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## THE BIOLOGICAL COMMUNITIES OF AN EXTREME ENVIRONMENT: THE BLUE HOLE OF FAANU MUDUGAU, MALDIVES

### LE COMUNITÀ BIOLOGICHE DI UN AMBIENTE ESTREMO: IL BLUE HOLE DI FAANU MUDUGAU, MALDIVE

**Abstract** - The Faanu Mudugau Blue Hole (Maldives) opens at 30 m depth and descends to 85 m. At 40-50 m the water' temperature, salinity and pH change significantly. Below 50 m oxygen concentration collapses, while hydrogen sulphide increases. This work provides a first characterisation of the maldivian blue hole benthic communities. Data were collected from 30 m to 75 m by taking photographs every 5 m depth. Each photoquadrat was analysed to calculate the percent cover of any organism, on which a Correspondence Analysis (CA) was applied. Three zones was identified: i) a photic zone at 30-40 m depth, dominated by encrusting algae, sponges and scleractinians; ii) a mesophotic zone at 45 m, dominated by Chrysophyceae and Cyanobacteria; and iii) an aphotic zone below 50 m, where only chemosynthetic bacteria are present. Further investigations on the Faanu Mudugau Blue Hole are worthy to better understand the functioning of this extreme ecosystem.

**Keywords:** benthic communities, tropical ecosystems, extreme environments, blue hole, Maldives

**Introduction** - Blue holes are underwater voids that descend several meters below the sea surface in carbonate banks and islands, formed through karstic processes such as the dissolution and/or collapse of carbonate rock along fractures (Mylroie *et al.*, 1995; Yao *et al.*, 2020 and references therein). Most oceanic blue holes originated during the last glacial period, when sea level was 100–120 m lower than today; as the oceans rose, these voids became submerged (Hatcher, 2006). Typically, blue holes have a near-circular shape with steep vertical walls. Their waters may be marine, fresh, or of mixed chemistry, depending on the influence of tides and/or bottom water sources. Some blue holes open directly to the sea surface, making them sensitive to tidal fluctuations and allowing exchange with surrounding ocean water (Mylroie *et al.*, 1995). Others are more isolated, with minimal exchange with external waters, and display stable, vertically stratified physicochemical gradients. The relatively enclosed shape of the cavities allows minimal water exchange, that promotes vertical stratification in the water column's geochemical properties (Doni *et al.*, 2024a). In certain cases, blue holes host extreme environments, including anoxic conditions and elevated concentrations of hydrogen sulphide (Canganella *et al.*, 2007; Yao *et al.*, 2020). The Faanu Mudugau Blue Hole in the Maldives opens on the floor of an atoll' lagoon at a depth of 30 m, with an entrance about 70 m wide, and extends downward to a depth of 85 m. Along its vertical to overhanging walls, as well as on ledges and recesses at around 50 m depth, speleothems such as stalactites and stalagmites are found, confirming the karstic origin of this system (Colantoni *et al.*, 2003). The water chemistry of Faanu Mudugau Blue Hole varies markedly with depth: around 50 m, a chemocline separates distinct layers, where temperature, salinity, pH, and redox potential drop sharply. Below this layer, oxygen (O<sub>2</sub>) concentrations fall to nearly zero, while levels of carbon dioxide (CO<sub>2</sub>) and hydrogen sulphide (H<sub>2</sub>S) rise significantly (Colantoni *et al.*, 2003; Cutroneo *et al.*, 2023). This work provides the first characterisation of the biological communities

inhabiting the walls of the Faanu Mudugau Blue Hole, focusing on their distribution according to depth.

**Materials and methods** - Data on the biological communities of Faanu Mudugau Blue Hole were collected by scuba diving in 2019. Along two vertical transects three photoquadrats (each covering an area of 24×36 cm<sup>2</sup>) were taken every 5 m depth, from 30 m to 75 m to characterise the benthic communities (Fig. 1). Each photoquadrat was visually analysed to calculate the percent cover of any organism present at the lowest possible taxonomic level together with abiotic components. When species identification was not possible, a generic classification category, grouping different taxa based on similar morphological and structural characteristics, was adopted (i.e., OTUs = Operational Taxonomic Units; Schiavo *et al.*, 2024). Species, OTUs and abiotic components represent community descriptors. Cover data of any descriptor were organised in a matrix (depth × descriptor) and transformed applying  $\arcsin\sqrt{(x/100)}$ . The matrix was then subjected to Correspondence Analysis (CA) to analyse benthic communities according to the depth.

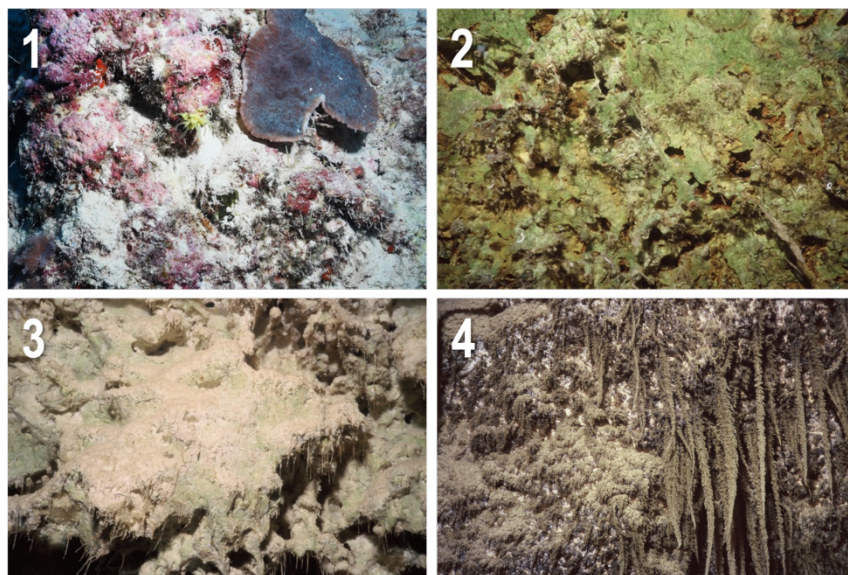


Fig. 1 - Example of photoquadrats sampled at different depths along the Faanu Mudugau Blue Hole walls: 1) 30 m, 2) 45 m, 3) 60 m, 4) 75 m.

*Esempi di fotoquadrati campionati a differenti profondità lungo le pareti del Blue Hole di Faanu Mudugau: 1) 30 m, 2) 45 m, 3) 60 m, 4) 75 m.*

**Results** - A total of 25 descriptors were identified (Table 1). CA applied to cover data ordered photoquadrat points according to a depth gradient along the 1st (horizontal) axis which was an expression of increasing depth from the left (30 m) to the right (75 m) (Fig. 2). The two first axes explain 48.2% and 27.5% of the total variation, respectively; both are significant ( $p < 0.05$ , Lebart's test). Three depth-related zones with different communities can be recognised (Fig. 2): i) a photic zone between 30 m and 40 m depth, with a diverse benthic community dominated by encrusting algae, sponges and scleractinian corals; ii) a mesophotic zone at 45-50 m, dominated by mats of Chrysophyceae and Cyanobacteria; and iii) an aphotic zone below 50 m depth, where the community is characterised by chemosynthetic bacteria.

Tab. 1 - List of the Faanu Mudugau Blue Hole benthic descriptors ordered by code.

*Elenco dei descrittori bentonici del Blue Hole di Faanu Mudugau ordinati per codice.*

Benthic descriptor	Code	Benthic descriptor	Code
<i>Acanthella cavernosa</i> Dendy, 1922	Aca	<i>Leuclathrina translucida</i> Voigt, Ruthensteiner, Leiva, Fradusco & Wörheide, 2018	Ltr
Antipatharia	Ant	<i>Mycedium</i> Milne Edwards & Haime, 1851	Myc
<i>Acarnus topsenti</i> Dendy, 1922	Ato	<i>Peyssonnelia</i> Decaisne, 1841	Pey
Corrosion	Cor	<i>Pseudaxinella</i> Schmidt, 1862	Pse
<i>Dendrophyllia gracilis</i> Milne Edwards & Haime, 1848	Dgr	<i>Pachyseris speciosa</i> (Dana, 1846)	Psp
Golden mat (Chrysophyceae)	Dmt	Rock	Rck
Encrusting ascidians	Eas	<i>Sinularia brassica</i> May, 1898	Sbr
Encrusting corals	Eco	Sediment	Sed
Encrusting corallinales	Ecr	Small serpulids	Sse
Encrusting orange sponge	Eos	<i>Tabastraea faulkneri</i> Wells, 1982	Tfa
Filamentous bacteria	Fba	Turf	Tuf
Green mat (Cyanobacteria)	Gmt	Yellow mat (Crysophyceae)	Ymt
Hydrozoans	Hyd		

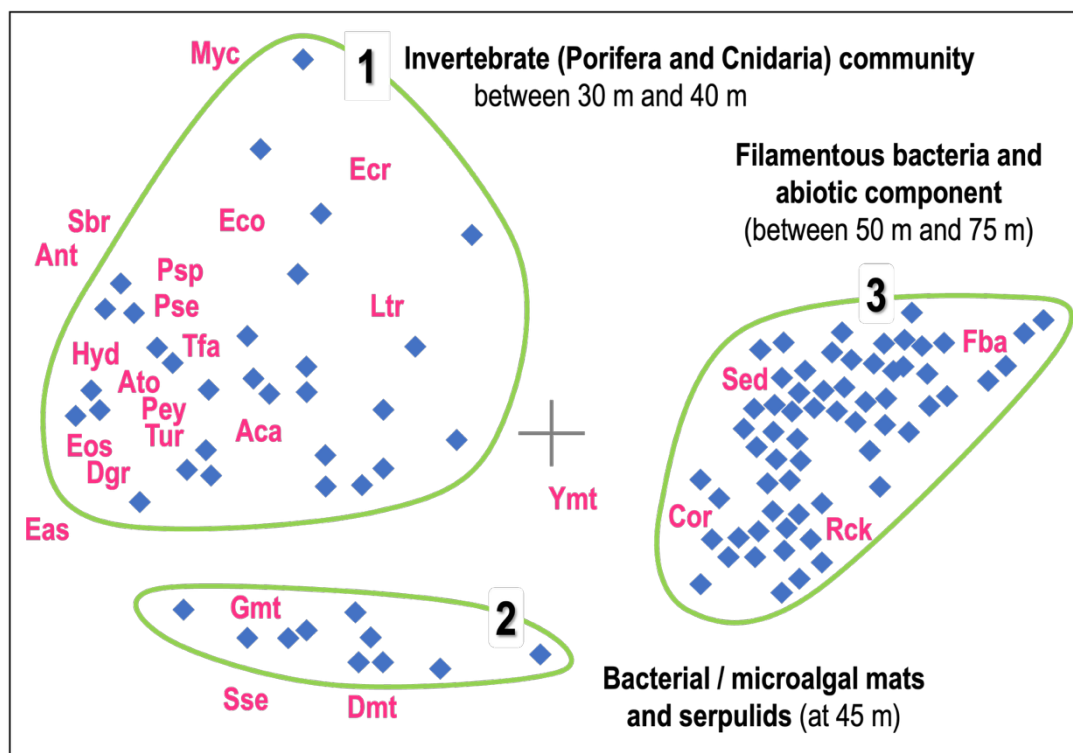


Fig. 2 - Correspondence analysis (CA) plot of Blue Hole photoquadrats (blue points) and benthic descriptors (purple codes as reported in Table 1). The three depth-related zones (1, 2, 3) with different communities are highlighted by the green contours.

*Grafico dell'Analisi delle Corrispondenze (CA) dei fotoquadrati raccolti nel Blue Hole (punti blu) e dei descrittori bentonici presenti (codici fucsia, come riportati in Tabella 1). Le tre zone batimetriche (1, 2, 3) caratterizzate da diverse comunità sono evidenziate dai contorni verdi.*

**Conclusions** - The results of this study revealed a clear vertical distribution of benthic organisms along the Faanu Mudugau Blue Hole walls. Between 30 m and 40 m the benthic assemblage is composed of taxa also occurring on the outer reef. At around 45 m, corresponding to the beginning of the mesophotic zone, mats of Chrysophyceae and Cyanobacteria become dominant while photophilic organisms gradually disappear. Finally, below 50 m, in the aphotic zone, the community is characterised by the exclusive presence of chemosynthetic bacteria belonging to the phyla Chloroflexota, Proteobacteria, and Desulfobacterota (Doni *et al.*, 2024a). This distribution mirrors the stratification of the water column, with communities clearly adapting to the distinct physicochemical environmental conditions. In fact, three distinct layers according to a physicochemical gradient have been described in the Faanu Mudugau Blue Hole: the first layer, consisting of normal marine water, extends between 30 m and 40 m depth; the second layer, located between 45-50 m depth, is marked by a sharp decrease in temperature, salinity, pH and Eh; and the third zone, below 50-55 m depth, is characterised by deep sulphide-rich waters (Colantoni *et al.*, 2003). The presence of a distinct three-layered structure had previously been documented also in the distribution of microbial communities, for which maximum metabolic activity and diversity of both aerobic and anaerobic organisms had been recorded at the oxic-anoxic transition zone at depths of 45–50 m (Doni *et al.*, 2024b), making this zone particularly interesting for scientific research. Blue holes represent natural laboratories that provide unique opportunities for the ecological investigation of extreme environments. In this context, further research on the Faanu Mudugau Blue Hole is essential to elucidate the structure and functioning of this unique ecosystem.

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