J. Asiat. Soc. Bangladesh, Sci. **52**(1): 45-59, June 2026
DOI: https://doi.org/10.64298/jasbsci.v52i.004

DECIPHERING PALEO CORAL REEF DYNAMICS USING THE FORAM INDEX IN ST. MARTIN'S ISLAND, BANGLADESH

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Abstract

Coral reefs at St. Martin's Island represent a vital coastal ecosystem in Bangladesh and are increasingly threatened by a variety of anthropogenic and climatic stressors. The present study investigates the paleoenvironmental conditions associated with fossil coral reefs on the St. Martin's Island using FORAM Index (*FI*) and foraminiferal assemblages. Coral fossil samples were collected from the island at different depths, and subjected to ^{14}C dating. Sediments were also analyzed for foraminiferal composition and *FI* calculation. The obtained results specify two distinct phases of coral development on the island. The first phase occurred in between 2058 and 1866 BP, while the second phase sustained from 1290 to 797 BP. Hallock's *FI* was calculated for both phases of corals development to evaluate the water and sediment quality of the coral habitat. The obtained result shows that the value of the first cycle is 2.71, indicating marginal environmental conditions for reef growth. In contrast, *FI* values for the second cycle are 1.74-1.98, suggesting conditions unfavorable for reef development and recovery. Among the three functional groups of foraminifera, Heterotrophic were most abundant (>80%) followed by Opportunistic (6-17%) and Symbiont Bearing (2-10%) in both the cycle. The decreasing FI values over time signify a gradual deterioration in environmental conditions in the coral habitat. The findings elucidate the paleoenvironmental history of St. Martin's Island and illustrate the utility of benthic foraminiferal assemblages and the *FI* in reconstructing past reef conditions.

Key words: Coral reef, Foraminifera, Paleoenvironment, FORAM Index.

Introduction

Coral reefs are dynamic coastal ecosystems that provide necessary services and resources to tropical and subtropical maritime nations (Costanza *et al.*, 1997). However, various natural and anthropogenic disruptions are responsible for declining of coral habitat globally (reviewed in Hoegh-Guldberg *et al.*, 2007; Richmond 1993). The deterioration of coral reefs might indirectly result in human prosperity owing to ecological imbalance

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(Hallock *et al.*, 2003). If effective and sustainable management is not implemented, it is projected that 15% of global coral reefs would be lost within next 20 to 40 years (Knowlton and Jackson, 2008; Bellwood *et al.*, 2004). The coral reef ecosystem primarily comprises coralline algae and scleractinian corals, with foraminiferal assemblages significantly contributing to this ecosystem (Chen and Lin, 2017). Foraminifera and coral assemblages are affected by similar kind of environmental variables. Natural stressors such as temperature and light conditions that are responsible for coral bleaching, may also affect foraminiferal assemblages. Moreover, foraminifers have a short lifespan in contrast to the longevity of colonial corals which aids in distinguishing between prolonged deterioration in water quality and episodic stress events (Hallock *et al.*, 2003). Over the last ten years, benthic foraminiferal assemblages have been utilized as rapid and reliable indicators for assessing coral reef conditions (Cooper et al. 2009). They also have been used to assess coral reef water quality in Florida and the Caribbean Sea (Hallock, 2000; Hallock *et al.*, 2003), the Great Barrier Reef (Uthicke and Nobes, 2008), and the Hawaiian Islands (Smith *et al.*, 1981). Therefore, foraminifera cannot precisely forecast the paleoenvironment of coral colonies, but a significant correlation can be made between the two assemblages. Hallock *et al.* (2003) created the Foraminifera in Reef Assessment and Monitoring (FORAM) Index (FI), a numerical metric that links reef health and water quality. If the water and sediment quality is the key environmental constraint, the number of symbiont-bearing foraminifera should track the coral growth (Natsir and Subkhan, 2011).

This relationship enables the evaluation of environmental quality in relation to coral health through the use of foraminifera as well as the calculation of *FI*. However, it should be noted that the values only represent sediment and water quality (Hallock *et al.* 2003). Since foraminifera are not affected by many coral specific diseases and exhibit rapid recovery from bleaching and storms events, the *FI* does not capture stressors such as bleaching events, thermal anomalies, physical storm damage, or coral diseases (Schueth and Frank, 2008).

The applications of the *FI* in diverse reef settings has revealed the effectiveness of foraminifera as dependable bioindicators of reef conditions in regions such as the Aegean Sea (Koukousioura *et al.*, 2011), Colombia (Velásquez *et al.*, 2011), Brazil (Barbosa *et al.*, 2012), Florida (Carnahan *et al.*, 2009), the Great Barrier Reef (Nobes and Uthicke, 2008), Belitung Islands, Indonesia (Natsir and Subkhan, 2011), Dongsha atoll lagoon, South China (Chen and Lin, 2017).

It has long been known that coral islands, such as Saint Martin's in Bangladesh, are particularly sensitive to the effects of climate change and anthropogenic environmental stress (Ahmed *et al.,* 2023 and references therein). Saint Martin Island is separated from the main land of Bangladesh and has a distinct flora and fauna (Hasan, 2009). It is a sedimentary continental island with a dumb-bell form, encircled by a coastal environment which supports the growth of coral colonies (Hossain and Islam, 2006; Tomascik, 1997). This island supports 10 of the 15 known reef-building scleractinian coral families, encompassing approximately 22 genera and 66 species. 39 species among these have been found to inhabit the surrounding reef ecosystem (Thompson and Islam, 2010). The island's eastern part has three dead coral colonies, while the western coast has one colony (Mondal *et al.,* 2018). Over the past ten years, St. Martin Island has grown to be one of Bangladesh's top tourist destinations. Due to the tourism industry, it has recently become a rapidly expanding economic area. The growth of unplanned industrialization, emerging tourism, and urbanization drive microplastic and trace elements pollution on St. Martin's Island (Tajwar *et al.,* 2022, 2026; Saha *et al.,* 2024). As a result, the ecosystem and natural surroundings are continuously deteriorating at an alarming rate (Alam *et al.,* 2015). Foraminifera can be used as a biomonitoring tool to assess environmental quality degradation (Bouchet *et al.,* 2012). However, no known study has yet assessed these environmental changes using biomonitoring methods, either on St. Martin's Island or elsewhere along Bangladesh's coastline.

This study aims to infer their benthic environment using the *FI* as a biomonitoring tool as well as to ascertain the ages of these fossil coral colonies. The *FI* offers an efficient and practical approach for assessing whether benthic settings are suitable for communities controlled by algal symbiotic organisms. Moreover, the abundance of foraminifers in the study area enables quick collection of statistically significant sample sizes in an economically viable manner, making it suitable for integration into comprehensive environmental monitoring programs.

Study area: St. Martin's Island is located at the northeastern margin of the Bay of Bengal, 9 km south of the Cox's Bazar-Teknaf peninsula and 8 km west of the northwest coast of Myanmar, near the mouth of the Naf River. Geographically, the Island extends between latitudes 20°34´ to 20°39´N, and longitudes 92°18´ to 92°21´E

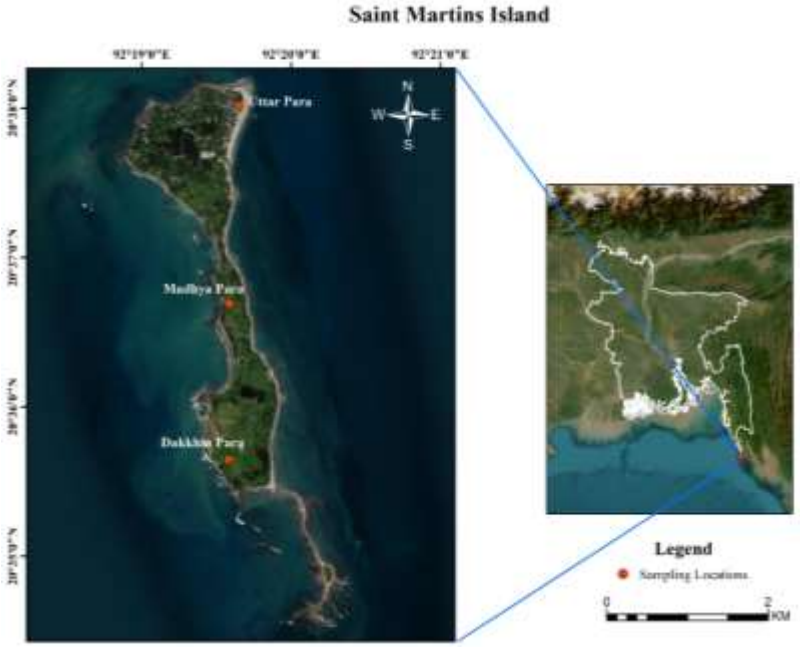


Fig. 1. Location map of St. Martin's Island highlighting sampling location.

The island is roughly 7.315 km in length, oriented in an NNW-SSE direction. It has an area of about 8 km^2, which changes with tidal variations. It is characterized by an almost flat topography, with a mean elevation of about 2.5m above mean sea level (MSL), and a maximum reaching up to 6.5m. The island is apart from the mainland by a shallow 9.66 km wide channel. (Thompson, *et al.*, 2010).

Materials and Methods

This study involves a combination of field investigation, laboratory analysis, and interpretation.



Fig. 2. Sequence of analytical procedure.

Fieldwork and sampling: Extensive fieldwork was carried out in St. Martin's Island during the month of March, 2018. The island was broadly divided into three sections and samples were taken with the help of a hand-drilled auger. The total investigated depth was 2.5m as auger couldn't be penetrated below that depth due to the hard Miocene rock which is considered the bedrock of the island by many authors. Fossil coral samples were taken at different depths from the dug wells which are used by the local people as water sources. Collected samples were carried in an individual plastic bag labeled with their respective locations and depths.

Table 1. Sampling locations and depths.

Sample ID	Location Name	Latitude	Longitude	Depth (m)
SM-01	Dakkhin Para	$20^0$35´38.9´´	$92^0$19´34.9´´	1.5
SM-02				2.5
SM-03				0.06
SM-04	Uttar Para	$20^0$38´01´´	$92^0$19´39.0´´	1.5
SM-05				1.0
SM-06				0.5
SM-07	Madhya Para	$20^0$36´41.6´´	$92^0$19´35.3´´	1.0
SM-08				1.5

Sample preparation: At first the samples were washed with clean water to remove the unwanted materials. Then every sample was put into an individual beaker and oven-dried at 100^0C for 30 minutes. After drying, the samples were crushed carefully with a rubber hammer so that the grains do not stick together and get ready for sieving. A 100gm subsample was weighed and placed in a stack of ASTM sieves (0.5mm = 1Φ, 0.25mm = 2Φ, 0.125mm = 3Φ, 0.063mm = 4Φ and <0.063mm= >4 Φ) and mechanically shaken for 15 minutes. Each mesh number's retained grain weight was measured and tallied. Following sieving, the grains were stored in separate plastic bags marked with the mesh number and retained weight.

A possible constraint of the preparation method is that drying and mechanical disaggregation may selectively harm delicate foraminiferal tests. Sensitive taxa might therefore be possibly underrepresented in the assemblages that were recovered.

Extraction of microfossils and microphotography: In order to extract various Foraminifera species, the sieved samples were placed onto a gridded picking tray and closely inspected under a 10x100 magnification microscope. After that, the specimens

were moved into the Chapman slide (assemblage slide) using a brush and determined under a microscope. When this is completed for every specimen within a particular sample, they can be counted. The counted split fraction may return to an adequately labeled storage vial. Every counted specimen was examined under LEICA EZ4E stereomicroscope with 35x magnification for high-resolution images.

Taxonomic approach: Various morphological attributes such as test type, chamber number, shape and formation, aperture position and inclination, ornamentation, and additional chamber were examined carefully under the microscope. A number of previous studies on the identification of Foraminifera were reviewed. For the detailed taxonomy studies the image plates from Loeblich and Tappan (1964) and Cushman (1928) were used as a reference to classify the recorded foraminifera assemblages. Subsequently, systematic examination and quantitative analyses were performed further to determine the abundance of the foraminiferal assemblages. The comparatively low total number of specimens restricts statistical confidence and might not adequately represent assemblage variability. Future investigations with expanded sample volumes and higher specimen counts are advised.

Development of FORAM Index: The *FI* was calculated according to the approach proposed by Hallock *et al.* (2003). In this method, foraminiferal assemblages are classified into three functional groups; opportunistic taxa, symbiont-bearing taxa, and other small heterotrophic taxa. The basic principle of the *FI* is that symbiont-bearing taxa proliferate in similar environmental conditions that are suitable for coral formation. Opportunistic taxa are pollution tolerant and proliferate in a high-stress condition where the concentration of oxygen is low. Small heterotrophic taxa are abundant when there is high availability of nutrients and oxygen concentration in the environment.

To develop the *FI*, foraminiferal assemblages were classified into genus levels and separated into three functional groups. The proportional contribution of each functional class was determined by dividing the quantity of specimens in each group by the overall number of specimens in the sample.

The *FI* then computed following the formulation proposed by Hallock *et al.* (2003):

$$FI = (10P_s) + (P_o) + (2P_h).$$

where,

$P_s = {}^{N_s}/_{T}$; with N_s representing the number of symbiont-bearing foraminifera,

$P_o = {}^{N_o}/_{T}$; with N_o representing the number of opportunistic foraminifera,

$P_h = {}^{N_h}/_{T}$; with N_h representing the number of other small heterotrophic foraminifera.

T = total specimens counted

The *FI* values were interpreted according to the following ranges:

- *FI* > 4: Environment favorable for reef growth.
- 3 < *FI* < 5: Indication of environmental change or transitional condition (Coefficient of Variation > 0.1).
- 2 < *FI* < 4: Environment is marginal for reef growth, generally unsuitable for recovery.
- *FI* < 2: Stressed environmental conditions, unsuitable for reef development.

Carbon dating of selected samples: During the investigations, coral fossils were collected from the island at different locations and at different depths. At some places of Uttar Para, coral fossils were exposed at the surface or very close to the surface whereas at some locations of Dakkhin Para they were found at a depth of 1.5m to 2.5m. Four coral fossils were selected for radiocarbon dating, as ^{14}C is widely applied to marine carbonate materials and provides reliable fossil corals age estimation. The selected samples were sent to the laboratory "Beta Analytic Inc.", Miami, Florida, USA for analysis.

Prior to analysis, the samples underwent standard pretreatment procedures. The outer portion of the shell was removed to eliminate potential secondary carbonate. Physical pretreatment of samples involves removal of visible impurities without the use of any chemicals as well as size reduction. The outer layers were abraded using a drill and corundum paper to isolate aragonite. Recrystallized calcite, which is white and chalky, considered a contaminant and removed during this process. After that, the samples were passed through the process of "Delta+ R correction". After that at least 5-10mg of samples have been used to measure $\delta^{13}C$, an isotopic signature representing the ratio of stable isotopes ^{13}C to ^{12}C, expressed in ppt (Libes, 1992).

Results and Discussion

Investigations based on radiocarbon dating: The obtained result suggests the presence of two dead coral colonies on the island. The first colonies have an age of 2058-1866 BP which are found at Uttar para at about 1.5 m depth.

Table 2. Radiocarbon dating chart of selected coral samples.

Sample No.	^{14}C age yr BP	95.4 % (2σ) cal age ranges	δ13C (‰)	δ18O (‰)	Pretreatment
1.	1350 ± 30 BP	988–1153 cal AD 962–797 cal BP	-2.1	-4.91	Acid Etch
2.	1560 ± 30 BP	730–916 cal AD 1220–1034 cal BP	-3.0	-4.57	Acid Etch
3.	2340 ± 30 BP	109 cal BC – 84 cal AD 2058–1866 cal BP	-3.5	-5.84	Acid Etch
4.	1670 ± 30 BP	660–784 cal AD 1290–1166 cal BP	-1.9	-5.06	Acid Etch

The second colonies clustered at around 1290 BP and continued up to 797 BP which are found at 1.5 m depth at Dakkhin para and near the surface at Uttar Para. There is a distinct time gap between these two cycles which is approximately 700-1000 yrs.

Environmental Monitoring: FORAM Index: Quantitative analysis of foraminifera collected from the associated sediments of fossil coral colonies shows 300 specimens. Among them, 299 specimens are benthic foraminifera and only 1 is planktonic foraminifera.

Relative abundance of foraminiferal genera shows that Astrorhiza (12.56%) and Elphidium (9.86%) are present in all samples collected from the three sections and have higher relative abundance. Eponoides is also present in all samples though its relative frequency is low (7.14%). Other genera that are present in almost all samples are Robulus (9.18%), Cyclammina (8.16%), Triloculina (6.46%) and Trochammina (5.44%).

Among the identified 38 genera of benthic foraminifera, 29 small heterotrophic genera, 6 pollution tolerant opportunistic genera and only 3 large symbiont bearing foraminiferal genera were identified.

The three sampling sites show different percentages of functional groups at different times. The variations are likely due to differences in substrate type and other environmental factors. The associated sediments with cycle-1 corals have higher percentages of the heterotrophic group (84%). Symbiont-bearing foraminifera constitute 10%, while opportunistic species account for 6.45%. Associated sediments with other different ages of corals belonging to cycle-2 also show a higher percentage of the heterotrophic group (81-87%). But the opportunistic group is in higher percentage (10-17%) than the symbiont bearing group (2-3%) in the associated sediments of these coral colonies.

Table 3. Identified foraminiferal genus and their frequency of occurrences in the study area.

Sl. No.	Foraminiferal genus	Dakkhin para section		Uttar para section			Maddhya para section		
		SM01	SM02	SM03	SM04	SM05	SM06	SM07	SM08
1.	*Eponoides*	4	4	1	3	2	4	2	1
2.	*Robulus*	7		4	1	4	2	9	
3.	*Cyclammina*	3	1	5	6	0	7	2	
4.	*Triloculina*	3	5	5		4	1	1	
5.	*Elphidium*	1	2	2	6	4	5	5	5
6.	*Trochammina*	3			1	4	4	2	2
7.	*Astrorhiza*	4	6	4	4	6	3	5	5
8.	*Sigmoilina*	3							
9.	*Subedentostomina*	1	1					2	
10.	*Asterorotalia*	3	1				1		
11.	*Nonionina*	2		3					
12.	*Spiroloculina*	1	3				2	2	1
13.	*Cibicides*	2	7			1			1
14.	*Gordiospira*		1	1	4				
15.	*Massilina*		2	1		2	5	2	
16.	*Discorbis*		2				1		
17.	*Cribroelphidium*		2			1	1	2	
18.	*Eponidella*		1						
19.	*Cycloclypeus*			3		3			
20.	*Agathamminoides*			1					
21.	*Hastigerinoides*				1				
22.	*Elphinoides*				1				
23.	*Operculina*				2				
24.	*Elphidella*				1	1			
25.	*Pseudohauerina*					1	1		
26.	*Involutina*					1			
27.	*Quinqueloculina*					1		6	
28.	*Anomallina*					1			
29.	*Polystomella*					2			
30.	*Ammoelphidiella*						1		
31.	*Woodella*						2	1	2
32.	*Carterina*							6	7
33.	*Truncatulina*							2	
34.	*Discammina*							1	
35.	*Caribeanella*							1	
36.	*Serpula*							1	
37.	*Gyroidina*							1	8
38.	*Calcarina*						3		1

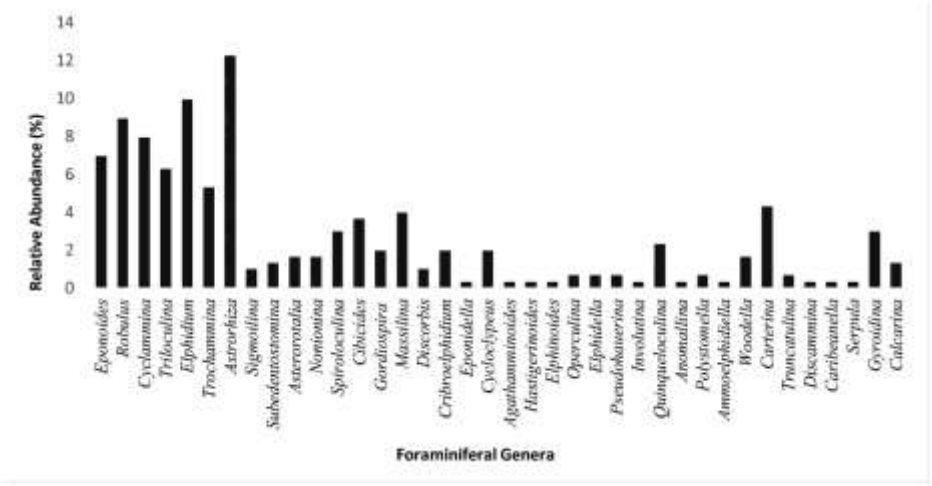


Fig. 3. Relative abundances of foraminiferal genera.

Table 4. Identified three functional groups of benthic foraminifera.

Symbiont bearing	Opportunistic	Heterotrophic
Calcarina *Cycloclypeus* *Operculina*	*Cribroelphidium* *Discammina* *Elphidella* *Elphidium* *Polystomella* *Trochammina*	*Agathamminoides, Ammoelphidiella, Anomallina, Asterorotalia, Astrorhiza, Caribeanella, Carterina, Cibicides, Cyclammina, Discorbis, Elphinoides, Eponidella, Eponoides, Gordiospira, Gyroidina, Hastigerinoides, Involutina, Massilina, Nonionina, Pseudohauerina, Quinqueloculina, Robulus, Serpula, Sigmoilina, Spiroloculina, Subedentostomina, Triloculina, Truncatulina, Woodella*

Table 5. Functional group (%) and FORAM Index values of different times.

Ages (BP)	Functional Group (%)			FORAM Index	Cycle No.
	Symbiont Bearing	Opportunistic	Other Heterotrophic		
962-797	2.7	10.81	86.49	1.74	Cycle-2
1220-1034	2.63	10.52	86.84	1.94	
1290-1166	1.85	16.67	81.48	1.98	
			Time Gap		
2058-1866	9.67	6.45	83.87	2.71	Cycle-1

The FI value of the oldest coral colonies (2058-1866 BP) is 2.71. According to Hallock et al. (2003), this environmental situation is marginal for reef growth and unfavorable for regaining. This indicates that, while water parameters may preserve the living coral community, the ecosystem lacks the resilience necessary for post-disturbance recovery. Such conditions are typical of substrate types influenced by mud rather than a stable reef ecosystem.

The second colonies (1290- 797 BP) has the FI value ranging from 1.74-1.98 which indicates that the water and sediment parametres were not suitable for new coral growth in that environment and the existent corals would gradually die down (Hallock, *et al.*, (2003). A gradual decline of FI value has been observed from cycle-1 to cycle-2.

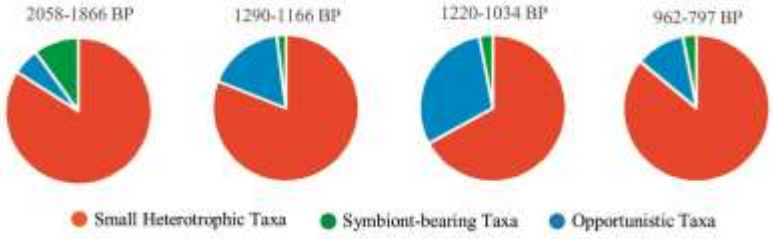


Fig. 4. Functional groups of foraminifera with the coral colonies of different ages.

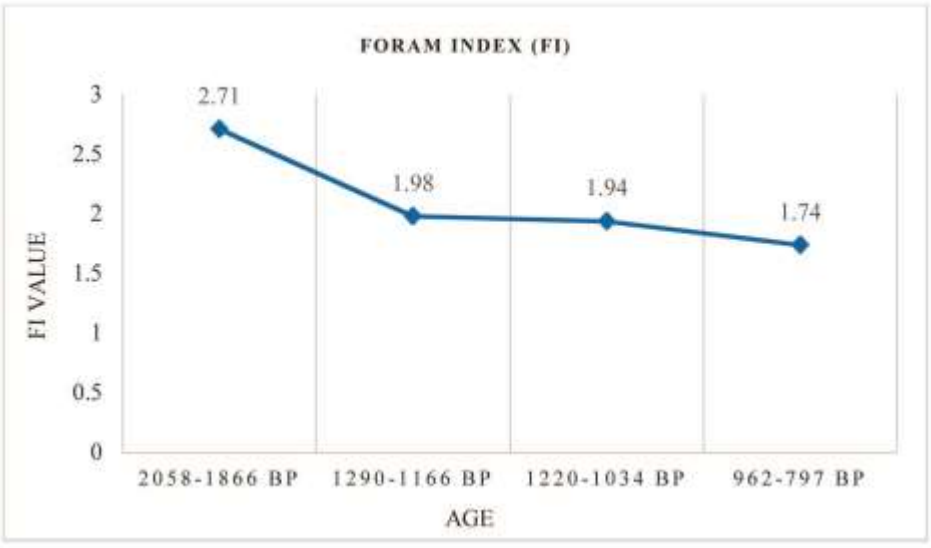


Fig. 5. Trend of decreasing FI values with time.

The results of the FORAM Index indicate that during the times represented by the dated coral assemblages, there may have been unfavorable environmental circumstances for reef persistence and recovery. During 2058-1866 BP, water and sediment quality were marginal for reef growth. This implies that while the living coral community may be sustained by the water quality in that setting, any harm to the coral cover will not be recovered. The type of substrate in these areas is influenced by mud rather than a reef environment. Environmental conditions were deteriorating gradually during the time gap between cycle-1 and cycle-2. During 1290-797 BP, the FI value decreased from 1.98 to 1.74 which indicates that the coral communities were affected by a major mortality event. Previous studies carried out in St. Martin's Island also suggest coral-killing events. Mondal et al. (2018) suggest that U-Th dating of St. Martin's Island coral indicates several coral-killing events at prehistoric time.

There are several possible causes behind the coral-killing events. During the Holocene time the earth has faced several climatic variations which resulted in sea level transgression followed by regression (Kemp *et al.,* 2011). The cyclic variations of the sea level rise and fall may have caused the growth of these coral colonies at different times. Moreover, St. Martin's island is positioned in close proximity to the tectonically active Sunda and Indo-Burma subduction systems. As a result, continuous tectonic deformation in this region plays a key role in driving relative sea-level fluctuations in the Bay of Bengal (Mondal *et al.,* 2018).

Living colonies are limited to growing only above the spring low tide level as they cannot survive extended exposure to sunlight and air (Lough and Cooper, 2011; Lough and Barnes, 2000). Elevation survey conducted on St. Martin's Island by Mondal et al. (2018) indicated that dead microatolls are situated approximately 1.8 to 2.5 m above the level of present-day living corals. There is little evidence of global sea-level changes ~2 m during the past millennium, so the elevation changes indicate local tectonics. There is also evidence of the recent uplift of St. Martin's Island due to the 1762 earthquake which is responsible for a recent mortality event of another coral colony (Mondal *et al.,* 2018). Therefore, it is reasonable to infer that, two prehistoric earthquakes that might have uplifted the island, caused the death of these two coral colonies as well. The other natural causes may include a decrease in salinity and increase in turbidity, temperature variations, annual solar radiation changes, and algal blooms, etc. which can cease the coral growth and instigate their gradual die down. However, the growth band analysis of the dead corals reveals little evidence of such oceanographic changes (Thompson, *et al.,* 2010).

The comparatively low number of foraminiferal specimens obtained and analyzed is one of the study's limitations. This restricts statistical confidence and might not adequately represent assemblage variability. Future investigations with expanded sample volumes and higher specimen counts are advised.

Conclusion

This study was an approach to investigate the paleoenvironmental conditions of dead coral colonies of St. Martin's Island. The carbon dating of coral fossils confirms the presence of two dead coral colonies on the island. The first colonies have an age of 2058-1866 BP and the second colonies have an age of 1290- 797 BP. There is a distinct time gap between the two cycles which is approximately 700-1000yrs. The time gap between these two cycles is probably due to local tectonics that interrupted the coral growth of the first cycle which needs further investigations. The FORAM Index (*FI*) of Hallock et al. (2003) was used in this study to represent the relationship of different functional groups of foraminifera with their associated coral colonies. Among the three functional groups of benthic foraminifera, *Heterotrophic* were most abundant (>80%) followed by *Opportunistic* (6-17%) and *Symbiont Bearing* (2-10%) in both the cycle. The calculated FI value for the first cycle of corals is 2.71 which can be interpreted as marginal conditions of the environment for reef association. The FI value for the second cycle varies from 1.74-1.98 in different times of the cycle which indicates a stressed condition and gradual die down of the existent coral colonies.

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(Revised copy received on 21/06/2026)