Rhodolith-forming coralline red algae in the CaCO₃ biofactory — A case study from the Serravallian of tropical northeastern Indian Ocean

Rikee DEY, Daniela BASSO, Arindam CHAKRABORTY, Lopamudra ROY, Ajoy Kumar BHAUMIK & Amit K. GHOSH
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Rikee DEY
Birbal Sahni Institute of Palaeosciences, 53 University Road, Lucknow — 226 007, Uttar Pradesh (India)
and Department of Applied Geology, Indian Institute of Technology (Indian School of Mines), Dhanbad — 826 004, Jharkhand (India)

Daniela BASSO
University of Milano-Bicocca, Department of Earth and Environmental Sciences, Piazza della Scienza 4, I-20126, Milano (Italy)

Arindam CHAKRABORTY
Birbal Sahni Institute of Palaeosciences, 53 University Road, Lucknow — 226 007, Uttar Pradesh (India)
and Department of Geology, Faculty of Science, Universiti Malaya, 50603 Kuala Lumpur (Malaysia)

Lopamudra ROY
Birbal Sahni Institute of Palaeosciences, 53 University Road, Lucknow — 226 007, Uttar Pradesh (India)
and Centre of Advanced Study in Geology, University of Lucknow, Lucknow — 226007, Uttar Pradesh (India)

Ajoy Kumar BHAUMIK
Department of Applied Geology, Indian Institute of Technology (Indian School of Mines), Dhanbad — 826 004, Jharkhand (India)

Amit K. GHOSH
Birbal Sahni Institute of Palaeosciences, 53 University Road, Lucknow — 226 007, Uttar Pradesh (India)
akghosh_in@yahoo.com, amitk_ghosh@bsip.res.in (corresponding author)

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ABSTRACT
Rhodolith-forming non-geniculate coralline red algae have been recorded from the Long Formation, exposed in four different outcrops at Little Andaman Island (Hut Bay) in the northeastern Indian Ocean. The non-geniculate corallines are represented by species of Sporolithon Heydrich, 1897, Mesophyllum Lemoine, 1928, Lithothamnion Heydrich, 1897, Phymatolithon Foslie, 1898,
Rhodoliths are unattached nodules composed of calcareous red algae, more commonly Coralliniphyceae Le Gall & Saunders, 2007 (coralline algae) and species of family Peyssoneliaceae Denizot, 1968. The name rhodolite was coined by Bosellini & Ginsburg (1971) and they defined them as a spherical form of calcareous nodules and detached branched growths which are principally composed of coralline red algae. Binda (1973) commented that the usage of the term rhodolite is ambiguous, as it is traditionally used for a variety of garnet. Subsequently, Ginsburg & Bosellini (1973) proposed the name rhodolith for those nodules. Earlier, Barnes et al. (1970) also used the term rhodolith to indicate red algal nodules, without any definition. Rhodoliths are widely distributed and their excellent fossil record can provide valuable insights into palaeoecology and palaeobiogeography (Bosellini & Ginsburg 1971; Adey & Macintyre 1973; Bosence 1983a, b; Basso & Tomaselli 1994; Aguirre et al. 2000, 2012; Basso et al. 2009, 2017; Rebelo et al. 2014). Rhodoliths are sensitive to burial and smothering, and need active hydrodynamics or bioturbation to prevent their detrimental effects (Bosence 1983a, b; Braga & Martin 1988; Littler et al. 1990; Foster et al. 1997; Marrack 1999; Foster 2001; Braga et al. 2003; Bracchi et al. 2019, 2022). Geographically, rhodolith beds are distributed from the tropical to polar oceans and from the intertidal zones down to about 200 m of water depth (Foster 2001; Nelson 2009).
According to Bosellini & Ginsburg (1971), rhodolith shape is dependent on the water movement. In general, spheroidal and ellipsoidal rhodoliths are formed in moderate to high-energy environment. On the other hand, flat discoidal and ameboidal rhodoliths are more stable and ellipsoidal rhodoliths are more easily transported than spheroidal ones (Bosence 1976). Accordingly, discoidal rhodoliths are expected to be abundant in calm water; whereas, ellipsoidal and spheroidal rhodoliths should be dominant in moderate to high energy conditions. However, a growing body of evidence demonstrates that the relationship between rhodolith shape and hydrodynamics is not straightforward (Adey & Macintyre 1973; Steller & Foster 1995; Bracchi et al. 2022). The occurrence of a lithic nucleus may control the final shape and change the mean density of the rhodoliths, influencing the frequency of displacement by currents, depending on the stream competence (Basso & Tomaselli 1994; Basso et al. 2009). Although the growth form of the composing coraline species is also one of the obvious controls of rhodolith morphology (Nebelsick & Bassi 2000), field data showed a correspondence of spherical and compact rhodoliths with higher current velocity, while open structures of unattached branches are related to weaker, occasional currents (Basso 1998; Bracchi et al. 2022).

Coralline algae are one of the most significant carbonate producers of the photic zone in modern oceans (Basso 2012; Riosmena-Rodríguez 2017). In the tropical shelf environments, coralline algae are considered one of the most important carbonate producers and habitat formers that contribute to reefs and rhodolith beds. The global carbonate (CO$_3^{2-}$) budget is predominantly influenced by calcium carbonate (CaCO$_3$) production by marine biota. Distribution of coralline red algae ranges from tropical to polar zones and they can survive in low light intensity (Adey & Macintyre 1973; Coletti...
et al. 2015) owing to the presence of phycoerythrin, a unique photosynthetic pigment (Lee 1989; Van Den Hoek et al. 1995). During the Late Cretaceous their occurrence has been recorded in the shelf environment and in the Oligocene they were widespread in the photic zone (Nebelsick et al. 2005). In the Cenozoic, corallines became abundant throughout the globe (Bourrouilh & Hottinger 1988; Halfar & Mutti 2005; Braga et al. 2010; Pomar et al. 2017).

In the Mediterranean, Indo-Pacific and Caribbean regions rhodagal carbonate factories were well developed during the Miocene (Civitelli & Brandano 2005; Braga et al. 2010). In the northeast Indian Ocean, middle Miocene algal-foraminiferal limestones are exposed in different islands of Andaman and Nicobar Group (Sharma & Srinivasan 2007). Specifically, in the Little Andaman Island (Hut Bay) of the Andaman Group there are previous records of coralline red algae from the Serravallian limestones (Sarkar & Ghosh 2015; Sarkar et al. 2016; Ghosh et al. 2017 and references therein), however, rhodolith-forming coralline red algae were not assessed.

The present study is focused on the Serravallian of Long Formation outcropping at four sections in Little Andaman Island. The aim is to analyze the coralline red algal association forming the rhodoliths, to identify the different facies recorded in the four outcrops, to decipher the depositional environment in which the rhodoliths were formed, and to reconstruct the main steps of their diagenetic history.

GEOGRAPHY AND GEOLOGICAL SETTING

The Andaman-Nicobar region is one of the most seismically active subduction zones in this part on Earth, situated between 6° and 14° N in the northeastern Indian Ocean (Fig. 1A). Gaubolambe, the native name of Little Andaman Island (Hut Bay) is derived from the Onge tribes and this is the fourth largest island among the Andaman Group that occupies an area of about 707 km². The island is located about 120 km south of capital city Port Blair (Fig. 1B). The Little Andaman Island (Hut Bay), the southernmost island of the Andaman Group is located between the South Andaman and Car Nicobar Island. Geographically, Little Andaman Island is situated between 10°30’N-10°54’N, and 92°20’E-92°37’E, which is separated from the South Andaman by the Duncan Passage and Car Nicobar by the Ten-Degree Channel respectively (Fig. 1C). The Long Formation is well exposed in this island which has been designated as Ongeian Regional Chronostratigraphic Stage (Sharma & Srinivasan 2007). The Long Formation was dated as Serravallian (13.9 to 11.5 Ma) based on the planktonic foraminiferal zones Fohsella (synonym of Globorotalia) fohsi fohsi and Fohsella (synonym of Globorotalia) fohsi robusta respectively (Srinivasan 1988; Sharma & Srinivasan 2007). The sediments belonging to the Long Formation are exposed in the two cliffs of Butler Bay and two limestone quarries, i.e., Limestone Quarry No. 4 and New Quarry on the Little Andaman Island (Fig. 1C). This study has been carried out from four different outcrops: Butler Bay Section-I and Section-II, Hut Bay Quarry No. 4 Section and New Quarry Section. The two outcrops of Butler Bay (Butler Bay Section-I 10°39.482’N, 92°34.937’E and Butler Bay Section-II 10°39.516’N, 92°34.907’E) are lithologically comprised of dark grey to white motting hard fossiliferous limestone, with significantly high (45%) vuggy as well as moldic porosity (Srinivasan & Chatterjee 1981; Sarkar & Ghosh 2015) rich in coralline red algae forming rhodoliths, halimedacean green algae (Ghosh et al. 2017) and foraminifers (Fig. 2A, B). Samples collected from Hut Bay Quarry No. 4 (10°34.568’N, 92°32.491’E) are lithologically distinguished on the base of their dark grey fossiliferous limestone with rhodoliths, passing up section to a white colored foraminiferal limestone, which in turn is overlain by concretions with coral rags and bioherms (Fig. 2C). The lower part of New Quarry Section (10°34.500’N, 92°32.480’E) comprises of yellowish-white algal-foraminiferal limestone with rhodoliths, whereas the upper part is overlain by concretions with coral rubble and bioherms (Fig. 2D).

MATERIAL AND METHODS

Samples were collected from two outcrops on Butler Bay (Sections I and II) (Fig. 2A, B) and two outcrops situated at Hut Bay Limestone Quarry (HB Quarry No. 4 and New Quarry Section) (Fig. 2C, D). The Butler Bay Section-I is c. 15 m thick and twenty-seven samples were collected from this outcrop (Sample no. 8114/01 to 8114/27). Thirty samples were collected from the Butler Bay Section-II which is c. 7 m in thickness (Sample no. 8898/01 to 8898/30). Eight samples were collected from HB Quarry No. 4 which is c. 11 m in thickness (Sample no. 8900/01 to 8900/08). The thickness of New Quarry Section is c. 3.5 m, from where seven samples were collected (Sample no. 8901/01 to 8901/08).

For the description of coralline microanatomy, the term hypothallus corresponds to the ventral core of cell filaments (VC), and the term perithallus corresponds to the peripheral filaments (PF) arising from the ventral core (Hrabovský et al. 2015). Other anatomical characters are described based on Hrabovský et al. (2015). Higher rank taxonomy follows AlgaeBase (Guiry & Guiry 2018).

Palaeontological thin sections (c. 2.5 x 3.5 cm) were prepared from each sample containing rhodoliths. Petrographic thin sections measuring 30 µm in thickness were prepared for microscopic study. Four microscopic slides from each sample were studied by Olympus BX 50 light microscope. The cells and conceptacle dimensions were measured under light microscope at magnifications of 4x, 10x, 20x and 40x. The study of thin sections with uniform microscopic field area is necessary to understand the diversity of the biotic components. All the photomicrographs were taken using Olympus DP 26 Digital camera having CellSens Standard software attached to the Olympus BX 50 light microscope. The figured slides are preserved in the repository of Birbal Sahni Institute of Palaeosciences, Lucknow.
Fig. 2. — Lithologs of the outcrops: A, Butler Bay Section-I; B, Butler Bay Section-II; C, Hut Bay Quarry No. 4 Section; D, New Quarry Section.
ABBREVIATIONS
PF peripheral filaments;
Po postigenous filaments;
Pr primigenous filaments;
MMCO middle-Miocene climatic optimum;
VC ventral core of cell filaments.

RESULTS

SYSTEMATIC PALEONTOLOGY

Order CORALLINALES Silva & Johansen, 1986
Family HAPALIDIACEAE Gray, 1864
Genus Lithothamnion Heydrich, 1897

Lithothamnion valens (Fig. 3A, B)

DESCRIPTION
Thallus fruticose, with protuberances 2898-3017 μm in length and 826-1391 μm in diameter. Thallus monomerous, non-coaxial, cell fusions present both in the VC and PF. Cells of the VC measure 16 to 18 μm in length and 8 to 11 μm in diameter (Table 1). Cells of the PF 8 to 15 μm in length and 8 to 10 μm in diameter (Table 1), squarish to rectangular in shape. Conceptacles not observed.

REMARKS
The vegetative anatomy of the described specimens resembles to some extent to that of Lithothamnion valens Foslie (1909) in having large branched thallus, presence of zonation in the PF and numerous and multiple cell fusions (Basso et al. 1997). However, owing to absence of conceptacles, this form is only tentatively assignable to the genus Lithothamnion. Lithothamnion valens is one of the most common species of non-geniculate corallines identified in the Austrian Leitha Limestone (Basso et al. 2008). This species commonly shows a free-living, branching growth-form and is endemic in present day Mediterranean Sea. Moussavian (1984) reported its oldest occurrence from the Priabonian of Northern Calcareous Alps. During lower to middle Miocene L. valens was distributed from Iraq to the Tertiary Piedmont Basin. However, the species was restricted to the Mediterranean region starting from the upper Miocene (Basso et al. 1997).

Genus Phymatolithon
Foslie, 1898

Phymatolithon sp. (Fig. 3C, D)

DESCRIPTION
Growth form encrusting to foliose, thallus monomerous; more or less rectangular, measuring 16-20 μm in length and 12-14 μm in diameter (Table 1). Peripheral filaments composed of 6 to 12 cells thick, each zone showing a gradual transition of long and short cells, cells of the peripheral filaments measure 8-10 μm in length and 6-9 μm in diameter. Cell fusions present in both VC and PF. Epithallial cells are visible and non-flared in some specimens. Tetra/bisporangial conceptacles are multipartite, buried within the thallus, conceptacle roof distinct, conceptacles raised above the thallus surface. Conceptacle chambers 360 to 480 μm in diameter and 140 to 180 μm in height (Table 1).

REMARKS
The illustrated specimens are similar to the Phymatolithon calcareum (Pallas) Adey & McKibbin described from the upper Miocene of Santa Maria Island, Azores, NE Atlantic Ocean (Rebelo et al. 2014), but the encrusting to foliose growth form does not match the description of P. calcareum, which is commonly fruticose. For this reason, we leave this specimen in open nomenclature. According to Rasser & Piller (1999) the genus Phymatolithon is common in the late Eocene of the Austrian Molasse Zone.

Family MESOPHYLLUMACEAE Schneider & Wynne, 2019
Genus Mesophyllum Lemoine, 1928

Mesophyllum sp. (Fig. 3E)

DESCRIPTION
Growth form encrusting to warty, thallus measures 1141-1322 μm in length and 600-715 μm in thickness, monomerous. Cells of the VC are coaxial, more or less rectangular in shape and measures 12 to 24 μm in length and 6 to 10 μm in diameter (Table 1). Cells of the PF are 8 to 25 μm in length and 6 to 20 μm in diameter (Table 1). A wavy zonation is present in the PF. Cell fusions clearly discernible both in the VC and PF. Epithallial cells not clearly visible.

REMARKS
Based on the presence of cell fusions both in VC and PF, zonations in the PF and monomerous thallus with coaxial VC the specimen is confidently assigned to the genus Mesophyllum. The vegetative anatomical features and growth form recall Mesophyllum curtum Lemoine, re-described from the Tortonian of Algeria (Aguirre & Braga 1998) and from the Langhian of southern Moravia, Carpathian Foredeep, Czech Republic (Hrabovský et al. 2015).

Mesophyllum roveretoi
Conti, 1943
(Fig. 3F)

Mesophyllum roveretoi Conti, 1943: 55.
**Description**

Protuberances with a lumpy growth form. Thallus monomeric with presence of cell fusions in both VC and PF. The VC is coaxial (Fig. 3F) and the cells of VC measure 14-20 μm in length and 8-12 μm in diameter. The cells of PF measuring 14-31 μm in length and 8-28 μm in diameter. Multiporate conceptacles are flat, 229-235 μm in diameter and 71-96 μm in height (Table 1).

**Remarks**

The features of thallus organization, growth form, anatomical features and nature of conceptacles are consistent with the description of *Mesophyllum roveretoi* provided by Basso et al. (2008) from the Miocene “Lithothamnium Limestone” of northern Croatia. The taxon stratigraphically ranges from the upper Eocene to the middle Miocene (Conti 1946; Fravega et al. 1987) (Table 2).
Family **Mastophoraceae** Townsend & Huisman, 2018  
Subfamily **Mastophoroideae** Setchell, 1943  
Genus **Lithoparella** Foslie, 1909

**Lithoparella melobesioides** (Foslie) Foslie, 1909  
( crossed under **Mastophora** melobesioides, 1903: 24.  
**Lithoparella melobesioides** (Foslie) Foslie, 1909; 59.

**Description**
Encrusting growth form, forming either single thallus or multiple overgrowth, primigenous filaments composed of large vertically elongated cells forming unistratose layers, thallus dimerous, cells of the VC measuring 12 to 18 μm in length and 22 to 38 μm in diameter, postigenous filaments arise from the primigenous filaments and mostly occur around the conceptacles. Cells of the postigenous filaments measure 16 to 32 μm in length and 8 to 20 μm in diameter. Conceptacles are uniporate, measuring 174 to 400 μm in diameter and 8 to 20 μm in diameter. Cell fusions are present both in VC and PF. Epithallial cells flattened to round, measuring 5 to 7 μm long and 8 to 14 μm in diameter. Cell fusions are present both in the PF and VC (Table 1). Uniporate conceptacles raised above the thallus surface, cell linings in the pore canals more or less parallel to the roof of the conceptacle.

**Remarks**
According to Woelkerling (1988) the status of the species of **Lithoparella** is uncertain, though **Lithoparella melobesioides** has been described as fossils from the Palaeogene and Neogene sediments from different parts of the world. Our observations confirm the description provided by Rasser & Piller (1999) for the late Eocene material of the Austrian Molasse zone. The earliest record of the taxon is from the late Jurassic (Aguirre et al. 2000). In India, **Lithoparella melobesioides** has been recorded earlier from the late Eocene (Sarma et al. 2014), Miocene to Holocene (Kundal et al. 2011, 2016) (Table 2).

Suborder **CORALLININAE** Athanasiadis, 2016  
Family **Spongitiaceae** Kützing, 1843  
Subfamily **Neogoniolithoideae** Kato & Baba, 2011  
Genus **Neogoniolithon** Setchell & Mason, 1943

**Neogoniolithon** sp.  
( Fig. 4C)

**Description**
Thallus encrusting, monomorous; non-coaxial VC, cells of the VC measure 16 to 24 μm in length and 12 to 18 μm in diameter. Cells of PF irregularly arranged with variable shapes that measure 12 to 22 μm in length and 8 to 18 μm in diameter. Epithallial cells flattened to round, measuring 5 to 7 μm long and 8 to 14 μm in diameter. Cell fusions are present both in the PF and VC (Table 1). Uniporate conceptacles raised above the thallus surface, cell linings in the pore canals more or less parallel to the roof of the conceptacle.

**Remarks**
The specimens resemble the material described from the middle Miocene of Gârbova de Sus Formation, Transylvanian Basin, Romania (Chelaru & Bucur 2016). **Spongites fruticulosus** Kützing stratigraphically ranges from the Oligocene to Recent (Chelaru & Bucur 2016 and references therein). This species is widespread in the Mediterranean Sea as a rhodolith-forming coralline alga (Basso & Rodondi 2006) (Table 2).

Family **Lithophyllaceae** Athanasiadis, 2016  
Subfamily **Lithophyllioideae** Setchell, 1943  
Genus **Titanoderma** Nägeli, 1858

**Titanoderma pustulatum** (Lamouroux) Nägeli, 1858  
( Fig. 4F)

**Melobesia pustulata** Lamouroux, 1816: 315.  
**Titanoderma pustulatum** (Lamouroux) Nägeli, 1858: 532.

**Description**
Encrusting growth form, thallus dimerous, dorsiventral. Cells of VC 12 to 18 μm in length and 8 to 15 μm in diameter, palisade-like. Cells of PF are more or less squarish to rectangular, measuring 7 to 18 μm in length and 8 to 16 μm in diameter. Cell fusions occurring both in VC and PF. Epithallial cells are poorly preserved. Conceptacles uniporate, rose above the thallus surface, with chambers appearing hemispherical to elongated in section. Conceptacle chambers measure 110 to 140 μm in diameter and 72 to 94 μm in height (Table 1).
Remarks

This non-endophytic species of *Titanoderma* shows the growth-form, size and shape of the conceptacle chamber and pore canal, conceptacle roof and thickness of the thallus that resemble *Titanoderma pustulatum*, as described by previous authors (Chamberlain & Irvine 1994; Harvey et al. 2009; Van Der Merwe & Maneveldt 2015). The oldest record of *T. pustulatum* is from the early Oligocene of Iran (Basso et al. 2019) (Table 2).
### TABLE 1. — Comparison of biometric measurements of the identified geniculate and non-geniculate coralline algae. Abbreviations: D, diameter; H, height; L, length; PF, peripheral filaments; Po, postigenous filaments; Pr, primigenous filaments; VC, ventral core.

<table>
<thead>
<tr>
<th>Taxa</th>
<th>Features/Characteristics</th>
<th>Dimensions</th>
<th>Number of measurements (n)</th>
<th>Range</th>
<th>Mean (M)</th>
<th>Standard Deviation (SD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>?Lithothamnion valens (Fig. 3A, B)</td>
<td>VC</td>
<td>L</td>
<td>15</td>
<td>16 to 18 µm</td>
<td>16.8</td>
<td>0.74</td>
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<tr>
<td></td>
<td>D</td>
<td>15</td>
<td>8 to 11 µm</td>
<td>9.2</td>
<td>1.1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>PF</td>
<td>L</td>
<td>30</td>
<td>8 to 15 µm</td>
<td>10.6</td>
<td>2.41</td>
</tr>
<tr>
<td></td>
<td>D</td>
<td>30</td>
<td>8 to 10 µm</td>
<td>8.8</td>
<td>0.74</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Multiporate</td>
<td>D</td>
<td>5</td>
<td>84 to 117 µm</td>
<td>96.6</td>
<td>12.611</td>
</tr>
<tr>
<td></td>
<td>conceptacles</td>
<td>H</td>
<td>5</td>
<td>50 to 91 µm</td>
<td>70.2</td>
<td>14.42</td>
</tr>
<tr>
<td></td>
<td>Protuberances</td>
<td>L</td>
<td>3</td>
<td>2898 to 3017 µm</td>
<td>2942.6</td>
<td>54.08</td>
</tr>
<tr>
<td></td>
<td>D</td>
<td>3</td>
<td>826 to 1391 µm</td>
<td>1072</td>
<td>236</td>
<td></td>
</tr>
<tr>
<td>Phymatolithon sp. (Fig. 3C, D)</td>
<td>VC</td>
<td>L</td>
<td>20</td>
<td>16 to 20 µm</td>
<td>18</td>
<td>1.67</td>
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<td>D</td>
<td>20</td>
<td>12 to 14 µm</td>
<td>12.8</td>
<td>0.74</td>
<td></td>
</tr>
<tr>
<td></td>
<td>PF</td>
<td>L</td>
<td>50</td>
<td>8 to 10 µm</td>
<td>8.8</td>
<td>0.74</td>
</tr>
<tr>
<td></td>
<td>D</td>
<td>50</td>
<td>6 to 9 µm</td>
<td>7.4</td>
<td>1.01</td>
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<tr>
<td></td>
<td>Epithallial cells</td>
<td>L</td>
<td>9</td>
<td>8 to 15 µm</td>
<td>10.6</td>
<td>2.41</td>
</tr>
<tr>
<td></td>
<td>D</td>
<td>9</td>
<td>±5 µm</td>
<td>–</td>
<td>–</td>
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<tr>
<td></td>
<td>Multiporate</td>
<td>D</td>
<td>10</td>
<td>360 to 480 µm</td>
<td>400</td>
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<td></td>
<td>conceptacles</td>
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<td>160</td>
<td>14.1</td>
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<tr>
<td>Mesophyllum sp. (Fig. 3E)</td>
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<td>L</td>
<td>25</td>
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<td>18</td>
<td>9.4</td>
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<td></td>
<td>D</td>
<td>25</td>
<td>6 to 10 µm</td>
<td>8</td>
<td>1.41</td>
<td></td>
</tr>
<tr>
<td></td>
<td>PF</td>
<td>L</td>
<td>50</td>
<td>8 to 25 µm</td>
<td>15.6</td>
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<td>12.8</td>
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<td>140 to 180 µm</td>
<td>160</td>
<td>14.14</td>
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<tr>
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<td>3</td>
<td>85 to 140 µm</td>
<td>115</td>
<td>22.72</td>
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<tr>
<td></td>
<td>Thallus</td>
<td>L</td>
<td>3</td>
<td>1141 to 1322 µm</td>
<td>1221</td>
<td>75.36</td>
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<tr>
<td></td>
<td>D</td>
<td>3</td>
<td>600 to 715 µm</td>
<td>643.3</td>
<td>51.456</td>
<td></td>
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<tr>
<td>Mesophyllum roevereti Conti, 1943 (Fig. 3F)</td>
<td>VC</td>
<td>L</td>
<td>20</td>
<td>14 to 20 µm</td>
<td>16.6</td>
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<td></td>
<td>D</td>
<td>20</td>
<td>8 to 12 µm</td>
<td>10</td>
<td>1.41</td>
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<tr>
<td></td>
<td>PF</td>
<td>L</td>
<td>20</td>
<td>14 to 31 µm</td>
<td>21</td>
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<td>D</td>
<td>20</td>
<td>8 to 28 µm</td>
<td>17.2</td>
<td>7.98</td>
<td></td>
</tr>
<tr>
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<td>Multiporate</td>
<td>D</td>
<td>3</td>
<td>229 to 235</td>
<td>231</td>
<td>2.8</td>
</tr>
<tr>
<td></td>
<td>conceptacles</td>
<td>H</td>
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<td>71 to 96</td>
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<tr>
<td>Lithoporella melobesiodies (Foslie) Foslie, 1909 (Fig. 4A, B)</td>
<td>Pr</td>
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<td>15</td>
<td>12 to 18 µm</td>
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<tr>
<td></td>
<td>Po</td>
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<td>8 to 20 µm</td>
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<tr>
<td></td>
<td>Uniporate</td>
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<td>3</td>
<td>174 to 400 µm</td>
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<tr>
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<td>H</td>
<td>3</td>
<td>71 to 140 µm</td>
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<td></td>
<td>D</td>
<td>20</td>
<td>7 to 12 µm</td>
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<tr>
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<td>PF</td>
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<td>9 to 20 µm</td>
<td>14.4</td>
<td>4.3</td>
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<tr>
<td></td>
<td>D</td>
<td>50</td>
<td>5 to 11 µm</td>
<td>9.4</td>
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<td>L</td>
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<td>16 to 24 µm</td>
<td>19.4</td>
<td>2.6</td>
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<td></td>
<td>D</td>
<td>50</td>
<td>12 to 18 µm</td>
<td>15</td>
<td>2</td>
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</tr>
<tr>
<td></td>
<td>PF</td>
<td>L</td>
<td>100</td>
<td>12 to 22 µm</td>
<td>16.4</td>
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<td>8 to 18 µm</td>
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<td>D</td>
<td>6</td>
<td>8 to 14 µm</td>
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<td>L</td>
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<td>12 to 18 µm</td>
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<td>D</td>
<td>20</td>
<td>8 to 15 µm</td>
<td>12</td>
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<tr>
<td></td>
<td>PF</td>
<td>L</td>
<td>50</td>
<td>7 to 18 µm</td>
<td>12.6</td>
<td>3.8</td>
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<td></td>
<td>D</td>
<td>50</td>
<td>8 to 16 µm</td>
<td>11.2</td>
<td>2.9</td>
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<tr>
<td></td>
<td>Uniporate</td>
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<td>17</td>
<td>110 to 140 µm</td>
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<td></td>
<td>conceptacles</td>
<td>H</td>
<td>17</td>
<td>72 to 94 µm</td>
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<td>Amphiroa sp. (Fig. 4G–J)</td>
<td>Core region</td>
<td>L</td>
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<td>50 to 90 µm</td>
<td>66.6</td>
<td>17.25</td>
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<td></td>
<td>(long cells)</td>
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<td>8 to 20 µm</td>
<td>12.8</td>
<td>4.2</td>
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<tr>
<td></td>
<td>Core region</td>
<td>L</td>
<td>60 to 80</td>
<td>16 to 40 µm</td>
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<td>(short cells)</td>
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<td>9 to 19 µm</td>
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<tr>
<td></td>
<td>Intergenicula</td>
<td>L</td>
<td>12 to 20</td>
<td>651 to 1109 µm</td>
<td>920</td>
<td>195</td>
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<td></td>
<td>D</td>
<td>12 to 20</td>
<td>256 to 338 µm</td>
<td>298</td>
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<td>Corallina sp. (Fig. 5A–C)</td>
<td>Core region</td>
<td>L</td>
<td>105 to 245</td>
<td>18 to 24 µm</td>
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<tr>
<td></td>
<td>D</td>
<td>105 to 245</td>
<td>8 to 12 µm</td>
<td>10</td>
<td>1.4</td>
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Rhodoliths in the CaCO₃ biofactory from the Serravallian of NE Indian Ocean

Table 1. — Continuation.

<table>
<thead>
<tr>
<th>Taxa</th>
<th>Features/Dimensions</th>
<th>Number of measurements (n)</th>
<th>Range</th>
<th>Mean (M)</th>
<th>Standard Deviation (SD)</th>
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<td></td>
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<td>L  7 to 35</td>
<td>350 to 1092 μm</td>
<td>647.33</td>
<td>330</td>
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<td></td>
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<td>134 to 180 μm</td>
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<td>19.07</td>
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<td>Sporolithon cf. airoldii (Fig. 5D)</td>
<td>VC</td>
<td>L  25</td>
<td>8 to 16 μm</td>
<td>11.4</td>
<td>2.6</td>
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<td></td>
<td>D  25</td>
<td>3 to 8 μm</td>
<td>5.4</td>
<td>1.85</td>
</tr>
<tr>
<td></td>
<td>PF</td>
<td>L  50</td>
<td>5 to 12 μm</td>
<td>9.4</td>
<td>2.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>D  50</td>
<td>4 to 10 μm</td>
<td>7.6</td>
<td>2.2</td>
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<td>Sporangial compartments</td>
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<td>D  70</td>
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<td>4.2</td>
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<tr>
<td>Vannucci, Piazza, 2000</td>
<td></td>
<td>D  50</td>
<td>10 to 12 μm</td>
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<td>Fravega &amp; Basso, 2000 (Fig 5E, F)</td>
<td>Sporangial compartments</td>
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<td></td>
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<td>D  15</td>
<td>59 to 68 μm</td>
<td>61</td>
<td>10</td>
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</table>

Genus Amphiraoa Lamouroux, 1812

Amphiraoa sp. (Fig. 4G-J)

DESCRIPTION
The intergeniculal segments measure 651 to 1109 μm in length and 256 to 338 μm in diameter. Core region is composed of 3 to 6 layers of long cells alternating with 1 to 2 layers of short cells. Peripheral region not observed. Long cells measure 50 to 90 μm in length and 8 to 20 μm in diameter, short cells are 16 to 40 μm in length and 9 to 19 μm in diameter. Conceptacles are not preserved (Table 1).

REMARKS
Based on the diagnostic features, the form is assignable to the genus Corallina. However, owing to lack of preservation of adequate taxonomic characteristics it is not possible to assign it to any known species of the genus. Different species of Corallina have been reported earlier from the Miocene of Kutch Basin, India (Kundal & Humane 2003).

Order SPOROLITHALES Le Gall, Payri, Bittner & Saunders, 2009
Family SPOROLITHACEAE Verheij, 1993
Subfamily SPOROLITHOIDEAE Setchell, 1943
Genus Sporolithon Heydrich, 1897

Sporolithon cf. airoldii (Fig. 5D)

DESCRIPTION
Encrusting to warty growth form, thallus monomorous, dorsiventral, non-coaxial VC. The cells of VC are rectangular in shape that measure 8 to 16 μm in length and 3 to 8 μm in diameter. Cells of PF are more or less squarish with no distinct zonation, 5 to 12 μm in length and 4 to 10 μm in diameter. Cell fusions present. Epithallial cells and trichocytes are indiscernible. Sporangia elliptical, formed within calcified compartments and grouped into sori. Each sporangium measures 80 to 120 μm in height and 35 to 48 μm in diameter (Table 1).

REMARKS
The specimen is comparable to Sporolithon airoldii described from the lower Oligocene of NW Iran (Basso et al. 2019) in having small size of the vegetative cells and other anatomical features, but the maximum length of the sporangia exceeds that of the specimens described by Basso et al. (2019) as well as the type material of S. airoldii. Vannucci et al. (2010) re-described S. airoldii from the upper Rupelian-Chattian of Sassello while re-assessing Airoldi’s (1932) specimens.
Fig. 5. — **A-C**, Corallina sp. (BSIP Slide No. 17036, 17027, 17030); **D**, Sporolithon cf. airolidi (BSIP Slide No. 17039) encrusting to warty growth form, thallus monomorous, cell fusions present, sporangia elliptical and grouped into sori; **E, F**, Sporolithon praerythraeum (Airoldi) Vannucci, Piazza, Fravega & Basso, 2000 (BSIP Slide No. 17041) lumpy to protuberant growth form, cell fusions present in PF, sporangia grouped into sori; **G, H**, Amphistegina sp. (BSIP Slide No. 17033, 17037); **I, J**, Cycloclypeus sp. (BSIP Slide No. 17034, 17035); **K**, Heterostegina sp. (BSIP Slide No. 17036). **Arrows**: G, H, J, K, indicate compaction. Scale bars: A-C, 50 µm; D, F, 500 µm; E, I, K, 100 µm; G, H, J, 200 µm.
Fig. 6. — A, B, Heterostegina sp. (BSIP Slide No. 17037, 17033); C, unidentified nummulid (BSIP Slide No. 17033); D, Operculina sp. (BSIP Slide No. 17038); E, Quinqueloculina sp. (BSIP Slide No. 17040); F, Triloculina sp. (BSIP Slide No. 17013); G, Biloculina sp. (BSIP Slide No. 17013); H-J, Globigerinoides sp. (BSIP Slide No. 17023); K, L, Dentoglobigerina sp. (BSIP Slide No. 17013); M, N, thin sections showing petrographic features. Scale bars: A, F, H-L, 50 µm; B, C, E, G, 100 µm; D, M, N, 500 µm;
Sporolithon airolodi was recorded earlier from the Oligocene of Molare Formation of the Tertiary Piedmont Basin, NW Italy (Vannucci et al. 2010), from the lower and middle Rupelian of Prasco and Ovrano, Alessandria (Mastrorilli 1968), Val Lemme, Carrosio, Alessandria (Fravega et al. 1988), from the upper Rupelian to Chattian of Sassello, Savona (Airoldi 1932; Fravega et al. 1987), from the upper Burdigalian to Serravallian of St. Florent, N. Corsica and Bonifacio, Cala de Labra, S. Corsica (Mastrorilli in Bellini & Mastorilli 1975) and from the lower Oligocene of NW Iran (Basso et al. 2019).

Sporolithon praerythraeum (Airoldi) Vannucci, Piazza, Fravega & Basso, 2000
(Fig. 5E, F)

Archaeolithothamnium praerythraeum Airoldi, 1932: 63, pl. 9, fig. 2.


DESCRIPTION
Lumpy to protuberant thallus, VC filaments indiscernible. The peripheral filaments (PF) show horizontal layers of elliptical cells. Cell fusions are present in the PF, the cells of PF measure 14 to 26 μm in length and 10 to 12 μm in diameter. Sporangia grouped in sori, individual sporangia measuring 30 to 36 μm in diameter and 59 to 68 μm in height (Table 1).

REMARKS
Vannucci et al. (2000) revised and re-documented this species of Sporolithon and transferred Airoldi's (1932) Archaeolithothamnium praerythraeum under the genus Sporolithon with a new combination. The species has been identified from the late Eocene to early Oligocene of Italy and Bulgaria (Francavilla et al. 1970; Bakalova 1983). The overall thallus organization, shape and size of the sporangia and the arrangement of the sporangia are closely comparable to the middle Miocene specimens recorded by Vannucci et al. (2000) and Chelaru & Bucur (2016).

BENTHIC AND PLANKTONIC FORAMINIFERS
In addition to the above mentioned coralline red algae, some benthic and planktonic foraminifers are also present, but owing to their poor preservation they are identifiable only up to generic level. The commonly occurring benthic foraminifers are represented by Amphistegina sp. (Fig. 5G, H), Cyclolypeus sp. (Fig. 5I, J), Heterostegina sp. (Figs 5K; 6A, B), unidentified nummulitids (Fig. 6C), Operculina sp. (Fig. 6D), Quinqueloculina sp. (Fig. 6E), Triloculina sp. (Fig. 6F), Biloculina sp. (Fig. 6G). The planktonic foraminifers are indeed difficult to identify in thin sections, however, on the basis of some distinguishing features some of them are identifiable up to genus level, namely Globigerinoides sp. (Fig. 6H-J), and Dentoglobigerina sp. (Fig. 6K, L).

FACIES AND SEDIMENTOLOGY
The different types of facies along with sedimentological features recognized in each outcrop are described as follows:

Butler Bay Section-I
MFT 1 Coralline algal wackestone (Sample no. 8114/01 to 8114/11, from base to 5.3 m; Fig. 7).
Rhodoliths in the CaCO₃ biofactory from the Serravallian of NE Indian Ocean

The texture of this facies is mud-supported wackestone dominated by the rhodolith forming non-geniculate corallines such as melobesoids (80%). Subordinate components are undentifiable coral fragments (10%) and biogenic debris (10%).

MFT 2 Foraminiferal-Coralline algal grainstone-packstone (Sample no. 8114/12 to 8114/18, from 5.3 to 9.08 m; Fig. 7)

This facies is characterized by poorly sorted grainstone to packstone with biogenic components dominated by the benthic foraminiferal genera belonging to Nummulitidae and rotaliids (30%). The non-geniculate coralline association is dominated by melobesoids (20%) and the geniculate corallines represented by Amphiroa (5%) with other biogenic debris (45%).

MFT 3 Coralline algal-foraminiferal grainstone-packstone (Sample no. 8114/19 to 8114/27 from 9.08 to 14.48 m; Fig. 7)

This facies is characterized by poorly sorted grainstone to packstone, dominated by geniculate corallines mainly Amphiroa (18%), unidentified non-geniculate corallines (17%) Nummulitidae and rotaliids (25%) along with other biogenic debris (45%). Effects of fragmentation, disarticulation and abrasion are clearly visible in the coralline algae.

**Butler Bay Section-II**

MFT 1 Foraminiferal packstone (Sample no. 8898/01 to 8114/09, from base to 1.6 m; Fig. 8).

This facies consists of densely packed, poor to moderately sorted packstone with Nummulitidae (45%). Fragments of non-geniculate coralline algae of sub family Melobesioidae (20%) and coral fragments are also present in minor quantities. High rates of fragmentation, disarticulation and abrasion are observed in the coralline algae. Echinoid spines (5%) and other biogenic debris (30%) are also present.

MFT 2 Coralline algal-foraminiferal grainstone-packstone (Sample no. 8898/10 to 8114/16, from 1.6 to 3.35 m; Fig. 8).

This grainstone-packstone facies is composed of poor to moderately preserved melobesioids (30%) and unidentified geniculate coralline algae (20%) and benthic foraminifers, especially Nummulitidae and rotaliids (20%) associated with unidentified coral fragments (5%) and biogenic debris (25%). Disarticulation in geniculate corallines is common.

MFT 3 Foraminiferal-Coralline algal grainstone-packstone (Sample no. 8898/17 to 8114/20, from 3.35 to 4.35 m; Fig. 8).
Both benthic foraminifers and coralline algae are present but the former is preponderant. Nummulitidae and rotaliids are dominant (60%), geniculate coralline algae *Amphiroa* (10%), echinoid spines (5%), unidentified coral fragments (10%) and biogenic debris (15%) are also present. Sparse grains of sparry calcite occur (Fig. 6M, N).

MFT4 Coralline algal-foraminiferal grainstone-packstone (Sample no. 8898/21 to 8114/30, from 4.35 to 6.85 m; Fig. 8).

This grainstone-packstone facies is composed of coralline algae represented by Sporolithales (20%) and melobesiods (30%), unidentified geniculate corallines (5%). Small Nummulitidae (15%) are also associated with the broken fragments of corals and other biogenic debris (30%).

**Hut Bay Quarry No. 4 Section**

MFT 1 Coralline algal wackestone (Sample no. 8900/01 to 8900/02 from base to 2 m; Fig. 9).

The texture of the facies is a mud-supported wackestone. This facies consists of large non-geniculate coralline algal thalli, especially of melobesiods (50%) and fragments of geniculate coralline algae *Amphiroa* (20%) and biogenic debris (30%). Both planktonic and benthic foraminifers are absent.

MFT 2 Foraminiferal-Coralline algal grainstone-packstone (Sample no. 8900/03, from 2 to 4 m; Fig. 9).

This facies is also characterized by mud-supported wackestone. A major change in this facies has been noticed from the previous one, due to the appearance of large benthic foraminifers, especially Nummulitidae (30%) with subordi-
nate components represented by fragments of coralline algae (20%) and biogenic debris (50%). Due to severe abrasion, the algal forms are difficult to identify even up to generic level.

MFT 3 Coralline algal wackestone (Sample no. 8900/04, from 4 to 4.88 m; Fig. 9).

Large coralline algal thalli in a mud supported wackestone characterize this facies. High rates of fragmentation, disarticulation and abrasion are observed in the geniculate coralline algae and non-geniculate melobesioids (45%). Some echinoid spines are also present in minor quantities (10%) along with biogenic debris (45%).

MFT 4 Foraminiferal grainstone-packstone (Sample no. 8900/05 to 8900/08, from 4.88 to 10.52 m; Fig. 9).

Poor to moderately preserved larger benthic foraminifers are abundant in this grainstone-packstone facies. Abundance of rotaliids and taxa belonging to Nummulitidae (20%) has been observed along with echinoid spines (20%) and biogenic debris (60%). This facies is devoid of coralline algae.

New Quarry Section
MFT 1 Coralline algal-foraminiferal grainstone-packstone (Sample no. 8901/01 to 8901/04, from base to 9.9 m; Fig. 10).
This grainstone-packstone facies is dominated by non-geniculate melobesoids (40%), unidentified geniculate corallines (15%) along with Nummulitidae foraminifers (20%), echinoid spines (10%) and broken fragments of corals and other biogenic debris (40%). The overall texture is a poorly sorted grainstone-packstone.

MFT 2 Coralline algal wackestone (Sample no. 8901/05, from 9.9 to 1.32 m; Fig. 10).

A moderately sorted wackestone, rich in melobesoids (50%) in association with echinoids (10%) and broken fragments of corals and other biogenic debris (40%).

MFT 3 Foraminiferal grainstone-packstone (Sample no. 8901/06 to 8901/08, from 1.32 to 3.48 m; Fig. 10).

This facies is characterized by poorly sorted grainstone-packstone, dominated by foraminifers, especially Nummulitidae (50%) and unidentifiable geniculate coralline algae (30%) and other biogenic debris (40%).

**Coralline growth form and rhodolith morphotypes**

Various types of growth forms in coralline algae have been encountered in the present study such as encrusting (Figs 3A-D; 4A, B, F), or protuberant (Figs 5D; 11E, F), foliose (Fig. 3C), layered lamellae (Fig. 3A, B) and arborescent (Figs 4G-J; 5A-C). Corallines formed rhodoliths 30-50 mm in diameter, with irregular to ellipsoidal shapes and a boxwork morphotype (Basso 1998) (Fig. 11A-D). The boxwork rhodoliths (Fig. 11A-D) have laminar concentric to columnar internal structure (Bosence 1983b; Basso 1998) and are dominated by *Mesophyllum* sp. (Fig. 3E), *Mesophyllum roveretoi* (Fig. 3F) and ?*Lithothamnion valens* (Fig. 3A, B). The commonly occurring rhodolith-forming algae are *Listhoporella melobesiodies* (Foslie) Foslie, 1909 (Fig. 4A, B) and *Sporolithon cf. airoldii* (Fig. 5D). In addition, some algal taxa are rarely represented in the rhodoliths, e.g. *Phymatolithon* sp. (Fig. 3C, D), *Spongites fruticulosus* (Fig. 4D, E), *Titanoderma pastulatum* (Fig. 4F), *Sporolithon praecryptaecum* (Fig. 5E, F) and *Neogoniolithon* sp. (Fig. 4C). Boxwork morphotypes show numerous macroscopic voids which are occupied with sediments.

**Taphonomic features**

The taphonomic processes left an important overprint on the studied fossil assemblages. Based on the major biostratinomic
features in coralline algae and foraminifers, encrustation (Fig. 3A-D; 4A, B, F), abrasion (Fig. 11E, F), bioerosion (Figs 3E; 11F), and fragmentation (Figs 4I, J; 5C) (Nebelsick & Bassi 2000; Basso et al. 2009) have been envisaged. Moreover, geniculate species of Amphiroa (Fig. 4I, J) and Corallina (Fig. 5C) underwent disarticulation. Diagenetic alteration was observed in corallines and in both larger benthic and planktonic foraminifers. Micritization, cementation and compaction are some of the diagenetic signatures that have been identified. The diagenetic micritization has been detected as a dark rim surrounding the skeletal grains of some benthic foraminifers such as Quinqueloculina sp. and

Fig. 11. — A-D, Polished surface of the sliced rock samples showing boxwork laminar concentric rhodoliths; E, F, melobesiods (BSIP Slide No. 17040) showing abrasion (E) and bioerosion (F). Scale bars: A, C, 5 mm; B, D, 10 mm; E, F, 500 µm.
Triloculina sp. (Fig. 6E, F). Fine crystalline rim cement around the planktonic foraminifers has been observed that may also be due to diageneric (Fig. 6H-L). Compaction of bioclastic carbonate sand occurred both mechanically and chemically (Croizé et al. 2010). Sediment progressively loses its porosity by compaction due to the effects of pressure from loading. In our material, compaction has been detected as low porosity and contact of grains. In case of mechanical compaction both point contact (Fig. 6C) and tangential contact (Figs 5G, H, K; 6B) are clearly discernible. Partial chemical dissolution is apparent in the poor preservation of finest details of coralline algae (Fig. 3B-D; 4A-C, F) and the effect of consequent compaction, one of the important diagenetic processes in a burial environment, has been observed in benthic foraminifera, such as Cycloclypeus sp. (Fig. 5J). The compaction might have occurred after diffused chemical dissolution that also affected the preservation potential of coralline red algae.

DISCUSSION

Facies characterization of the carbonate sediments of the Long Formation on Little Andaman Island has been assessed to interpret the paleoenvironment. On the basis of biogenic composition and depositional fabric three facies types have been demarcated in the Butler Bay Section-I (Fig. 7), four facies types have been recognized in Butler Bay Section-II (Fig. 8), four facies have been identified in Hut Bay Quarry No.4 (Fig. 9) and three different facies have been recognized in the New Quarry Section (Fig. 10). As far as biogenic composition and depositional fabric of the carbonate sediments are concerned, all the four outcrops are characterized by more or less same features with minor alternation and variation.

It is well established that rhodoliths occur in carbonate or mixed siliciclastic deposits from the intertidal down to c. 200 m water depth, and are globally distributed from the equator to circumpolar latitudes (Foster 2001; Riosmena-Rodriguez et al. 2017; Rebello et al. 2021). Although there are many published records on the rhodolith facies from the Paleogene (Manker & Carter 1987; Rasser & Piller 2004), they became more abundant during the Neogene (Halfar & Mutti 2005). In the Miocene, coralline algae and rhodoliths were at their acme and they more or less replaced the coral-reefs, which was associated with the decline of other carbonate-producing phototrophs (Halfar & Mutti 2005; Pomar et al. 2017). The Miocene rhodoliths accumulated in the Tethys and Paratethys regions as well as in a number of localities in the tropical Pacific, Southeast Asia, and the Caribbean regions (Halfar & Mutti 2005). Coralline algae and rhodoliths were dominant in the circum-Mediterranean region during Burdigalian to Serravallian (Esteban 1996). Abundant occurrences of rhodalgal carbonates during late Burdigalian to the early Serravallian are synchronous with the Monterey event (Halfar & Mutti 2005; Braga 2017; Pomar et al. 2017). This event is defined by a prominent and long-lasting phase of the middle Miocene (17.5-13.5 Ma) carbon-isotope excursion represented by the higher δ13C values known as the Middle-Miocene Climatic Optimum (MMCO). The dominance of rhodalgal facies over coral-reef carbonates can be correlated to the carbon-isotope excursion (Halfar & Mutti 2005; Pomar et al. 2017). Therefore, the dominance of coralline algae in the studied sections of Little Andaman Island (Hut Bay) which has been dated earlier based on planktonic foraminifers (Srinivasan 1988; Sharma & Srinivasan 2007) may be correlated with the terminal phase of the MMCO event. After the MMCO event the global temperature declined, along with a decrease of the carbonate content and mass accumulation rate in the paleoceanographic record of the Equatorial Indian Ocean (Lübbers et al. 2019) that was accompanied by an intertropical belt contraction and the consequent reduction of the distribution of some tropical coralline genera (Braga & Bassi 2007).

Various rhodolith forming red algal flora have been reported from the middle Miocene. Two main types of rhodolith-building coralline associations were reported by Martín et al. (1993) from the Marion Plateau (Northeastern Australia). The first type is composed of Lithothamnion and Sporolithon with subordinate representation of Hydrolithon, Meophyllum, Spongites, and Lithoporella. The other type is principally made up of Meophyllum and the present assemblage is to some extent comparable to this type in having dominance of Meophyllum.

Since the time of their definition (Bosellini & Ginsburg 1971), it was suggested that rhodolith shape, growth form and inner algal arrangement provide significant information on the palaeoenvironment. Water energy is an important factor which controls the growth of rhodoliths in a particular environment (Bosence 1991; Basso 1998; Bracchi et al. 2022). Different types of rhodolith shapes have been proposed by Bosellini & Ginsburg (1971). Bosence (1991) opined that the rhodoliths composed of radially developed, twig-like branches generally inhabit in quieter environments where transportation of rhodoliths is minor. On the other hand, the densely branched forms and the pralines grow in higher energy conditions (Basso 1998; Sánchez et al. 2016; Bracchi et al. 2022). Based on the present-day distribution of the various rhodolith morphologies and structures, it was proposed a simplified system for a rapid identification of the main rhodolith morphotypes, depending mainly on substrate stability/hydrodynamics and sedimentation rate (Basso 1998; Basso et al. 2009, 2016).

Different types of processes are involved in the development of fossil rhodolith beds such as growth forms, taphonomic filters, water energy, types of deposition, i.e., allochthonous or autochthonous (Bosence 1991; Aguirre et al. 2017). Important palaeoecological constraints can be derived from a combination of observations such as rhodolith morphotypes, taxonomic composition and succession of the coralline algae within the rhodoliths, morphology and growth forms of the algal thalli, internal arrangement of the rhodoliths, taphonomic signatures and interactions of organisms (Basso 1998; Basso et al. 1998; Nebelsick & Bassi 2000; Basso et al. 2009; Aguirre et al. 2017; Coletti et al. 2018).

In the present study, rhodoliths are present in all the sections and most of them are irregular to elliptical in shape.
The rhodolith morphotype is dominantly boxwork, with laminar concentric to columnar internal structure. This indicates a moderate to low hydrodynamics (Basso 1998). The rhodoliths are multispecific with abundant representation of melobesioids viz., *Mesophyllum* sp., *Mesophyllum rorereoi* and *Lithothamnion valensi*. The commonly occurring rhodolith-forming corallines are represented by *Lithoporella melobesoides* and *Sporolithon cf. airodii* (Fig. 5D). Some taxa rarely form rhodoliths, e.g., *Phymatolithon* sp., *Spongites fruticulosus*, *Titanoderma pastulatum*, *Sporolithon praeerythraeum* and *Neogoniolithon* sp.

Palaeobathymetry is one of the most important aspects that can be derived from the coralline algal assemblages, in addition to the hydrodynamic and palaeoclimatic conditions (Bosence 1983b, 1991; Aguirre et al. 2000; Braga & Aguirre 2001; Piller 2003; Coletti et al. 2018). In a recent study, Li et al. (2021) estimated the palaeobathymetry of several non-geniculate coralline genera in the northern South China Sea since the Pliocene. According to their estimation, the bathymetric range of the genera *Lithoporella*, *Lithothamnion*, *Mesophyllum*, *Spongites* and *Titanoderma* is intertidal to 25 m water depth. This conclusion is not supported by the worldwide distribution of the genera *Mesophyllum* and *Lithothamnion* that basically thrive below 20 m of water depth, even down to 100 m (Adey 1986; Braga & Aguirre 2004). However, Coletti & Basso (2020) reported the occurrence of both the genera from 20–40 m water depth. The distribution of modern species of *Lithothamnion* indicates that this genus occurs in deeper water than *Mesophyllum* (Adey 1986; Lund et al. 2000). Though the genus *Mesophyllum* has a wide depth distribution, its occurrence has been documented from 15 to 30 m water depth in the recent coralline algal assemblage of the Ryukyu Group, Japan (Iryu 1992), in the modern and Pleistocene coral reefs of eastern Australia (Lund et al. 2000; Braga & Aguirre 2004), and in the early Miocene of the Sommières Basin, Southern France (Coletti et al. 2018). The genus *Lithophyllum* is widely distributed and common in shallow waters, especially in the intertropical belt (Vieira-Pinto et al. 2014; Basso et al. 2015; Jeseonk et al. 2016; Kato & Baba 2019). Though there is no record of depth distribution of *Spongites*, *Neogoniolithon* and *Phymatolithon* in the Indian Ocean, it has been suggested that *Spongites fruticulosus* is widespread in the present day Mediterranean Sea at a depth range of 12 to 75 m (Hrabovský et al. 2015). Mateo-Cid et al. (2014) reported the occurrence of *Neogoniolithon mamillare* in the Mexican Caribbean at a water depth ranging from intertidal to 30 m. The depth distribution of *Phymatolithon* is known from Namibia and Mozambique, spanning 8–14 m of water depth (Van Der Merwe & Maneveldt 2014). According to Minnery et al. (1985), sporolithaceans predominantly occur between 20 and 50 m water depth. Later, Rasser & Piller (1997) estimated that the genus *Sporolithon* is dominant between 20 and 40 m water depth, while Aguirre et al. (2000) opined that in the modern tropical ocean sporolithaceans are abundant between 40–50 m water depth. Very shallow occurrences of *Sporolithon* also have been recorded (Verheij 1993; Basso et al. 2009; Neill et al. 2015) and a poleward emergence of the genus was postulated (Basso et al. 2009). Therefore, sporolithaceans are globally distributed both in shallow and moderately deep-water settings (Adey 1986), and no direct evidence in the geological record indicates that the sporolithaceans increase with increasing water depth (Fravega et al. 1989; Brandano et al. 2005, 2007; Braga et al. 2009; Coletti et al. 2018; Chelaru et al. 2019). However, the dominance of boxwork rhodoliths and the coralline assemblage do point to a fore slope paleoenvironment. This interpretation is also supported by the foraminifers association, including the occurrence of the deep water genus *Cy clochlopes* (Novak & Renema 2018). In fact, on a global scale, geniculate coralline algae are more abundant in shallow water (c. 15 to 20 m), while non-geniculate corallines are more frequently dominant in deeper water (Johansen 1974; Konar & Foster 1992).

Various taphonomic features have been visualized in thin section analysis, e.g. encrustation has been specifically noted in the non-geniculate corallines such as *Lithoporella*, *Neogoniolithon* and *Phymatolithon* (Figs. 3; 4) etc. Disarticulation and fragmentation are common in geniculate corallines, e.g. *Amphipora* (Fig. 9G-J) and *Corallina* (Fig. 5A-C), as expected for bioclasts produced in shallow water. Other taphonomic features such as abrasion (Fig. 11E), bioerosion (Figs. 3E; 11F), chemical dissolution (Figs. 3B, D; 4A, C, F), compaction (Fig. 6G, H, J, K) are also commonly observed. After deposition, the sediments undergo increase of temperature and pressure due to burial under successive younger layers. The evidence of diagenetic effect in carbonate sediments in the microscopic study of thin sections analysis is a common feature in larger benthic foraminifers. The common diagenetic effects identified are micritization, cementation and compaction. Due to micritization, changes in the original grain structure took place.

Studies have been carried out earlier on the reconstruction of the lost carbonate factories built by skeletal elements of coralline red algae and benthic foraminifers (Nebelsick et al. 2001; Rasser & Nebelsick 2003; Basso et al. 2012; Leszczyński et al. 2012; Coletti et al. 2015). These skeletal remains that were transported basinward could provide information on the original depositional environment. The coralline red algal assemblage along with benthic foraminifers recorded herein from the Serravallian sections of Little Andaman also provides substantial information on their depositional environment. Geniculate corallines, milliolid and coral rubble, together with evidence of fragmentation and abrasion, support the occurrence of a shallow-water platform with colonial z-coral, that was the source of the below wave base gravity deposits produced by storms, accumulated on a fore-reef slope. There, an in-situ biogenic production could still take place, adding to the transported sediment and explaining the occurrence of relatively deep-water coralline species and the formation of boxwork rhodoliths.

Though quantification of rhodolith density and mass accumulation rate is beyond the scope of the present study, our results indicate that carbonate production was still considerably high in the tropical northeast Indian Ocean during the Serravallian.
CONCLUSIONS

This is the first comprehensive record of rhodoliths from the Serravallian of tropical northeast Indian Ocean. The Serravallian age for the studied outcrops is based on the earlier study on index planktontic foraminifers (Srinivasan 1988; Sharma & Srinivasan 2007). Most of the rhodolith morphotypes are boxwork in nature with concentric to laminar internal structure that designate moderate to low energy settings. Owing to such hydrodynamic settings, various taphonomic signatures (encrustation, disarticulation, fragmentation, bioerosion, abrasion and diagenesis) were noted in the rhodolith forming coralline red algae. Diagenetic effects are represented by micritization, cementation and compaction. Genulate coralline algae are also common in the studied thin sections, though they were not abundant and never observed within the rhodoliths. Most of the genulates show fragmentation and disarticulation that also implies transport. The growth forms in non-genulate corallines are represented by encrusting, warty, lumpy, layered and foliose, whereas in genulate forms arborescent growth form is common. Different faces types were identified from the four sections, where most of them are wackestone and packstone which are characterized by algal-foraminiferal bioclastic limestone composed of coralline red algae, benthic and planktonic foraminifers, echinoid spines and coral fragments. The observed bioclastic associations suggest that most of the carbonate production occurred on a shallow-water high-energy platform, though exact bathymetric estimation is very much speculative. Gravity deposits occurred in a slope off-reef environment, with in situ formation of multispecific boxwork rhodoliths composed of deeper coralline species associated with planktonic foraminifiers, the latter probably transported from offshore settings. The present study envisages that the carbonate production flourished during the Serravallian of tropical northeast Indian Ocean.

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