



Coastal caves on the Interview Island of Andaman Islands, India

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Abstract

By the presence of well-developed terraces on the Interview Island of Middle Andaman, we conducted an exploratory study on the Interview Island of Andaman and Nicobar Islands to understand the development of coastal caves here. During the investigation, we identified seven coastal caves on the island. Morphometric data of these study caves were used for further quantitative analysis by following the area/perimeter (A/P) and entrance width/maximum width (E/M) ratios to classify the cave types. We recognized from the results that the coastal caves could not be easily differentiated as flank margin caves based on A/P and E/M ratios. Nevertheless, based on their morphometry, we could confirm the occurrence of sea caves on the East and West coast of the Interview Island. The present study, as part of the more extensive ongoing research to conserve a cave-dwelling bird, allowed us to report and discuss the occurrence of the coastal caves, and their importance to understanding the speleological significance of the Interview Island.

Keywords Cave morphometry · Flank margin caves · Freshwater lens · Littoral caves · Simple carbonate island · Sea caves

Introduction

Seacoasts are the major geomorphic systems with abundant landforms (Lace and Mylroie 2013). They occur in different types, shapes, origins, and functions, and are the eco-tones formed at the intercept of marine and terrestrial environments (Moore 1954). Amongst the diverse array of coastlines, the rocky ones usually take part in the evolution of the coastal caves (Lace and Mylroie 2013; Wilkens et al. 2009). The classification of the coastal caves as karst and pseudokarst is by the evolutionary process and rock composition on the sea coast (Moore 1954; Mylroie and Mylroie 2013a). Karst consists of the landforms developed by the water flow system on and within the soluble rock material. Pseudokarsts are karst-like features evolved by the processes other than rock dissolution, such as lava tubes, tafoni, talus, fissures, sea caves, and arches (Palmer 2007). Karst terranes provide freshwater resources, and are fragile underground landscapes of biological and archaeological significance. The caves provide archives of natural processes that control

evolution of karst phenomenon (Mylroie and Carew 1995b; Ekmekci 2005; Audra et al. 2007; Mylroie and Mylroie 2007; Klimchouk 2013).

Geomorphologists termed the karstic caves as flank margin caves (FMC) when the dissolution of rock material forms them by the seawater and freshwater (Lace and Mylroie 2013; Mylroie and Mylroie 2007). FMCs develop at the coasts of the carbonate islands in the distal margin of the freshwater lens buoyantly supported by the marine water (Mylroie and Carew 1990, 1995a; Fig. 1). These caves evolve from inside, and the entrances are opened later by surface erosion or collapse (Mylroie 2007). These caves are indicators of the presence of freshwater underneath in the past and probably even today (Jenson et al. 2006; Mylroie and Carew 1995b). Recently, to determine properties of the freshwater lens on the carbonate islands, configuration, size, and locations of the flank margin caves were used (Larson and Mylroie 2018; Mylroie and Mylroie 2013b).

According to Moore (1954), sea caves evolve when (a) sea cliff is in direct contact with erosive forces of waves and currents, (b) exposed face of the cliff is with geological structures or textures, and (c) rock of the cliff compose resistance to the waves. However, Waterstrat et al. (2010) highlighted that variations in rock structure might not be necessary for the formation of coastal caves. The caves occur at almost all terrace levels. They are wave-cut platforms

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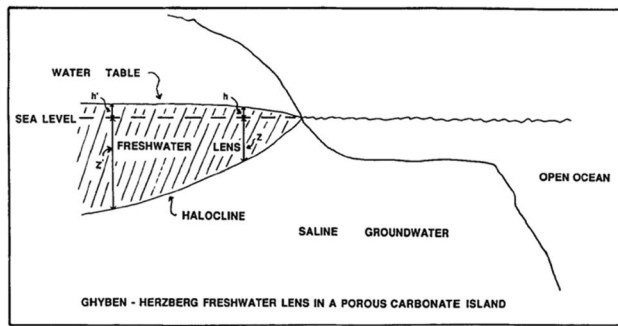


Fig. 1 Ghyben–Herzberg principle representing the freshwater lens in a porous carbonate island (adopted from Mylroie and Carew 1990)

carved during the previous sea high-stand located above the present sea cliff forming the terrace levels (Mylroie and Carew 1990; Fig. 1). Terraces are also the construction structures produced by corals, subsequently eroded by waves, and after exposure, by karst processes. These terrace levels represent relatively old sea levels still standing and, thus, long-term stability of the freshwater lens (Mylroie and Carew 1995b).

There have been archaeological explorations (Murty 1985), laboratory experiments for the possible origin of stalactites (Baskar et al. 2006, 2007), and floral and faunal diversity studies (Biswas and Shrotriya 2011) in caves of India. However, there have been rare efforts to describe the structure of the caves in the Indian tropical Islands (Mane and Manchi 2017; Sankaran 1998). Moreover, there are scarce attempts to explore the morphology of the caves in India. The present study is a part of the more extensive research to unveil cave structures as the habitat of the cave-dwelling swiftlets in the Andaman and Nicobar Islands, which allowed us to describe and report the occurrence of the coastal caves and, also, discuss their potential role to understand the speleological significance of the Interview Island.

Materials and methods

Study area

Andaman and Nicobar Island arc is located between $06^{\circ}45'9''$ N and $13^{\circ}41'9''$ N, and $92^{\circ}12'9''$ E and $93^{\circ}57'9''$ E, extending from the Arakan–Yoma ranges of Western Myanmar (Burma) in the north to Sumatra in the south (Fig. 2). The Andaman Sea flanks the archipelago in the east and Bay of Bengal in the west. Andaman and Nicobar Islands have tropical to a subtropical climate with humidity of 79–89% and temperature of 21–33 °C. These islands experience both north-east and south-west winds and rains (Rajendran et al.

2008), and the dense tropical forest dominates the region (Champion and Seth 2005). The archipelago comprises 70% Paleogene sedimentary rocks deposited on Upper Cretaceous sandstone, siltstone, and shale. Intrusions of the basic and ultrabasic igneous rocks associated with a disjointed ophiolitic suite are present. Volcanic rocks cover around 15% of the region. The remaining 85% of rocks are mostly young coralline limestone formations and colluvium. One such island, Interview Island in North and Middle Andaman district, is with the evidence of past several land uplifts along its western margin (Rajendran et al. 2008). The uninhabited Interview Island ($12^{\circ}56'17''$ N and $92^{\circ}42'31''$ E) is a westernmost island of the Middle Andaman group (Fig. 2). It is the largest Wildlife Sanctuary (133.40 km²) in the archipelago (Murthy 2007). Oldham (1885) distinguished the two sedimentary formation rocks beside the serpentine series. Interview Island belongs to the Archipelago series comprising of soft limestone formed of coral and shell and soft calcareous sandstones and soft white clays with occasional bands of conglomerates. In 1850, Quingely observed that the island comprises sedimentary formations, but the extreme west of the island is composed of igneous rocks described as ‘granite–greenstone’ (Murthy 2007).

The Andaman arc has a long history of tectonic events (Eguchi et al. 1979) because of its location in the proximity to a subduction zone west to Indonesian Archipelago (Awasthi et al. 2013; Kunz et al. 2010; Rajendran et al. 2008). The most recent Tsunami of December 2004 following the mega-earthquake M_w 9.3 in the region caused severe damage by creating around 2–3 m of land uplift in the northern part of the Andaman arc (Bandopadhyay and Carter 2017). These tectonic movements further resulted in the development of the terraces in the coastal zones. The Interview Island has the oldest and best-developed series of terraces (Awasthi et al. 2013). The 2004 earthquake caused around 2 m upliftment along both the western and eastern coasts of the Island (Rajendran et al. 2008, Fig. 3). There are 35 known limestone caves on the Interview Island (Manchi and Mane 2012; Sankaran 1998), of which 13 are coastal caves. However, we could explore and study only 7 caves of these 13 coastal caves known from the island.

Data collection

We surveyed the coastline of Interview Island using a dug-out dingy with an engine. The caves were approached by swimming or on foot. To understand their morphometry, we surveyed the caves using Distometer (Leica Disto™ S910). Cave survey considered setting-up a survey station concerning the cross-sections of the cave at each 1-m distance. We measured the morphometric parameters [distances to the Left wall, Right wall, Up and Down (LRUD), vertical angle, and azimuthal degrees] at each survey station to produce a

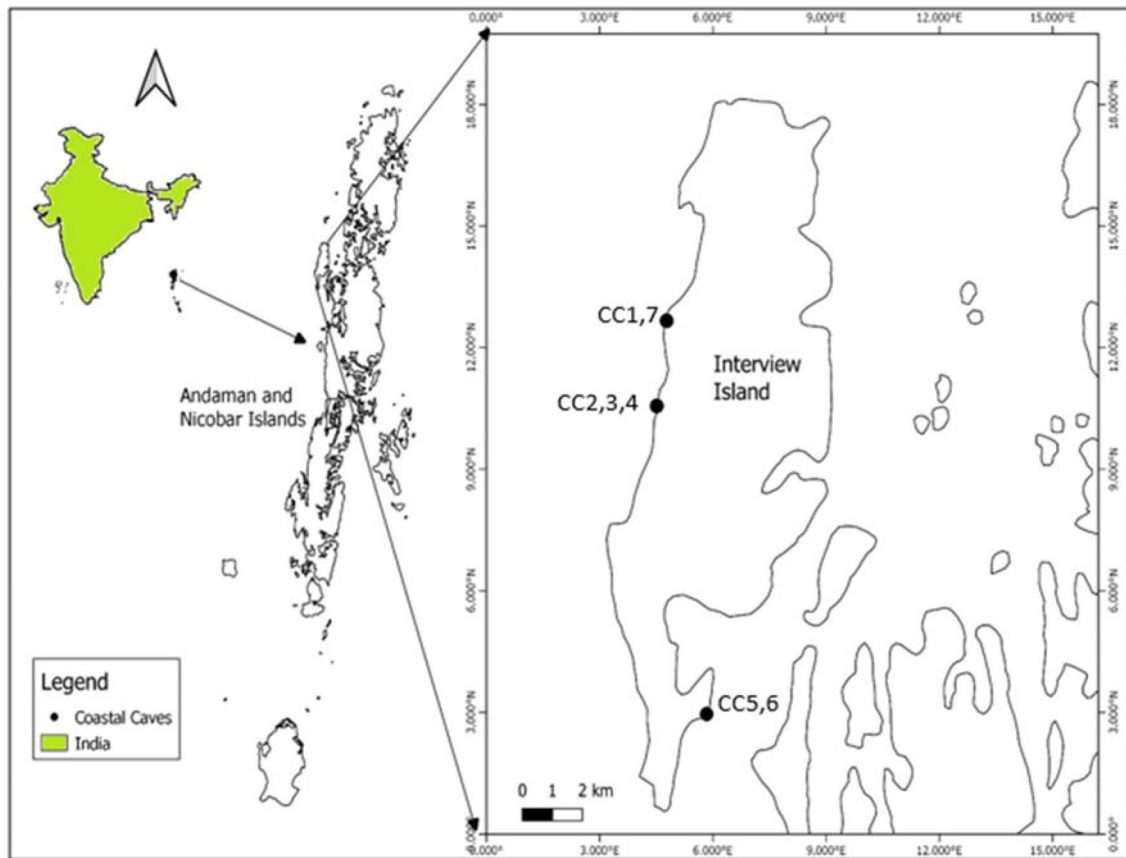


Fig. 2 The location of the Interview Island and the coastal caves (CC) surveyed



Fig. 3 Shoreline on the Western margin of the Interview Island

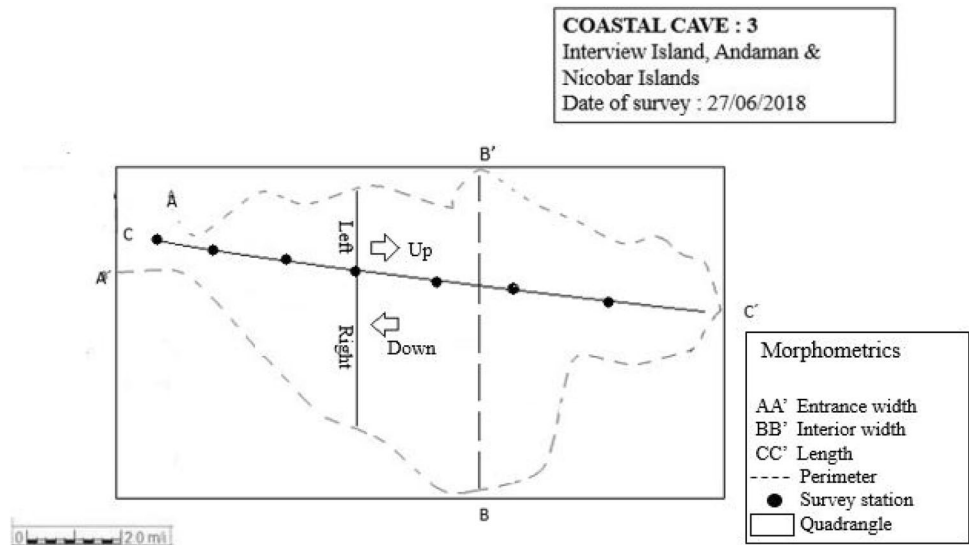
cave map (Waterstrat et al. 2010). We also noted the presence of speleothem, boulders, rock structures, water, and sand inside the caves. Towards accuracy, each inaccessible part inside the cave was measured by establishing survey stations and shooting splay shots (Myroie 2007), especially

at the corners to determine the area of cave walls, floors, and even complex shapes such as crevices. We processed the morphometric measurements using WinKarst (Ver. 12.5), Compass Project Manager (Ver. 5.18.6.29.216) software to develop two-dimensional maps of the caves surveyed. Morphometric parameters: (a) perimeter, (b) area (c) entrance width, (d) maximum width (roughly parallel to entrance measurement), and (e) the length of the axes of the smallest possible rectangle to enclose the entire cave were derived from cave map (Davis and Gamble 2006; Roth 2004; Fig. 4). We identified the FMCs by assessing the morphometric data (Roth 2004; Myroie et al. 2008; Waterstrat et al. 2010; Piccini 2011). We estimated various multiple spatial geometric parameters viz area/perimeter ratio (A/P) and entrance width/maximum width (E/M) ratios to differentiate types of caves (Piccini 2011; Waterstrat et al. 2010).

Results

Of the 13 known coastal caves (CC) on the Interview Island, we could survey only seven caves (two caves on east coast and five caves on west coast). All the caves were identified to

Fig. 4 Map of Coastal Cave 3 explaining different morphometric measurements of a cave (followed from Waterstrat et al. 2010)



be belonging to two origins sea cave and flank margin cave. We also produced to the scale maps of each cave (Fig. 5) to derive further details of the morphometry (Table 1). The spatial geometric parameters, i.e., area/perimeter (A/P) ratio and entrance width/maximum width (E/M) ratio, were used to classify the types of the caves (Roth 2004).

Area-to-perimeter ratio (A/P)

Area-to-perimeter ratio is a measure of the complexity of the perimeter for a given size (based on area) of a cave (Waterstrat et al. 2010). A linear trend line ($R^2 = 0.98$; Fig. 6a) resulted by plotting the area and perimeter of the caves suggests that surveyed caves fall in the range of small sea caves.

Entrance width-to-maximum width (E/M)

The entrance width vs. maximum width parameter (E/M ratio) is an indicator of the type of cave origin. Flank margin caves form with no entrance, and are entered only by later erosional intersection, so are expected to have small E/M values. Sea caves usually have relatively wide entrances because they form by mechanical erosion, and wave energy attenuates further into the cave, which limits littoral erosive power and typically leads to generally an inland tapering of sea caves (Moore 1954). However, FMC may have wide entrances if enough erosion has occurred to breach into a large cave chamber. The E/M ratio of the caves in Interview Island is < 1 . The small sea caves are known to have the E/M ratio ~ 1 (CC1 and CC7 have the ratios 0.91 and 0.94 respectively). The other five caves (Table 1) have much lower E/M ratio (mean = 0.37) may have littoral origins, maybe remnants of FMC's.

Discussion

Coastal karst cave development globally is biased towards the tropics and subtropics, where limestone deposition is currently ongoing and as a result, the limestones are considered eogenetic (Myroie 2013). As explained by Myroie (2013), the most tropical islands are young, with eogenetic limestone, and the varied island size ranges from very small to very large. We understand that the tropical islands of India are no exception. According to one of the principles of the Carbonate Island Karst Model (CIKM), the karst is commonly eogenetic in that it has developed on rocks that are young and have never been buried below the zone of meteoric diagenesis; however, telogenetic rocks do occur on carbonate islands and coasts. Hence, we consider the Interview Island to be a Simple Carbonate Island according to the CIKM classification.

Carbonate coasts on these islands commonly contain two types of caves: sea caves developed by wave erosion processes, and flank margin caves developed by dissolution at the edge of the freshwater lens (Dipova and Okudan 2011). This differentiation of the caves in the coastal settings is vital as it provides paleoclimatic information. It also creates an interest in assembling a database on coastal caves and, also, answers questions concerning rock qualities versus wave energy in the generation of sea caves (Waterstrat 2007). The area versus perimeter (A/P) approach was used by to differentiate sea caves from flank margin caves in the Bahamas. The morphometric analysis of the studied caves, although resembled the E/M ratio of flank margin structures documented in other island settings (Lace 2008; Roth 2004). Akin to the caves on Puerto Rico, Flank margin caves on Interview Island are segregated graphically by plotting area (A) v/s perimeter (P). In Puerto Rico, this

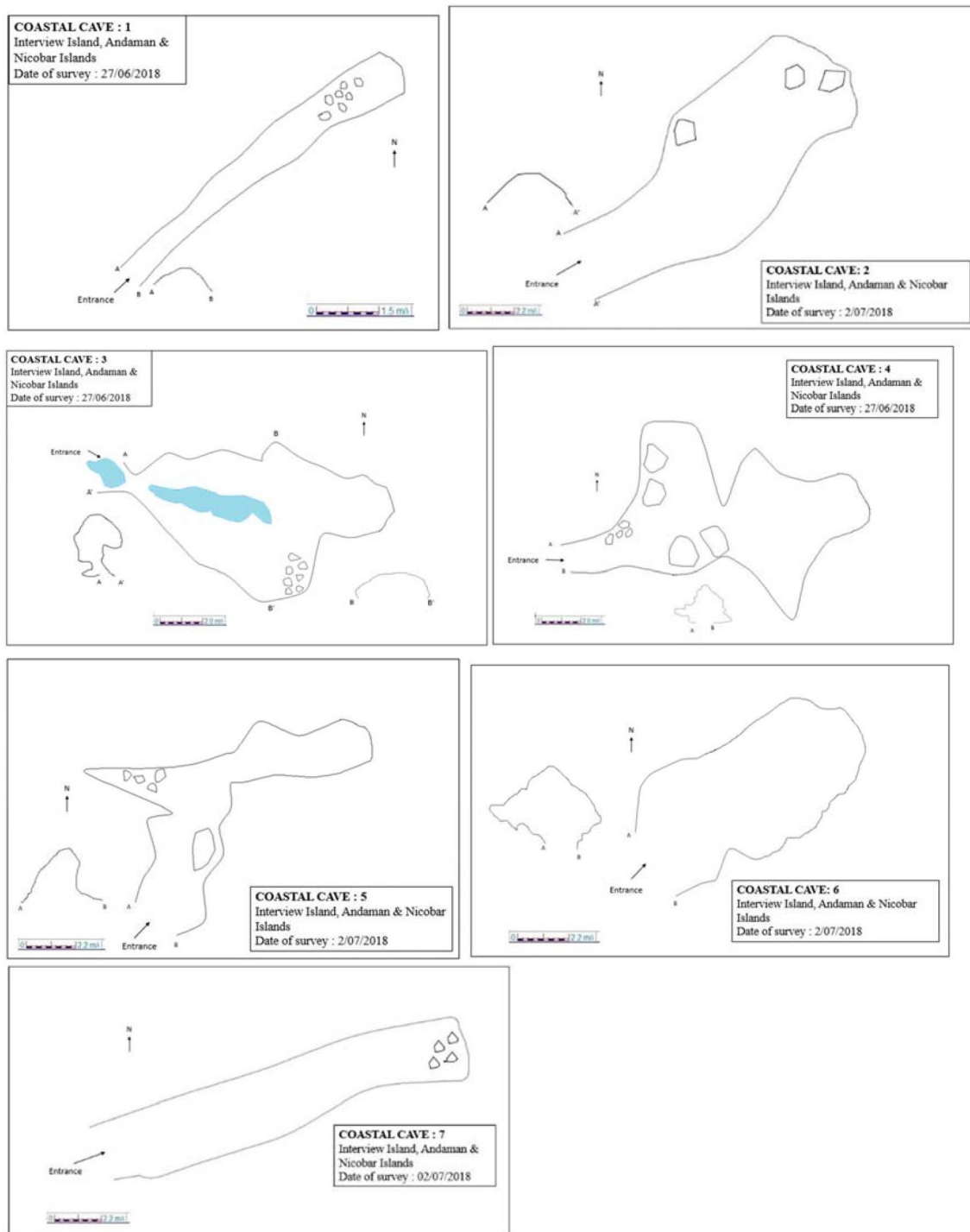


Fig. 5 Maps of the coastal caves on the Interview Island (Note: all the surveyed caves are facing the sea coast)

lineation was more effective for the flank margin caves with perimeter > 100 m. Whereas, from this study, the lineation has not been proven effective for the caves having perimeter < 100 m. Simultaneous comparisons of multiple spatial geometric parameters, i.e., both A/P ratio and E/M ratio, permitted A/P range > 1.0 – 2.0 and E/M < 1.0 (caves in the

Bahamas and Puerto Rico have E/M < 0.5 , Fig. 6b). Most FMCs have a much lower E/M value than San Salvador sea caves (mean = 0.52 for flank margin caves; 0.93 for San Salvador sea caves). Furthermore, these two cave types were differentiated with more than 99% confidence (Waterstrat et al. 2010). However, the caves in Interview Island cannot

Table 1 The morphometric measurements and statistics obtained from the surveyed coastal caves (CC)

Cave Id	Length (m)	Area (A) (m ²)	Perimeter (P) (m)	Volume (m ³)	Entrance width (E) (m)	Maximum width (M) (m)	Negative drop (Dn) (m)	Positive drop (Dp) (m)	Vertical range (m)	Vertical alignment (m)	A/P	E/M
CC1	15.90	262.51	89.05	75.43	0.82	1.34	2.53	3.93	6.46	11.95	2.95	0.61
CC2	11.70	50.37	37.50	273.27	3.33	3.65	3.47	9.32	12.79	7.81	1.34	0.91
CC3	19.60	142.55	53.88	1844.20	2.20	8.00	6.76	7.57	14.33	13.86	2.65	0.27
CC4	21.50	186.23	63.65	1678.94	1.50	9.50	4.65	10.80	15.45	14.44	2.93	0.15
CC5	20.90	158.99	55.90	2113.16	2.22	8.67	5.57	10.92	16.49	15.86	2.84	0.25
CC6	13.90	95.60	41.66	1057.93	4.15	7.07	2.14	6.24	8.38	7.79	2.29	0.58
CC7	8.50	42.14	40.69	193.56	1.13	1.19	2.58	2.44	5.02	4.74	1.04	0.94

be classified only using this parameter. Morphologically, only CC3 had a larger maximum width than any other sampled cave. Therefore, E/M-ratio differentiation may not be applicable in these smaller sized coastal caves.

According to Lace (2008), it is also possible that some of the smaller caves may have littoral origins, maybe remnants of flank margin caves, so profoundly modified by tidal erosion as to exhibit no overt sign of the true mechanism. Therefore, there is an equal possibility of all the caves to be sea cave or littoral caves with no signs of flank margin origin in the present site. Also, understanding that the sea caves development in the Bahamas appears to be controlled by wave energy differences produced by wave interference, lagoon, and reef physiography, tides, and wind direction and magnitude (Myroie and Myroie 2013a) and, in this case, the identified smaller caves seems to be carved into the terrace/cliff by wave action. As Moore (1954), had described the pre-requisites of the formation of the sea cave, the identified sea caves on the Interview island fulfils the conditions. Being the most commonly occurring type of cave found in coastal environments, it primarily functions as a potential refuge for many organisms, marine mammals, as well as birds, which roost in the ceiling ledges above the reach of waves (Myroie and Myroie 2013a).

On the other hand, FMC forms in the distal margin of the freshwater lens, contains information about the configuration, discharge, and other properties of that lens (Waterstrat et al. 2010) and the cave configurations, sizes, and locations have been successfully used to determine past freshwater lens properties in carbonate islands (Myroie et al. 2008). The Andaman and Nicobar Islands, especially Interview Island, similar to Fais Island of the Caroline Islands, has tectonic uplift combined with glacio-eustasy to create more complex and more complicated exposure and submersion history of the limestone that has occurred in Bermuda and the Bahamas (Waterstrat et al. 2010; Roth 2004). It was observed in Bahamas and Bermuda that freshwater discharge is minimized on beaches and related young carbonate rocks, but is enhanced in the older rocks that have experienced long-term contact with a freshwater lens (Davis and Gamble 2006; Myroie and Carew 1995b).

Understanding that the island hydrogeological system presents a delicate balance between the sea level and the rainfall recharge, recent climate change and anthropogenic usage might deplete freshwater resources soon. Freshwater lenses are the primary but already naturally limited drinking water resources in oceanic islands and thus need to be adequately evaluated and protected (Yang et al. 2020). However, in the present study looking at the morphologies and the ratios, it does not confirm the presence of FMC's. Hence, further detailed studies can help in confirmation of FMCs on the interview and other similar islands in the archipelago. Also, using the data of all the known 35 caves, the

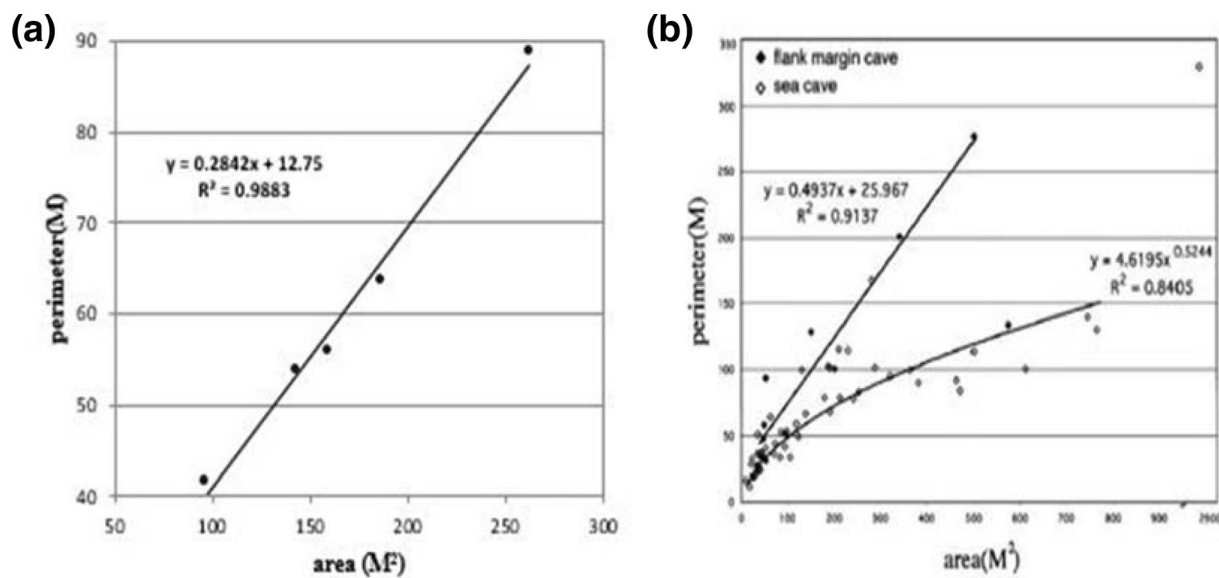


Fig. 6 **a** Plot for cave area (A) versus perimeter (P) for the coastal caves of Interview Island (trend line for other two caves could not be plotted as the number of caves is minimal), and **b** plot of cave perim-

eter versus cave area for coastal caves of Puerto Rico, using the protocols established by Waterstrat (2007)

evolution of either sea-level changes or karst development can be reconstructed, which may reveal significant indications of the geomorphic evolution of the Interview Island. Furthermore, a statistical approach can be used to locate the former sea stands as a karstification base (Ekmekci 2005). Moreover, the combination of cave morphology and datable sediments allows to reconstruct the timing of both paleoclimatic changes as well as landscape evolution (Audra et al. 2007).

Conclusion

This study is the first attempt to record the occurrence and simultaneously to identify coastal caves in India. It is also clear now that based on the A/P and E/M ratio, differentiating the flank margin caves is not easy. Hence, we require further fractal indices which can help us to categorize the different types of caves. However, identification of the sea caves based on their morphologies allowed us to confirm the occurrence of sea caves on the East and West coast of Interview Island.

Furthermore, we classified Interview island into the Carbonate Island Karst Model scheme (Myloie and Myloie 2007), which provided an understanding of the constraints and controls under which island karst systems operate. Flank margin caves develop at the margin of freshwater lenses; however, if this had happened in the geologic past, so there is a possibility of not finding the lens today.

Also, determining whether a coastal cave is a flank margin cave or a real sea cave has essential implications regarding denudational processes, and as a result, paleoclimate for that region (Waterstrat et al. 2010). Therefore, we recommend geologic and exploratory studies to understand the geomorphic evolution and speleological potential of these tropical islands. We also suggest survey of other islands of the archipelago to document the presence of coastal caves, which can majorly contribute in the adding to understand the karst and pseudokarst diversity of the Andaman and Nicobar Islands of tropical India.

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Author contributions CRediT (Contributor Roles Taxonomy). DK: conceptualization, data curation, formal analysis, methodology, and writing—original draft; SM: conceptualization, methodology, funding acquisition, project administration, resources, and writing—review and editing.

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Availability of data and material The raw data are available in the manuscript in the form of a table.

Compliance with ethical standards

Conflict of interest The authors have no conflict of interest to disclose.

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