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CHANGES AND CRISES IN THE MEDITERRANEAN SEA

Foraminiferal ecozones in two submarine caves of the Orosei Gulf (Sardinia, Italy)

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Abstract
Because submarine caves are affected by wide spatial and temporal environmental variability, they are ideal environments for studying the effects of environmental changes on ecological indicators. Benthic foraminifera are protozoa living in marine and transitional habitats, developing typical assemblages as a response to different environmental conditions. For this, they have been increasingly used as ecological indicators for environmental characterization and monitoring. This study was the first one aimed to compare benthic foraminiferal fauna of two different submarine caves of temperate areas, Bel Torrente and Bue Marino, in the Orosei Gulf (Sardinia, Italy). It resumes the main results obtained in Bel Torrente cave by a previous research, implemented by new data acquired by the study of Bue Marino cave. The caves were surveyed and sampled by GUE (Global Underwater Explorers) divers for the first 450 m to recognize distinct ecozones, their ecological significance, and to compare them as regards species composition and extent. The succession of Marine, Entrance and Transitional Ecozones was recognized in both the caves. While the Marine Ecozone pointed out environmental conditions very similar to those of shallow water marine environment, the Entrance and Transitional Ecozones indicated increasing environmental stress. In the Entrance Ecozone, the dominance of tolerant species was probably due to the high environmental variability for the episodic high energy floods and, locally, reduced oxygenation events. In the Transitional Ecozone, the decrease of seawater salinity and temperature, especially after rainy periods, probably encouraged the prevalence of agglutinated taxa, which are normally rare in Mediterranean shallow water marine environment, while they are common in high latitude basins.

Keywords Submarine cave · Benthic foraminifera · Ecological indicators · Orosei Gulf

1 Introduction

Submarine caves are transitional environments which experience wide variability of environmental parameters, due to the contribution of marine and continental origin and the mixing of different water masses. Consequently, they may be considered as natural laboratories to study the effects of environmental changes in the marine system. The identification of reliable ecological indicators for these changes is a basic need for a multidisciplinary approach in the marine environmental research.

The study of marine cave communities in the Mediterranean Sea started in the middle of the last century, primarily focusing on the benthic communities of hard substrates, while very little efforts have been devoted to the study of soft-bottom communities. A common feature in these studies is a decrease in species richness and biomass of benthic organisms from the outermost to the innermost part of the cave, depending on physical and chemical gradients inside

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the cave due to changes of parameters such as light, oxygen, salinity and nutrients (Navarro-Barranco et al. 2012).

Benthic foraminifera are a group of eukaryotic protozoa very abundant in sediments, which live in most marine and transitional environments and constitute different assemblages as a response to changes of environmental parameters such as salinity, sediment texture, dissolved oxygen and nutrient load. Most of them have a hard shell called "test" which may be calcareous perforate (hyaline), calcareous imperforate (porcelaneous) or made of sediment grains (agglutinated), which is preserved after the death of the organism. Because they are generally abundant in transitional environments, they are supposed to be an ideal tool to identify distinct environments in submarine caves, where a strong environmental gradient is present. Few studies are focused on this habitat, where benthic foraminifera were used both as paleoenvironmental indicators of sea level changes and as environmental tools for ecological zonation (van Hengstum et al. 2008; van Hengstum and Scott 2011); nevertheless, none of these considered caves from temperate marine areas.

The Sardinian Cave Project was planned to carry out an environmental assessment of the submarine caves of the Orosei Gulf using benthic foraminifera as ecological indicators; it is still in progress and includes annual sampling of the caves, to characterize also temporal variability. This research reports the outcome of the first campaign, resuming the main results obtained in Bel Torrente cave (Romano et al. 2018) and integrating it with new data from the study of Bue Marino cave. It is aimed to characterize the foraminiferal fauna of Bel Torrente and Bue Marino caves, to recognize distinct ecozones, their ecological significance and to compare them as regards species composition and extent.

2 Geological and hydrological setting of the caves

Karst systems, located on the coastal zone of the Mediterranean Sea, are generally characterized by the presence of several cave passages, due to the dissolution of limestone along structural weaknesses occurred during Quaternary, when climatic variability determined sea-level changes. The Orosei Gulf shows a typical fluvial-karst landscape with crystalline Paleozoic basement, constituted by granites and metamorphic rocks covered by Mesozoic sedimentary sequence constituted by conglomerates, dolostones and limestones (Fig. 1).

The hydrographic network is mainly characterized by Codula Ilune and Codula Sisine gorges, where waters from heavy rainfall flow together forming a stream and ending in the sea. The first one has more than 60% of its drainage basin extended upon granites, while the second one drains part of the basaltic San Pietro plain (De Waele 2005). At present, surface drainage is activated only after heavy rain periods, usually twice a year (De Waele 2004). Water flows in through various sinkholes in the western part of the area and flows out of the system through several submarine resurgences, among which Bel Torrente is the most important.

The Bel Torrente cave starts with a cavern area at sea level with the bottom at about 3 m and still with an open water area; it is characterized by a 5–20 m wide tunnel with an average height of 5 m and a depth down to 12 m (Fig. 2), where flow rate ranges from 100 to 1000 $l\ s^{-1}$ during overflow periods, while during dry conditions the water discharge is scarce (10 $l\ s^{-1}$). For this reason, in the first section of the cave, the bottom is generally covered by thick sandy layer, fallen speleothems and rocky boulders with scallops and gravelly deposits with evident ripples indicating high energy flow while, in the inner part, bottom and walls are characterized by big rocky boulders (Fancello et al. 2000; De Waele et al. 2009; Romano et al. 2018).

The Bue Marino cave has a total development of more than 15 km. The system is composed of three main branches: a southern (*Ramo Sud*), a northern (*Ramo Nord*) and an intermediate one (*Ramo di Mezzo*). Most of these subterranean environments have large dimensions (mean diameter of 10 m) and are developed close to the present sea level, reaching their maximum depth (43 m) in one of the sumps in *Ramo Nord* (Fig. 3). The largest conduit is the *Ramo Sud* that carries large amounts of fresh water originating in the Codula Ilune canyon during important floods, but it has a very low base flow (some 1 s^{-1}). Also the *Ramo Nord* is characterized by large conduits, draining water from the Codula Fuili recharge area and long succession of more than 40 sumps and many dry parts for a total development of 7 km. This branch has a base flow of 40 $l\ s^{-1}$, coming from four different subterranean springs (three fresh water inlets and a brackish one) at 2 km linear distance from the present coastline, and discharges large amounts of fresh water (over one $m^3\ s^{-1}$) during periods of significant flooding. The *Ramo di Mezzo* is the least impressive in dimension and it is probably linked to some smaller sinks in the Codula Ilune river bed. During base flow, sea water penetrates 300 m into the southern branch where a flowstone dam inhibits further mixing, and 1500 m into the northern one. The huge pre-sump passage is characterized by sediments prevalently composed of granites, dolostones, and limestones (De Waele 2004; Sanna and De Waele 2010).

3 Materials and methods

GUE (Global Underwater Explorers) divers carried out the survey of both caves, positioned a georeferenced line on which 15 sampling stations were placed at 30 m distance one

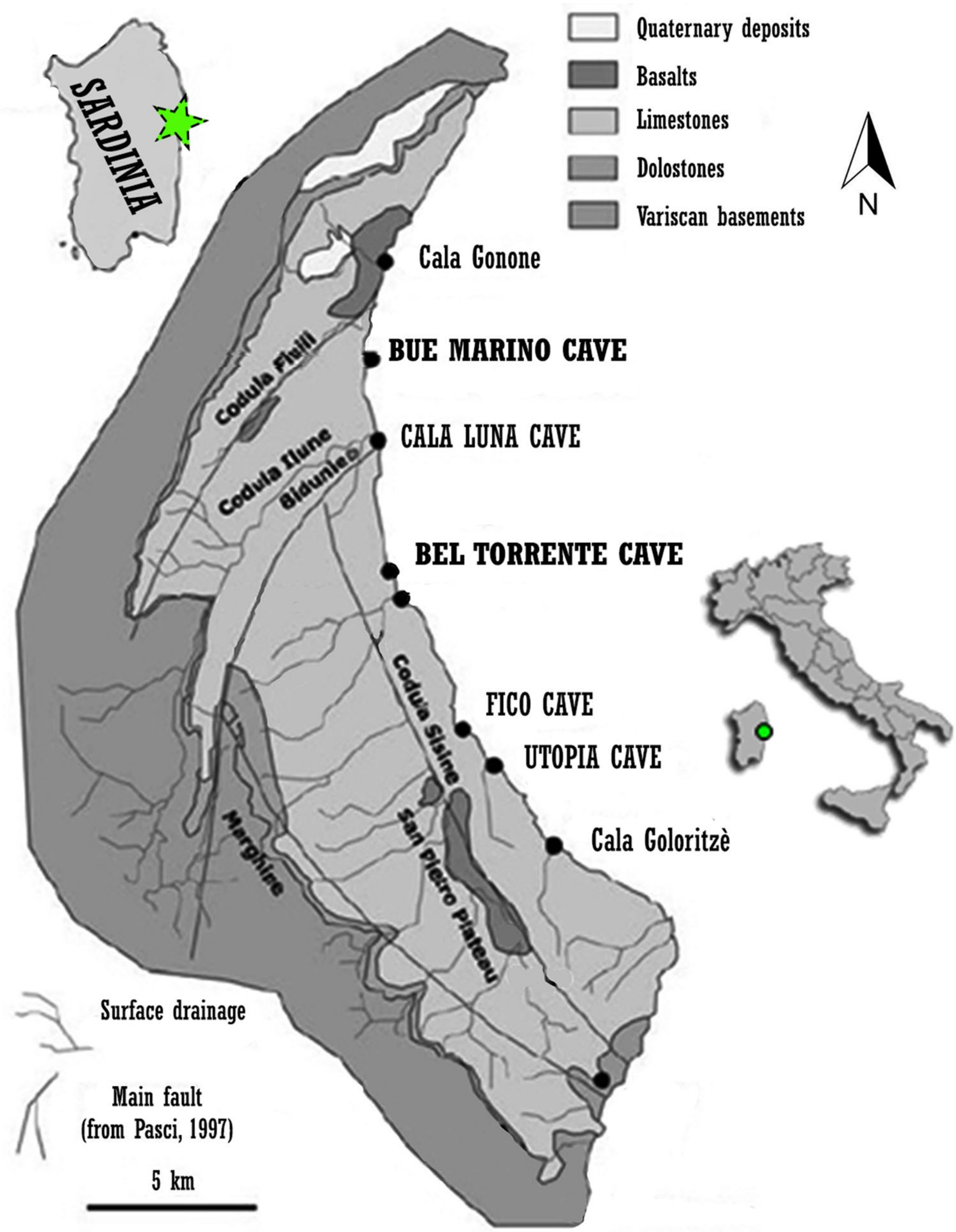

Fig. 1 Geological scheme of the Orosei Gulf (from Romano et al. 2018, modified from INQUA SEQS 2012)

from another, from the entrance to the inner zone; in the Bue Marino cave station 3 was not sampled because of the rocky bottom. On each station sediment and water samples were manually collected (Figs. 2, 3). In particular, water sample was stored in plastic containers, while the upper 2 cm layer of the cave bottom sediment was stored in two different containers: two aliquots of 50 and 100 cm^3, respectively, were collected for grain size and foraminiferal analyses; the second one was immediately stained by means of an ethanol solution with Rose Bengal (2 g l^{-1}) for the identification of living foraminifera.

For grain size analysis, samples were pre-treated with a solution of hydrogen peroxide (30%) and distilled water (1:3) to remove salts and organic matter. Then, they were wet-separated into coarse and fine fraction using a sieve with 63-μm mesh. The coarse fraction was sieved using ASTM series sieves, with meshes ranging from -1 to $+4$ ϕ, while the $>5\%$ fine fraction was analyzed by means of laser granulometer (Sympatec Helos, FKV) after being put into a dispersant solution (Romano et al. 2009). Sediments were classified according to Shepard (1954).

For the study of foraminifera, samples were wet sieved at 63 μm, dried and picked under stereo microscope. Count of living and dead foraminifera was conducted separately and based on the census of at least 300 specimens, when present. To prevent the inclusion of reworked or transported specimens, only well-preserved tests, without breakages or abrasion signs, were picked, counted and

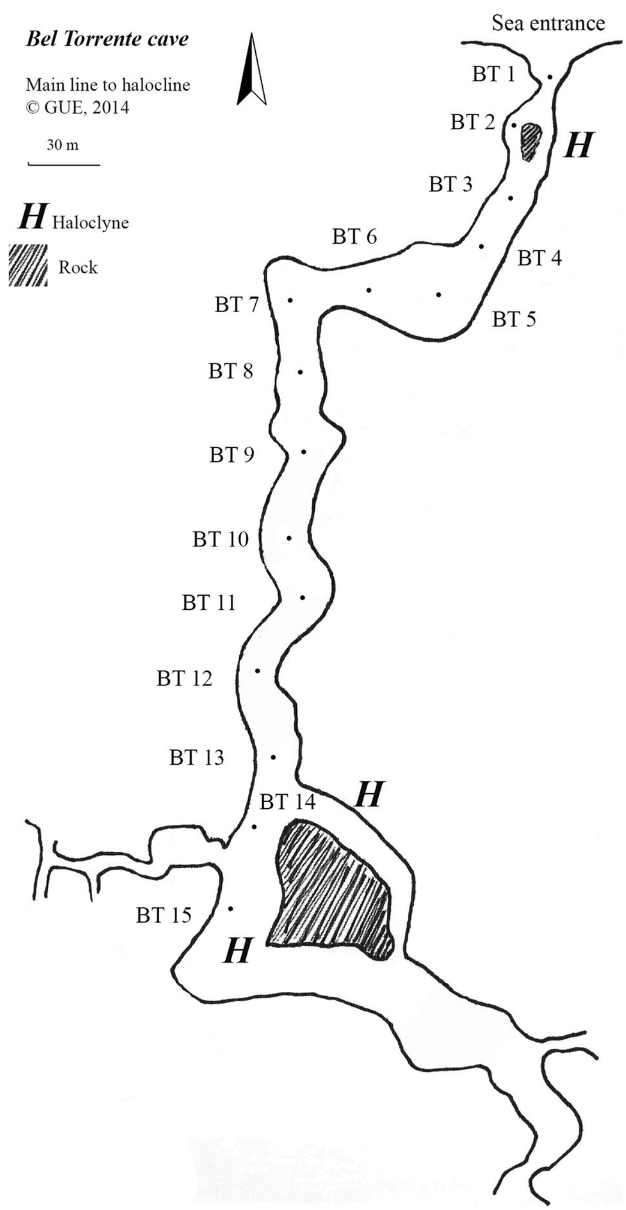

Fig. 2 Sampling map of Bel Torrente cave (from Romano et al. 2018)

classified. Moreover, according to Van Hengstum and Scott (2011), one species was considered as autochthonous in one sample and included in multivariate analysis only when at least one stained specimen of that species was found (Romano et al. 2018). The classification of foraminifera at the genus level was made according to the most used taxonomical study on foraminiferal genera (Loeblich and Tappan 1987), while species were determined according to some important studies on the Mediterranean area (Cimerman and Langer 1991; Sgarrella and Montcharmont-Zei 1993) and to the World Modern Foraminifera Database (Hayward et al. 2011). The species diversity was given as α-index (Fisher et al. 1943).

To apply a reliable statistical analysis, taking into account the low foraminiferal density of dead and living specimens, it was necessary to consider their sum to create the matrix. The two-way (Q-mode and R-mode) Hierarchical Cluster Analysis (HCA) was applied to the quantitative foraminiferal data (living + dead) of commonly occurring species (> 5% in at least one sample), to recognize groups of samples with homogeneous faunal content, corresponding to foraminiferal ecozones (Scott et al. 2001). Statistical analysis was carried out by means of the statistical package PAlaeontological Statistics-PAST ver. 3.18 using the Euclidean distance coefficient to compare samples, and Ward's method of minimum variance to assemble clusters (Parker and Arnold 1999; Hammer et al. 2001).

4 Results

4.1 Bel Torrente cave

The results of Bel Torrente cave are published in Romano et al. (2018) and summarized here. The sediments are generally characterized by coarse grains with sand as prevailing fraction, while the fine fraction is generally very scarce. They are constituted by coarse, or very coarse, gray grains with scarce organic fraction represented by bivalves, gastropods, echinoids, annelids, and foraminifera. The inorganic fraction is mainly constituted by quartz, plagioclases, k-feldspars, biotite, volcanic lithic fragments, rare schists and carbonate fragments. The last ones have a significant presence only in BT1 and BT2. They are classified, according to Shepard (1954), as sand, gravelly sand and, only for one sample, sandy gravel, highlighting scarce grain size variability (Fig. 4).

Benthic foraminifera were found from BT1 to BT11 stations, while samples from the inner sector (BT12–BT15) were barren. The results of quantitative analysis, expressed as absolute abundance, are reported in Table S1. Considering the overall absolute abundance in the total assemblage, the dominant species were *Gavelinopsis praegeri*, *Reophax dentaliniformis* and *Eggerella advena*, with 533, 485, and 406 specimens, respectively. Abundant species were also *Ammonia inflata* (304), *Cribrostomoides jeffreysii* (250) and *Rosalina bradyi* (217). The α-index (Table 1), which represents species diversity, ranges between 4 and 20, with a clear decreasing pattern from the entrance to the inner cave (Romano et al. 2018).

The HCA, based on the relative abundance of commonly occurring species (Table 1), recognized two main clusters according to the distribution of samples in the cave, and left alone BT11 (Fig. 5). Cluster A, which includes samples from BT1 to BT5, is clearly subdivided into two sub-clusters. The first one (A1: BT1–BT3) shows the highest diversity

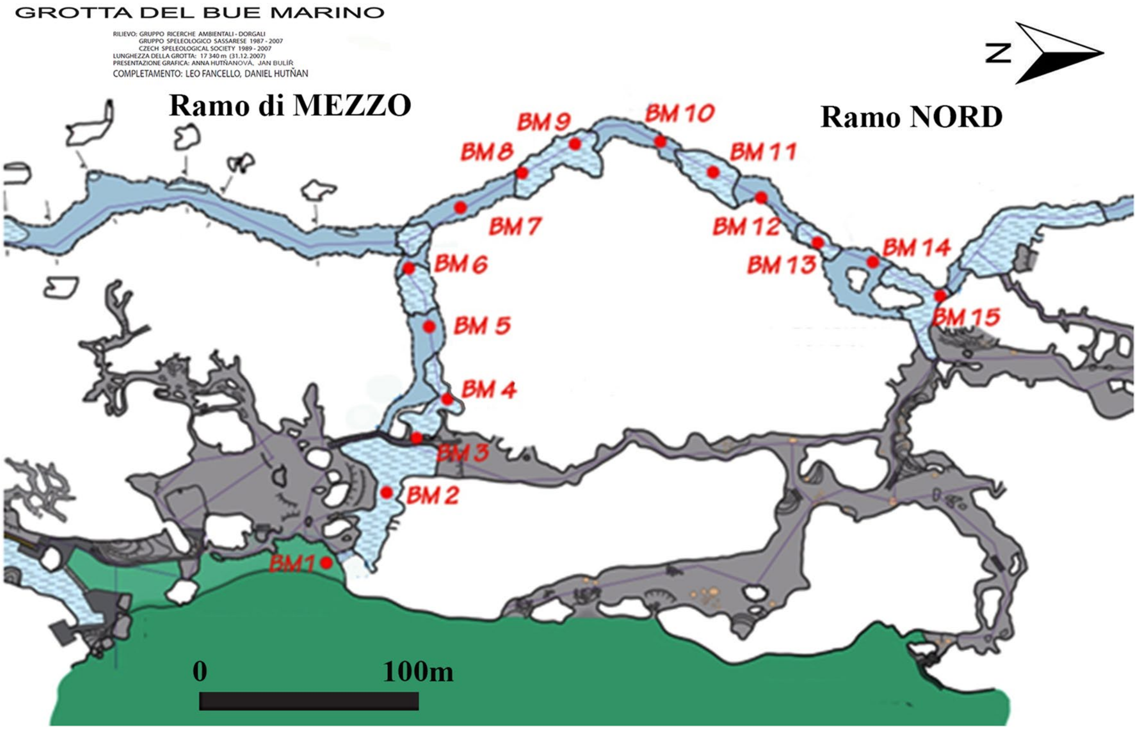

Fig. 3 Sampling map of Bue Marino cave

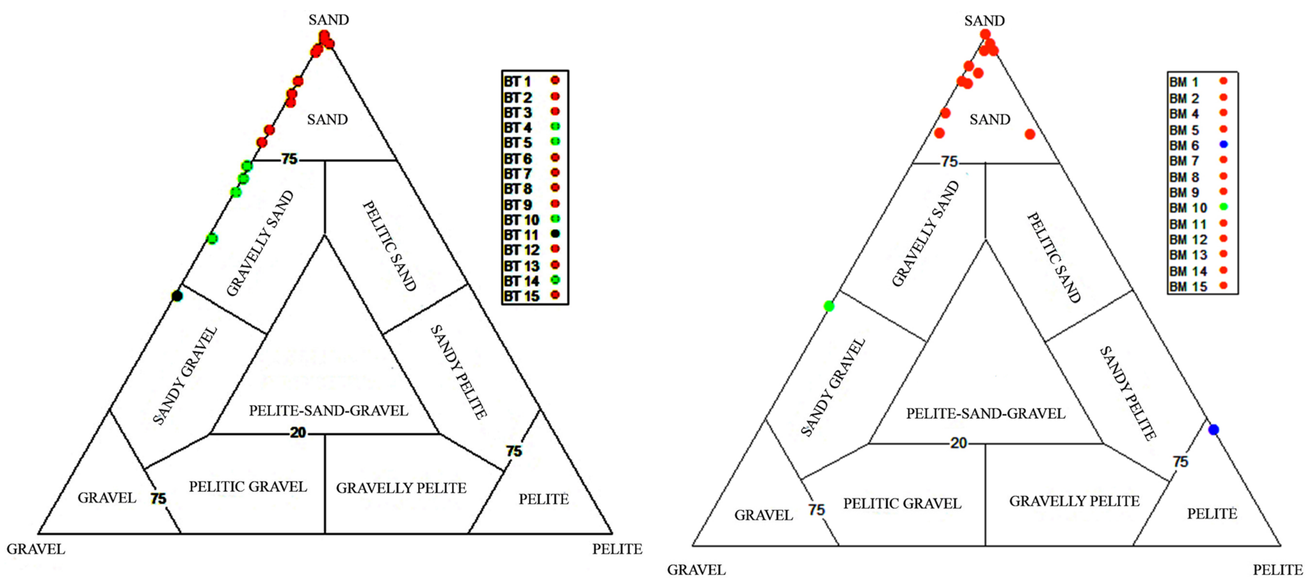

Fig. 4 Classification, according to Shepard (1954), of Bel Torrente (from Romano et al. 2018) and Bue Marino cave sediments. The color in the diagram identify the different textural classes

(median α-index 19.2) and is marked out by an assemblage with strongly prevailing hyaline species (*G. praegeri*, up to 22%), with typical shallow water species (*Peneroplis pertusus* and *Elphidium crispum*, up to 18 and 7%, respectively; Table 2). The second one (A2: BT4–BT5) has a median α-index of 14 and is characterized by the strong increase of agglutinated taxa (Fig. 6), mainly *R. dentaliniformis*, up to 27%, associate to the hyaline *G. praegeri* and *Bolivina* spp. (up to 15 and 14%, respectively). Also cluster B, less diversified than A (median α-index of 9.8), includes samples from

Table 1 Bel Torrente cave: relative abundance of commonly occurring species (> 5% in at least one sample) in the total assemblage and α-index

	BT1	BT2	BT3	BT4	BT5	BT6	BT7	BT8	BT9	BT10	BT11
Ammoglobigerina globigeriniformis	0.0	0.0	0.0	6.5	4.6	1.0	2.8	2.2	2.9	5.4	8.6
Ammonia beccarii	5.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Ammonia inflata	0.0	0.0	0.0	0.0	0.8	31.1	11.9	2.9	3.5	2.7	0.0
Ammonia parkinsoniana	8.3	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Bolivina pseudoplicata	0.0	4.7	10.5	9.3	8.0	2.6	2.4	2.2	4.0	0.0	2.9
Bolivina sp.	0.0	0.2	0.6	0.0	0.4	0.3	0.1	0.7	0.0	0.0	5.7
Bolivina variabilis	2.1	2.4	1.9	4.8	3.3	4.4	3.0	2.9	0.0	5.4	0.0
Cibicides refulgens	1.4	0.8	6.0	0.3	0.6	0.2	0.1	0.0	0.0	0.0	0.0
Cribrostomoides jeffreysi	0.7	0.6	0.4	4.4	3.4	8.9	14.3	10.1	2.9	0.0	2.9
Cribrostomoides subglobosum	0.0	0.0	0.0	0.0	0.0	0.3	2.8	3.6	6.9	0.0	0.0
Eggerella advena	0.7	0.4	1.2	0.5	8.0	8.1	21.8	28.1	34.7	21.6	2.9
Elphidium crispum	6.9	0.4	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Gavelinopsis praegeri	10.3	21.5	14.0	14.9	10.1	11.1	8.3	4.3	7.5	21.6	0.0
Lobatula lobatula	4.1	7.7	5.1	0.9	0.5	0.2	0.4	2.2	0.6	0.0	0.0
Milammina fusca	0.0	0.2	0.2	2.6	5.1	0.5	0.0	0.0	0.0	0.0	0.0
Miliolinella subrotunda	1.4	5.7	5.8	3.6	2.3	2.1	1.1	2.9	0.0	0.0	5.7
Peneroplis pertusus	17.9	5.1	3.7	0.3	0.1	0.0	0.0	0.0	0.0	0.0	0.0
Pseudotriloculina laevigata	0.0	0.4	0.0	0.0	0.0	0.5	0.5	0.0	0.0	13.5	11.4
Quinqueloculina lata	1.4	3.2	1.9	8.7	1.5	3.7	1.6	5.0	0.0	2.7	0.0
Quinqueloculina stelligera	0.7	4.7	4.5	6.8	3.1	1.6	1.5	0.7	1.7	2.7	0.0
Reophax dentaliniformis	0.7	2.2	7.4	19.0	26.7	4.4	6.8	10.1	1.7	2.7	2.9
Rosalina bradyi	3.4	2.4	2.3	1.8	2.7	2.7	7.6	10.1	21.4	18.9	57.1
Rosalina floridana	4.1	5.7	4.1	0.6	0.3	0.2	0.3	0.7	0.0	0.0	0.0
Spirillina vivipara	2.8	4.7	3.9	1.2	1.0	1.6	1.4	0.7	0.0	0.0	0.0
α-***index***	***19.8***	***19.2***	***17.6***	***12.5***	***15.5***	***12.5***	***9.8***	***10.0***	***7.1***	***5.3***	***3.9***

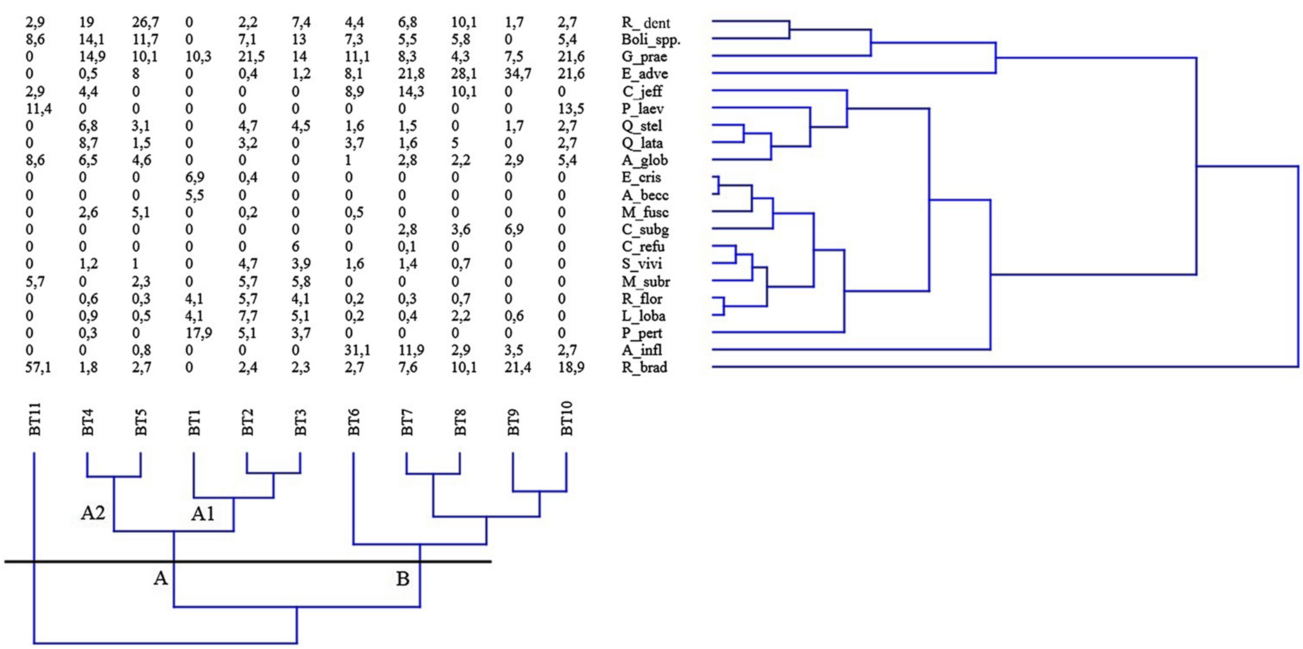

Fig. 5 Hierarchical Cluster Analysis (Q-mode and R-mode) based on relative abundance of foraminiferal species in samples of Bel Torrente cave (from Romano et al. 2018)

Table 2 Faunal characters of clusters obtained by Hierarchical Cluster Analysis in Bel Torrente cave: range and median value of α-index and Relative Abundance (RA) of prevalent species

Cluster	α-index range	α-index median	Prevalent species	RA range (%)	RA median (%)
A1	17.6–19.8	19.2	*Gavelinopsis praegeri*	10.3–21.5	14.0
			Peneroplis pertusus	3.7–17.9	5.1
A2	12.5–15.5	14.0	*Reophax dentaliniformis*	19.0–26.7	22.8
			Gavelinopsis praegeri	10.1–14.9	12.5
B	5.3–12.5	9.8	*Eggerella advena*	8.1–34.7	21.8
			Rosalina bradyi	2.7–21.4	10.1

BT6 to BT10 in which agglutinated taxa are generally prevailing. An exception is due to high percentage of *A. inflata* in BT6, which accounts for 31% of the total assemblage, mostly with living specimens, and showing an α-index of 12.5. Sample BT11 displays a very poor and peculiar foraminiferal fauna, mostly constituted by living *R. bradyi* (57%), and the lowest α-index in the cave (3.9).

4.2 Bue Marino cave

Sediments are mainly constituted by sands with only two exceptions in BM10, characterized by significant presence of gravel, and BM6 where fine fraction is prevailing (Fig. 4). They are gray-brown, varying in texture from medium to very coarse, with sporadic bioclasts (shells and fragments of bivalves, gastropods, echinoids, annelids, foraminifera). They are predominantly composed by quartz, variable from hyaline to translucent, rounded or well-formed bipyramidal crystals, associated to light-colored plagioclases, orange K-feldspars, biotite, muscovite, and sporadic volcanic and carbonatic grains and magnetite. Organic fraction, mainly constituted by vegetal remains, is present just in BM4 and BM6.

Benthic foraminifera were found in all the samples and the results expressed as absolute abundance (Table S2). *E. advena*, *G. praegeri* and *R. bradyi* were the dominant species in terms of absolute abundance (565, 479 and 440 specimens on the whole, respectively); also *Lepidodeuterammina ochracea, C. jeffreysii* and *Bolivina variabilis* were abundant, with 368, 306 and 206 specimens, respectively; among these, *G. praegeri* and *R. bradyi* were recorded in all sampling stations. Hyaline taxa prevailed from BM1 to BM10, with the exception of BM6, while agglutinated taxa were prevalent from BM11 to BM15. Porcelaneous taxa (mainly *Quinqueloculina parvula, Q. stelligera*) were always a minor component of the assemblage (Fig. 6). Species diversity (α-index) ranged between 5 (BM6) and 20 (BM4), without a definite pattern with respect to the distance from the entrance (Table 3).

The HCA, based on the relative abundance of commonly occurring species (Table 3), identified three main clusters with the exception of BM6 (Fig. 7). Cluster A includes the two samples close to the entrance (BM1–BM2), characterized by typical shallow water taxa, mainly *P. pertusus* (up to 34%) and *E. crispum* (up to 12%), which are exclusive (Table 4), accompanied by *G. praegeri* (up to 6%). This cluster is well diversified, with a median α-index of 12.8. Cluster B includes samples between BM3 and BM10, with the exception of BM6 and BM7, with prevailing hyaline taxa (Fig. 6). The most abundant species are *G. praegeri* and *R.*

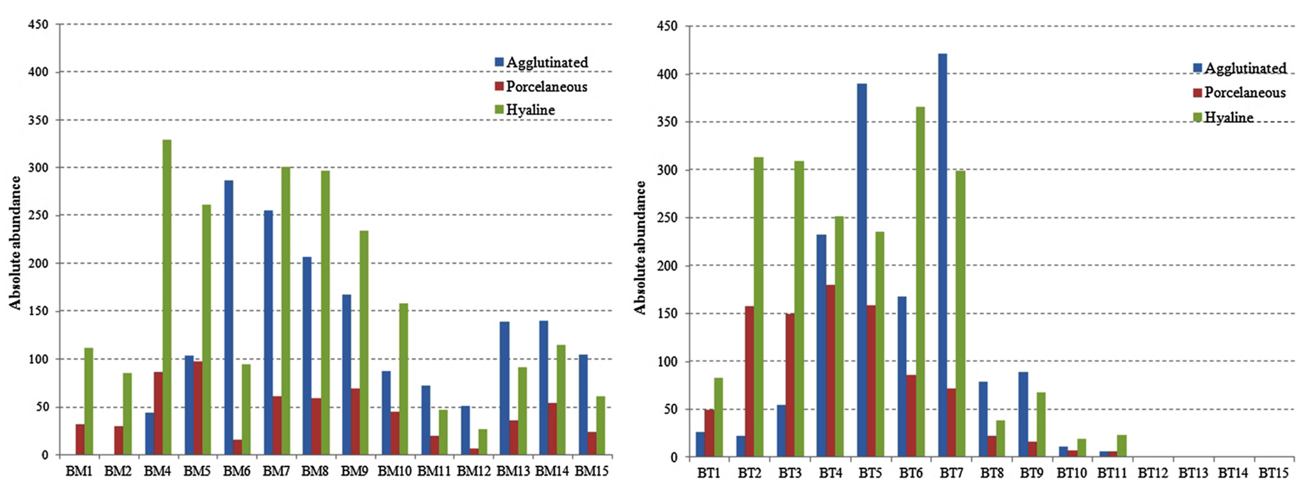

Fig. 6 Absolute abundance of the main foraminiferal groups in Bue Marino and Bel Torrente caves

Table 3 Bue Marino cave: relative abundance of commonly occurring species (> 5% in at least one sample) in the total assemblage and α-index

	BM1	BM2	BM4	BM5	BM6	BM7	BM8	BM9	BM10	BM11	BM12	BM13	BM14	BM15
Ammoglobigerina globigeriniformis	0.0	0.0	0.0	0.6	0.5	0.3	2.3	4.7	4.2	3.7	0.0	2.7	4.6	2.1
Ammonia inflata	0.9	0.0	1.9	2.1	12.6	0.0	0.0	1.3	0.7	0.7	1.2	1.1	0.3	0.5
Ammonia parkinsoniana	6.6	7.3	0.0	0.0	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0
Astronion stelligerum	0.9	0.6	1.1	0.0	0.0	0.3	1.4	2.9	5.2	3.0	0.0	0.4	0.7	0.0
Bolivina variabilis	0.0	0.6	7.1	7.7	0.3	4.1	5.3	2.7	4.9	0.0	4.7	6.1	6.8	6.8
Cibicides refulgens	3.8	7.8	3.9	0.6	0.8	1.3	0.4	0.9	1.4	1.5	1.2	0.0	0.3	0.0
Cribrostomoides jeffreysi	0.0	0.0	0.6	0.9	10.8	9.2	10.7	7.1	10.4	12.6	9.4	4.5	6.8	10.5
Eggerella advena	0.0	0.0	6.3	7.7	58.3	8.7	9.1	6.0	8.0	15.6	20.0	10.6	6.8	14.1
Elphidium crispum	11.8	5.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Gavelinopsis praegeri	5.2	6.1	19.9	19.5	0.0	14.0	11.6	10.2	7.3	4.4	4.7	5.7	7.2	5.2
Globocassidulina subglobosa	0.0	0.0	0.9	1.1	0.0	1.5	3.2	2.9	3.5	2.2	1.2	4.5	2.6	4.2
Lepidodeuterammina ochracea	0.0	0.0	0.0	4.5	0.3	17.5	6.6	7.5	4.2	7.4	20.0	20.5	16.9	12.6
Laptohalysis scottii	0.0	0.0	0.0	4.5	0.0	0.0	0.0	0.4	0.0	0.0	0.0	0.0	0.0	0.0
Lobatula lobatula	5.2	1.1	4.5	0.4	0.3	0.7	0.4	0.0	0.3	0.0	0.0	0.0	0.0	0.5
Peneroplis pertusus	30.8	33.5	0.9	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Reophax dentaliniformis	0.0	0.0	0.2	2.6	0.5	2.5	5.2	7.3	2.4	8.1	3.5	9.5	6.8	11.5
Rosalina bradyi	5.7	8.4	4.5	4.9	6.0	11.6	13.5	11.1	21.9	11.1	11.8	8.3	6.8	9.4
Sigmoilinita costata	0.0	0.0	0.4	1.7	0.0	2.3	2.3	3.1	8.0	5.2	0.0	0.0	1.3	1.6
Sigmoilinita tenuis	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.9	1.3	5.2
Spirillina vivipara	0.0	1.1	2.8	2.4	0.0	5.3	2.1	2.2	1.4	2.2	2.4	0.8	3.6	0.5
Trochammina inflata	0.0	0.0	1.7	0.0	0.8	1.7	0.7	0.4	0.0	3.0	4.7	2.3	1.3	2.6
α-index	***11.5***	***14.2***	***19.7***	***15.8***	***4.7***	***12.9***	***14.0***	***15.6***	***13.1***	***11.3***	***8.2***	***11.3***	***11.4***	***10.5***

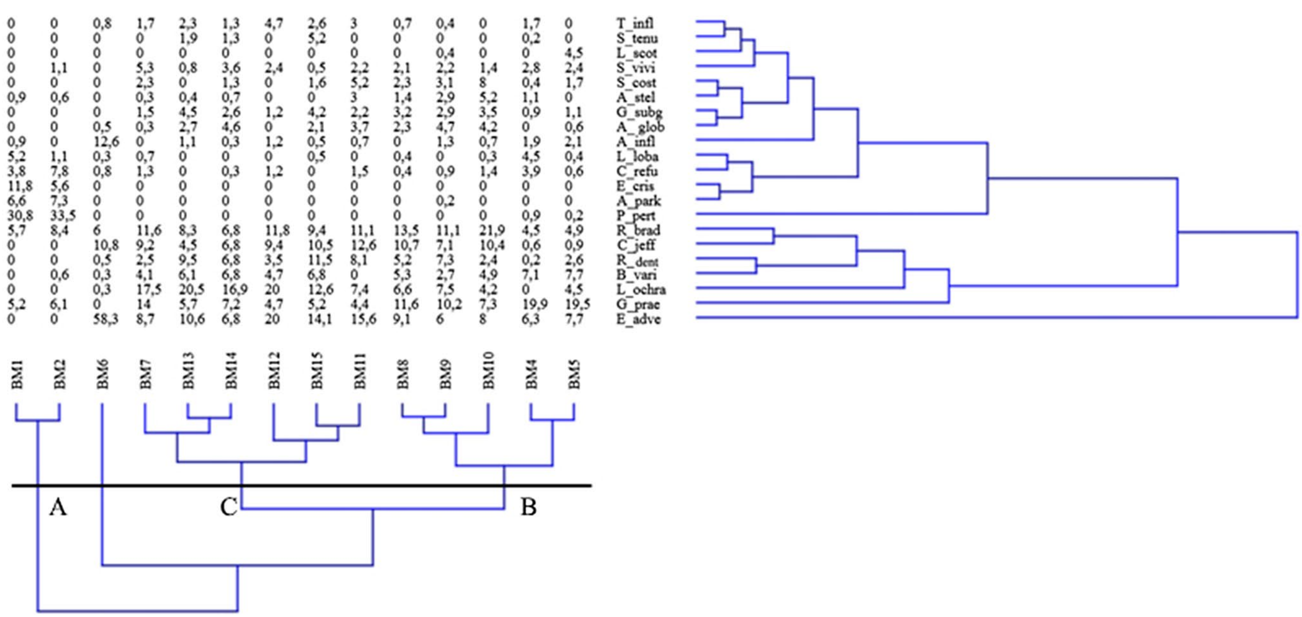

Fig. 7 Hierarchical Cluster Analysis (Q-mode and R-mode) based on relative abundance of foraminiferal species in samples of Bue Marino cave

bradyi, up to 20 and 22%, respectively, but also agglutinated taxa such as *E. advena*, *L. ochracea* and *R. dentaliniformis* start to be frequent (up to 9, 8 and 7%, respectively), as well as *Bolivina* spp. These samples show the highest species diversity, with a median α-index of 15.6. BM6 highlights unique features, because of very low species diversity and the strong dominance of *E. advena* (58%). Cluster C includes samples from the inner cave, from BM11 to BM15,

Table 4 Faunal characters of clusters obtained by Hierarchical Cluster Analysis in Bue Marino cave: range and median value of α-index and Relative Abundance (RA) of prevalent species

Cluster	α-index range	α-index median	Prevalent species	RA range (%)	RA median (%)
A	11.5–14.2	12.8	*Peneroplis pertusus*	30.8–33.5	32.2
			Elphidium crispum	5.6–11.8	8.7
B	13.1–19.7	15.6	*Gavelinopsis praegeri*	10.2–19.9	11.6
			Rosalina bradyi	4.5–21.9	11.1
C	10.5–12.9	11.3	*Lepidodeuterammina ochracea*	7.4–20.5	17.2
			Eggerella advena	6.8–20.0	12.4

with prevailing agglutinated taxa, mainly *L. ochracea*, *E. advena* and *C. jeffreysii*, up to 21, 20, and 13%, respectively. Although sample BM7 has prevailing hyaline taxa, it is included in cluster C because of the high percentage of *L. ochracea* (18%).

5 Discussion

HCA allowed recognizing groups of samples characterized by homogeneous foraminiferal assemblages, corresponding to specific environmental conditions, which permitted to identify an ecozone (Scott et al. 2001). In spite of the different position at hierarchical level of the clusters, the same ecozones were recognized in the two caves.

In both caves a Marine Ecozone was recognized as a small sector which goes from the entrance to 60 and 90 m inside Bue Marino and Bel Torrente, respectively. Hyaline species are clearly prevalent, porcelaneous taxa are abundant, while the agglutinated ones are scarce or absent; some abundant species such as *P. pertusus* and *E. crispum* are exclusive of this zone. In particular, *P. pertusus* lives at sediment–water interface, clinging on plants or hard substrates and hosting the red algal symbiont *Porphyridium* that needs sunlight. Also *E. crispum*, which may live on sediment or vegetated sea-bottom, bears algal chloroplasts interpreted as symbionts (Murray 1991). Because these species are common in shallow water assemblages of Sardinian marine area, they indicate environmental conditions very similar to the normal marine ones (Cherchi et al. 2009; Buosi et al. 2012, 2013). Also *G. praegeri* is frequent in this zone, although not so abundant as in the inner sectors of the caves.

The entrance ecozone is the widest zone in Bue Marino, where it ranges from 60 to 300 m, while it is very narrow in Bel Torrente (90–120 m). Hyaline taxa generally prevail, but also agglutinated ones may be very abundant. The dominant species are the hyaline *G. praegeri* and *R. bradyi*, and the agglutinated *R. dentaliniformis*. The first two are epifaunal taxa which may live clinging or attached to sediment. In particular, the first one may be recovered in a wide range of water depth (Sgarrella and Montcharmont-Zei 1993; Murray 2006); de Stigter et al. (1996) found *G. praegeri* common as living species in shelf samples of the Adriatic Sea at 146 m water depth, while it was occasionally present also deeper, down to 1200 m. *R. dentaliniformis* is an infaunal species which can live at water depth ranging from 46 to 168 m in the Baltic Sea (Hermelin 1983) and at shallower water in fjord environment (Polovodova et al. 2009); on the contrary, it is uncommon in the Sardinian shelf. *Bolivina variabilis* is common in this zone and in the innermost one; it lives in infaunal microhabitat enriched in organic matter and it tolerates dysoxic conditions. In this ecozone, environmental stress determined by high environmental energy due to episodes of continental water flood is testified by species microhabitat, epifaunal clinging or infaunal. The coarse sediment grain size also confirms these conditions. Another stress component, testified by abundant *Bolivina*, may be connected to episodic oxygen deficiency conditions in the summer period, determined by oxygen consumption for the decomposition of organic material. Nevertheless, the prevalence of hyaline taxa suggests a still strong marine influence.

The Transitional Ecozone starts at 300 m at Bue Marino, where the inner limit was not attained, while it ranges from 120 to 300 m in Bel Torrente. A faunal turnover with a transition from prevailing-hyaline to prevailing-agglutinated taxa occurs. *E. advena* is abundant in both caves, accompanied mainly by *R. dentaliniformis* in Bel Torrente and *L. ochracea* in Bue Marino. *E. advena* is an infaunal species typical of high latitude basins, tolerating also low-salinity conditions (Murray 1991, 2006), and considered as a stress-tolerant opportunistic species; it was supposed to benefit from refractory organic material reflecting its opportunistic behavior in BM6 (Schafer et al. 1975; Alve 1995). *R. dentaliniformis* was recognized as a successful opportunistic species in re-colonization experiments (Kaminski et al. 1988). *L. ochracea* is epifaunal clinging species, typically living in cold waters (Murray 2006). In general, the prevalence of agglutinated taxa, uncommon in the Mediterranean basin but ordinary at higher latitudes (Murray 1991), may be indicative of the reduced carbonate water saturation; this is associated to decreased water salinity and temperature, especially occurring during rainy season (Trask 1936). Nevertheless, the abundance in this ecozone of *R. bradyi*, predominantly represented by living specimens, let us suppose that during dry periods, such as the sampling one, environmental conditions, were favorable to the development of carbonate tests. Moreover, because the agglutinated taxa are not present in typical shallow water assemblages of Sardinian coast, a very effective dispersal as propagules (juvenile specimens, < 32 µm, in a cryptic stage) may be supposed (Alve and Goldstein 2003, 2010).

6 Conclusion

The study carried out on sediment samples from Bel Torrente and Bue Marino caves, indicated that benthic foraminifera may live in cave environment, not only close to the entrance, but even at considerable distance from it and respond to changes of environmental parameters. The foraminiferal assemblages follow a general scheme, showing the same succession of ecological zones in the two caves, although significant differences in the ecozone extent were recognized. For this reason, they may be used as a tool for the ecological zonation of this environment.

The increasing environmental stress, probably due to high environmental variability for episodic high energy floods and periods of reduced oxygen levels, determined the presence, also in the outer part of the caves, of tolerant species not common in shallow water assemblages of Sardinian coast. The decrease of seawater salinity and temperature probably promoted reduced carbonate water saturation, especially after rainy periods, encouraging the presence of agglutinated taxa, which are normally rare in Mediterranean shallow water marine environment. Consequently, assemblages similar to the ones of high-latitude marine coastal zone, may be found especially far from the cave entrance. However, no endemic cave taxa were recorded, to suggest that caves have no the role of *refugia* for benthic foraminifera, while the colonization of caves by benthic foraminifera was supposed to occur through the transport from the sea of juvenile specimens in a cryptic stage.

The barren samples in the inner zone, recognized only in Bel Torrente cave, indicate a general environmental instability due to the alternating of continental with marine waters; instead, the presence of foraminifera up to 450 m in Bue Marino is probably due to the bearing of this tunnel with respect to the coast line, where marine contribution prevails.

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