Received: 4 August 2021 | Revised: 2 January 2022 | Accepted: 7 January 2022
DOI: 10.1111/maec.12698

RESEARCH ARTICLE

marine ecology WILEY

Are CO_2-rich seafloor pockmarks a suitable environment for ostracod assemblages? The example of the Zannone Giant Pockmark (central-eastern Tyrrhenian)

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Funding information
Open access funding provided by CNR within the CRUI-CARE Agreement. No funding was received for conducting this study.

Abstract

Despite their high abundance and diversity, ostracods adapted to a particular chemosynthetic environment and its surroundings have rarely been studied. Therefore, the thresholds and environmental characteristics shaping their assemblages are poorly known. Here, we report a detailed study of the ostracod assemblages occurring around the Zannone Giant Pockmark, a CO_2 hydrothermal vent system recently discovered in the central-eastern Tyrrhenian Sea. Although among crustaceans, ostracods seem to have the longest stratigraphic record in fossil seeps and hydrothermal vents starting in the Palaeozoic, our results indicate that their occurrence is driven by CO_2 that represents an insurmountable threshold for ostracods' life.

KEYWORDS
$CaCO_3$ undersaturated waters, circalittoral, hydrothermal vents, Mediterranean Sea, Ostracoda, volcanic areas

1 | INTRODUCTION

Pockmarks are circular depressions, formed where upward seepage of methane, sulphide, or other reduced chemicals causes a collapse of sediment, and are common features where gas pockets are present in near-surface sediments of the sea bottom (Cathles et al., 2010), both in the shallow and deep sea. Submarine hydrothermal vents change the physico-chemical characteristics of waters, affecting diversity, abundance and composition of benthic assemblages.

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The generation of acidic waters, due to carbon dioxide emissions (Boatta et al., 2013), hinders the growth of calcium carbonate hard parts (Rodolfo-Metalpa et al., 2010) and promotes the formation of live and dead assemblages where calcareous-shelled organisms are rare (Cigliano et al., 2010; Pettit et al., 2013, 2015; Ricevuto et al., 2012; Uthicke et al., 2013) or absent (Carey et al., 2013; Dias et al., 2010). In Papua New Guinea, corals species-specific responses to elevated CO_2, linked to volcanic seeps, lead to variable responses at the population level (Strahl et al., 2015).

Crustaceans are frequently reported from fossil and recent hydrothermal vents and cold seeps environments (Karanovic & Brandão, 2015; Martin & Haney, 2005) but not often in the Mediterranean Sea. Although ostracods never represent one of the major meiofaunal component inside pockmarks, many authors report their general occurrence (Coles et al., 1996; Yamaguchi et al., 2016) seldom identifying the taxa (Barbieri & Cavalazzi, 2005; Sánchez et al., 2021; Taviani et al., 2012; Zeppilli et al., 2012). A study about the biodiversity associated with seafloor pockmarks in the Gulf of Lion, western Mediterranean Sea, highlighted the fact that Ostracoda account to <1% of total meiofaunal abundance around inactive pockmarks and are completely absent inside and around active pockmarks (Zeppilli et al., 2012). In cold methane seepage, it seems that although the overall assemblage does not differ much from the typical soft bottom assemblage, indicator species, defined as endemic species or genus linked to methane seeps, could be used to identify depositional paleoenvironments under the influence of such emissions (Ambrose et al., 2015; Yasuhara et al., 2018).

In our experience on the Quaternary successions of the Campanian volcanic areas, the recordings of sediments in which the biogenic component is almost entirely siliceous are not unusual and are interpreted as due to the formation of acidic bottom or interstitial waters that prevent the life or the preservation of calcareous assemblages (Aiello et al., 2020; Aiello, Barra, Collina, et al., 2018; Aiello, Barra, Parisi, et al., 2018; Amato et al., 2019; Barra et al., 1992; De Natale et al., 2016; Isaia et al., 2019; Marturano et al., 2009). This interpretation is based on data from shelf seep sites, where sponges are major component of the biota (Bertolino et al., 2017; Morri et al., 1999) and their spicules are very common in bottom sediments (Tarasov et al., 1999).

The discovery of the Zannone Giant Pockmark (ZGP) (Ingrassia, Martorelli, et al., 2015), an active fluid emission area located on the central-eastern Tyrrhenian continental margin, has provided the opportunity to study a complex venting system in a middle shelf (circalittoral) environment. Previous investigations described benthic assemblages, especially focussing on foraminifera that displayed remarkable differences inside and outside the giant pockmark (Di Bella et al., 2016, 2018; Ingrassia, Di Bella, et al., 2015). These studies showed that within the hydrothermal area, where CO_2-rich gases with a mantle-derived signature ($^3He/^4He$ of 3.72–3.75), with equilibrium temperatures ranging between 150 and 200°C and H_2O pressures of ca. 5 bar occur (Italiano et al., 2019; Martorelli et al., 2016), benthic foraminiferal assemblages consist entirely of agglutinated species, whereas outside the pockmark calcareous tests occur in bottom sediments. The aim of the present investigation is to verify the presence of ostracod assemblages in a circalittoral environment under the influence of hydrothermal activities and examine the composition of the assemblages collected in nearby areas out of hydrothermal influence.

2 | STUDY AREA

The Pontine Archipelago (central-eastern Tyrrhenian Sea) consists of five main volcanic islands, Palmarola, Ponza and Zannone (western Pontine Islands) and Ventotene and Santo Stefano (eastern Pontine Islands) located about 35 km west of the Latium coastline.

On the outer insular shelf off Zannone, the northernmost of the Pontine Archipelago, a large hydrothermal area named the Zannone Hydrothermal Field was discovered (Martorelli et al., 2016). Within this area, a crater-like depression with a surface of 0.5 km^2, the Zannone Giant Pockmark (ZGP) was identified (Ingrassia, Martorelli, et al., 2015). It is an active fluid emission site, formed by at least five smaller craters developed in water depth ranging from 110 to 130 m. Hydrothermal activity, linked to a deep residual magma body, leads to the release of high temperature (60°C, temperature value recorded in the northern sector of the ZGP) venting fluids enriched in CO_2 (concentration >90% from vents inside ZGP), with minor amounts of CH_4 and H_2S (Italiano et al., 2019; Martorelli et al., 2016), and to formation of native sulphur crusts and secondary hydrothermal minerals (Conte et al., 2020). ROV videos of the pockmarks' activities (Ingrassia, Di Bella, et al., 2015; Ingrassia, Martorelli, et al., 2015) highlighted different discharge rates: continuous or intermittent bubble streams from single vent points; dispersed emission over lithified pavements; violent expulsions generating pockmarks and craters. As a result of these peculiar environmental conditions, the benthic assemblages show significant differences between vent and non-vent areas. Typical Tyrrhenian highly differentiated biota live in the western Pontine shelf outside the pockmark, and the biogenic fraction of the bottom sediments includes both siliceous (sponge spicules) and calcium carbonate (foraminifers, coralline algae, bryozoans, ostracods, molluscs, crinoids, echinids and serpulids) remains (Ingrassia, Martorelli, et al., 2015; Ingrassia et al., 2019; Martorelli et al., 2012). Within the pockmark area, venting activity is vigorous and affected by different modality and rate of discharges such as continuous or intermittent bubble streams from single vent points, dispersed emission over lithified pavements and violent expulsions generating pockmarks and craters (Di Bella et al., 2015; Martorelli et al., 2015). Moreover, the waters from the ZGP are enriched in anions and cations with respect to those of the local seawater, thus described as "concentrated seawater" and slightly depleted in magnesium (Italiano et al., 2019).

Within the ZGP, the seafloor is characterised by widespread bacterial mats (Rastelli et al., 2017)., The faunal remains consist of sponge spicules, radiolarians, diatoms and agglutinated foraminifera, whereas calcareous remains are not recorded (Di Bella et al., 2016, 2018). Finally, the study area is affected by surface geostrofic marine currents flowing towards north-west (Artale et al., 1994) playing a role in heat dispersion and distribution of the benthic assemblages.

3 | MATERIALS AND METHODS

3.1 | Sampling strategy

During the research cruise "Bolle 2014" on board of the R/V Urania, four seafloor sediment samples were collected by means of a 30L Van Veen grab from the eastern Zannone insular shelf as part of a detailed study of the relationship between hydrothermal fluid emissions and benthic assemblages (Ingrassia, Di Bella, et al., 2015). Three sampling stations (ST2_BNR3, ST3_BNR3, ST4_BNR1, respectively at 131, 136 and 133 m bsl) are located inside the ZGP (with active emissions during sampling activities), whereas one (ST6_BNR1), at 127 m bsl, is outside (2.6 km far from the ZGP), on the eastern Zannone insular shelf. Although grab sampling is not a very satisfactory method for micro- and meiofaunal analyses, the occurrence of lithified crusts and coarse-grained sediments prevented the use of a more suitable sampling gear like multiple corer or box corer (Di Bella et al., 2016). Four small cores (10–15 cm thick, 4 cm in diameter), collected inside the grab, were sampled continuously every 1 cm (Di Bella et al., 2016, 2018) (Table 1).

3.2 | Sample's collection and analyses

The cores were sliced into 1-cm layers to a depth of 10 cm (ST2_BNR3, ST3_BNR3, ST4_BNR1) or 9 cm (ST6_BNR1). All 39 subsamples thus obtained were analysed for ostracod content. The details of sampling procedure are given by Di Bella et al. (2016) (Figure 1). The sediment samples were washed through 230 and 120 mesh sieves (63 and 125 μm, respectively) and the residue examined under reflected light microscope. All the ostracod valves were picked for quantitative analysis. All samples were stained with Rose Bengal to distinguish the "live" individuals, but this method is

TABLE 1 Geographical coordinates, depth and location of the sampling stations (from Di Bella et al., 2016, modified)

Site station	Longitude	Latitude	Sample name	No. of sub-samples	m bsl	Sector
ST2	13°06′6.7319″ E	40°58′21.1866″ N	ST2_BNR3	10	131	Inside ZGP – North
ST3	13°06′5.9526″ E	40°57′56.1399″ N	ST3_BNR3	10	136	Inside ZGP – South
ST4	13°06′5.0241″ E	40°58′15.0946″ N	ST4_BNR1	10	133	Inside ZGP – Centre
ST6	13°05′12.9495″ E	40°56′56.8619″ N	ST6_BNR1	9	127	Outside ZGP – Eastern Zannone Insular shelf

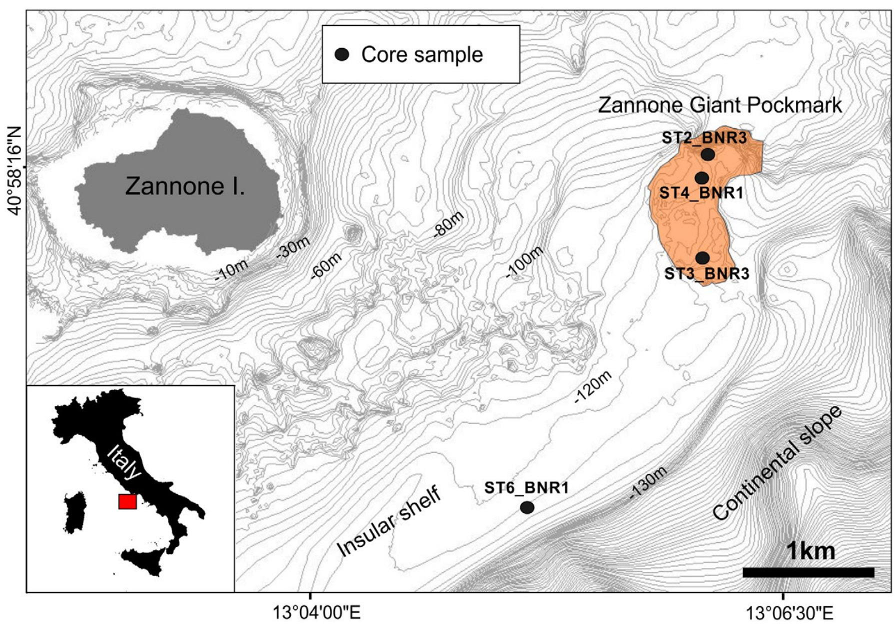

FIGURE 1 Bathymetric map of the seafloor surrounding the eastern sector of the Zannone Island (western Pontine Archipelago), with location of the core samples recovered within vent seafloor area (Zannone Giant Pockmark) and at non-vent seafloor area

TABLE 2 Ostracod absolute abundance I = minimal number of individuals (MNI); j indicates juvenile specimens

ST6_BNR1									
Samples	**BNR1 0–1**	**BNR1 1–2**	**BNR1 2–3**	**BNR1 3–4**	**BNR1 4–5**	**BNR1 5–6**	**BNR1 6–7**	**BNR1 7–8**	**BNR1 8–9**
Argilloecia caudata Müller, 1894		1	1j	2j	1j				
Argilloecia minor Müller, 1894						1j			
Argilloecia robusta Bonaduce, Ciampo & Masoli, 1976	1j	j		1		1j	1		1j
Aurila convexa (Baird, 1850)	j	1j	4j	2j	j	5j	1j	1j	j
Aurila aff. *interpretis* Uliczny, 1969		2	2j			1j			
Aurila speyeri (Brady, 1858)	1			1			1j	1j	
Basslerites berchoni (Brady, 1869)						1			
Bosquetina tarentina (Baird, 1850)	2j	2j	2j	5j	2j	2j	1j	1j	4
Buntonia sublatissima (Neviani, 1906)	1		1	3j	1	2j	2		1
Bythocythere puncticulata Ruggieri, 1976		1	j						
Callistocythere crispata (Brady, 1868)	2j	1	4j	2j	3j	5j	5j	1j	1j
Callistocythere flavidofusca (Ruggieri, 1950)			2j					1j	
Callistocythere praecincta Ciampo, 1976	2j	1	3j	5j	2j	6j	5j	1	3
Carinocythereis carinata (Roemer, 1838)	1j		1j	1j	2j	1j	2j	j	1j
Carinocythereis whitei (Baird, 1850)	1j	1j	1j	1j	2j	1j	2j	2j	
Cistacythereis turbida (Müller, 1894)			1			j	1j		
Cluthia keiji Neale, 1975	1		2j	1	3	2	2j	1j	j
Costa batei (Brady, 1866)			j						
Costa edwardsii (Roemer, 1838)					j				
Cytherella vulgatella Aiello, Barra, Bonaduce & Russo, 1996	2j	3j	1j	1j	j	4j	1j	j	1j
Cytheretta subradiosa (Roemer, 1838)							1		
Cytherois frequens Müller, 1894	1j	j					1		
Cytherois uffenordei Ruggieri, 1975			2			2j			
Cytherois sp. 1				j					
Cytherois sp. 2				j					
Cytherois sp. 3				j					
Cytheropteron hadriaticum Bonaduce, Ciampo & Masoli, 1976	1			1j	1	1j	1j		
Cytheropteron latum Müller, 1894		j			1	1		1j	1j
Cytheropteron sulcatum Bonaduce, Ciampo & Masoli, 1976			1						
Dopseucythere mediterranea (Bonaduce, Masoli, Pugliese & McKenzie, 1980)		1j	3j	2	j	5	3		
Echinocythereis laticarina (Brady, 1868)			1	j					
Eucythere curta Ruggieri, 1975	1j	1j	3j	1j	3j	3j	2j	2	
Eucytherura complexa (Brady, 1867)			2			1			j
Eucytherura gibbera Müller, 1894				1j		1	1		
Eucytherura mistrettai Sissingh, 1972			1	1					
Hemicytherura defiorei Ruggieri, 1953		1	7j	4	6j	9j	6j	6j	3j
Hemicytherura videns (Müller, 1894)	2j	3j		9j	3	4	3	1	1j
Hemiparacytheridea infelix (Bonaduce, Ciampo & Masoli, 1976)	j								j

TABLE 2 (Continued)

ST6_BNR1									
Samples	**BNR1 0–1**	**BNR1 1–2**	**BNR1 2–3**	**BNR1 3–4**	**BNR1 4–5**	**BNR1 5–6**	**BNR1 6–7**	**BNR1 7–8**	**BNR1 8–9**
Henryhowella parthenopea Bonaduce, Barra & Aiello,1999			1						
Heterocythereis albomaculata (Baird, 1838)						j			
Heterocythereis voraginosa Athersuch, 1979								j	j
Kangarina abyssicola (Müller, 1894)				1j	1j	3j	j	j	
Loxocauda decipiens (Müller, 1894)						1			
Loxoconcha affinis (Brady, 1866)	2j	1j	4j	3j	2j	5j	4j	5j	2j
Loxoconcha ovulata (Costa, 1853)	2j	1j	3j	3j	2j	6j	5j	3j	1j
Loxoconcha stellifera Müller, 1894	j	j						2j	
Microcythere depressa Müller, 1894	5j	1j	7j	8j	7j	8j	10j	5j	5j
Microcythere hians Müller, 1894	1	2j	4j	3	8	9j	13	8j	1j
Microcythere inflexa Müller, 1894	4	4j	2j	6j	4j	4j	9j	11j	6
Microcytherura angulosa (Seguenza, 1880)	11j	10j	20j	14j	18j	35j	28j	13j	8j
Microcytherura nigrescens Müller, 1894			j						
Microxestoleberis aff. *kykladica* Barbeito-Gonzalez, 1971				1j		1		1	
Microxestoleberis xenomys (Barbeito-Gonzalez, 1971)		3	1j	1j	1j	1j	1j	1j	1
Microxestoleberis sp. 1						2j			
Microxestoleberis sp.			j						
Monoceratina oblita Bonaduce, Ciampo & Masoli, 1976	1j	2j	1j	1j	1j	2j	1j	1	
Neonesidea formosa (Brady, 1868)			j		j	j	j	j	j
Neonesidea longevaginata (Müller, 1894)			j						
Neonesidea mediterranea (Müller, 1894)	4j	4j	3j	4j	1j	4j	2j	3j	1j
Occultocythereis dohrni Puri, 1963				j					j
Paracytheridea triquetra (Reuss, 1850)	1j	2j	3j	3j	2j	5j	3j	1j	j
Paracytherois flexuosa (Brady, 1867)	2j		1	1j				1	
Paracytherois oblonga Müller, 1894						2			
Paracytherois sp. 1			j						
Paracytheromorpha nana (Bonaduce, Ciampo & Masoli, 1976)			1						j
Paracytheromorpha sp. 1	1		1j	1j		2			
Paradoxostoma simile Müller, 1894				j					
Paradoxostoma aff. *versicolor* Müller, 1894			1	j					
Paradoxostoma sp.			j	j					
Parahemingwayella tetrapteron (Bonaduce, Ciampo & Masoli, 1976)		j							
Paranesidea reticulata (Müller, 1894)	j				j	j	j	j	
Phlyctocythere pellucida (Müller, 1894)		1	j	1j		2	3	j	
Polycope reticulata Müller, 1894						1		1	
Pontocypris acuminata (Müller, 1894)	1	j	j	j		j	j	j	
Pontocypris intermedia Brady, 1868				j					
Pontocythere turbida (Müller, 1894)		j			j			j	
Propontocypris dispar (Müller, 1894)				j					

(Continues)

TABLE 2 (Continued)

ST6_BNR1 Samples	BNR1 0–1	BNR1 1–2	BNR1 2–3	BNR1 3–4	BNR1 4–5	BNR1 5–6	BNR1 6–7	BNR1 7–8	BNR1 8–9
Propontocypris pirifera (Müller, 1894)			j	j					
Pseudocytherura strangulata Ruggieri, 1991		j	1j	1	1	1j			
Pseudolimnocythere sp. 1									j
Pterygocythereis jonesii (Baird, 1850)		1	1j	1j			j	1	j
Pterygocythereis coronata (Roemer, 1838)			1j		j				
Rostrocythere hastata (Bonaduce, Masoli, Pugliese & McKenzie, 1980)						1			
Sagmatocythere napoliana (Puri, 1963)			1	j					
"*Sagmatocythere*" sp. 1							1		
Sclerochilus gewemuelleri Dubowsky, 1939				j					
Sclerochilus aequus Müller, 1894					1j				
Sclerochilus sp.								j	
Semicytherura acuticostata (Sars, 1866)	1j	3j	5j	5j	6j	3j	4j	5	1j
Semicytherura aenariensis Bonaduce, Ciampo & Masoli, 1976	2j		1	2j		1	2j	j	1
Semicytherura alifera Ruggieri, 1959	4j	6	2j	6j	3j	14j	9j	7j	2j
Semicytherura dispar (Müller, 1894)		1	2	4	1	4	4j	2j	2
Semicytherura heinzei Puri 1963	1j	1	j			1			j
Semicytherura inversa (Seguenza, 1880)		1j					1		
Semicytherura occulta Bonaduce, Ciampo & Masoli, 1976								1	
Semicytherura paradoxa (Müller, 1894)		1	1j	1j	2j	1j	3j	1j	1
Semicytherura quadridentata (Hartmann, 1953)		1			j	j	j	1j	2
Semicytherura rara (Müller, 1894)	5j	8j	12j	10j	7j	10j	8j	9j	5j
Semicytherura simplex (Brady & Norman, 1889)			1j						
Semicytherura sulcata (Müller, 1894)						j			
Semicytherura sp.								j	
Tenedocythere prava (Baird, 1850)			1j		j	j	1j		j
Triebelina raripila (Müller, 1894)				j					
Urocythereis ilariae Aiello, Barra & Parisi, 2016			1j	1j		1j			
Urocythereis margaritifera (Müller, 1894)	j			j	j	j	j	j	
Xestoleberis communis Müller, 1894	2j	2j	3j	1j	1j	3j	2j	2j	2j
Xestoleberis dispar Müller, 1894	1j	1j	1j	2j	1j	1j	2j	1j	j
Xestoleberis aff. *intumescens* Klie 1942			1				1j	j	1
Xestoleberis aff. *perula* Athersuch, 1978		j						j	
Xestoleberis plana Müller, 1894			1j	2j	1j	1j	1j		1
Xestoleberis sp.				1					

unreliable with ostracods as they often contain sufficient organic material to be stained although dead (Horne et al., 2021). Thus, we decided to consider both the living and dead assemblages. Data consist of Minimum Number of Individuals (MNI, Tables 2 and 3) and Total Number of Valves (TNV, Tables 4 and 5). MNI is the greater number between right and left adult valves plus the number of adult carapaces; when only juvenile shells are recorded the MNI equals one. TNV includes all the juvenile and adult valves. The species have been identified according to classic and modern literature with special regard to the Mediterranean area (i.a. Aiello & Barra, 2010; Aiello, Barra, Parisi, et al., 2018; Bonaduce et al., 1976; Breman, 1976). Species are listed in Appendix 1.

The studied specimens are housed in the Aiello Barra Micropaleontological Collection (A.B.M.C.), Dipartimento di Scienze della Terra, dell'Ambiente e delle Risorse, Università degli Studi di Napoli Federico II.

TABLE 3 Ostracod relative abundance (relative species abundance = %; MNI = minimal number of individuals)

ST6_BNR1									
Samples	**BNR1 0–1**	**BNR1 1–2**	**BNR1 2–3**	**BNR1 3–4**	**BNR1 4–5**	**BNR1 5–6**	**BNR1 6–7**	**BNR1 7–8**	**BNR1 8–9**
Argilloecia caudata Müller, 1894		1.18	0.68	1.35	0.88				
Argilloecia minor Müller, 1894						0.49			
Argilloecia robusta Bonaduce, Ciampo & Masoli, 1976	1.33	1.18		0.68		0.49	0.60		1.35
Aurila convexa (Baird, 1850)	1.33	1.18	2.74	1.35	0.88	2.46	0.60	0.83	1.35
Aurila aff. *interpretis* Uliczny, 1969		2.35	1.37			0.49			
Aurila speyeri (Brady, 1858)	1.33			0.68			0.60	0.83	
Basslerites berchoni (Brady, 1869)						0.49			
Bosquetina tarentina (Baird, 1850)	2.67	2.35	1.37	3.38	1.77	0.99	0.60	0.83	5.41
Buntonia sublatissima (Neviani, 1906)	1.33		0.68	2.03	0.88	0.99	1.20		1.35
Bythocythere puncticulata Ruggieri, 1976		1.18	0.68						
Callistocythere crispata (Brady, 1868)	2.67	1.18	2.74	1.35	2.65	2.46	2.99	0.83	1.35
Callistocythere flavidofusca (Ruggieri, 1950)			1.37					0.83	
Callistocythere praecincta Ciampo, 1976	2.67	1.18	2.05	3.38	1.77	2.96	2.99	0.83	4.05
Carinocythereis carinata (Roemer, 1838)	1.33		0.68	0.68	1.77	0.49	1.20	0.83	1.35
Carinocythereis whitei (Baird, 1850)	1.33	1.18	0.68	0.68	1.77	0.49	1.20	1.67	
Cistacythereis turbida (Müller, 1894)			0.68			0.49	0.60		
Cluthia keiji Neale, 1975	1.33		1.37	0.68	2.65	0.99	1.20	0.83	1.35
Costa batei (Brady, 1866)			0.68						
Costa edwardsii (Roemer, 1838)					0.88				
Cytherella vulgatella Aiello, Barra, Bonaduce & Russo, 1996	2.67	3.53	0.68	0.68	0.88	1.97	0.60	0.83	1.35
Cytheretta subradiosa (Roemer, 1838)							0.60		
Cytherois frequens Müller, 1894	1.33	1.18					0.60		
Cytherois uffenordei Ruggieri, 1975			1.37			0.99			
Cytherois sp. 1				0.68					
Cytherois sp. 2				0.68					
Cytherois sp. 3				0.68					
Cytheropteron hadriaticum Bonaduce, Ciampo & Masoli, 1976	1.33			0.68	0.88	0.49	0.60		
Cytheropteron latum Müller, 1894		1.18			0.88	0.49		0.83	1.35
Cytheropteron sulcatum Bonaduce, Ciampo & Masoli, 1976			0.68						
Dopseucythere mediterranea (Bonaduce, Masoli, Pugliese & McKenzie, 1980)		1.18	2.05	1.35	0.88	2.46	1.80		
Echinocythereis laticarina (Brady, 1868)			0.68	0.68					
Eucythere curta Ruggieri, 1975	1.33	1.18	2.05	0.68	2.65	1.48	1.20	1.67	
Eucytherura complexa (Brady, 1867)			1.37			0.49			1.35
Eucytherura gibbera Müller, 1894				0.68		0.49	0.60		
Eucytherura mistrettai Sissingh, 1972			0.68	0.68					
Hemicytherura defiorei Ruggieri, 1953		1.18	4.79	2.70	5.31	4.43	3.59	5.00	4.05
Hemicytherura videns (Müller, 1894)	2.67	3.53		6.08	2.65	1.97	1.80	0.83	1.35
Hemiparacytheridea infelix (Bonaduce, Ciampo & Masoli, 1976)	1.33								1.35

(Continues)

TABLE 3 (Continued)

ST6_BNR1									
Samples	**BNR1 0–1**	**BNR1 1–2**	**BNR1 2–3**	**BNR1 3–4**	**BNR1 4–5**	**BNR1 5–6**	**BNR1 6–7**	**BNR1 7–8**	**BNR1 8–9**
Henryhowella parthenopea Bonaduce, Barra & Aiello,1999			0.68						
Heterocythereis albomaculata (Baird, 1838)						0.49			
Heterocythereis voraginosa Athersuch, 1979								0.83	1.35
Kangarina abyssicola (Müller, 1894)				0.68	0.88	1.48	0.60	0.83	
Loxocauda decipiens (Müller, 1894)						0.49			
Loxoconcha affinis (Brady, 1866)	2.67	1.18	2.74	2.03	1.77	2.46	2.40	4.17	2.70
Loxoconcha ovulata (Costa, 1853)	2.67	1.18	2.05	2.03	1.77	2.96	2.99	2.50	1.35
Loxoconcha stellifera Müller, 1894	1.33	1.18						1.67	
Microcythere depressa Müller, 1894	6.67	1.18	4.79	5.41	6.19	3.94	5.99	4.17	6.76
Microcythere hians Müller, 1894	1.33	2.35	2.74	2.03	7.08	4.43	7.78	6.67	1.35
Microcythere inflexa Müller, 1894	5.33	4.71	1.37	4.05	3.54	1.97	5.39	9.17	8.11
Microcytherura angulosa (Seguenza, 1880)	14.67	11.76	13.70	9.46	15.93	17.24	16.77	10.83	10.81
Microcytherura nigrescens Müller, 1894			0.68						
Microxestoleberis aff. *kykladica* Barbeito-Gonzalez, 1971				0.68		0.49		0.83	
Microxestoleberis xenomys (Barbeito-Gonzalez, 1971)		3.53	0.68	0.68	0.88	0.49	0.60	0.83	1.35
Microxestoleberis sp. 1						0.99			
Microxestoleberis sp.			0.68						
Monoceratina oblita Bonaduce, Ciampo & Masoli, 1976	1.33	2.35	0.68	0.68	0.88	0.99	0.60	0.83	
Neonesidea formosa (Brady, 1868)			0.68		0.88	0.49	0.60	0.83	1.35
Neonesidea longevaginata (Müller, 1894)			0.68						
Neonesidea mediterranea (Müller, 1894)	5.33	4.71	2.05	2.70	0.88	1.97	1.20	2.50	1.35
Occultocythereis dohrni Puri, 1963				0.68					1.35
Paracytheridea triquetra (Reuss, 1850)	1.33	2.35	2.05	2.03	2.65	2.46	1.80	0.83	1.35
Paracytherois flexuosa (Brady, 1867)	2.67		0.68	0.68				0.83	
Paracytherois oblonga Müller, 1894						0.99			
Paracytherois sp. 1			0.68						
Paracytheromorpha nana (Bonaduce, Ciampo & Masoli, 1976)			0.68						1.35
Paracytheromorpha sp. 1	1.33		0.68	0.68		0.99			
Paradoxostoma simile Müller, 1894				0.68					
Paradoxostoma aff. *versicolor* Müller, 1894			0.68	0.68					
Paradoxostoma sp.			0.68	0.68					
Parahemingwayella tetrapteron (Bonaduce, Ciampo & Masoli, 1976)		1.18							
Paranesidea reticulata (Müller, 1894)	1.33				0.88	0.49	0.60	0.83	
Phlyctocythere pellucida (Müller, 1894)		1.18	0.68	0.68		0.99	1.80	0.83	
Polycope reticulata Müller, 1894						0.49		0.83	
Pontocypris acuminata (Müller, 1894)	1.33	1.18	0.68	0.68		0.49	0.60	0.83	
Pontocypris intermedia Brady, 1868				0.68					
Pontocythere turbida (Müller, 1894)		1.18			0.88			0.83	
Propontocypris dispar (Müller, 1894)				0.68					

TABLE 3 (Continued)

ST6_BNR1 Samples	BNR1 0–1	BNR1 1–2	BNR1 2–3	BNR1 3–4	BNR1 4–5	BNR1 5–6	BNR1 6–7	BNR1 7–8	BNR1 8–9
Propontocypris pirifera (Müller, 1894)			0.68	0.68					
Pseudocytherura strangulata Ruggieri, 1991		1.18	0.68	0.68	0.88	0.49			
Pseudolimnocythere sp. 1									1.35
Pterygocythereis jonesii (Baird, 1850)		1.18	0.68	0.68			0.60	0.83	1.35
Pterygocythereis coronata (Roemer, 1838)			0.68		0.88				
Rostrocythere hastata (Bonaduce, Masoli, Pugliese & McKenzie, 1980)						0.49			
Sagmatocythere napoliana (Puri, 1963)			0.68	0.68					
"*Sagmatocythere*" sp. 1							0.60		
Sclerochilus gewemuelleri Dubowsky, 1939				0.68					
Sclerochilus aequus Müller, 1894					0.88				
Sclerochilus sp.								0.83	
Semicytherura acuticostata (Sars, 1866)	1.33	3.53	3.42	3.38	5.31	1.48	2.40	4.17	1.35
Semicytherura aenariensis Bonaduce, Ciampo & Masoli, 1976	2.67		0.68	1.35		0.49	1.20	0.83	1.35
Semicytherura alifera Ruggieri, 1959	5.33	7.06	1.37	4.05	2.65	6.90	5.39	5.83	2.70
Semicytherura dispar (Müller, 1894)		1.18	1.37	2.70	0.88	1.97	2.40	1.67	2.70
Semicytherura heinzei Puri 1963	1.33	1.18	0.68			0.49			1.35
Semicytherura inversa (Seguenza, 1880)		1.18					0.60		
Semicytherura occulta Bonaduce, Ciampo & Masoli, 1976								0.83	
Semicytherura paradoxa (Müller, 1894)		1.18	0.68	0.68	1.77	0.49	1.80	0.83	1.35
Semicytherura quadridentata (Hartmann, 1953)		1.18			0.88	0.49	0.60	0.83	2.70
Semicytherura rara (Müller, 1894)	6.67	9.41	8.22	6.76	6.19	4.93	4.79	7.50	6.76
Semicytherura simplex (Brady & Norman, 1889)			0.68						
Semicytherura sulcata (Müller, 1894)						0.49			
Semicytherura sp.								0.83	
Tenedocythere prava (Baird, 1850)			0.68		0.88	0.49	0.60		1.35
Triebelina raripila (Müller, 1894)				0.68					
Urocythereis ilariae Aiello, Barra & Parisi, 2016			0.68	0.68		0.49			
Urocythereis margaritifera (Müller, 1894)	1.33			0.68	0.88	0.49	0.60	0.83	
Xestoleberis communis Müller, 1894	2.67	2.35	2.05	0.68	0.88	1.48	1.20	1.67	2.70
Xestoleberis dispar Müller, 1894	1.33	1.18	0.68	1.35	0.88	0.49	1.20	0.83	1.35
Xestoleberis aff. *intumescens* Klie 1942			0.68				0.60	0.83	1.35
Xestoleberis aff. *perula* Athersuch, 1978		1.18						0.83	
Xestoleberis plana Müller, 1894			0.68	1.35	0.88	0.49	0.60		1.35
Xestoleberis sp.				0.68					

3.3 | Statistical analyses

Statistical analyses (Q-mode and R-mode cluster analysis and Principal Component Analysis) were performed using the freeware PAST version 4.06b (Hammer et al., 2001) on the ostracod abundance data of the nine subsamples of the ST6_BNR1, to test the differences among samples and the vertical distribution in the core. Number of specimens (I), Dominance (D), Equitability (J), Shannon diversity index H' (H'), number of Taxa (S) (Table 6; Figure 2) and abundances of ostracod species with relative species abundance (RSA) >5% in at least one sample were taken into account. Both the minimum number of individuals (MNI) and the total number of valves (TNV) have been considered separately.

TABLE 4 Ostracod absolute abundance I = total number of valves (TNV)

ST6_BNR1									
Samples	**BNR1 0–1**	**BNR1 1–2**	**BNR1 2–3**	**BNR1 3–4**	**BNR1 4–5**	**BNR1 5–6**	**BNR1 6–7**	**BNR1 7–8**	**BNR1 8–9**
Argilloecia caudata Müller, 1894		1	2	4	4				
Argilloecia minor Müller, 1894						4			
Argilloecia robusta Bonaduce, Ciampo & Masoli, 1976	2	2		1		3	1		6
Aurila convexa (Baird, 1850)	11	18	25	20	16	42	17	10	11
Aurila aff. *interpretis* Uliczny, 1969		3	4			4			
Aurila speyeri (Brady, 1858)	1			1			4	5	
Basslerites berchoni (Brady, 1869)						1			
Bosquetina tarentina (Baird, 1850)	7	3	15	23	6	15	4	6	6
Buntonia sublatissima (Neviani, 1906)	1		1	4	1	5	4		1
Bythocythere puncticulata Ruggieri, 1976		1	1						
Callistocythere crispata (Brady, 1868)	4	1	10	8	5	14	13	5	3
Callistocythere flavidofusca (Ruggieri, 1950)			8					3	
Callistocythere praecincta Ciampo, 1976	4	1	4	18	4	13	8	1	3
Carinocythereis carinata (Roemer, 1838)	2		9	4	6	3	3	1	4
Carinocythereis whitei (Baird, 1850)	4	7	2	6	4	5	3	5	
Cistacythereis turbida (Müller, 1894)			1			2	3		
Cluthia keiji Neale, 1975	1		3	2	3	4	4	2	1
Costa batei (Brady, 1866)			1						
Costa edwardsii (Roemer, 1838)					2				
Cytherella vulgatella Aiello, Barra, Bonaduce & Russo, 1996	8	5	5	10	8	12	3	1	4
Cytheretta subradiosa (Roemer, 1838)							1		
Cytherois frequens Müller, 1894	3	1					2		
Cytherois uffenordei Ruggieri, 1975			3			6			
Cytherois sp. 1				4					
Cytherois sp. 2				2					
Cytherois sp. 3				1					
Cytheropteron hadriaticum Bonaduce, Ciampo & Masoli, 1976	1			2	1	3	3		
Cytheropteron latum Müller, 1894		1			1	1		3	3
Cytheropteron sulcatum Bonaduce, Ciampo & Masoli, 1976			1						
Dopseucythere mediterranea (Bonaduce, Masoli, Pugliese & McKenzie, 1980)		2	9	4	1	7	3		
Echinocythereis laticarina (Brady, 1868)			1	1					
Eucythere curta Ruggieri, 1975	4	5	12	4	6	11	4	4	
Eucytherura complexa (Brady, 1867)			2			2			1
Eucytherura gibbera Müller, 1894				2		1	1		
Eucytherura mistrettai Sissingh, 1972			2	1					
Hemicytherura defiorei Ruggieri, 1953		1	18	5	8	19	13	10	6
Hemicytherura videns (Müller, 1894)	4	6		18	4	6	3	1	2
Hemiparacytheridea infelix (Bonaduce, Ciampo & Masoli, 1976)	1								1
Henryhowella parthenopea Bonaduce, Barra & Aiello,1999			1						
Heterocythereis albomaculata (Baird, 1838)						1			
Heterocythereis voraginosa Athersuch, 1979								1	1
Kangarina abyssicola (Müller, 1894)				3	2	7	3	1	

TABLE 4 (Continued)

ST6_BNR1									
Samples	BNR1 0–1	BNR1 1–2	BNR1 2–3	BNR1 3–4	BNR1 4–5	BNR1 5–6	BNR1 6–7	BNR1 7–8	BNR1 8–9
Loxocauda decipiens (Müller, 1894)						1			
Loxoconcha affinis (Brady, 1866)	16	7	36	29	20	43	9	24	14
Loxoconcha ovulata (Costa, 1853)	6	7	15	6	13	15	24	10	5
Loxoconcha stellifera Müller, 1894	1	1						3	
Microcythere depressa Müller, 1894	7	2	19	19	16	10	18	11	11
Microcythere hians Müller, 1894	2	7	10	3	12	33	33	29	3
Microcythere inflexa Müller, 1894	7	9	9	22	11	21	34	18	9
Microcytherura angulosa (Seguenza, 1880)	33	27	95	69	65	110	65	46	33
Microcytherura nigrescens Müller, 1894			1						
Microxestoleberis aff. *kykladica* Barbeito-Gonzalez, 1971				3		1		1	
Microxestoleberis xenomys (Barbeito-Gonzalez, 1971)		3	3	5	5	4	7	3	1
Microxestoleberis sp. 1						4			
Microxestoleberis sp.			1						
Monoceratina oblita Bonaduce, Ciampo & Masoli, 1976	2	3	3	3	3	3	2	1	
Neonesidea formosa (Brady, 1868)			4		2	10	5	5	1
Neonesidea longevaginata (Müller, 1894)			1						
Neonesidea mediterranea (Müller, 1894)	16	30	49	35	23	47	33	24	13
Occultocythereis dohrni Puri, 1963				1					1
Paracytheridea triquetra (Reuss, 1850)	8	9	14	10	10	17	10	9	2
Paracytherois flexuosa (Brady, 1867)	5		1	4				1	
Paracytherois oblonga Müller, 1894						2			
Paracytherois sp. 1			2						
Paracytheromorpha nana (Bonaduce, Ciampo & Masoli, 1976)			1						1
Paracyhteromorpha sp. 1	1		2	2		2			
Paradoxostoma simile Müller, 1894				1					
Paradoxostoma aff. *versicolor* Müller, 1894			1	1					
Paradoxostoma sp.			1	2					
Parahemingwayella tetrapteron (Bonaduce, Ciampo & Masoli, 1976)		1							
Paranesidea reticulata (Müller, 1894)	2				2	3	2	3	
Phlyctocythere pellucida (Müller, 1894)		1	1	3		2	3	1	
Polycope reticulata Müller, 1894						1		1	
Pontocypris acuminata (Müller, 1894)	1	3	8	5		4	1	1	
Pontocypris intermedia Brady, 1868				1					
Pontocythere turbida (Müller, 1894)		1			1			2	
Propontocypris dispar (Müller, 1894)				1					
Propontocypris pirifera (Müller, 1894)			1	1					
Pseudocytherura strangulata Ruggieri, 1991		1	2	1	1	4			
Pseudolimnocythere sp. 1									1
Pterygocythereis jonesii (Baird, 1850)		1	2	2			1	1	1
Pterygocythereis coronata (Roemer, 1838)			2		3				
Rostrocythere hastata (Bonaduce, Masoli, Pugliese & McKenzie, 1980)						1			
Sagmatocythere napoliana (Puri, 1963)			1	1					

(Continues)

TABLE 4 (Continued)

ST6_BNR1									
Samples	BNR1 0–1	BNR1 1–2	BNR1 2–3	BNR1 3–4	BNR1 4–5	BNR1 5–6	BNR1 6–7	BNR1 7–8	BNR1 8–9
"*Sagmatocythere*" sp. 1							1		
Sclerochilus gewemuelleri Dubowsky, 1939				1					
Sclerochilus aequus Müller, 1894					2				
Sclerochilus sp.								2	
Semicytherura acuticostata (Sars, 1866)	6	12	16	12	13	18	11	9	4
Semicytherura aenariensis Bonaduce, Ciampo & Masoli, 1976	4		1	4		1	3	2	2
Semicytherura alifera Ruggieri, 1959	9	7	28	14	24	30	20	13	4
Semicytherura dispar (Müller, 1894)		1	3	4	1	7	9	4	2
Semicytherura heinzei Puri 1963	2	1	1			1			1
Semicytherura inversa (Seguenza, 1880)		2					1		
Semicytherura occulta Bonaduce, Ciampo & Masoli, 1976								1	
Semicytherura paradoxa (Müller, 1894)		1	4	4	3	2	6	2	1
Semicytherura quadridentata (Hartmann, 1953)		1			3	5	2	3	2
Semicytherura rara (Müller, 1894)	9	12	22	17	16	23	17	14	11
Semicytherura simplex (Brady & Norman, 1889)			2						
Semicytherura sulcata (Müller, 1894)						1			
Semicytherura sp.								1	
Tenedocythere prava (Baird, 1850)			2		2	3	3		1
Triebelina raripila (Müller, 1894)				1					
Urocythereis ilariae Aiello, Barra & Parisi, 2016			9	4		3			
Urocythereis margaritifera (Müller, 1894)	1			2	2	3	1	1	
Xestoleberis communis Müller, 1894	27	30	48	43	21	63	48	49	22
Xestoleberis dispar Müller, 1894	15	12	35	33	26	36	20	21	9
Xestoleberis aff. *intumescens* Klie 1942			1				2	1	2
Xestoleberis aff. *perula* Athersuch, 1978		1						1	
Xestoleberis plana Müller, 1894			10	13	7	13	9		1
Xestoleberis sp.				1					

4 | RESULTS

The 30 subsamples from the short-cores ST2_BNR3, ST3_BNR3, ST4_BNR1 were devoid of calcareous remains and contained siliceous sponge spicules, radiolarians, diatoms and agglutinated foraminifers (Figure 3). A single left valve of *Parahemingwayella tetrapteron* was found in sub sample ST3_BNR3 [0–1].

The nine subsamples from the ST6_BNR1 station yielded well-preserved and diversified ostracod assemblages.

4.1 | Ostracoda abundance

From ST6_BNR1, a total of 3842 ostracod valves were studied. The assemblages consist of 111 species (12 in open nomenclature and 5 with affinitive status due to the poor state of preservation) in 54 genera (Appendix 1; Plates 1–5). The most diversified genera are *Semicytherura* (13 species) and *Xestoleberis* (6). *Microcytherura angulosa*, with a mean relative abundance (MRA) of 13.48% (MNI) and 13.97% (TNV) is the most common species. Further characteristic species are *Semicytherura rarecostata* [MRA (MNI) = 6.81%; MRA (TNV) = 3.88%], *Microcythere depressa* [MRA (MNI) = 5.02%; MRA (TNV) = 3.07%], *Semicytherura alifera* [MRA (MNI) = 4.47%; MRA (TNV) = 3.67%].

Microcythere inflexa [MRA (MNI) = 4.52%; MRA (TNV) = 3.53%], *Neonesidea mediterranea* [MRA (MNI) = 2.53%; MRA (TNV) = 7.19%], *Loxoconcha affinis* [MRA (MNI) = 2.46%; MRA (TNV) = 5.19%] and *Xestoleberis communis* [MRA (MNI) = 1.74%; MRA (TNV) = 9.58%], are considered accessory species.

4.2 | Ostracoda diversity and composition

Simple diversity (*S*) ranges from 38 to 65; abundance (I) is between 59 and 161 (MNI) and between 168 and 587 (TNV). Shannon index H' ranges from 3.35 to 3.75 (MNI) and from 3.17 to 3.46 (TNV). The mean H' values are: H' (MNI) = 3.514 and mean H' (TNV) = 3.28. Dominance (D) values in the assemblages are D (MNI) range = 0.03–0.05; D (TNV) range = 0.05–0.06.

TABLE 5 Ostracod relative abundance (relative species abundance = %; TNV = total number of valves)

ST6_BNR1									
Samples	**BNR1 0–1**	**BNR1 1–2**	**BNR1 2–3**	**BNR1 3–4**	**BNR1 4–5**	**BNR1 5–6**	**BNR1 6–7**	**BNR1 7–8**	**BNR1 8–9**
Argilloecia caudata Müller, 1894		0.40	0.33	0.75	1.03				
Argilloecia minor Müller, 1894						0.54			
Argilloecia robusta Bonaduce, Ciampo & Masoli, 1976	0.84	0.80		0.19		0.41	0.20		2.84
Aurila convexa (Baird, 1850)	4.62	7.17	4.12	3.77	4.11	5.69	3.40	2.65	5.21
Aurila aff. *interpretis* Uliczny, 1969		1.20	0.66			0.54			
Aurila speyeri (Brady, 1858)	0.42			0.19			0.80	1.33	
Basslerites berchoni (Brady, 1869)						0.14			
Bosquetina tarentina (Baird, 1850)	2.94	1.20	2.47	4.33	1.54	2.03	0.80	1.59	2.84
Buntonia sublatissima (Neviani, 1906)	0.42		0.16	0.75	0.26	0.68	0.80		0.47
Bythocythere puncticulata Ruggieri, 1976		0.40	0.16						
Callistocythere crispata (Brady, 1868)	1.68	0.40	1.65	1.51	1.29	1.90	2.60	1.33	1.42
Callistocythere flavidofusca (Ruggieri, 1950)			1.32					0.80	
Callistocythere praecincta Ciampo, 1976	1.68	0.40	0.66	3.39	1.03	1.76	1.60	0.27	1.42
Carinocythereis carinata (Roemer, 1838)	0.84		1.48	0.75	1.54	0.41	0.60	0.27	1.90
Carinocythereis whitei (Baird, 1850)	1.68	2.79	0.33	1.13	1.03	0.68	0.60	1.33	
Cistacythereis turbida (Müller, 1894)			0.16			0.27	0.60		
Cluthia keji Neale, 1975	0.42		0.49	0.38	0.77	0.54	0.80	0.53	0.47
Costa batei (Brady, 1866)			0.16						
Costa edwardsii (Roemer, 1838)					0.51				
Cytherella vulgatella Aiello, Barra, Bonaduce & Russo, 1996	3.36	1.99	0.82	1.88	2.06	1.63	0.60	0.27	1.90
Cytheretta subradiosa (Roemer, 1838)							0.20		
Cytherois frequens Müller, 1894	1.26	0.40					0.40		
Cytherois uffenordei Ruggieri, 1975			0.49			0.81			
Cytherois sp. 1				0.75					
Cytherois sp. 2				0.38					
Cytherois sp. 3				0.19					
Cytheropteron hadriaticum Bonaduce, Ciampo & Masoli, 1976	0.42			0.38	0.26	0.41	0.60		
Cytheropteron latum Müller, 1894		0.40			0.26	0.14		0.80	1.42
Cytheropteron sulcatum Bonaduce, Ciampo & Masoli, 1976			0.16						
Dopseucythere mediterranea (Bonaduce, Masoli, Pugliese & McKenzie, 1980)		0.80	1.48	0.75	0.26	0.95	0.60		

(Continues)

TABLE 5 (Continued)

ST6_BNR1									
Samples	**BNR1 0–1**	**BNR1 1–2**	**BNR1 2–3**	**BNR1 3–4**	**BNR1 4–5**	**BNR1 5–6**	**BNR1 6–7**	**BNR1 7–8**	**BNR1 8–9**
Echinocythereis laticarina (Brady, 1868)			0.16	0.19					
Eucythere curta Ruggieri, 1975	1.68	1.99	1.98	0.75	1.54	1.49	0.80	1.06	
Eucytherura complexa (Brady, 1867)			0.33			0.27			0.47
Eucytherura gibbera Müller, 1894				0.38		0.14	0.20		
Eucytherura mistrettai Sissingh, 1972			0.33	0.19					
Hemicytherura defiorei Ruggieri, 1953		0.40	2.97	0.94	2.06	2.57	2.60	2.65	2.84
Hemicytherura videns (Müller, 1894)	1.68	2.39		3.39	1.03	0.81	0.60	0.27	0.95
Hemiparacytheridea infelix (Bonaduce, Ciampo & Masoli, 1976)	0.42								0.47
Henryhowella parthenopea Bonaduce, Barra & Aiello,1999			0.16						
Heterocythereis albomaculata (Baird, 1838)						0.14			
Heterocythereis voraginosa Athersuch, 1979								0.27	0.47
Kangarina abyssicola (Müller, 1894)				0.56	0.51	0.95	0.60	0.27	
Loxocauda decipiens (Müller, 1894)						0.14			
Loxoconcha affinis (Brady, 1866)	6.72	2.79	5.93	5.46	5.14	5.83	1.80	6.37	6.64
Loxoconcha ovulata (Costa, 1853)	2.52	2.79	2.47	1.13	3.34	2.03	4.80	2.65	2.37
Loxoconcha stellifera Müller, 1894	0.42	0.40						0.80	
Microcythere depressa Müller, 1894	2.94	0.80	3.13	3.58	4.11	1.36	3.60	2.92	5.21
Microcythere hians Müller, 1894	0.84	2.79	1.65	0.56	3.08	4.47	6.60	7.69	1.42
Microcythere inflexa Müller, 1894	2.94	3.59	1.48	4.14	2.83	2.85	6.80	4.77	4.27
Microcytherura angulosa (Seguenza, 1880)	13.87	10.76	15.65	12.99	16.71	14.91	13.00	12.20	15.64
Microcytherura nigrescens Müller, 1894			0.16						
Microxestoleberis aff. *kykladica* Barbeito-Gonzalez, 1971				0.56		0.14		0.27	
Microxestoleberis xenomys (Barbeito-Gonzalez, 1971)		1.20	0.49	0.94	1.29	0.54	1.40	0.80	0.47
Microxestoleberis sp. 1						0.54			
Microxestoleberis sp.			0.16						
Monoceratina oblita Bonaduce, Ciampo & Masoli, 1976	0.84	1.20	0.49	0.56	0.77	0.41	0.40	0.27	
Neonesidea formosa (Brady, 1868)			0.66		0.51	1.36	1.00	1.33	0.47
Neonesidea longevaginata (Müller, 1894)			0.16						

TABLE 5 (Continued)

ST6_BNR1									
Samples	**BNR1 0–1**	**BNR1 1–2**	**BNR1 2–3**	**BNR1 3–4**	**BNR1 4–5**	**BNR1 5–6**	**BNR1 6–7**	**BNR1 7–8**	**BNR1 8–9**
Neonesidea mediterranea (Müller, 1894)	6.72	11.95	8.07	6.59	5.91	6.37	6.60	6.37	6.16
Occultocythereis dohrni Puri, 1963				0.19					0.47
Paracytheridea triquetra (Reuss, 1850)	3.36	3.59	2.31	1.88	2.57	2.30	2.00	2.39	0.95
Paracytherois flexuosa (Brady, 1867)	2.10		0.16	0.75				0.27	
Paracytherois oblonga Müller, 1894						0.27			
Paracytherois sp. 1			0.33						
Paracytheromorpha nana (Bonaduce, Ciampo & Masoli, 1976)			0.16						0.47
Paracytheromorpha sp. 1	0.42		0.33	0.38		0.27			
Paradoxostoma simile Müller, 1894				0.19					
Paradoxostoma aff. *versicolor* Müller, 1894			0.16	0.19					
Paradoxostoma sp.			0.16	0.38					
Parahemingwayella tetrapteron (Bonaduce, Ciampo & Masoli, 1976)		0.40							
Paranesidea reticulata (Müller, 1894)	0.84				0.51	0.41	0.40	0.80	
Phlyctocythere pellucida (Müller, 1894)		0.40	0.16	0.56		0.27	0.60	0.27	
Polycope reticulata Müller, 1894						0.14		0.27	
Pontocypris acuminata (Müller, 1894)	0.42	1.20	1.32	0.94		0.54	0.20	0.27	
Pontocypris intermedia Brady, 1868				0.19					
Pontocythere turbida (Müller, 1894)		0.40			0.26			0.53	
Propontocypris dispar (Müller, 1894)				0.19					
Propontocypris pirifera (Müller, 1894)			0.16	0.19					
Pseudocytherura strangulata Ruggieri, 1991		0.40	0.33	0.19	0.26	0.54			
Pseudolimnocythere sp. 1									0.47
Pterygocythereis jonesii (Baird, 1850)		0.40	0.33	0.38			0.20	0.27	0.47
Pterygocythereis coronata (Roemer, 1838)			0.33		0.77				
Rostrocythere hastata (Bonaduce, Masoli, Pugliese & McKenzie, 1980)						0.14			
Sagmatocythere napoliana (Puri, 1963)			0.16	0.19					
"*Sagmatocythere*" sp.1							0.20		

(Continues)

TABLE 5 (Continued)

ST6_BNR1									
Samples	**BNR1 0–1**	**BNR1 1–2**	**BNR1 2–3**	**BNR1 3–4**	**BNR1 4–5**	**BNR1 5–6**	**BNR1 6–7**	**BNR1 7–8**	**BNR1 8–9**
Sclerochilus gewemuelleri Dubowsky, 1939				0.19					
Sclerochilus aequus Müller, 1894					0.51				
Sclerochilus sp.								0.53	
Semicytherura acuticostata (Sars, 1866)	2.52	4.78	2.64	2.26	3.34	2.44	2.20	2.39	1.90
Semicytherura aenariensis Bonaduce, Ciampo & Masoli, 1976	1.68		0.16	0.75		0.14	0.60	0.53	0.95
Semicytherura alifera Ruggieri, 1959	3.78	2.79	4.61	2.64	6.17	4.07	4.00	3.45	1.90
Semicytherura dispar (Müller, 1894)		0.40	0.49	0.75	0.26	0.95	1.80	1.06	0.95
Semicytherura heinzei Puri 1963	0.84	0.40	0.16			0.14			0.47
Semicytherura inversa (Seguenza, 1880)		0.80					0.20		
Semicytherura occulta Bonaduce, Ciampo & Masoli, 1976								0.27	
Semicytherura paradoxa (Müller, 1894)		0.40	0.66	0.75	0.77	0.27	1.20	0.53	0.47
Semicytherura quadridentata (Hartmann, 1953)		0.40			0.77	0.68	0.40	0.80	0.95
Semicytherura rara (Müller, 1894)	3.78	4.78	3.62	3.20	4.11	3.12	3.40	3.71	5.21
Semicytherura simplex (Brady & Norman, 1889)			0.33						
Semicytherura sulcata (Müller, 1894)						0.14			
Semicytherura sp.								0.27	
Tenedocythere prava (Baird, 1850)			0.33		0.51	0.41	0.60		0.47
Triebelina raripila (Müller, 1894)				0.19					
Urocythereis ilariae Aiello, Barra & Parisi, 2016			1.48	0.75		0.41			
Urocythereis margaritifera (Müller, 1894)	0.42			0.38	0.51	0.41	0.20	0.27	
Xestoleberis communis Müller, 1894	11.34	11.95	7.91	8.10	5.40	8.54	9.60	13.00	10.43
Xestoleberis dispar Müller, 1894	6.30	4.78	5.77	6.21	6.68	4.88	4.00	5.57	4.27
Xestoleberis aff. *intumescens* Klie 1942			0.16				0.40	0.27	0.95
Xestoleberis aff. *perula* Athersuch, 1978		0.40						0.27	
Xestoleberis plana Müller, 1894			1.65	2.45	1.80	1.76	1.80		0.47
Xestoleberis sp.				0.19					

Equitability (J) ranges from 0.86 to 0.93 (MNI) and from 0.81 to 0.87 (TNV). The mean J values are 0.90 (MNI) and 0.84 (TNV).

Cluster analysis and Principal Component Analysis of the nine subsamples from the ST6_BNR1 station were performed in order to identify changes in ostracod assemblages. The analysis was run using abundance values. The cluster analysis generated the dendrograms shown in Figure 4 (MNI) and Figure 5 (TNV); Principal Component Analysis (PCA) ordination diagrams have been reported

TABLE 6 Ostracod assemblage indices; *S*, number of taxa; I, minimum number of individuals (MNI) per 10 cm^3 sediment volume and total number of valves (TNV) per 10 cm^3 sediment volume; D, dominance; *H′*, Shannon diversity index; J, Equitability; STD, standard deviation

ST6_BNR1	BNR1 0–1	BNR1 1–2	BNR1 2–3	BNR1 3–4	BNR1 4–5	BNR1 5–6	BNR1 6–7	BNR1 7–8	BNR1 8–9
MNI									
Taxa S	38	44	65	63	45	62	52	51	42
Individuals I	60	68	116	118	90	161	133	95	59
Dominance D	0.05	0.04	0.04	0.03	0.05	0.05	0.05	0.05	0.04
Shannon *H′*	3.35	3.47	3.73	3.75	3.38	3.56	3.43	3.47	3.46
Equitability J	0.92	0.92	0.89	0.90	0.89	0.86	0.87	0.88	0.93
TNV									
Individuals I	189	200	483	422	309	587	398	300	168
Dominance D	0.06	0.06	0.06	0.05	0.06	0.05	0.05	0.06	0.06
Shannon *H′*	3.17	3.17	3.36	3.46	3.26	3.40	3.32	3.23	3.19
Equitability J	0.87	0.84	0.81	0.83	0.86	0.82	0.84	0.82	0.85

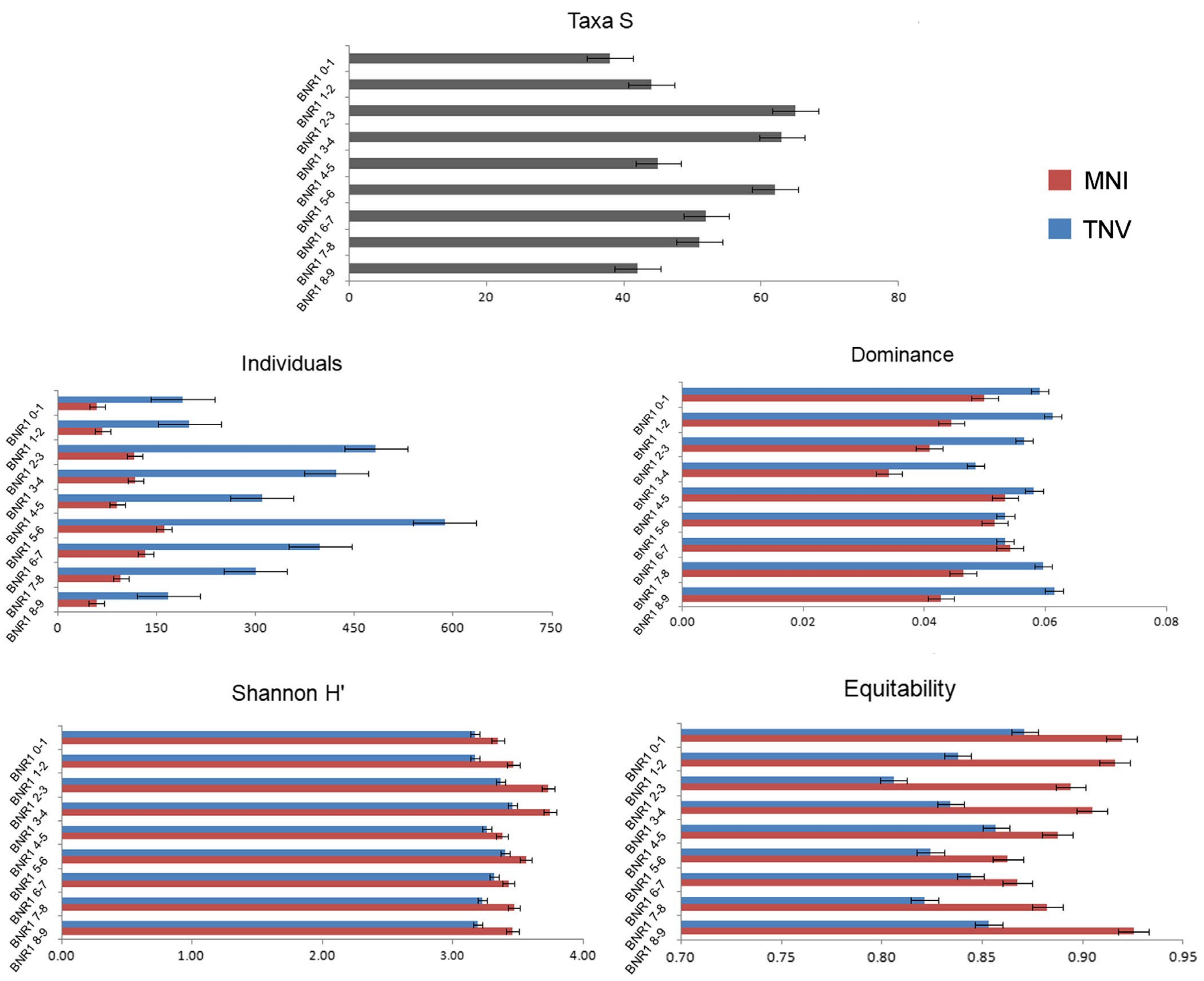

FIGURE 2 Vertical distribution of ostracods' assemblages and indices with standard error bars in ST6_BNR1. MNI, minimum number of individuals; TNV, total number of valves

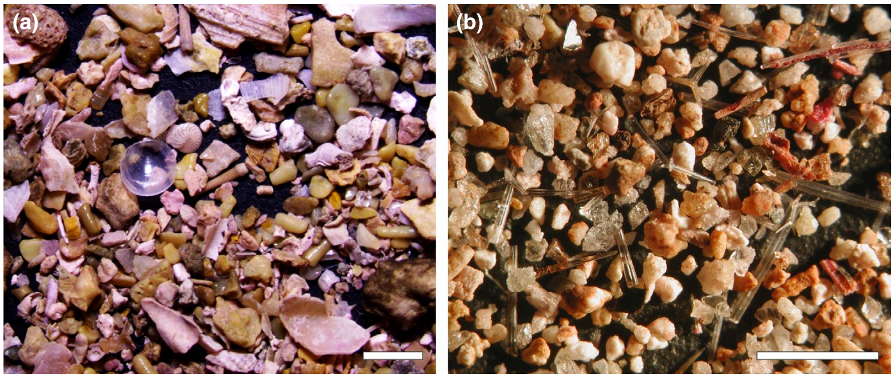

FIGURE 3 Optical microscope photos of bottom sediment residue (>125 μm): (a) Sediment outside the pockmark area (subsample ST6_BNR1 1–2), scale bar = 2 mm; (b) Sediment inside the pockmark area (subsample ST2_BNR3 0–1), scale bar = 1 mm

in Figure 6 (MNI and TNV). Analysis performed using Minimum Number of Individuals (MNI) and Total Number of Valves (TNV) lead to slightly different results.

MNI analysis divided the subsamples into clusters A (MNI) and B (MNI) and ostracod species into two groups [1 (MNI) and 2 (MNI)] to which is added the species *M. angulosa* that was individually discriminated. Cluster A (MNI) included the subsamples [ST6_BNR1 (0–1, 1–2, 8–9)] with low *H′* diversity (range: 3.35–3.47), abundance I (range: 59–68) and simple diversity S (range: 38–44); cluster B (MNI) grouped the subsamples [ST6_BNR1 (2–3, 3–4, 4–5, 5–6, 6–7, 7–8)] showing high diversity (*H′* range: 3.38–3.75, S range: 45–65) and abundance (I range: 90–161). Cluster 1 (MNI) included both species typical of upper infralittoral waters (*X. communis*, *Xestoleberis dispar*) infralittoral–circalittoral (*Aurila convexa*, *Hemicytherura videns*, *L. affinis*, *Semicyherura acuticostata*, *N. mediterranea*) and circalittoral species (*Bosquetina tarentina*), whereas the cluster 2 (MNI) consisted of species pertaining to *Microcythere* and *Semicytherura*, plus *Hemicytherura defiorei*, characteristic of circalittoral waters.

In the Principal Component Analysis, representative species were plotted as vectors to identify their distribution among the subsamples of station ST6_BNR1.

The first axis explained 42.3% of the variance of data (eigenvalue = 8.5) and was mainly related to the abundance I, equitability J, and abundance of *M. angulosa* and *H. defiorei*. The second axis, which explained 20.5% of the variance (eigenvalue = 4.1), represented a transition of assemblages with high Shannon diversity to assemblages showing high dominance D.

The low-diversity, high J subsamples, also grouped by cluster analysis in the cluster A, were placed in the left side of the ordination diagram and well segregated from those of cluster B, located in its central and right part. The very high diversity samples ST6_BNR1 2–3 and ST6_BNR1 3–4 had positive values for first and second components.

The Q-mode dendrogram resulting from TNV data confirmed the clusters A and B produced by MNI abundance analysis. In the R-mode dendrogram *M. angulosa* and *H. videns* were separated species, and the cluster 1 (TNV) included four species (*L. affinis*, *N. mediterranea*, *X. communis*, *X. dispar*) mainly recorded in infralittoral waters, whereas the cluster 2 (TNV) was dominated by the genera *Semicytherura* and *Microcythere*, well represented also in circalittoral environment.

In the Principal Component Analysis performed on TNV, the first axis accounted for the 62.7% of the variance and the second axis for the 14.3% (Axis 1: eigenvalue = 12.5, Axis 2: eigenvalue = 2.9). The diagram showed that also in this case the subsamples ST6_BNR1 (0–1, 1–2, 8–9) were grouped in the left part of the diagram. Two subsamples [ST6_BNR1 (2–3, 5–6)] with high I, *H′* and S, loaded on the positive side of the first axes in the lower right part of the diagram, whereas the subsample ST6_BNR1 (3–4), characterised by high RSA of *B. tarentina* and *H. videns*, showed positive values for both first and second components. The remaining subsamples are located in the central part of the diagram.

5 | DISCUSSION

The comparison between the samples collected within the ZGP and the subsamples of the short-core ST6_BNR1, located 2.6 km away from the hydrothermal area, highlighted that ostracod shells, as well as other calcareous meiofaunal remains, do not occur or are not preserved in bottom sediments under the influence of CO_2-rich emissions.

5.1 | Ostracod abundance, diversity and composition outside the ZGP

The Recent and sub-Recent assemblages occurring in the ST6_BNR1 short-core were rich, well-preserved and well diversified. They included species living in both infralittoral and circalittoral zone (e.g. *Callistocythere crispata*, *H. defiorei*, *H. videns*, *Semicytherura* spp.) and taxa very rare or completely absent in the uppermost areas of the shelf such as *Argilloecia*, *Bosquetina*, *Buntonia*, *Cytherella vulgatella*, *Cytheropteron*, *Dopseucythere* and *M. angulosa*. Valves of infralittoral species (i.a. *Basslerites berchoni*, *Loxoconcha stellifera*, *Urocythereis ilariae*, *U. margaritifera*), mainly juveniles, rarely occurred, most likely transported from shallower environments.

The common occurrence of *Microcythere* species requires a separate evaluation. In our opinion the relatively high abundances of the genus, rarely recorded in similar environments, is not due to particular ecological conditions, but rather to little consideration for small sized taxa from ostracodologists. For example, Breman (1976) in his

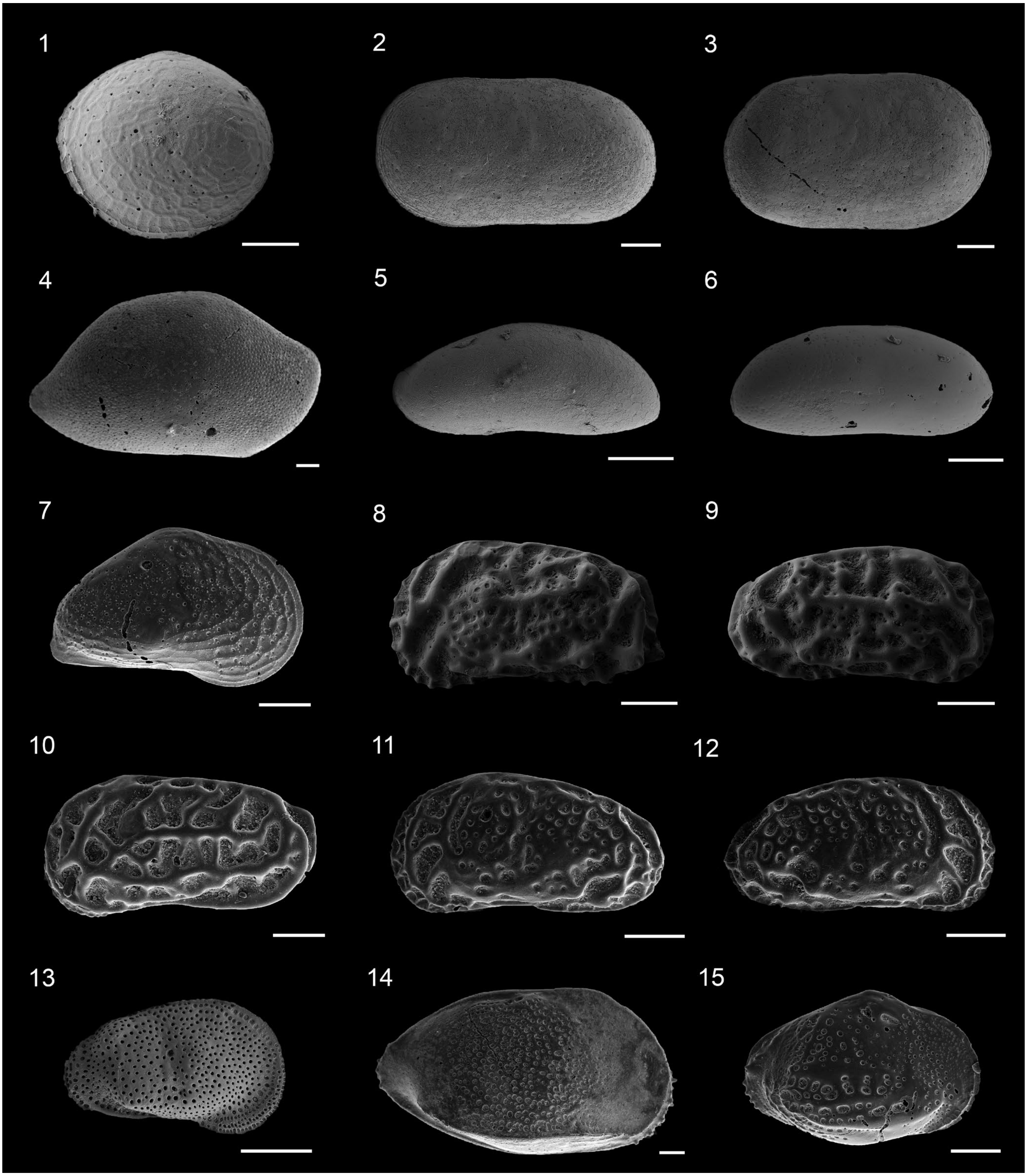

PLATE 1 (1) *Polycope reticulata* Müller, 1894, LV, sample ST6_BNR1 7–8, ABMC 2020/044; (2) *Cytherella vulgatella* Aiello, Barra, Bonaduce & Russo, 1996, LV, sample ST6_BNR1 5–6, ABMC 2021/058; (3) *Cytherella vulgatella* Aiello, Barra, Bonaduce & Russo, 1996, RV, sample ST6_BNR1 5–6, ABMC 2020/078; (4) *Neonesidea mediterranea* (Müller, 1894), RV, sample ST6_BNR1 5–6, ABMC 2020/017; (5) *Argilloecia robusta* Bonaduce, Ciampo & Masoli, 1976, LV, sample ST6_BNR1 3–4, ABMC 2020/051; (6) *Argilloecia caudata* Müller, 1894, RV, sample ST6_BNR1 1–2, ABMC 2020/065; (7) *Eucythere curta* Ruggieri, 1975, RV, sample ST6_BNR1 4–5, ABMC 2020/009; (8) *Callistocythere crispata* (Brady, 1868), LV, sample ST6_BNR1 6–7, ABMC 2020/082; (9) *Callistocythere crispata* (Brady, 1868), RV, sample ST6_BNR1 2–3, ABMC 2020/090; (10) *Callistocythere flavidofusca* (Ruggieri, 1950), LV, sample ST6_BNR1 7–8, ABMC 2020/005; (11) *Callistocythere praecincta* Ciampo, 1976, LV, sample ST6_BNR1 5–6, ABMC 2020/018; (12) *Callistocythere praecincta* Ciampo, 1976, RV, sample ST6_BNR1 5–6, ABMC 2020/019; (13) *Cluthia keiji* Neale, 1975, RV, sample ST6_BNR1 4–5, ABMC 2020/061; (14) *Bosquetina tarentina* (Baird, 1850), RV, sample ST6_BNR1 1–2, ABMC 2020/007; (15) *Buntonia sublatissima* (Neviani, 1906), RV, sample ST6_BNR1 8–9, ABMC 2020/001. Scale bars = 100 μm

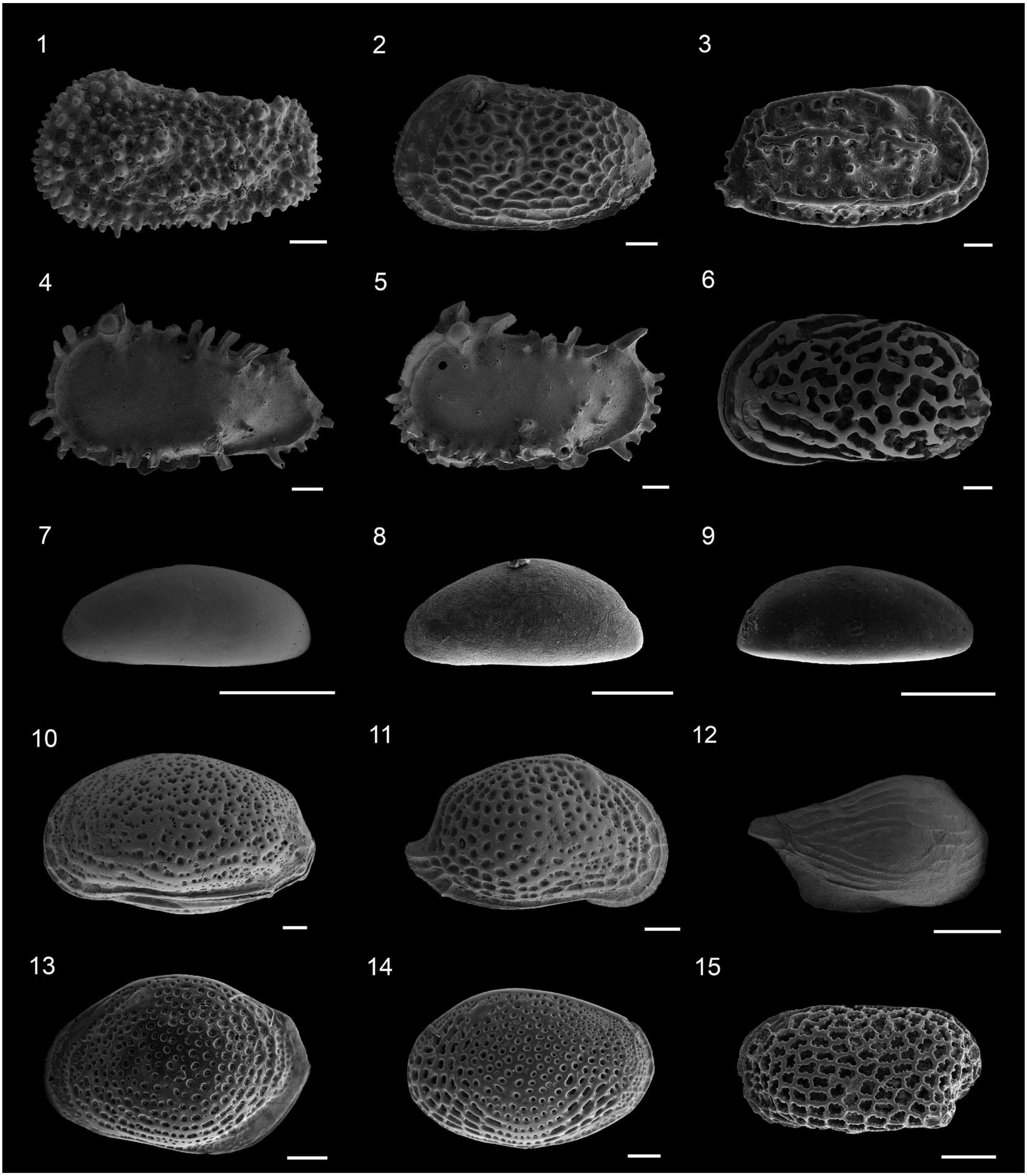

PLATE 2 (1) *Henryhowella parthenopea* Bonaduce, Barra & Aiello,1999, LV, sample ST6_BNR1 2–3, ABMC 2020/024; (2) *Echinocythereis laticarina* (Brady, 1868), LV, sample ST6_BNR1 2–3, ABMC 2020/073; (3) *Carinocythereis whitei* (Baird, 1850), RV, sample ST6_BNR1 3–4, ABMC 2020/022; (4) *Pterygocythereis coronata* (Roemer, 1838), LV, sample ST6_BNR1 2–3, ABMC 2020/074; (5) *Pterygocythereis jonesii* (Baird, 1850), LV, sample ST6_BNR1 2–3, ABMC 2020/050; (6) *Urocythereis ilariae* Aiello, Barra & Parisi, 2016, LV, sample ST6_BNR1 2–3, ABMC 2020/067; (7) *Microcythere hians* Müller, 1894, LV, sample ST6_BNR1 7–8, ABMC 2020/071; (8) *Microcythere inflexa* Müller, 1894, LV, sample ST6_BNR1 1–2, ABMC 2020/015; (9) *Microcythere depressa* Müller, 1894, RV, sample ST6_BNR1 2–3, ABMC 2020/013; (10) *Aurila speyeri* (Brady, 1858), LV, sample ST6_BNR1 6–7, ABMC 2020/045; (11) *Aurila convexa* (Baird, 1850), RV, sample ST6_BNR1 2–3, ABMC 2020/028; (12) *Loxocauda decipiens* (Müller, 1894), RV, sample ST6_BNR1 5–6, ABMC 2020/029; (13) *Loxoconcha affinis* (Brady, 1866), LV, sample ST6_BNR1 3–4, ABMC 2020/023; (14) *Loxoconcha ovulata* (Costa, 1853), LV, sample ST6_BNR1 1–2, ABMC 2020/002; (15) *Paracytheromorpha* sp. 1, LV, sample ST6_BNR1 3–4, ABMC 2020/020. Scale bars = 100 μm

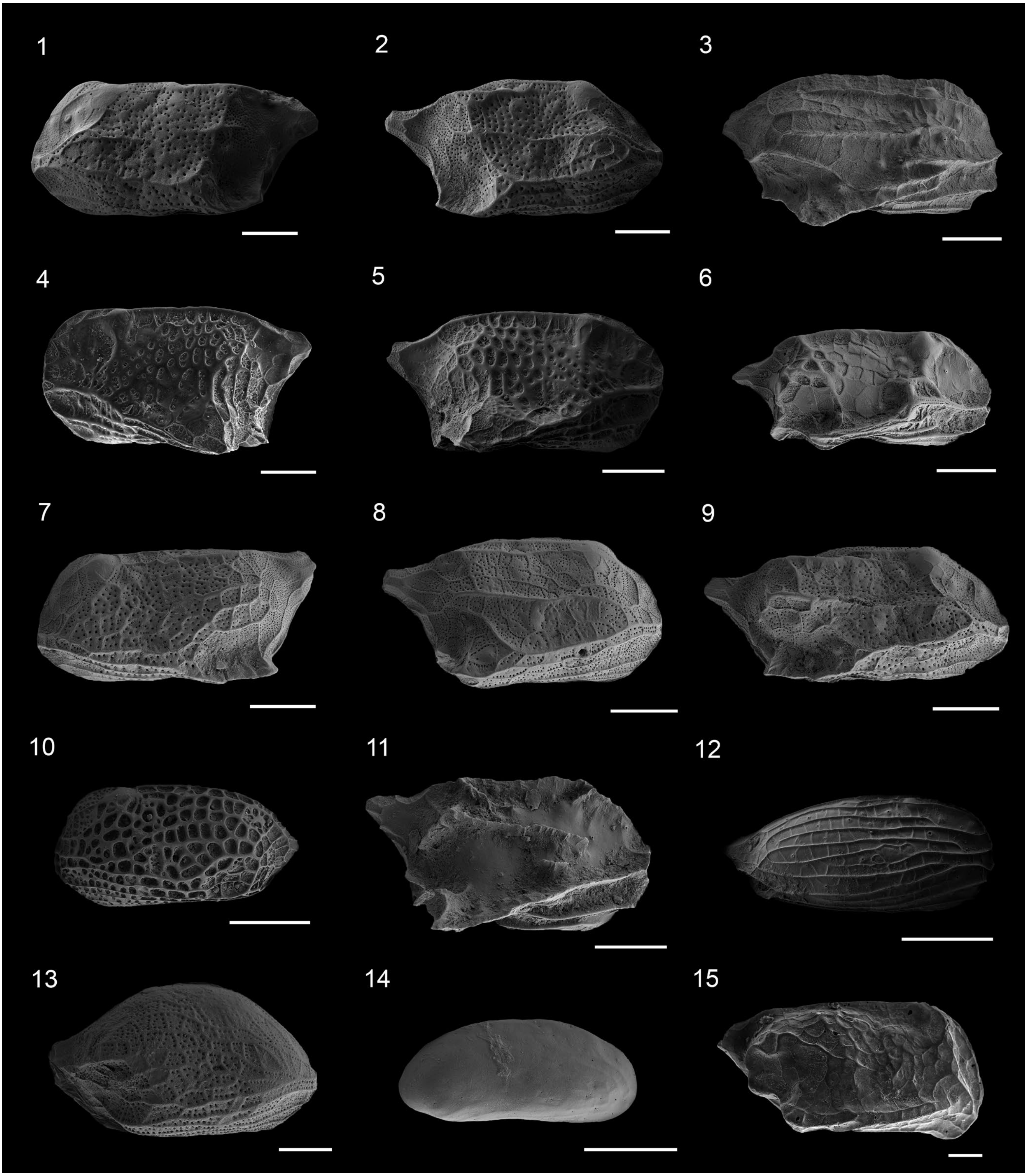

PLATE 3 (1) *Semicytherura aenariensis* Bonaduce, Ciampo & Masoli, 1976, LV, sample ST6_BNR1 2–3, ABMC 2020/081; (2) *Semicytherura aenariensis* Bonaduce, Ciampo & Masoli, 1976, RV, sample ST6_BNR1 6–7, ABMC 2020/080; (3) *Semicytherura acuticostata* (Sars, 1866), RV, sample ST6_BNR1 2–3, ABMC 2020/027; (4) *Semicytherura alifera* Ruggieri, 1959, LV, sample ST6_BNR1 6–7, ABMC 2020/003; (5) *Semicytherura alifera* Ruggieri, 1959, RV, sample ST6_BNR1 6–7, ABMC 2020/092; (6) *Semicytherura dispar* (Müller, 1894), RV, sample ST6_BNR1 5–6, ABMC 2020/057; (7) *Semicytherura occulta* Bonaduce, Ciampo & Masoli, 1976, LV, sample ST6_BNR1 7–8, ABMC 2020/041; (8) *Semicytherura heinzei* Puri 1963, RV, sample ST6_BNR1 1–2, ABMC 2020/040; (9) *Semicytherura heinzei* Puri 1963, RV, sample ST6_BNR1 0–1, ABMC 2020/059; (10) *Semicytherura rara* (Müller, 1894), LV, sample ST6_BNR1 5–6, ABMC 2020/077; (11) *Semicytherura paradoxa* (Müller, 1894), RV, sample ST6_BNR1 7–8, ABMC 2020/055; (12) *Semicytherura quadridentata* (Hartmann, 1953), RV, sample ST6_BNR1 8–9, ABMC 2020/094; (13) *Semicytherura inversa* (Seguenza, 1880), RV, sample ST6_BNR1 1–2, ABMC 2020/072; (14) *Semicytherura simplex* (Brady & Norman, 1889), RV, sample ST6_BNR1 2–3, ABMC 2020/033; (15) *Pseudocytherura strangulata* Ruggieri, 1991, RV, sample ST6_BNR1 4–5, ABMC 2020/006. Scale bars = 100 μm

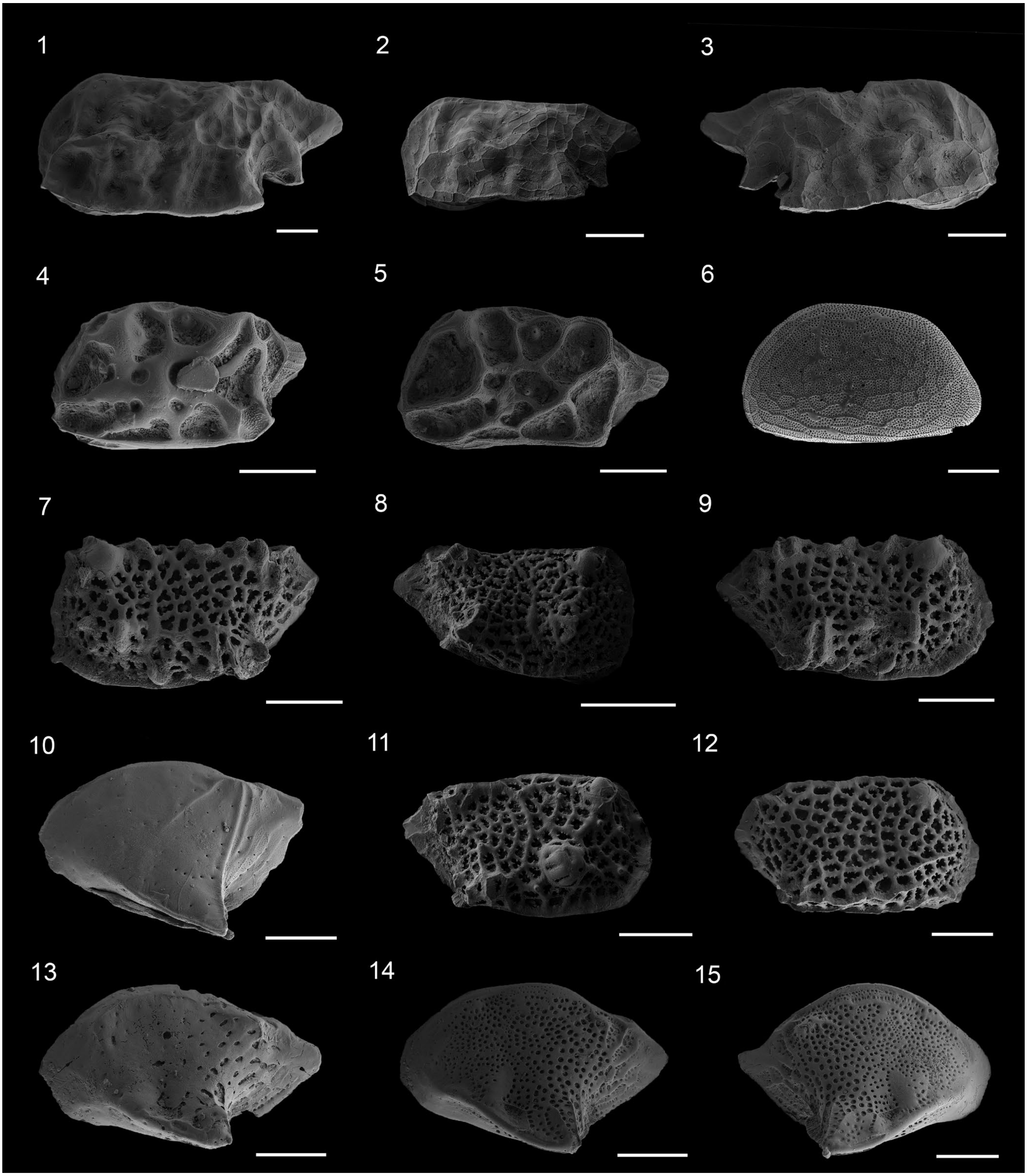

PLATE 4 (1) *Paracytheridea triquetra* (Reuss, 1850), LV, sample ST6_BNR1 2–3, ABMC 2020/066; (2) *Paracytheridea triquetra* (Reuss, 1850), LV juv, sample ST6_BNR1 5–6, ABMC 2020/083; (3) *Paracytheridea triquetra* (Reuss, 1850), RV, sample ST6_BNR1 5–6, ABMC 2020/039; (4) *Hemicytherura defiorei* Ruggieri, 1953, LV, sample ST6_BNR1 3–4, ABMC 2020/034; (5) *Hemicytherura videns* (Müller, 1894), LV, sample ST6_BNR1 5–6, ABMC 2020/031; (6) *Microcytherura angulosa* (Seguenza, 1880), LV, sample ST6_BNR1 2–3, ABMC 2020/010; (7) *Eucytherura gibbera* Müller, 1894, LV, sample ST6_BNR1 3–4, ABMC 2020/038; (8) *Eucytherura gibbera* Müller, 1894, RV, sample ST6_BNR1 6–7, ABMC 2020/076; (9) *Eucytherura gibbera* Müller, 1894, RV juv, sample ST6_BNR1 5–6, ABMC 2020/089; (10) *Cytheropteron sulcatum* Bonaduce, Ciampo & Masoli, 1976, LV, sample ST6_BNR1 2–3, ABMC 2020/048; (11) *Eucytherura complexa* (Brady, 1867), RV, sample ST6_BNR1 2–3, ABMC 2020/084; (12) *Eucytherura mistrettai* Sissingh, 1972, RV, sample ST6_BNR1 3–4, ABMC 2020/025; (13) *Cytheropteron latum* Müller, 1894, LV, sample ST6_BNR1 7–8, ABMC 2020/032; (14) *Cytheropteron hadriaticum* Bonaduce, Ciampo & Masoli, 1976, LV, sample ST6_BNR1 0–1, ABMC 2020/069; (15) *Cytheropteron hadriaticum* Bonaduce, Ciampo & Masoli, 1976, RV, sample ST6_BNR1 3–4, ABMC 2020/062. Scale bars = 100 μm

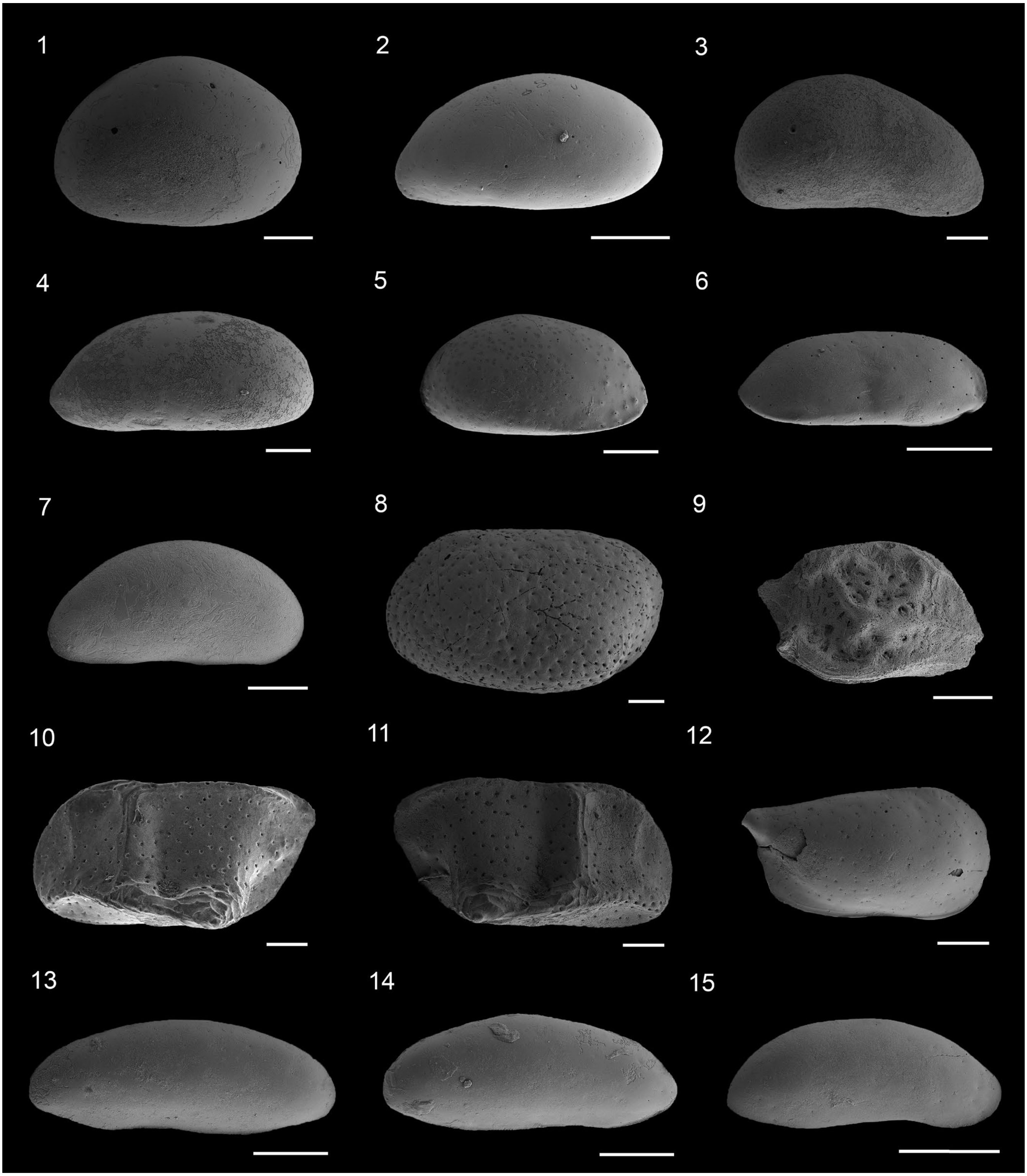

PLATE 5 (1) *Xestoleberis communis* Müller, 1894, LV, sample ST6_BNR1 1–2, ABMC 2020/070; (2) *Xestoleberis* aff. *intumescens* Klie 1942, LV, sample ST6_BNR1 2–3, ABMC 2020/049; (3) *Xestoleberis dispar* Müller, 1894, RV, sample ST6_BNR1 4–5, ABMC 2020/030; (4) *Xestoleberis plana* Müller, 1894, LV, sample ST6_BNR1 8–9, ABMC 2020/046; (5) *Microxestoleberis xenomys* (Barbieto-Gonzalez, 1971), LV, sample ST6_BNR1 4–5, ABMC 2020/052; (6) *Microxestoleberis* ? *kykladica* Barbeito-Gonzalez, 1971, RV, sample ST6_BNR1 3–4, ABMC 2020/060; (7) *Sclerochilus aequus* Müller, 1894, LV, sample ST6_BNR1 4–5, ABMC 2020/036; (8) *Bythocythere puncticulata* Ruggieri, 1976, LV, sample ST6_BNR1 1–2, ABMC 2020/037; (9) *Kangarina abyssicola* (Müller, 1894), RV, sample ST6_BNR1 3–4, ABMC 2020/035; (10) *Monoceratina oblita* Bonaduce, Ciampo & Masoli, 1976, LV, sample ST6_BNR1 7–8, ABMC 2020/004; (11) *Monoceratina oblita* Bonaduce, Ciampo & Masoli, 1976, RV, sample ST6_BNR1 3–4, ABMC 2020/075; (12) *Dopseucythere mediterranea* (Bonaduce, Masoli, Pugliese & McKenzie, 1980), RV, sample ST6_BNR1 5–6, ABMC 2020/054; (13) *Cytherois frequens* Müller, 1894, LV, sample ST6_BNR1 0–1, ABMC 2020/047; (14) *Cytherois frequens* Müller, 1894, RV, sample ST6_BNR1 0–1, ABMC 2020/043; (15) *Cytherois uffenordei* Ruggieri, 1975, RV, sample ST6_BNR1 2–3, ABMC 2020/064. Scale bars = 100 μm

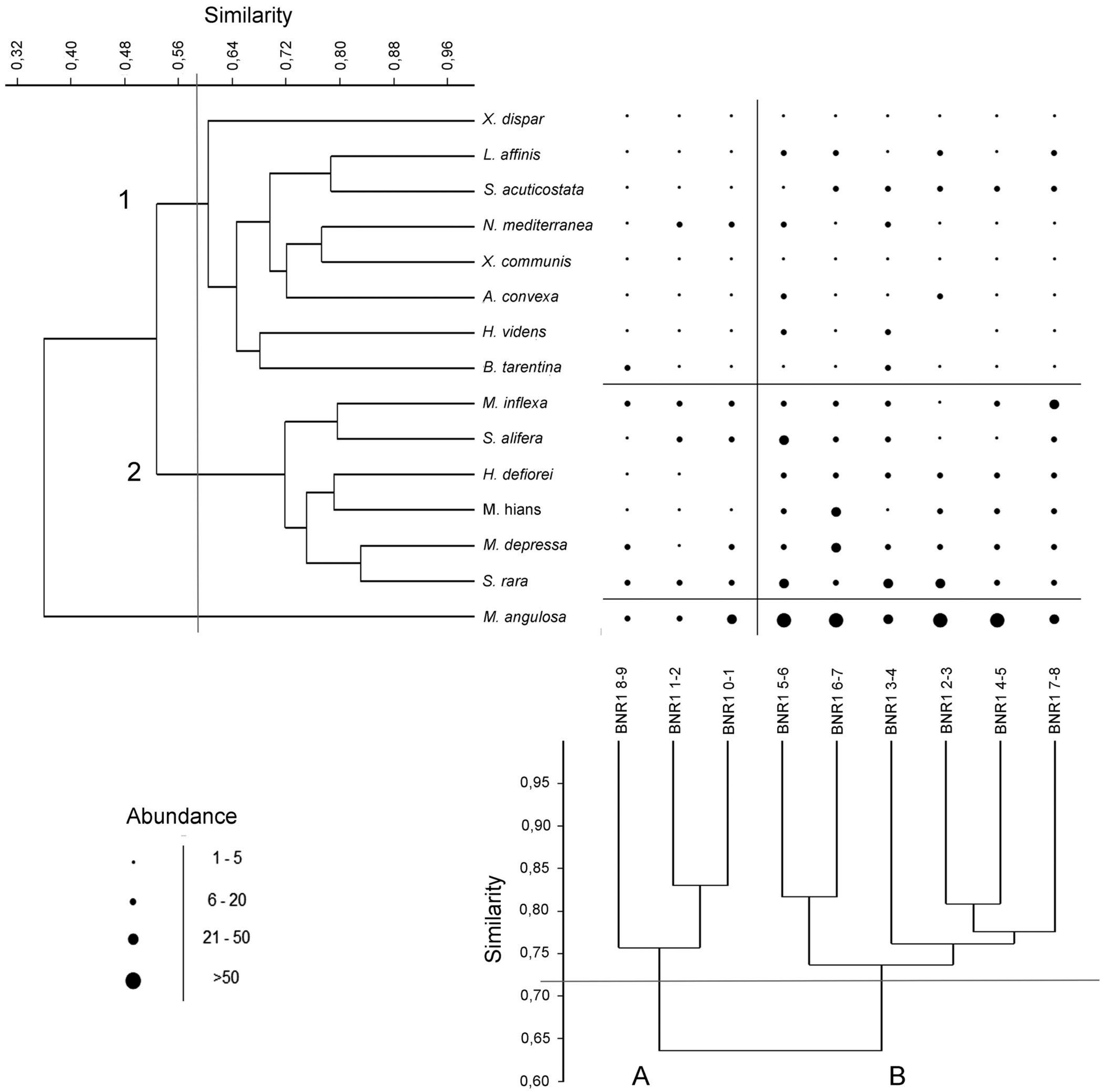

FIGURE 4 Two-way cluster analysis of ostracod assemblages (minimum number of individuals MNI) of the ST6_BNR1 subsamples identifying two different clusters. Refer to Table 2 for species names

investigation on Adriatic Sea assemblages, stated "The smallest fraction [60–150 μm] might contain adult specimens of very small species belonging to genera such as *Microcythere*", and, consequently, he recorded no species of *Microcythere* species. The majority of ostracod studies do not analyse the sediment fraction between 63 and 125μm, where adult specimens of small species occur together with dominant young instars of larger taxa. On the basis of the present record, we hypothesise that the presence of *Microcythere* in circalittoral Mediterranean waters is generally underestimated.

Although grain size data are quite homogeneus for the ST6_BNR1 short-core (Di Bella et al., 2016), the analysis of the ostracod assemblages showed two distinct depositional environments, defined, both for Minimum Number of Individuals (MNI) and Total Number of Valves (TNV), using two-way (Q-mode and R-mode) cluster and PCA analysis. The cluster A consisted of subsamples ST6_BNR1 [0–1] [1–2] [8–9], with low-diversity, low abundance, high equitability assemblages; the cluster B included the remaining six ST6 subsamples, showing high diversity, high abundance and low equitability. The ostracod species that characterised the clusters were different in MNI and TNV analyses. In cluster B (MNI) the circalittoral species *M. angulosa* and the shelf (i.e. living in infralittoral and circalittoral waters) species *H. defiorei*, *S. alifera*, *S. rara*, plus three *Microcythere* species were

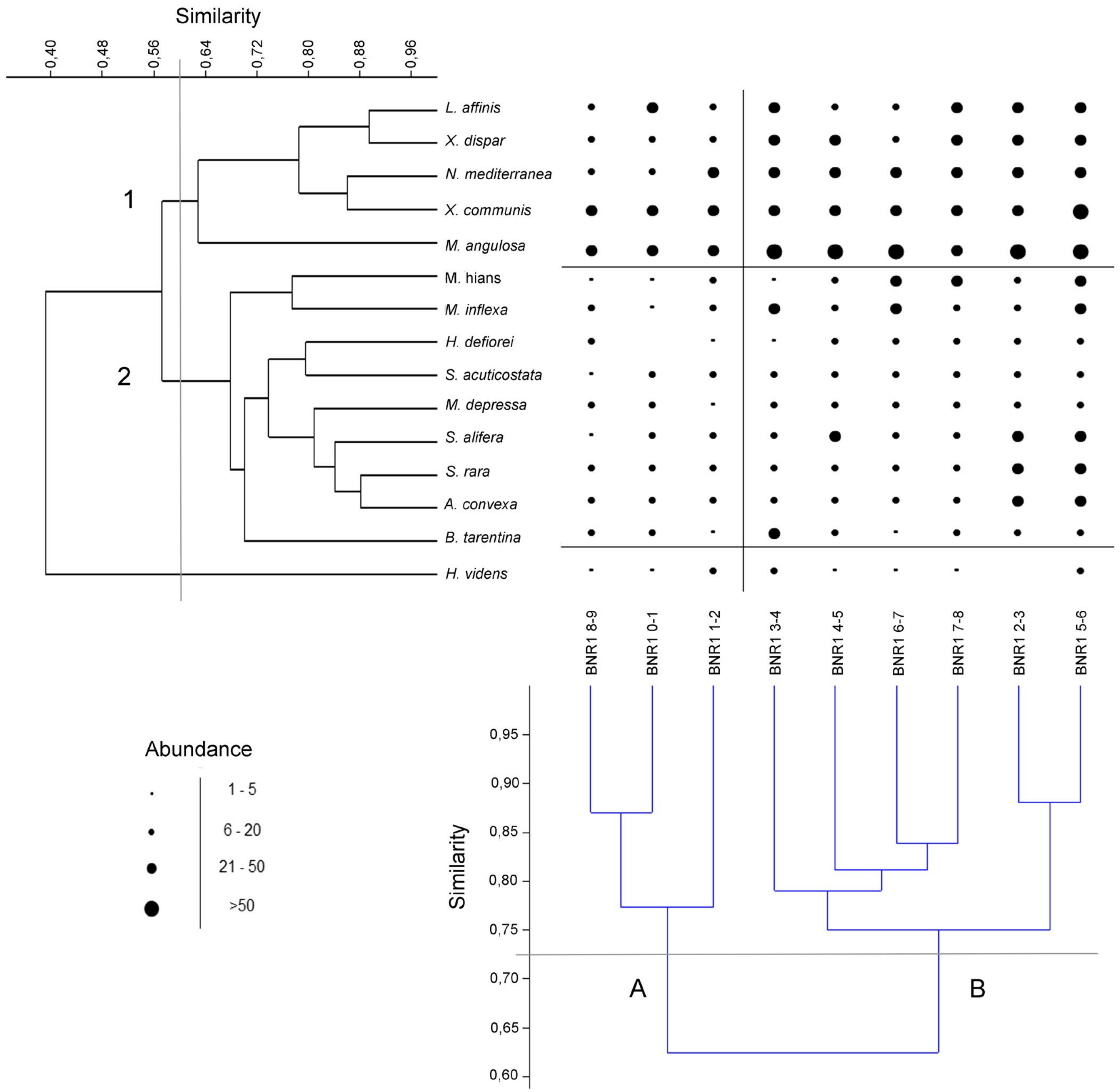

FIGURE 5 Two-way cluster analysis of ostracod assemblages (total number of valves TNV) of the ST6_BNR1 subsamples identifying two different clusters. Refer to Table 2 for species names

well represented. TNV cluster analysis revealed that the cluster B was characterised by species preferring shallow waters (*L. affinis*, *N. mediterranea*, *X. communis*, *X. dispar*) plus *M. angulosa*. In this case, the MNI results were more reliable than those obtained from TNV data, due to the influence of young instars on the latter. Evidences of low pH water influx on low-diversity–abundance assemblages, such as chemical dissolution on ostracod shells (v. Aiello et al., 2012), were not observed. We have also observed the presence of miliolids, benthic foraminifers that are typical of waters supersaturated in calcium carbonate (Aiello, Barra, Parisi, et al., 2018, and literature therein), confirming that CO_2 emissions had no impact on the ST6_BNR1 sediments.

Thus, the alternation of low and high abundance–diversity assemblages is possibly due to relatively rapid changes in dissolved oxygen and food supply in bottom waters linked to significant seasonal changes in water circulation (extensive references in: Aiello et al., 2015; Athersuch et al., 1989; Pokorný, 1978; Smith & Horne, 2002).

5.2 | The ZGP organic component

The occurrence of a single valve of *Parahemingwayella tetrapteron* in the top subsample of the short-core ST3_BNR3 was possibly

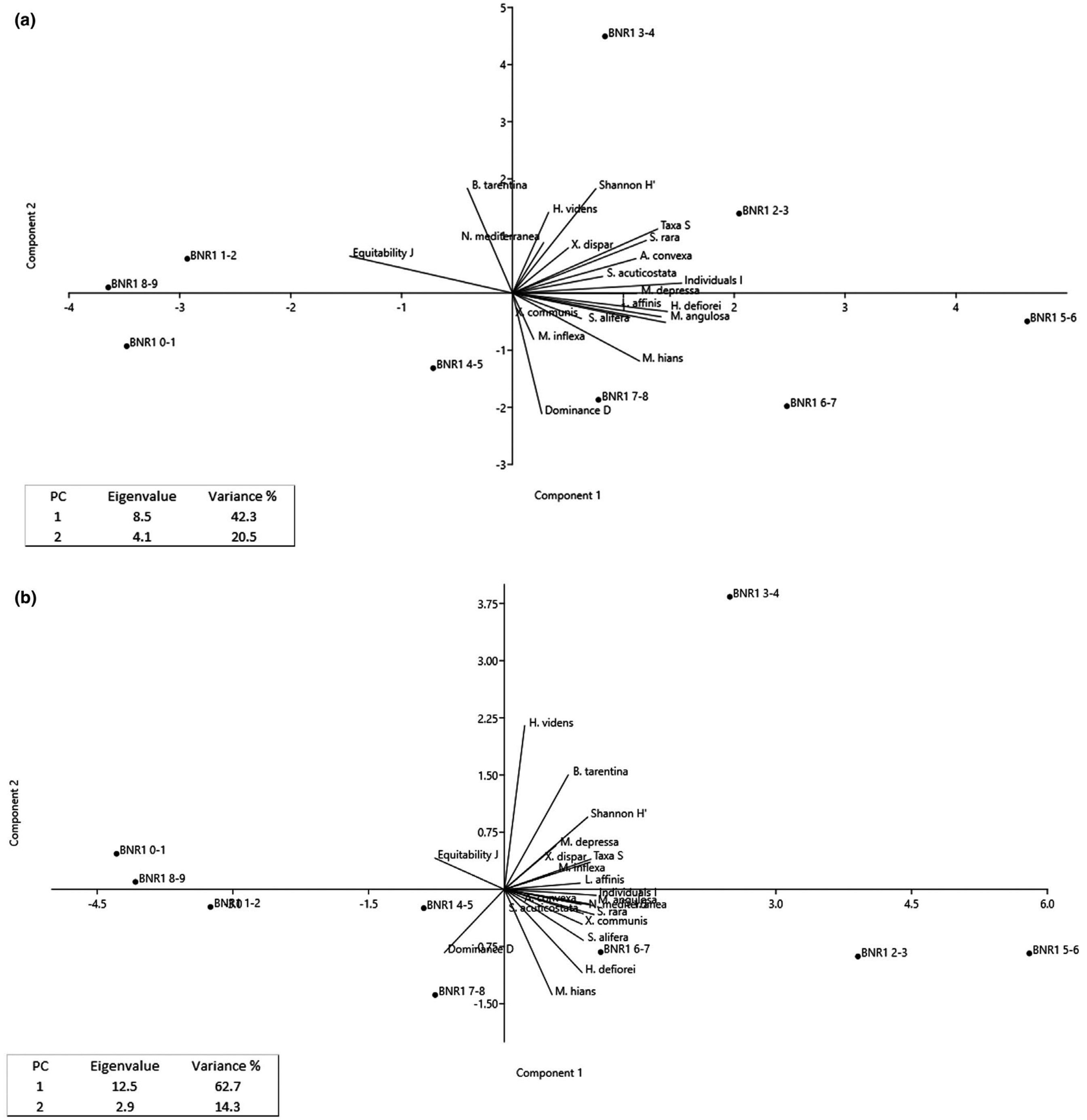

FIGURE 6 Scatter plot from principal component analysis (PCA) plotting first and second principal components: (a) minimum number of individuals (MNI); (b) total number of valves (TVN)

the result of bottom currents which transported the shell from nearby areas just before the sampling. The organic component of the bottom sediments of the ZGP consisted mainly of sponge spicules and other siliceous remains (radiolarians, diatoms) (Figure 3). The presence of benthic foraminiferal assemblages consisting entirely of agglutinated taxa, including *Spiculosiphon oceana*, a giant foraminifer agglutinating spicules of sponges (Di Bella et al., 2016, 2018) and confirmed by our observations, represented the response of foraminifers to low pH conditions under which ostracod valves were not recorded. The occurrence of *S. oceana* in the ZGP sediments rules out the possibility that sediment instability or trophic conditions could be limiting factors. Unfortunately, the lack of pH data from the thermal waters of the ZGP (Italiano et al., 2019) prevents us from drawing a firm conclusion regarding this possibility.

Studies conducted on benthic foraminifera and ostracoda from methane and CO_2 seep sites showed contrasting evidences on faunal density and diversity. Generally, calcareous benthic foraminifera assemblages disappear or their density decreases in correspondence of increasing CO_2 (Cigliano et al., 2010; Uthicke et al., 2013); they can be replaced by agglutinated foraminifera (Dias et al., 2010) or some species seem to occur even at low pH values (Pettit et al., 2013). In the Arctic, agglutinated foraminifera are less abundant in sediments influenced by methane seepage, suggesting that this group of foraminifera does not tolerate these geochemical conditions (Dessandier et al., 2019). Panieri (2006) reported the occurrence of dead foraminifera, shortly after an exceptional event of hydrothermal degassing activity off the coast of Panarea (Sicily). Just 10 days after the event, agglutinated foraminifera dominated the assemblages in the sediment samples whereas hyaline forms dominated the assemblage collected within the *Posidonia oceanica* meadows (Panieri, 2006). Most likely, the release of hot (49°C), acidic gases (HCl, HF, SO_2, and CO_2) had caused the death of the foraminifera and the dissolution of the carbonate tests (Panieri, 2006). This study highlights the importance of understanding the timing and the rate of seep events before drawing conclusions.

5.3 | The ostracod record in hydrothermal vents and cold seeps

Among crustaceans, ostracods seem to have the longest stratigraphic record in putative fossil cold seeps and hydrothermal vents starting from the Paleozoic (Klompmaker et al., 2018; Olempska & Belka, 2010). Van Harten (1992, 1993) was the first to report of Podocopid Ostracoda from deep-sea vents, from washings of *Riftia pachyptila* from East Pacific; he identified three species in open nomenclature and mentioned the presence of additional unspecified, smooth-shelled, fragile taxa. In Recent hydrothermal vents, the three genera *Propontocypris* Sylvester-Bradley (1947), *Thomontocypris* Maddocks (1991) and *Xylocythere* Maddocks and Steineck (1987) have been reported (Karanovic & Brandão, 2015). These three genera are also found in cold seeps and wood falls, occasionally in deep-sea and shallow oligotrophic environments (Karanovic & Brandão, 2015, Table 1) In the Miocene of the Northern Apennines (Italy), Russo et al. (2012) identified cold seeps through fossil ostracod assemblages They referred their ostracod fauna and the co-occurring lucinid molluscs to cold seeps. Recently, a critical reassessment of the lucinid fauna from the Western Atlantic Ocean by Taylor and Glover (2016) has identified 46 species mostly living at depth less than 200 msl and not close to cold seeps. Within the ostracod assemblage studied by Russo et al. (2012), 13 ostracod species were identified in the deposits with seepage activity: *Argilloecia* sp., *Neonesidea* cf. *B. conformis*, *Cytherella* sp., *Henryhowella asperrima*, *Krithe* sp., *Parakrithe dactylomorpha*, *Quasibuntonia radiotopora*, *Paleoblitacythereis bossioi*, *Xestoleberis* sp., *Abyssocypris* sp., *Cardobairdia glabra*, *Buntonia multicostata*. The latter three species were regarded as exclusive to seepage sites but *Abyssocypris* spp. are commonly recorded from seafloor environments (Alvarez Zarikian et al., 2009), whereas *B. multicostata* and *C. glabra* are exclusively found in the fossil record. Moreover, the occurrence of *Xestoleberis* sp. was regarded as evidence of an increase of nutrients linked to the seepage environment (Russo et al., 2012), but this genus often occurs in shallow and deep-sea habitats and it is one of the most common genera occurring in oligotrophic environments like the Tyrrhenian Sea (Aiello et al., 2021). *Xestoleberis* is one of the most represented genera in our record, with six species. *X. dispar* and *X. communis* are two of the most common species in the ST6_BNR1 samples. Studies based only on carapace morphologies in smooth-shelled ostracod species like *Xestoleberis* spp. can give rise to wider species definitions, thus artificially widespread geographical and stratigraphical distributions, than those based both on soft parts and valve morphology (Jellinek et al., 2006). It is interesting to note that recent abundant and well-preserved ostracod assemblages have been recovered from methane seepage areas in the western Svalbard margin (Yasuhara et al., 2018) and hydrocarbon seeps (Degen et al., 2012), implying that they can survive in peculiar geochemical conditions.

Further studies are needed to understand the colonisation mechanisms of in seeps and hydrothermal vents where highly diversified, taxonomically complex ostracods genera, living in shallow water and deep-sea oligotrophic environments as well, can be found.

6 | CONCLUSIONS

Notwithstanding the possible biases affecting the microfaunal analyses in the ZGP (generic environmental characterisation of each microhabitat), we have highlighted the role that CO_2 could play in the distribution of meio-benthos with calcitic shells. The absence of ostracod assemblages in samples from hydrothermal CO_2-rich areas and the occurrence of a well-preserved fauna in samples from nearby areas, out from the influence of the pockmark, demonstrate that, although ostracods could move between different environments characterised by variable salinities and depths, CO_2 represents an insurmountable threshold for ostracods' life.

The comparison with literature data about the identification of putative seeps through ostracod analysis, led us to question the attribution of some taxa as exclusive to seafloors with seepage. Fossil faunas often represent a time-integrated assemblage, difficult to relate to seep events that can last a very short time. Fossil ostracod assemblages could represent an artefact resulting from both transport of dead shells from surrounding environments and diachronic accumulation.

In an increasing ocean acidification scenario, habitat availability and quality will potentially reduce for many calcifying invertebrates whose life strongly depends on the alkalinity of environments they live in. A better understanding of the distribution of living ostracod assemblages in correspondence of cold seeps and hydrothermal vents, coupled with detailed information about chemical characteristics of the environment where they live, could shed light on the adaptations of meiofauna to extreme environmental conditions.

ACKNOWLEDGEMENTS

The authors wish to thank Letizia Di Bella (Sapienza, Rome University) and Eleonora Martorelli (CNR IGAG) for providing the samples and useful discussions on a preliminary draft of the paper and Roberto de' Gennaro (DiSTAR, Università di Napoli Federico II) who took the SEM micrographs. Two anonymous reviewers are thanked for fruitful and constructive comments.

DATA AVAILABILITY STATEMENT

Data available within the article or its supplementary materials.

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How to cite this article: Aiello, G., Mazzini, I., Parisi, R., Ingrassia, M., & Barra, D. (2022). Are CO_2-rich seafloor pockmarks a suitable environment for ostracod assemblages? The example of the Zannone Giant Pockmark (central-eastern Tyrrhenian). *Marine Ecology*, 00e1–32. https://doi.org/10.1111/maec.12698

APPENDIX 1

List of ostracod species

Argilloecia caudata Müller, 1894

Argilloecia minor Müller, 1894

Argilloecia robusta Bonaduce, Ciampo & Masoli, 1976

Aurila convexa (Baird, 1850)

Aurila aff. *interpretis* Uliczny, 1969

Aurila speyeri (Brady, 1858)

Basslerites berchoni (Brady, 1869)

Bosquetina tarentina (Baird, 1850)

Buntonia sublatissima (Neviani, 1906)

Bythocythere puncticulata Ruggieri, 1976

Callistocythere crispata (Brady, 1868)

Callistocythere flavidofusca (Ruggieri, 1950)

Callistocythere praecincta Ciampo, 1976

Carinocythereis carinata (Roemer, 1838)

Carinocythereis whitei (Baird, 1850)

Cistacythereis turbida (Müller, 1894)

Cluthia keiji Neale, 1975

Costa batei (Brady, 1866)

Costa edwardsii (Roemer, 1838)

Cytherella vulgatella Aiello, Barra, Bonaduce & Russo, 1996

Cytheretta subradiosa (Roemer, 1838)

Cytherois frequens Müller, 1894

Cytherois uffenordei Ruggieri, 1975

Cytherois sp. 1

Cytherois sp. 2

Cytherois sp. 3

Cytheropteron hadriaticum Bonaduce, Ciampo & Masoli, 1976

Cytheropteron latum Müller, 1894

Cytheropteron sulcatum Bonaduce, Ciampo & Masoli, 1976

Dopseucythere mediterranea (Bonaduce, Masoli, Pugliese & McKenzie, 1980)

Echinocythereis laticarina (Brady, 1868)

Eucythere curta Ruggieri, 1975

Eucytherura complexa (Brady, 1867)

Eucytherura gibbera Müller, 1894

Eucytherura mistrettai Sissingh, 1972

Hemicytherura defiorei Ruggieri, 1953

Hemicytherura videns (Müller, 1894)

Hemiparacytheridea infelix (Bonaduce, Ciampo & Masoli, 1976)

Henryhowella parthenopea Bonaduce, Barra & Aiello,1999

Heterocythereis albomaculata (Baird, 1838)

Heterocythereis voraginosa Athersuch, 1979

Kangarina abyssicola (Müller, 1894)

Loxocauda decipiens (Müller, 1894)

Loxoconcha affinis (Brady, 1866)

Loxoconcha ovulata (Costa, 1853)

Loxoconcha stellifera Müller, 1894

Microcythere depressa Müller, 1894

Microcythere hians Müller, 1894

Microcythere inflexa Müller, 1894

Microcytherura angulosa (Seguenza, 1880)

Microcytherura nigrescens Müller, 1894

Microxestoleberis aff. *kykladica* Barbeito-Gonzalez, 1971

Microxestoleberis xenomys (Barbieto-Gonzalez, 1971)

Microxestoleberis sp. 1

Microxestoleberis sp.

Monoceratina oblita Bonaduce, Ciampo & Masoli, 1976

Neonesidea formosa (Brady, 1868)

Neonesidea longevaginata (Müller, 1894)

Neonesidea mediterranea (Müller, 1894)

Occultocythereis dohrni Puri, 1963

Paracytheridea triquetra (Reuss, 1850)

Paracytherois flexuosa (Brady, 1867)

Paracytherois oblonga Müller, 1894

Paracytherois sp. 1

Paracytheromorpha nana (Bonaduce, Ciampo & Masoli, 1976)

Paracytheromorpha sp. 1

Paradoxostoma simile Müller, 1894

Paradoxostoma aff. *versicolor* Müller, 1894

Paradoxostoma sp.

Parahemingwayella tetrapteron (Bonaduce, Ciampo & Masoli, 1976)

Paranesidea reticulata (Müller, 1894)

Phlyctocythere pellucida (Müller, 1894)

Polycope reticulata Müller, 1894

Pontocypris acuminata (Müller, 1894)

Pontocypris intermedia Brady, 1868

Pontocythere turbida (Müller, 1894)

Propontocypris dispar (Müller, 1894)

Propontocypris pirifera (Müller, 1894)

Pseudocytherura strangulata Ruggieri, 1991

Pseudolimnocythere sp. 1

Pterygocythereis jonesii (Baird, 1850)

Pterygocythereis coronata (Roemer, 1838)

Rostrocythere hastata (Bonaduce, Masoli, Pugliese & McKenzie, 1980)

Sagmatocythere napoliana (Puri, 1963)

"*Sagmatocythere*" sp. 1

Sclerochilus gewemuelleri Dubowsky, 1939

Sclerochilus aequus Müller, 1894

Sclerochilus sp.

Semicytherura acuticostata (Sars, 1866)

Semicytherura aenariensis Bonaduce, Ciampo & Masoli,1976

Semicytherura alifera Ruggieri, 1959

Semicytherura dispar (Müller, 1894)

Semicytherura heinzei Puri 1963

Semicytherura inversa (Seguenza, 1880)

Semicytherura occulta Bonaduce, Ciampo & Masoli,1976

Semicytherura paradoxa (Müller, 1894)

Semicytherura quadridentata (Hartmann, 1953)

Semicytherura rara (Müller, 1894)

Semicytherura simplex (Brady & Norman, 1889)

Semicytherura sulcata (Müller, 1894)

Semicytherura sp.

Tenedocythere prava (Baird, 1850)

Triebelina raripila (Müller, 1894)
Urocythereis ilariae Aiello, Barra & Parisi, 2016
Urocythereis margaritifera (Müller, 1894)
Xestoleberis communis Müller, 1894
Xestoleberis dispar Müller, 1894
Xestoleberis aff. *intumescens* Klie 1942
Xestoleberis aff. *perula* Athersuch, 1978
Xestoleberis plana Müller, 1894
Xestoleberis sp.