

Silvia Cocito · Maja Novosel · Anđelko Novosel

## Carbonate bioformations around underwater freshwater springs in the north-eastern Adriatic Sea

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**Abstract** Large carbonate, bryozoan-serpulid constructions, made by *Pentapora fascialis* and *Salmacina dysenteri* respectively, were found around karstic freshwater springs, called *vruljas*, in the Senj Archipelago (Velebit Channel, Croatia). In June 2002, several sites were investigated by SCUBA divers on the rocky cliffs of Grmac and Ždralova at depths ranging from 19 to 32 m. Mean colony diameter decreased with increasing distance from the *vruljas*: in the vicinity the mean diameter was  $65.8 \pm 21$  cm, at 2-m distance it was  $40.4 \pm 8.2$ . Carbonate contribution was to a great extent due to the bryozoan ( $5,784 \pm 1,186$  g·m<sup>-2</sup> CaCO<sub>3</sub>) rather than to the serpulid ( $383 \pm 218$  g·m<sup>-2</sup> CaCO<sub>3</sub>). *P. fascialis* carbonate standing stock was remarkably high if compared with data from literature for shallow carbonate producers. The bryozoan-serpulid constructions can be indicated as important, even if localised, contributions to the carbonate budget in the Adriatic Sea.

**Keywords** Bryozoan-serpulid constructions · Karst · Freshwater springs ( *vruljas* ) · NE-Adriatic

### Introduction

Calcium carbonate is one of the major components of sediments in temperate waters (Nelson 1988), as at the

end of the benthic organism life-cycle skeletal carbonate may become sediment and eventually limestone. Detailed and thorough studies aiming to increase knowledge of carbonate standing stocks and distribution of biogenic carbonate buildups are scarce (Cebrian et al. 2000). In particular, a high variability of carbonate standing stock and production related to species richness and habitat diversity is expected in accordance with the physiographic complexity of the Mediterranean coasts.

Continental climate and freshwater inflow dominate the east coast of the northern Adriatic. In the area of the Velebit Channel (Croatia), large quantities of freshwater enter the marine area through a system of karstic underground canals ending undersea in the form of temporary freshwater springs, the so-called *vruljas*. Localised mixing of fresh and marine waters and related hydrodynamics make this environment peculiar, although these settings are still poorly documented.

Bryozoans and serpulids produce calcareous skeletons, which encrust the substrate or give rise to layers or erect masses, often reaching significant size (Laborel 1987). Bryozoans, acting with the 'clonal building block' strategy (Smith et al. 2001), can form a wide dimensional range of carbonate structures, and, under certain environmental conditions, they give rise in the marine environment to the structural bases of biohermal mounds (Battershill et al. 1998). Serpulids generate, within dense populations, thick layers of intertwined tubes that grow vertically (Ten Hove 1979). These buildups mainly occur in the intertidal zone of the open coast, in enclosed embayments or in brackish water habitats (Bianchi and Morri 1996).

Large bryozoan-serpulid constructions were found around the *vruljas* in the Senj Archipelago (Velebit Channel). This paper aims to quantify the importance of these constructions, describing their occurrence, development, and quantifying their carbonate standing stock and potential carbonate production.

S. Cocito (✉)  
ENEA Marine Environment Research Centre,  
P.O. Box 224, 19100 La Spezia, Italy  
e-mail: silvia.cocito@santateresa.enea.it  
Tel.: +39-187-978285  
Fax: +39-187-978273

M. Novosel  
Department of Biology,  
Faculty of Science,  
Rooseveltov trg 6, 10000 Zagreb, Croatia

A. Novosel  
Institute of Geology,  
Sachsova 2, 10000 Zagreb, Croatia

## Materials and methods

### Geologic and hydrographic setting

The area of the Velebit Channel is characterised by numerous *vruljas* and coastal springs that are the result of intensively tectonically fractured rocks and the karstification of carbonate rocks. High secondary porosity of the carbonate rocks enables water to circulate through many underground channels and crevices. Thus, in the hinterland of the Velebit Mountain, freshwater sinks underground and outflows in the coastal area. The contact zone between fresh and sea water inside underground channels and crevices provides upward flow of the ground water and its rising on the sea bottom and along the coast.

Structural geological features of the Velebit Channel are based on the mobilistic view of the Dinarides genesis and structure (Herak 1986, 1991) which results today in hydrological activity. According to that view, the surveyed area is situated in the contact zone of the Adriatic and Dinaric carbonate platforms. This results in the regional Velebit fault that extends in the N–S direction, while the ground water mainly comes into *vruljas* and coastal springs from a number of NW-SE faults (Kuha and Novosel 2000).

The karst aquifer that is partially drained by the surveyed *vruljas*, is recharged with waters from the rivers Lika and Gacka in the hinterland, as was proved by fluorescein ground water tracing (Biondić and Goatti 1976). The average outflow speed from the Gacka sinkhole, at four coastal springs near the surveyed area, was 11.4 and 11.8 cm/s from the Lika sinkhole. The primary ground water channel flows as well as the high level of the karstification were also determined by tracing.

*Pentapora fascialis* (Pallas 1766)  
and *Salmacina dysteri* (Huxley 1855)

The bryozoan *Pentapora fascialis* (Cheilostomata, Ascophora) forms orange, erect, rigid, heavily calcified colonies, giving rise to a three-dimensional mound structure. It is one of the largest and most conspicuous living, calcified bryozoans, with colonies growing to a diameter of 20–30 cm, occasionally up to 82 cm (Cocito et al. 1998). It occurs on hard subtidal bottoms and current-swept coarse grounds, from the Hebrides and the western coasts of Britain and Ireland southwards, and throughout the Mediterranean (Hayward and McKinney 2002). Fossil formations were found in outcropping Pleistocene sediments in south-eastern Sicily (Rosso 1987). In the Adriatic Sea, particularly offshore of Rovinj, *P. fascialis* grows in exposed positions, on cobbles and boulders, and attached to gorgonian stalks or flexible bryozoans (Hayward and McKinney 2002; Nikolić 1960, as *Hippodiplosia foliaceae*). In the Ligurian Sea (NW Mediterranean), where the species forms very large colonies, the carbonate standing stock ranged from 281 to 2,490 g·m<sup>-2</sup> CaCO<sub>3</sub>, the carbonate production from 358 to 1,214 g·m<sup>-2</sup>·y<sup>-1</sup> CaCO<sub>3</sub> (Cocito and Ferdeghini 2001).

*Serpulidae* constitute a family of sedentary polychaetes whose main features include the production of a calcareous tube (Bianchi and Morri 1996). Serpulid buildups are known from the geological past (Fagerstrom 1987) and in the Recent have been reported from many sites (Zibrowius 1991). Like bryozoans, serpulids are suspension feeders: cilia on the tentacles create a current that draws water and food particles to the worm. *Salmacina dysteri* is a gregarious species characterised by very slender, white tubes. Aggregations of this species can form thick anastomosing bundles of tubes that interweave in a rope-like mass, named 'pseudocolonies'. It grows on hard substrates or overgrowing other fouling invertebrates in sheltered waters, especially harbours and embayments, or among algal populations, on detritic and coralligenous bottoms. Nomenclatural problems surround the genus *Salmacina*; it is often confounded with the genus *Filograna* or considered as synonymous. So far, data on carbonate standing stock and production of *Salmacina dysteri* have not been estimated.

### Image and data analysis

Several sites were surveyed down to a depth of 35 m on the rocky cliffs of Grmac and Ždralova (Senj Archipelago) in order to map the *vruljas* and the physiographic characteristics of the bottom. At four selected sites, video images of bioconstructions were recorded by a SCUBA diver-deployed digital video camera Sony DV1000 equipped with a 112° extra-wide-angle aspheric lens Thalaspheer Pro DV. The work was done in June 2002 at depths ranging from 19 to 32 m.

A 3-D reconstruction method (Cocito et al. 2003) based on image processing was applied to compute volume and other morphometric measurements. Within each site, at a depth of 20 and 25 m, size measurements were made on four colonies for each species in two replicated areas of about 2 m side. Due to the large size of the bryozoan-serpulid formations, a cube of 25 cm side was used as reference object for image calibration (Fig. 1A, B). During the field work, the number of colonies per square meter was annotated.

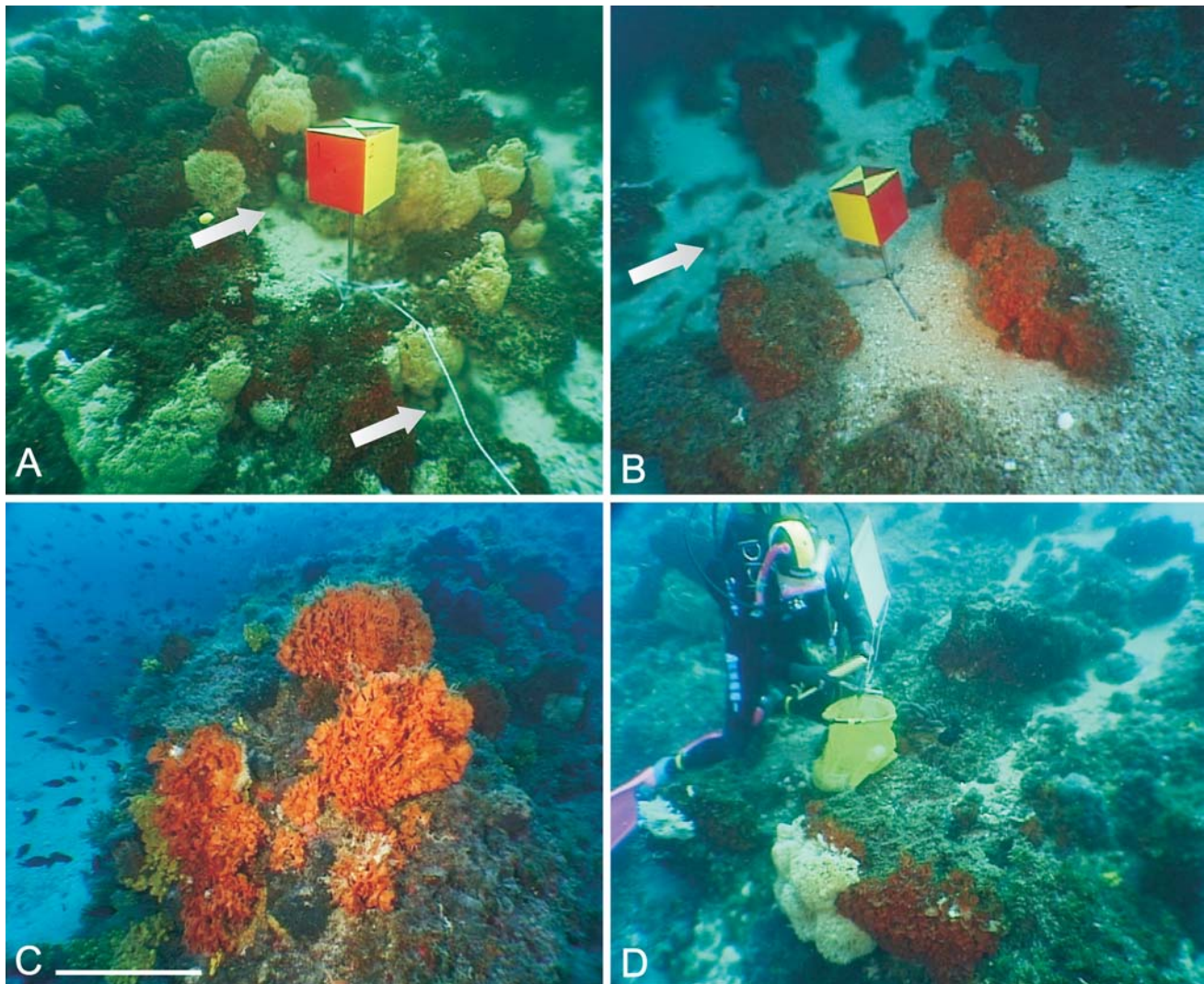
The two species forming the carbonate constructions were sampled in order to check their taxonomic identity. Relationship between colony volume (or 'pseudocolony' in the case of the serpulid) (V) and carbonate dry weight (CDW) was calculated on in situ measurements for the bryozoan applying the conversion factors according to Cocito and Ferdeghini (2001). Seven 'pseudocolonies' of the serpulid were collected to measure carbonate skeleton weight (CDW), i.e. dry weight of carbonate portion of 'pseudocolony'. Total dry weight, i.e. dry weight of carbonate portion plus organic matter, was measured after drying at 100 °C for 24 h to constant weight. To destroy the organic matter, 'pseudocolonies' were immersed in sodium hypochlorite (solution 4:1) for 5 h, rinsed and dried at 100 °C for 24 h to constant weight. For the bryozoan, conversion factors were used also to estimate carbonate standing stock and carbonate production (i.e. the amount of CaCO<sub>3</sub> produced per unit area per year) from volume and density data of colonies, measured per squared meter in the field. Potential carbonate production was estimated only for the bryozoan, for which the mean annual growth rate (3.6±1.57 cm·y<sup>-1</sup>) is known for the Ligurian Sea from the Alizarin staining method (Cocito and Ferdeghini 1998).

## Results

Along the coastline and the rocky cliffs of the Senj Archipelago, numerous *vruljas* were observed and the majority of them were temporarily active. *Vruljas* were found at wide depth range, from 0.5 to 35 m in rocky fractures, in debris, in clastic sediment and on soft bottoms, and their occurrence was variable both in abundance and in position. Their funnel diameter ranged from few cm to a maximum of 2.5 m found on a sandy bottom.

A well-developed ring of sessile, carbonate-producing organisms, almost exclusively suspension feeders such as bryozoans and serpulids, namely *Pentapora fascialis* (Pallas 1766) and *Salmacina dysteri* (Huxley 1855), was found around the funnel border of the *vruljas* outflow (Fig. 1A). Serpulids always grew as epibionts on the bryozoan colonies. Bioconstructions grew closely adjacent to each other in the vicinity of *vruljas* (mean colony density 1.8±0.4) and less packed at increasing distance (mean colony density 2.2±0.8). The average volume of the bioconstructions growing close to the *vruljas* and those growing approximately 2 m away were recorded (Table 1). At Grmac, one elliptic colony 100 cm in





**Fig. 1** **A** Carbonate bioformations made by the bryozoan *Pentapora fascialis* (orange when living and grey-brown when covered with epiphytes) and the serpulid *Salmacina dysteri* (whitish) growing close to the *vrvuljas* (white arrows). The cube 25 cm on a side has been used for image calibration. **B** At increasing distance

from the *vrvuljas* the bioformations were made exclusively by *P. fascialis*. **C** *P. fascialis* colonies growing on the rocky bottom of Ždralova at 22-m depth (scale bar =45 cm). **D** In situ measurement of colony sizes

**Table 1** Diameter, volume, carbonate standing stock and potential carbonate production of the bryozoan-serpulid constructions measured close to the *vrvuljas* outflow and at some 2-m distance. Size

measurements were made at four selected sites at Grmac and Ždralova (Senj Archipelago), at 20 m and 25 m depth, on four colonies for each species in two replicated areas of about 2 m side

	Diameter (cm)±s.d.		Volume (cm <sup>3</sup> )±s.d.		Carbonate standing stock (g·m <sup>-2</sup> CaCO <sub>3</sub> )±s.d.		Carbonate production (g·m <sup>-2</sup> ·y <sup>-1</sup> )±s.d.	
	Close	2 m	Close	2 m	Close	2 m	Close	2 m
<i>P. fascialis</i>	65.8±21.2	40.4±8.2	10,132±149,673	3,768±20,279	5,784±1,186	2,073±708	1,258±418	679±207
<i>S. dysteri</i>	15.8±4.7	n.p.	354±1,779	n.p.	383±218	n.p.	-	-

s.d. standard deviation; n.p. not present

diameter and 55 cm high was reported in the proximity of one of the major outflow.

Large, mound colonies of *P. fascialis*, approaching as form a cut short ellipsoid, grew with the living, convex portion towards the upstream outflow of brackish water,

whereas the side of the colony sheltered from the brackish outflow were necrotic and covered with epiphytes, mainly Dictyotales.

The majority of the colonies growing closer to the *vrvulja* outflow bore on the living portion densely-packed

tubes of *S. dysteri*, whereas at increasing distance, some 2 m from the funnel border, *S. dysteri* was almost absent (Fig. 1B).

*P. fascialis* carbonate standing stock was  $5,784 \pm 1,186 \text{ g}\cdot\text{m}^{-2} \text{ CaCO}_3$  in proximity to the *vruljas* and  $2,073 \pm 708 \text{ g}\cdot\text{m}^{-2} \text{ CaCO}_3$  at 2-m distance (Table 1). For *S. dysteri* the following equation resulted:

$$\text{CDW(g)} = 0.0488 \cdot V(\text{cm}^3) + 0.124 (\text{R}^2 = 0.97)$$

according to which the mean carbonate standing stock was  $383 \pm 218 \text{ g}\cdot\text{m}^{-2} \text{ CaCO}_3$ .

Due to the lack of data on *S. dysteri* growth rate, potential carbonate production was estimated only for *P. fascialis*: it was  $1,258 \pm 418 \text{ g}\cdot\text{m}^{-2}\cdot\text{y}^{-1} \text{ CaCO}_3$  close to the *vruljas* and  $679 \pm 207 \text{ g}\cdot\text{m}^{-2}\cdot\text{y}^{-1} \text{ CaCO}_3$  at a distance of 2m (Table 1).

## Discussion

Large dimension, and significant substratum cover by the bryozoan-serpulid formations were noted at all four studied sites, particularly on substrate close to *vruljas*, where the largest *Pentapora fascialis* colony was found (100 cm in diameter). The occurrence and development of these conspicuous bioformations seemed to be largely influenced by their proximity to the *vruljas*, but whether hydrodynamic conditions, or mixing of different waters, or nutrient and carbonate input enhance such a peculiar constructional ability has still to be investigated.

Whereas geological and hydrological properties of *vruljas* are relatively well known, their influence on biological communities, particularly benthos living on the surrounding substrate, has not yet been studied in detail. Petricioli et al. (1995) found that in the Velebit Channel some organisms living close to the *vruljas* were periodically subjected to 'salinity shock', which occurred when

freshwater suddenly flushed through karstic underground canals changing salinity, temperature and other properties of the seawater in the close vicinity of the *vruljas*.

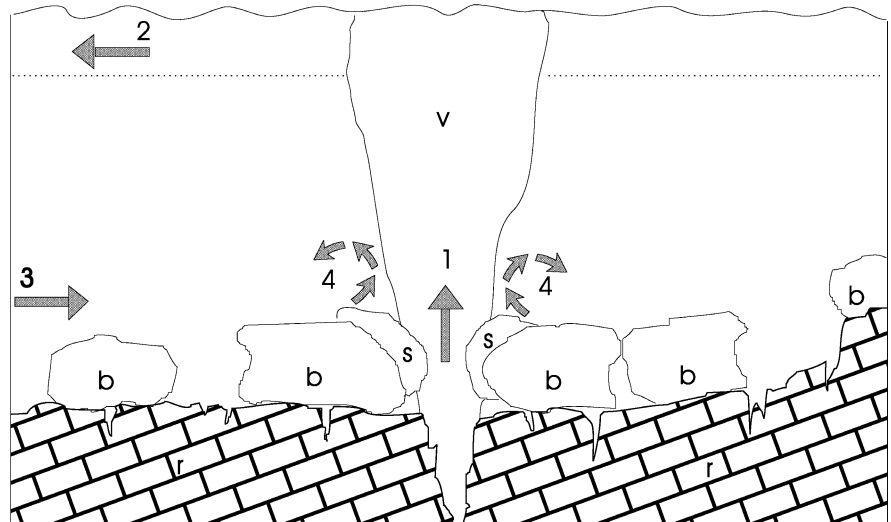
Nikolić (1960) described *P. fascialis* in the northeast Adriatic near Rovinj as a 'benthic association centre', but he did not report the development of exceptionally large colonies. Hayward and McKinney (2002) described the species as the largest and most conspicuous calcified bryozoan in the northern Adriatic, with colonies up to 0.3 m in diameter, especially common on cobbles and gorgonian stalks, before the anoxic event of the late 1980s. *P. fascialis* colonies were noted by Štirn et al. (1969) as 'oases' of high diversity that develop on bottoms with strong currents. They recorded the presence of *P. fascialis* near *vruljas* in the Velebit Channel and described the species as euryhaline. Novosel et al. (2002), investigating hard bottom benthic communities in the northern part of the Velebit Channel, found *P. fascialis* in areas where *vruljas* were present.

Several environmental factors related to *vruljas* can be hypothesised as determinants in the establishment and development of the bryozoan-serpulid constructions. Ground water transports nutrients and carbonates into the sea which bryozoans and serpulids may use as food or building material. Strong water currents and low rate of sedimentation (Štirn et al. 1969) may enhance the growth of these suspension-feeders. As a matter of fact, the bryozoan is known to spread from the Hebrides to the current-swept brackish canal to the south-east coasts of Tunisia (Ben Mustapha, personal communication).

The possible setting of these carbonate bioformations may be schematised in Fig. 2. The freshwater spring ( $v = vrulja$ ) flows turbulently upward from the bottom mixing with the seawater (1). The different density of the two water masses is clearly distinguishable at sight by SCUBA diver. Depending on the flow pressure and delivery volume, the freshwater flow may convey upward fragments of algae, bryozoans and other organic debris. A

**Fig. 2** Schematic drawing of the *vrulja* outflow and the bryozoan-serpulid constructions.

1 Upward brackish water flow.  
2 Surface brackish water flow.  
3 Bottom compensation seawater flow.  
4 Local bottom compensation seawater flows toward the *vrulja*. *r* Rocky bottom. *v* *Vrulja*. *b* The bryozoan *Pentapora fascialis*. *s* The serpulid *Salmacina dysteri*





thin layer of brackish water is present on the sea surface (2). The upward flow made by the *vrulja* generates a compensatory seawater flow on the bottom towards the *vrulja* (3). Local bottom compensatory seawater flows toward the *vrulja* (4). This has been demonstrated by dye tracing tested by SCUBA divers during the field activities. Bryozoan colonies (b) grow with the living, convex portion towards the upstream outflow of brackish water, bearing on this portion the serpulid masses (s). Both bryozoans and serpulids, which are active suspension feeders, could take advantage of the water flowing enhancing feeding performance.

Within the studied bioconstructions, carbonate contribution was to a great extent due to the bryozoan rather than to the serpulid. The carbonate standing stock of about  $5,784 \pm 1,186 \text{ g}\cdot\text{m}^{-2} \text{ CaCO}_3$  displayed by *P. fascialis* in close proximity to the *vruljas* is remarkably high, especially if compared with the maximum value ( $2,490 \text{ g}\cdot\text{m}^{-2} \text{ CaCO}_3$ ) found in the La Spezia region (Ligurian Sea), where a conspicuous population grows, both in term of colony volume and density (Cocito and Ferdegnini 2001). The constructional ability of *P. fascialis*, estimated through the potential carbonate production, is comparable to estimates made for the La Spezia population and to the maximum theoretical production for *Adeonellopsis* sp. (Smith et al. 2001). Comparison with the few data available for bryozoans as groups indicates a higher constructional ability for *P. fascialis* (Smith and Nelson 1994; Bader 2000).

Few available data on carbonate standing stock of shallow, coastal benthic constructors from Mediterranean localities indicate that in rocky bottom infralittoral and circalittoral communities values reach 1,100 and  $2,400 \text{ g}\cdot\text{m}^{-2} \text{ CaCO}_3$ , respectively (Cebrian et al. 2000), with few exceptions for single species:  $5,000 \text{ g}\cdot\text{m}^{-2} \text{ CaCO}_3$  for the coral *Cladocora caespitosa* (Peirano et al. 2001),  $13,200 \text{ g}\cdot\text{m}^{-2} \text{ CaCO}_3$  for the mussel *Mytilus galloprovincialis* beds (Bellan-Santini 1968). The bryozoan-serpulid constructions developing under the close influence of *vruljas* can be indicated as important contributions to the carbonate budget in the shallow, coastal bottoms of the Adriatic Sea.

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