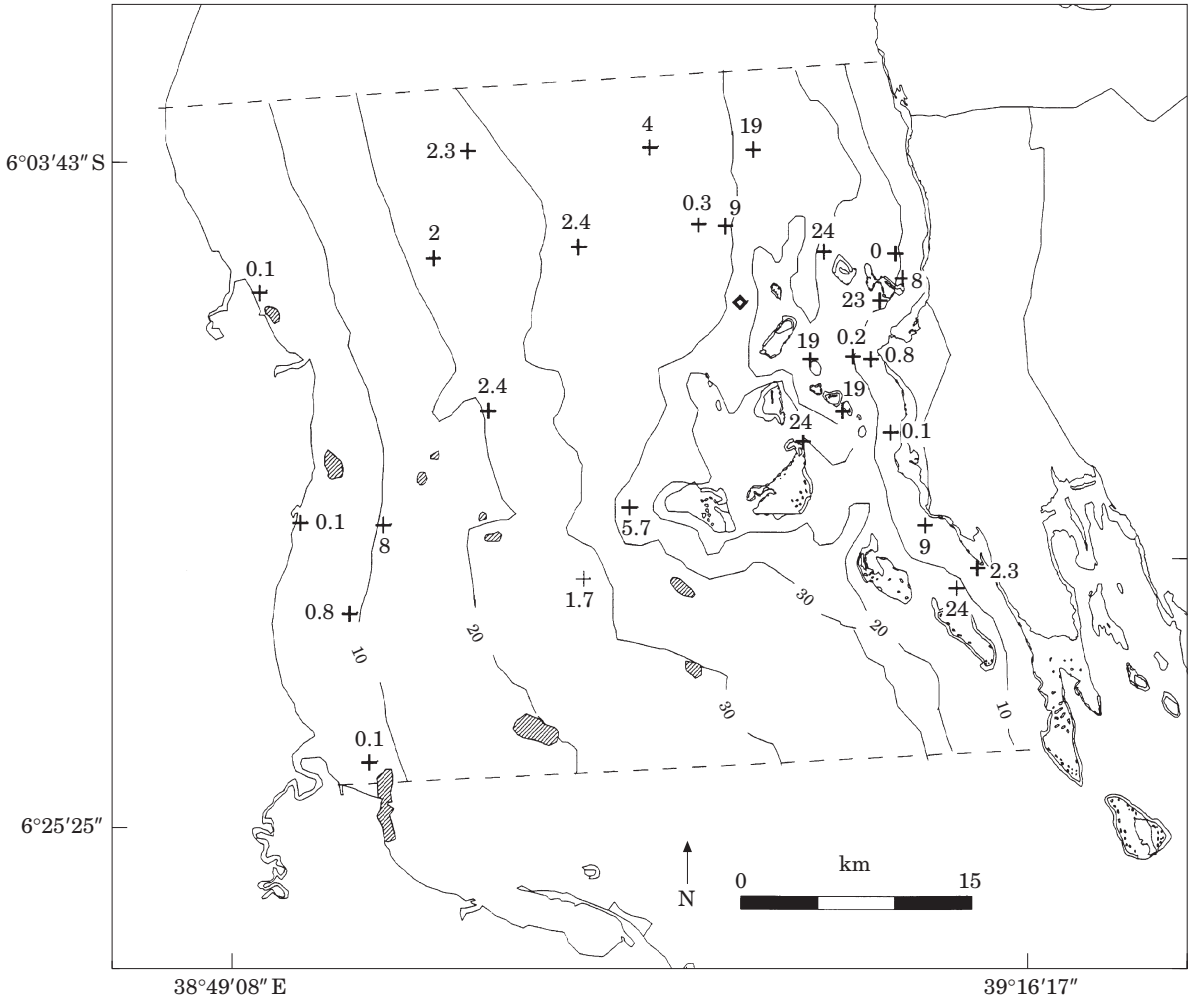


FIGURE 3. Distribution map of the biogenic:quartz ratio in the three bio-physiographic zones. The bathymetric isolines (m) are modified after Shaghude and Wannäs (1998) and the biogenic:quartz ratios were calculated using the data in Table 1.

components over silici-clastic components in the samples. The samples from the coastal zone have the lowest (<2) biogenic:quartz ratios; reflecting the higher influence of the silici-clastic components in the samples. The biogenic:quartz ratios in the central channel zone generally lies between the two extremes (more than two but less than 10) which probably reflects the mixing between the coastal zone sediments and the reef platforms/patch reef sediments.

A few exceptions to the above general trends are evident, namely, in sample Nos. 7 and 39 (coastal zone samples), sample No. 1 (a central channel sample) and sample No. 37 (a reef platform/patch reef sample). The two coastal zone samples have higher than expected biogenic:quartz ratios and so does the central channel sample, while the reef sample has a lower than expected value. The higher values for samples Nos. 39 and 7 are attributed to the fact that the samples are collected near the fringing reef and reef platform respectively at Zanzibar Island. It is unclear why sample No. 1 has a biogenic:quartz ratio similar to reef platforms/patch reef samples. While sample No. 37 is identified as a reef platform/patch reef sample it is about equidistant from the shore and the nearest patch reef.

The physiographic setting of the reef platform/patch reefs on the western side of the channel is slightly different from the physiographic setting of the reef platform/patch reefs zone on the eastern side of the channel. The western side of the channel is characterized by patch reefs rather than reef platforms which characterize the eastern side of the channel. We statistically compared the samples again, with the three reef platform/patch reef samples (Nos. 36, 37 and 50) on the western side of the channel excluded from the reef platforms/patch reef samples and

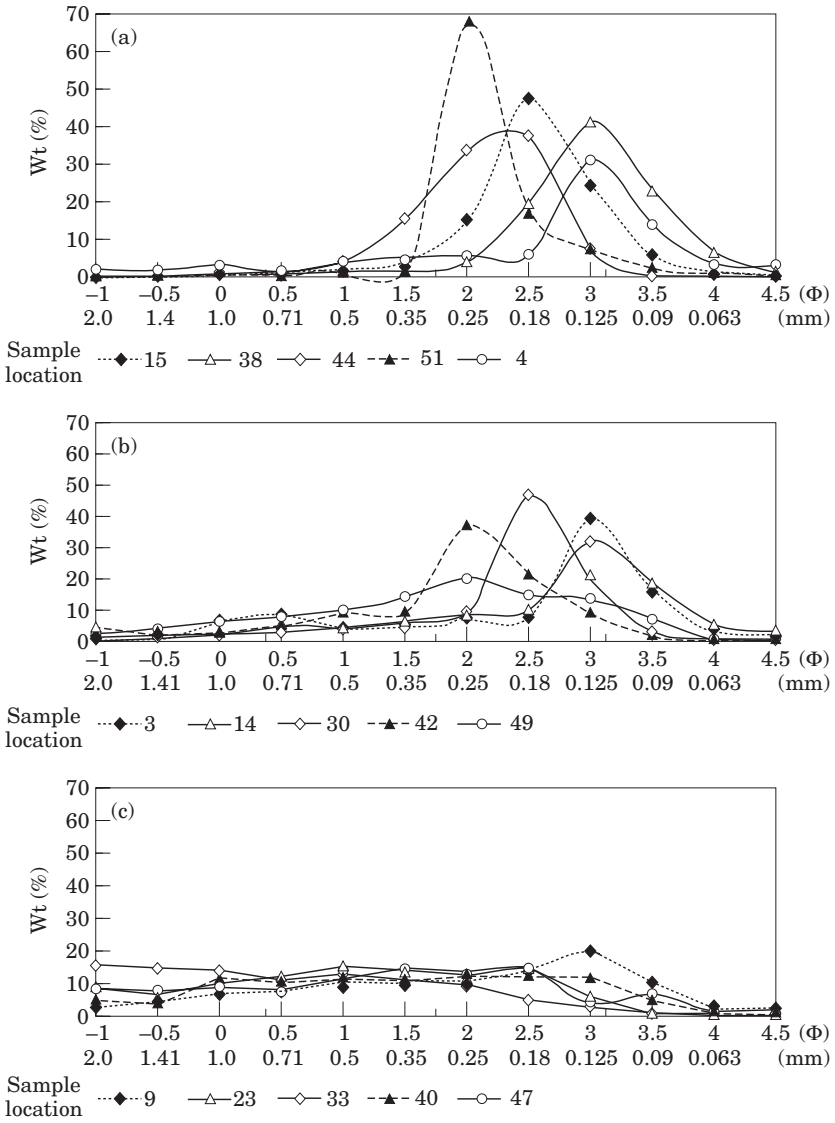


FIGURE 4. Grain size frequency curves for representative samples along north–south profiles in each of the three bio-physiographic zones. (a) coastal; (b) central channel; (c) reef platforms/patchreefs.

assigned to the central channel zone. The results did not differ from the previous results, suggesting that the 'depth definition' in the model is robust.

Figure 4(a–c) shows the grain size frequency curves for the samples taken along three north-south profiles representing each of the three bio-physiographic settings. In Figure 1, the samples for the idealized profiles are marked by a cross attached below the symbol for the sample location. The coastal zone samples [Figure 4(a)] are characterized by frequency curves with a prominent fine mode (between 0·25 and 0·125 mm) which reflects the influence of silici-clastic sediments from the land. The samples of the central channel [Figure 4(b)] look similar to the coastal zone samples in that they also have a prominent fine mode (between 0·25 and 0·009 mm), but the grain size distribution of most samples from the central channel have in addition a coarse tail.The nature of the sample of the central channel zone reflects the possibility of mixing between the coastal zone and reef platforms/ patch reef zone sediments. The samples from the reef platforms/patch reefs zone [Figure 4(c)] are on the other hand, characterized by more or less flattened curves with a broad, indistinct modes. The absence of a prominent fine mode in the reef platforms/patch reef zone is attributable to the fact that the reef zone receives insignificant proportion of silici-clastic sediments. The grain size frequency curves discussed above are comparable to the grain size frequency curves discussed by Shaghude and Wannäs (1998).

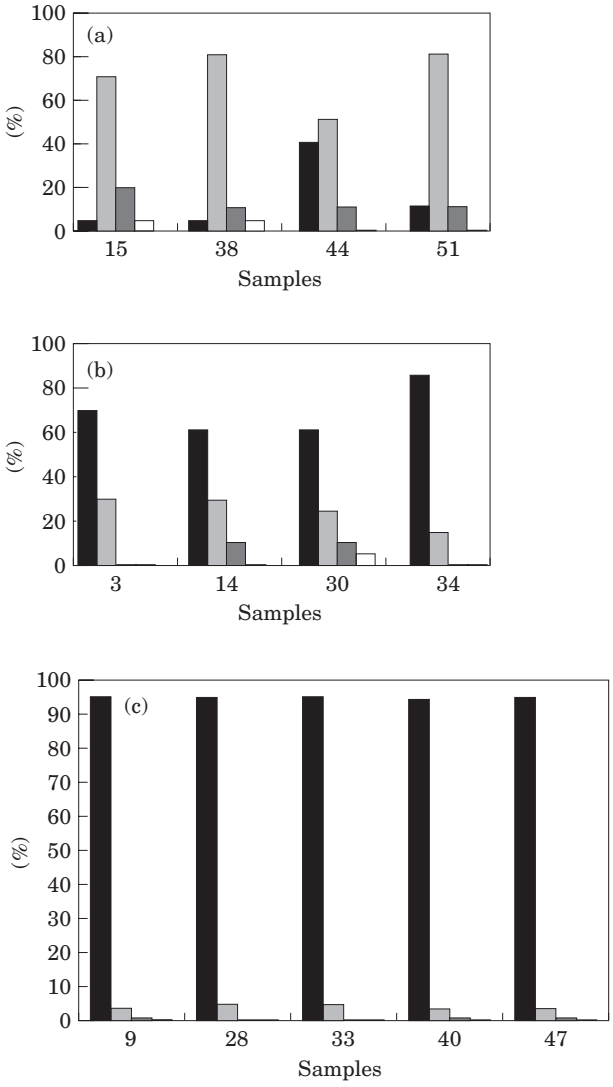


FIGURE 5. Histograms illustrating the mineralogical and biogenic abundance in representative samples along north–south profiles in the three bio-physiographic zones. Note that samples Nos. 4 and 49 were not analysed for mineralogy. (a) coastal; (b) central channel; (c) reef platforms/patchreefs. Biogenic=black; hornblende=white; quartz=light grey; feldspar=dark grey.

Figure 5 illustrates the mineralogical composition in thin sections of the samples discussed in the above north–south profiles (excluding samples Nos. 4 and 7 which were not analysed). As can be seen from the figure, a distinction among the three bio-physiographic zones is also evident. The coastal zone samples [Figure 5(a)] generally contain a significant proportion of at least two of the three mineral components, quartz, feldspar and hornblende with quartz (the leading mineral component) in most cases being at least 45%. The biogenic component is generally less than 40%. The central channel samples [Figure 5(b)] contain significant proportions of at least one of the three mineral components; quartz, feldspar and hornblende with the leading mineral group, quartz, varying between 15 and 30%. The biogenic component is generally higher than in the coastal zone samples (50–80%). The reef platforms/patch reef samples [Figure 5(c)] are generally dominated by the biogenic components (>90%) and contain very low proportions (<10%) of any of the three mineral components.

Thus, there appears to be three bio-physiographic zones: the coastal zone consists of the sea bottom adjacent to the Tanzania mainland/Zanzibar Island and receives significant fine silici-clastic sediments from the land. On the eastern side of the channel the coastal zone is very narrow (<2 km width), probably owing to the steepness and irregularity in the topography, for this side of the channel has been influenced by a different tectonic development history and also receives less silici-clastic sediment from the land (Shaghude & Wannäs, 1995, 1998). However, on the western side of the channel, the coastal zone is relatively wider (at least 5 km wide) as it receives more silici-clastic sediments from the mainland through the two major rivers, the Ruvu and the Wami.

The sediments in the coastal zone are dominantly fine sand. The proportion of benthic foraminifera is generally lowest in this zone (Table 3), averaging to 35–45%. The proportion of other biogenic groups may also differ from the other zones but the present data could not confirm this observation. The lithogenic fraction in the coastal zone samples is generally higher than in the other two zones (Table 4), constituting at least 25% of the sediment. The biogenic: quartz ratios in the coastal zone are very low (<2). The sediments are characterized by three mineral components, quartz, feldspar and hornblende, and all of them occur in significant proportions. Quartz, is generally higher than 45%, and the biogenic component in the samples is generally lower than 40%.

The reef platform/patch reef zone comprises the sea bottom between 10–20 m depth. Numerous Pleistocene coral platforms and carbonate sand banks characterize the eastern side of the channel. On the western side of the channel, coral platforms are missing and are instead replaced by patch reefs. The reef platform/patch reef is generally shallow with low siltation of terrigenous sediments. The shallow water and low siltation are considered important factors for coral growth (Muhando, 1997; Semesi *et al.*, 1999; Wagner, 1999; Wilkinson *et al.*, 1999). The reef platform/patch reef zone generally contain coarse to medium sand (Shaghude & Wannäs, 1998). The proportion of benthic foraminifera in the sediments is

generally more than 80% (Table 3). Other less common biogenic groups include pelecypods (>5%), corals (>4%), and gastropods (>1%). Each of the remaining biogenic groups (bryozoans, ostracods and sea urchins) and lithogenic materials are found in insignificant proportions (<1%). The biogenic:quartz ratios of the sediments in the reef platforms/patch reefs zone is generally very high (>10). All the lithogenic minerals (quartz, feldspar and hornblende) abundant in the coastal zone are insignificant in the reef platform/patch reef zone, instead, biogenic components constitute the bulk of the sediments (>95%).

The central channel zone which comprises the sea bottom deeper than 20 m is characterized by fine to medium grain sized sand (Shaghude & Wannäs, 1998) with a prominent fine sand mode and a coarse tail. The proportion of benthic foraminifera in this zone is generally between 70–75%. Less common biogenic groups include pelecypods (>5%), gastropods (>3%), corals (>1·5%) and bryozoans (>1%). The lithogenic materials in the sediment average between 5 and 20%. The biogenic quartz ratio in the sediments is intermediate between the other two zones. The sediments also contain significant proportions of at least one of the three mineral components, quartz, feldspar and hornblende with, quartz, varying between 15 and 30%. The biogenic component is generally higher than in the coastal zone samples (50%–80%) but lower than in the reef zone.

Conclusions

The carbonate components of the sediments are dominated by benthic foraminifera, which average between 65 and 70%. Other common biogenic groups are molluscs (pelecypods and gastropods) and corals. The bryozoans and ostracods are less common and sea urchins are minor. We propose a simple model for distinguishing three bio-physiographic settings in the Zanzibar Channel on the basis of depth contours as follows: (1) the coastal zone (0–10 m depth), (2) the reef platforms/patch reefs zone (10–20 m depth); and (3) the central channel zone (>20 m depth).

The silici-clastic components of the Zanzibar Channel sediments are dominated by quartz, feldspar and hornblende, with quartz being primary. Zircon, muscovite, augite and biotite occur as accessory components. The silici-clastic sediments west of the channel are derived from the metamorphic Precambrian rocks of the Mozambique belt and find their way into the sea via two major rivers, Ruvu and Wami. The silici-clastic sediments east of the channel are re-worked sediments derived from Masingini Ridge sandstones, north of Zanzibar Town.

The coastal zone is generally characterized by fine sand with a very prominent fine mode, with a relatively low proportion of benthic foraminifera (25–45%). The lithogenic fraction in the coastal zone samples is generally higher than in the other two zones (>25%) and biogenic:quartz ratios are very low (<2). the mineralogical assemblage in the sediments is characterized by quartz, feldspar and hornblende, with quartz dominant.

The reef platform/patch reef zone is characterized by coarse to medium sand with no significant mode. The lithogenic fraction in the reef sediments is lower than in the other two zones and the biogenic: quartz ratios are higher (>10). The proportion of benthic foraminifera in the sediment is more than 80% and all three lithogenic minerals are insignificant.

The central channel zone is characterized by medium to fine sand, with a coarse tailed distribution and a fine mode (between 0·25 and 0·009 m). The proportion of lithogenic components are higher than in the reef platform/patch reef zone but lower than in the coastal zone (5–20%) and the biogenic:quartz ratios are intermediate between the two extremes. The proportion of benthic foraminifera in averages between 70–75% and at least one of the three lithogenic minerals occurs in significant proportions. The biogenic proportion in the sediments is higher than in the coastal zone but generally lower than in the reef zone.

The present model did not discuss the energy regime of the three bio-physiographic zones suggested due to lack of oceanographic studies in the Zanzibar Channel. Comparing oceanographic data such as tides, ocean currents and wave dynamics with the three bio-physical zones would obviously enhance the model presented. It is therefore suggested that future research projects be directed towards collecting such basic oceanographic information across the channel. In the absence of such oceanographic data, only a few general comments can be discussed, concerning the expected energy regime in the three bio-physiographic zones. The EACC which is reported to be influenced by the seasonal monsoon winds (Newell, 1957) could be more effective in the central channel zone than in the other zones which are generally shallow. In the near shore areas the EACC is modified by tides (Mohammed *et al.*, 1993) and so the tides are probably important in these shallow areas. The reef platforms are also expected to modify the wave energy approaching the shore due to diffraction and refraction, causing the wave energy to be concentrated in some areas.

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Appendix

Sediment samples from Shaghude and Wannäs (1998) used for this study. X, Y=samples UTM coordinates, 1 to 55=samples indexes; their provinces defined by bathymetry [<10 m=Coastal (C), 10–20 m=reef platform/ patch reefs (R), >20 m=central channel (CH)].

No.	Sample	X	Y	No.	Sample	X	Y
1 (CH)	ZC1	512949	9331350	29 (CH)	ZC31	501104	9315617
2 (CH)	ZC2	506476	9331394	30 (CH)	ZC30	493668	9315556
3 (CH)	ZC4	491586	9331403	31 (C)	B7	521667	9314211
4 (C)	ZC6	479572	9331405	32 (R)	ZC23	518479	9310213
5 (C)	B1	523291	9326019	33 (R)	ZN65	516102	9313734
6 (c)	ZN22	522397	9324793	34 (CH)	ZC25	505169	9309612
7 (c)	ZN8	522959	9322483	35 (CH)	ZC26	498813	9309177
8 (R)	ZN13	520902	9326738	36 (R)	ZC27	493212	9308653
9 (R)	I2	521355	9322813	37 (C)	ZC28	489800	9308653
10 (R)	ZC11	517376	9325141	38 (C)	ZC37	484383	9308653
11 (CH)	ZN30	511926	9322521	39 (C)	ZN81	523818	9308581
12 (CH)	ZC13	512165	9322086	40 (R)	I5	519191	9306252
13 (CH)	ZN21	509499	9326738	41 (CH)	ZC22	514922	9307191
14 (CH)	ZC8	492684	9324682	42 (CH)	ZC20	502221	9305300
15 (C)	ZC43	481745	9322646	43 (CH)	ZC19	494971	9304183
16 (C)	ZN39	520337	9320444	44 (C)	ZC18	487486	9303205
17 (R)	ZN37	518480	9320587	45 (C)	ZN86	526934	9305820
18 (R)	ZN35	515764	9320376	46 (C)	ZN87	526365	9305514
19 (R)	I8	514478	9320550	47 (R)	ZN88	525852	9305430
20 (C)	ZN53	520492	9318821	48 (R)	14	521238	9304577
21 (R)	ZN54	519397	9318904	49 (CH)	ZC14	505232	9300951
22 (R)	ZN56	517438	9318822	50 (R)	ZC15	498412	9298232
23 (R)	ZN57	516658	9318749	51 (C)	ZC17	488736	9294243
24 (CH)	ZN60	512379	9318871	52 (CH)	ZN20	511201	9326723
25 (CH)	ZN52	510177	9319076	53 (CH)	ZC9	501991	9325360
26 (CH)	ZC34	519735	9315757	54 (R)	ZN7	523438	9322483
27 (R)	ZC33	514535	9315617	55 (C)	ZC44	480655	9323772
28 (R)	I7	518646	9315570				