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Impact of submarine karst sulfur springs on benthic foraminiferal assemblage in sediment of northern Adriatic Sea

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Abstract

Purpose This work highlights the sedimentary characteristics and the role of submarine sulfur-rich karstic springs in the distribution of benthic foraminifera in the northern part of the Adriatic Sea (Bay of Koper). Little is known about how local conditions such as temperature and sulfur bursts may influence sediment properties, benthic habitat variability, and composition of foraminiferal assemblages. Here we compare the distribution of total and living benthic assemblages in surface sediment samples collected from a funnel-shaped depression created by submarine sulfur springs.

Materials and methods Sampling was performed at water depths between 24.6 and 32.2 m in fine-grained sandy silt to silty sand (partially washed). Sedimentological, mineralogical, and geochemical analyses of the sediment were carried out and the distribution of benthic foraminifera living around the springs was studied.

Results and discussion In general, sediment characteristics (i.e., mineralogical, geochemical, and organic content) around the sulfur springs do not show prominent deviations from the marine surface sediment of the area; however, some differences exist among depressions of different depths. Deeper depressions in the lower parts probably extend to older continental sediments of Late Pleistocene age with alluvial features, while shallower depressions were formed entirely in Holocene marine sediments typical of a wider area. Only one of the five samples (M05) contained living foraminifera in sufficient abundance for biocenosis research. The benthic foraminiferal assemblages of moderate diversity are composed of opportunistic species. *Elphidium translucens*, *Ammonia* ex gr. *tepida*, *Haynesina depressula*, and *Porosononion granosum* dominate, while *A. neobeccarii*, *Reussella spinulosa*, and *Textularia bocki* are subordinate.

Conclusions The distribution and diversity of foraminifera in the sediment near sulfur springs can be explained by several factors and their interactions. The intensity of the spring discharge affects the mixing/oxygenation of the sediment, the shape of spring depressions, and the granulometry of the coarser sediment around the springs. Sediment characteristics indicate different types of sediment origin. This is related to and can be explained by the depth of spring depressions.

Keywords Marine sediments · Benthic foraminifera · Mineralogy and geochemistry · Organic matter · Submarine sulfur spring · Northern Adriatic

1 Introduction

1.1 Scientific background of study area

Submarine springs, characterized by fresh or brackish water, are common along the karstic Mediterranean coast (Bakalowicz 2018). Springs on the eastern Adriatic (Obhođaš et al. 2020) are also called brojnice or vrulje (Gams 2004; Fleury et al. 2007). Their formation was influenced by the Messinian event (Miocene), when the Strait of Gibraltar was closed due to the northward movement of the African plate and the inflow of fresh ocean

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water was less than evaporation. Sea level was 1500 to 2500 m lower than today, and weathering of carbonate rocks resulted in a deep karst landscape that was flooded at the end of the Messinian event when the strait reopened (Bakalowicz 2018). Carbonate coastal aquifers in the Mediterranean have been frequently exposed to sea-level fluctuations since the end of the Miocene (Fleury et al. 2007).

The high temperatures (up to 29.6 °C) and H_2S content (Žumer 2004, 2008; Faganeli et al. 2005) distinguish the submarine springs on the northern Adriatic shelf (Izola offshore) from many others in the Mediterranean. First described by Žumer (2004, 2008), these geomorphological depressions with the spring are now called Žumrove kotanje (means Žumer basin) after him. Žumer (2004, 2008) described eight depressions with the springs. Later, during a detailed investigation, four more were revealed (Slavec 2012). The fine-grained clastic sediments (sandy silt, clayey silt, silt, and silty sand) of the northern Adriatic Sea contain abundant remains of foraminifera, bivalves, and gastropod shells (Ogorelec et al. 1981, 1987, 1991, 1997; Covelli et al. 2006). The sediments overlie the fractured carbonate rocks (Pleničar et al. 1973) with karstic aquifers that have local or intermediate flow.

The interest and exploration of the sulfur springs in Izola offshore date back to the seventeenth century (Bishop Tommasini; Kramar 2003), due to the healing properties of sulfur and the warmer water. The warm sulfur spring in the abyss at St. Peter (northern coast of Izola) was used for thermal baths at that time. The first investigations were carried out in the nineteenth century (Kramar 2003). The water was reported to have a temperature of 21 °C and a high content of ammonia, sulfur, magnesium, nitrate, copper, and chloride (*ibidem*). The physical and chemical properties of Izola submarine sulfur springs were studied in the early twenty-first century by Žumer (2004, 2008) and Faganeli et al. (2005), while the springs have been the subject of detailed analyses in recent years (Žvab Rožič et al. 2021a, b; Šušmelj et al. 2021, 2022; Šušmelj 2022). Sulfurous thermal water was also described in the deep well LIV-1/01 (501 m) south of Izola (Benedik and Rožič 2002; Lapanje 2006) and higher mineralized water in a well in Lucia near Portorož (801 m) (Brenčič 2009).

1.2 Benthic foraminifera as ecological indicators

Ecological studies of modern environments reveal that there are over 4000 species of living benthic foraminifera. Ćosović et al. (2011) report a large number of species (581) along the eastern coast of the Adriatic Sea. They colonize a wide range of aquatic environments, from the transition zone to the deep sea, from stable to unstable environments considered extreme due to one or more parameters (e.g., salinity, temperature, light, nutrients, dissolved oxygen). They show great variability and can quickly recolonize the bottom after disturbance. The composition of benthic assemblages depicts their sensitivity to physiochemical changes in their habitats, including pH, salinity, and dissolved oxygen. Their short life cycles (a few months for most taxa) allow for complete assemblage's renewal. For this reason, and also in terms of sedimentation rates, surface sediment samples may contain many generations of dead specimens deprived of seasonal effects (Scott and Medioli 1980; Murray 2006). In addition, they are easy to study and occur in large numbers even in small amounts of sediment, so benthic foraminifera are used as indicators of changes in marine environments. There are few data on the distribution of benthic foraminifera in relation to the surrounding sediments and physicochemical properties of the water in the northern Adriatic shelf (Hohenegger et al. 1989; Coccioni et al. 2009; Popadić et al. 2013; Vidović et al. 2016; Melis et al. 2019; Bouchet et al. 2021; Žvab Rožič et al. 2022), but none yet on benthic foraminifera near submarine sulfur springs.

The aim of this study was to investigate sediment characteristics in the vicinity of submarine sulfur karst springs in depressions along the coast near Izola (northern Adriatic Sea). We were interested in the sedimentological, mineralogical, and geochemical properties of the sediment and, in particular, in the distribution of benthic foraminifera living around the springs. We hypothesized that the composition of benthic foraminifera assemblages would differ from spring to spring, depending on the activity of the spring and the resulting changes in physical–chemical composition of the water (sulfur content), and that they would differ from those of nearby unaffected seafloor sediments. This study will shed light on the potential response of benthic foraminifera to future increases in CO_2 concentration and associated decreases in pH and carbonate ion concentration.

2 Methods

2.1 Study area

The study area is located near the town of Izola, in the central part of the Slovenian coast, between the town of Koper in the north and Piran in the south. The area is part of the Gulf of Trieste in northern Adriatic Sea, the northernmost "gulf" of the Mediterranean Sea (Fig. 1).

Structurally, the Slovenian coast belongs to the undeformed Adria microplate placed in front of the Dinaric thrust belt. The area is characterized by only minor deformation, with the Izola anticline being the most prominent structural element (Placer 2008; Placer et al. 2010). In the core of the WNW-ESE trending anticline, Eocene limestones outcrop in the area of the town of Izola, while the limbs consist first of transitional marls followed by the Eocene flysch (Pleničar

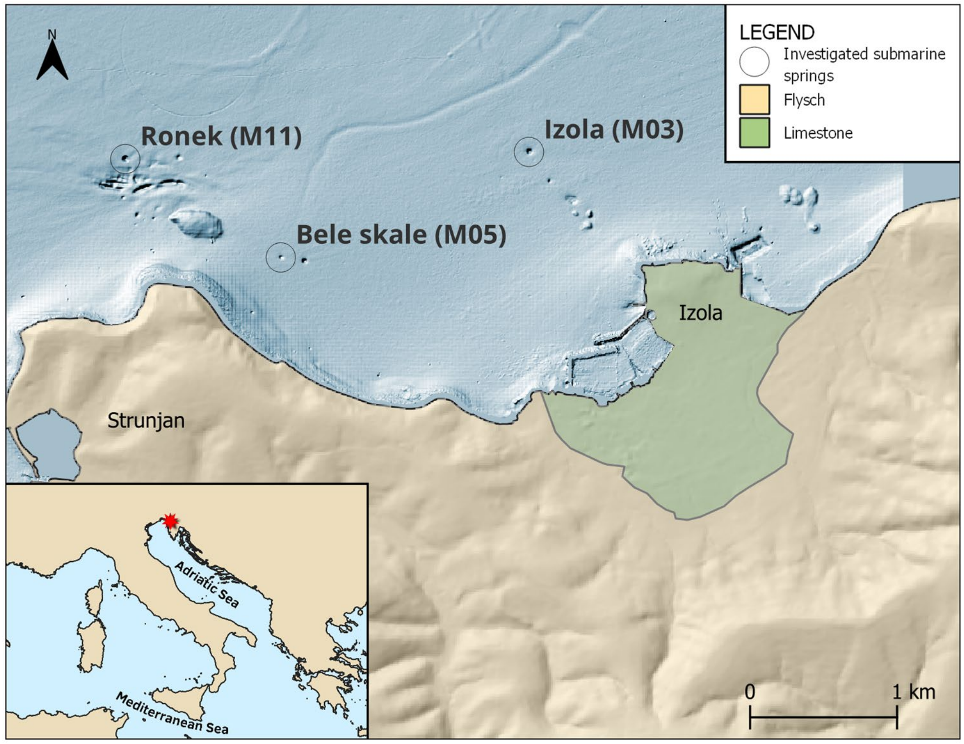

Fig. 1 Simplified geographical and geological map (modified after Pleničar et al. 1969, 1973; for details see Rožič and Žvab Rožič in press) of investigated area with location of sampling sites (black circles)

et al. 1973; Rožič and Žvab Rožič in press). The southern limb of the anticline outcrops in the Strunjan cliff and in areas south of Izola, while the northern limb is mostly covered by the Adriatic Sea but outcrops in the cliff between the towns of Izola and Koper. Within the sea, these rock sequences are covered by Quaternary deposits that become progressively thicker toward the inner parts of the Gulf of Trieste (Romeo 2009; Vrabec et al. 2014; Trobec et al. 2018). The sedimentary cover starts with fluvial deposits (mainly sand, gravel, and silty clay) occasionally interrupted by marine and brackish sediments. The upper unit is represented by Holocene marine fine-grained clastic sediments (sandy silt, clayey silt, silt, and silty sand) with common foraminifera, bivalve, and gastropod shells (Ogorelec et al. 1981, 1987, 1991, 1997; Covelli et al. 2006). Sulfur karst springs occur as cone-shaped depressions in the otherwise flat sea floor. Their position is governed by two factors: (A) by geologic structure, i.e., they occur at the stratigraphic contact between the limestone aquifer and the overlying clastic barrier on either side of the Izola limestone core, and (B) by the thickness of Quaternary deposits, i.e., in areas where the sediment cover is thin enough to be penetrated by spring water (for details see Rožič and Žvab Rožič in press).

The submarine sulfur springs are located in the funnel-shaped depression on the seabed near Izola (Fig. 2) and are divided into three groups according to their location (Fig. 1). Three springs (M01–M03) belong to the Izola group, located NNW of the town of Izola, the Bele skale group with two springs (M04–M05) is located west (toward Strunjan), not far from the beach of Bele skale, and the furthest west, off Cape Ronek, is the Ronek group with seven springs (M06–M12). Sediment samples were collected from three sampling sites, one from each group (M03, M05, and M11) (Fig. 1, Table 1). The springs differ in the intensity of spring water discharge and in the depth and shape of the depressions. Spring M03 is the most active (personal communication with a diver), it is located in one of the deepest depressions (30.8 m bsl), and the walls of the depression are steep (Fig. 2). The deepest depression (32.2 m bsl) was measured at the spring site M11. In contrast, spring M05 is less active, is located in a shallower depression (bottom at 24.6 m bsl), and the slopes are gentler (bowl-shaped).

2.2 Sample collection and treatment

Sediment samples were collected from the bottom of depressions near three sulfur springs: in October 2020 at springs M03 and M05 and in April 2021 at springs M03, M05, and M11 (Fig. 1, Table 1). Sediment samples were manually taken by scuba divers in plastic cores (10 cm diameter) to avoid metal contamination. The uppermost part of the sediment cores was used for further analyses.

A total of four cores from the first sampling period (October 2020) were collected for sedimentological (grain size), mineralogical, and geochemical analyses to test for possible differences in sediment properties around the sulfur springs. The sediment was immediately frozen and latter dried until a constant weight was reached. Samples were

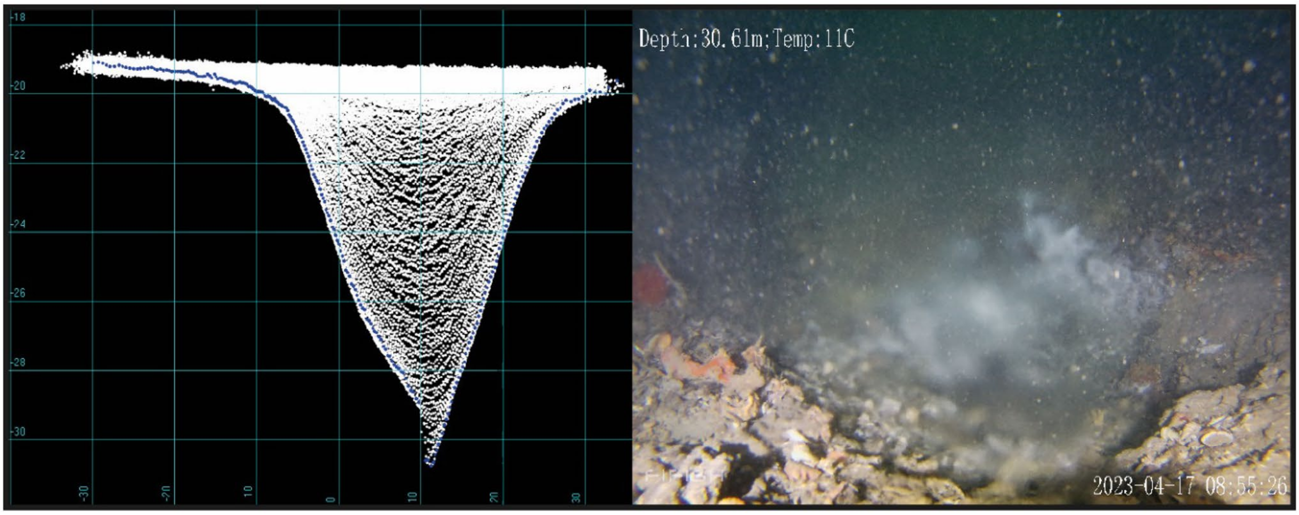

Fig. 2 Vertically exaggerated sonar-data cross section (modified from Slavec 2012) and photo (author M. Dolenec) of the M03 submarine sulfur spring (Izola group)

then washed through a 0.5-mm mesh sieve to remove larger biogenic fragments (shells) and other organic particles. For granulometric analyses, particles finer than 0.5 mm were quartered to obtain representative sample. For mineralogical and geochemical analyses, the sediment was homogenized and ground to a fine powder using an agate mortar.

In April 2021, six sediment cores (five for micropaleontological analyses) were taken in the vicinity of three sulfur springs (M03, M05, and M11). During this sampling period, sediment samples were additionally dedicated to meiofaunal analysis and of organic carbon, total carbon, and total nitrogen composition measurements. Freeze-dried sediments for organic carbon (C_{org}), total carbon (C_{tot}), and total nitrogen (N_{tot}) analyses were first sieved onto a 250-µm sieve and ground to powder in an agate mortar for instrumental analysis or further treatments. For the determination of C_{org}, samples were weighed into silver containers and then treated with 1 M HCl to remove the inorganic carbon. This procedure was followed until the effervescence ceased, indicating complete removal of the inorganic carbon. For the determination of C_{tot} and N_{tot}, the samples were weighed in tin containers and analyzed without pretreatment of the samples.

Sediment cores for meiofaunal analysis were sampled using a cut plastic syringe (inner diameter 2.7 cm), resulting in three replicates per sampling station. For analysis of the top 1 cm of sediment, samples were stained using 95% ethanol and 2 g L^{-1} Rose Bengal and kept for next 2 weeks to distinguish the living (stained) and dead (unstained) specimens. Samples were washed over a 63-µm mesh sieve and dried for at least 48 h. A replicate of each sampling station was found to contain sufficient foraminiferal tests for ecological analyses. However, preliminary examination also revealed the absence or low number of stained tests. For this reason, the replicates were pooled, and sufficient stained tests were found in the sediments from M05-1, while 29 foraminiferal stained tests were found in the pooled replicates from M11-2. On the other hand, the pooled replicates from stations M03-1, M03-2, and M11-1 contained one or no stained test. Therefore, standardized aliquots of approximately 200–300 foraminiferal tests from pooled replicates (unstained tests only in samples M03-1, M03-2, M11-1;

Table 1 Details of sampling locations

Sampling site	Sampling group	Coordinates (WGS84)	Sampling period	Sea bottom depth (m)	Depression depth (m)	Water temperature (°C, max)
M03 (M03-1, M03-2)	Izola	LAT 45.5485° N, LONG 13.6459° E	October 2020, April 2021	20	30.8	20.1
M05 (M05-1, M05-2)	Bele skale	LAT 45.5418° N, LONG 13.6245° E	October 2020, April 2021	16.5	24.6	23.6
M11 (M11-1, M11-2)	Ronek	LAT 45.5477° N, LONG 13.6108° E	April 2021	22.5	32.2	22.6

stained and unstained in M05-1 and M11-2) were identified and counted. For biocenosis characterization (M05-1), all stained specimens were taken from the pooled replicates (stained tests used for the total assemblage count were added to this count). The criteria of Loeblich and Tappan (1987) were used to identify taxa. Species identification was based primarily on subsequent work (Cimerman and Langer 1991; Sgarrella and Moncharmont-Zei 1993; Milker and Schmiedl 2012; Hayward et al. 2021; Schönfeld et al. 2021), and species designation followed the World Register of Marine Species (WoRMS) for taxonomic nomenclature.

Strict staining criteria, all chambers except the last, which was stained in light pink, were applied to distinguish living specimens from dead specimens that retained protoplasm for longer period due to specific bottom conditions (Bernhard 2000). For all samples (which contained between one and 29 stained specimens after pooling), the total assemblages (dead + living) were studied, except for sample M05-1, where the stained tests accounted for a significant proportion, so the total assemblage and biocenosis were studied.

2.3 Sample analysis

Granulometric analyses of particles finer than 0.5 mm were measured using the Fritch Analysette 22–28 laser granulometer with dynamic image analysis. Each sample was measured three times and as a result an average of the three measurements was calculated.

The general mineral composition of the sediment was measured by X-ray powder diffraction using a Philips PW3710 X-ray diffractometer with CuKa1 radiation and a secondary graphite monochromator. Data were collected at 40 kV with a current of 30 mA at a speed of 3.4_ 2″ per minute over a range of 2 to 70_ (2″). Diffraction patterns were identified using X'Perth Highscore Plus 4.6 diffraction software using the PAN-ICSD database and the complete pattern matching method (Rietveld) for quantitative mineral phase analysis.

Multi-elemental analyses of total element concentrations were performed using a portable, handheld ThermoFisher Niton XL3t-GOLDD 900S-He X-ray fluorescence (XRF) analyzer. Powdered sediment samples were pressed into pellets using stainless steel capsules, a hammer, and a pellet press tool. Two factory-set modes were used for the measurements: the "Mining" mode for major elements and the "Soil" mode for trace elements. During the measurements in the "Mining" mode, helium (He) was injected into the analyzer, which allowed better detection of light elements (Mg, Si, Al, S, and P). The measurement time for each sample was 210 s in the "Mining" mode and 180 s in the "Soil" mode. The accuracy and precision of the sediment analyses were evaluated using the pre-calibrated 24 reference standards (NIST, USGS) and the standards NIST-1d (limestone), NIST-88b (dolomitic limestone), and NIST-1633a (coal fly ash) standards at the beginning and end of the measurement. After the two replicate measurements of sediment samples and measured references, the analytical quality was satisfactory for almost all elements.

Analyses of total carbon (C_{tot}), nitrogen (N_{tot}), and organic carbon (C_{org}) were performed using an Elementar vario Micro cube CHNS/O analyzer. The precision of the measurements, expressed as standard deviation, was 3–5%. The reference material used to verify our measurements was the "High organic sediment standard OAS; Cert. No.: 175032," with certified values of $N_{tot} = 0.57 \pm 0.02$ wt% and $C_{tot} = 7.17 \pm 0.09$.

Diversity indices Fisher α, Shannon–Wiener [H(S)], dominance indices (Simpson and Berger-Parker), and equitability were calculated using the program Past SOFTWARE (Hammer et al. 2001). Diversity indices were calculated using total number of individuals (N) and number of species (S).

We applied the ecological groups defined for the calculation of the Foram-AMBI index (Jorissen et al. 2018; O'Malley et al. 2021; Žvab Rožič et al. 2022). To calculate this index, species are distinguished according to their sensitivity to organic enrichment: group 1 is considered sensitive, group 2 indifferent, and groups 3–5 are categorized as third-, second-, and first-order opportunists. The latter increased in abundance as organic enrichment increases, while the sensitive species will disappear. We assigned our species to the five ecological groups (Table 5) and calculated their relative abundance in each sample. Foram-AMBI index was calculated (Foram-AMBI = $[(0\times\%GRI)+(1.5\times\%GRII)+(3\times\%GRIII)+(4.5\times\%GRIV)+(6\times\%GRV)]/100$) according to Borja et al. (2000), applying the Žvab Rožič et al. (2022) way of the calculation.

Coastal waterbodies are classified according to their ecological quality status in five EcoQs categories, ranging from good to poor. The Exp (H'_{bc}) was used to determine the EcoQs (Bouchet et al. 2012). The species diversity index H' was calculated using the SpadeR program (2016 version; Chao and Shen 2003; Chao et al. 2016). Class boundaries between the categories are from Bouchet et al. (2012) and Hess et al. (2020).

The *Ammonia-Elphidium* foraminiferal index (IAE) was used as a hypoxia tracer (Sen Gupta and Platon 2006). Both genera are resistant to hypoxia conditions, but *Ammonia* shows greater resistance than *Elphidium*. The representatives of these two genera were abundant in the samples studied, and this index is well correlated with the organic carbon in the surface sediments. The index is given by $IAE = [NA/(NA + NE)] \times 100$, where NA and NE are the number of individuals of *Ammonia* and *Elphidium*, respectively.

To determine if a correlation exists between species diversity, total carbon content, IAE, Foram-AMBI, and

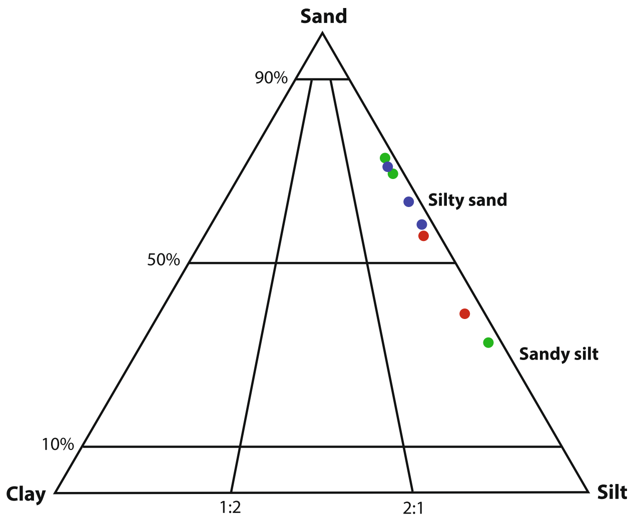

Fig. 3 Triangular diagram of clay-silt-sand to determine the textural group of sediments. The dots show the individual sediment samples; red dots of M03, green dots of M05, and blue dots of M011 sampling group

EcoQs index, a Pearson analysis was conducted using the program Past SOFTWARE (Hammer et al. 2001). A strong correlation exists when the coefficient varies between ± 0.5 and ± 1, and when the value is zero, there is no correlation between the variables.

3 Results

3.1 Granulometric, mineralogical, and geochemical analyses

The sediment samples belong to the textural group of silty sand and sandy silt (Fig. 3). In all samples, the proportion of clay particles (< 2 µm) is low, less than 4.4%, and all samples also contain gravel-sized particles of biogenic shells (2 mm), mostly less than 8.3%. The multimodal particle size distribution is characterized for all sediment samples. At least three modal peaks were defined, mainly for sandy silt size and additionally for clay and gravel particles. The last ones are represented by shell fragments and organic material.

Mineralogical analysis of the sediments shows the following mineral composition (Fig. 4): calcite (24.2–33.2%, median 28.0%), quartz (12.7–35.0%, median 17.5%), dolomite (3.5–32.6%, median 24.9%), illite (13.0–23.7%, median 17.2%), albite (1.7–7.3%, median 4.9%), clinochlore (2.5–5.5%, median 3.5%), aragonite (0.4–7.2%, median 2.6%), microcline (0.6–2.8%, median 1.4%), pyrite (0.5–1.4%, median 0.7%), and kaolinite (0.0–1.5%, median 0.5%). Certain differences in mineral composition between sampling sites were noted in both sampling periods. Significantly higher dolomite concentrations (more than eight times) were measured at submarine sulfur springs M03 and M11 compared to sediment from spring M05, while calcite and especially quartz concentrations were lower (20% for calcite and 55% for quartz).

The geochemical analysis of the sediments is shown in Table 2. Some differences were noted between sediments at different sampling sites (springs M03 and M11 versus M05) and slightly between samples taken at the same spring site (M03-1 versus M03-2, M05-1 versus M05-2, M11-1 versus M11-2). Similar patterns were observed in both sampling periods.

Silicon (Si) has the highest concentrations of the major elements in all samples, with higher concentrations at sampling sites M05 and M11 and up to 33% lower concentrations at site M03. Conversely, concentrations of calcium (Ca; for 41%) and especially magnesium (Mg; for 90%) are higher at M03 than at M05 and M11. Other major and minor elements do not show characteristic differences between sampling sites. Trace element concentrations do not reveal consistent significant trends among sampling sites. Slightly higher concentrations of As, Cu, Rb, and Zn could be observed at M03-1.

The content of total nitrogen (N_{tot}) and organic carbon (C_{org}) in the sediments is within the range of the typical composition of organic matter in the sediments for the Gulf of Trieste. In some samples, the relatively low atomic ratio of C_{org}/N_{tot}, which is close to the Redfield value, clearly indicates a marine source of organic matter in the uppermost centimeter of the sediment. This is true for M03 and M05, although M11 also has a C_{org}/N_{tot} ratio < 10, which was described by Faganeli et al. (1991) as typical for the area (Table 3).

3.2 Foraminifera analysis

All results are shown in Table 4. A total of 61 benthic foraminiferal and four planktonic species were identified in all samples examined from five stations, of which 10 species were rare (less than 1% in each of the total assemblages). Five agglutinated taxa accounted for 5.38 to 10.2% of the total foraminiferal assemblages. Nearly all identified species are epifaunal or epifaunal/shallow infaunal (Murray 2006), except for rare occurrences of infaunal Buliminidae (0.4 to 1.94%). No morphological abnormalities were noted in the specimens.

The studied total assemblages showed a uniform composition with no major differences in species richness, diversity, and community structure. Species richness (S) ranged from 25 (sample M03-2) to 40 (sample M05-1). Of all identified species, most individuals belonged to the genera *Ammonia* (14.77–34.88%) and *Elphidium* (10.6–35.6%) and showed considerable morphological variability (Fig. 5). This is an expected result for foraminiferal distribution in the non-polluted northern Adriatic shelf (Žvab Rožič et al.

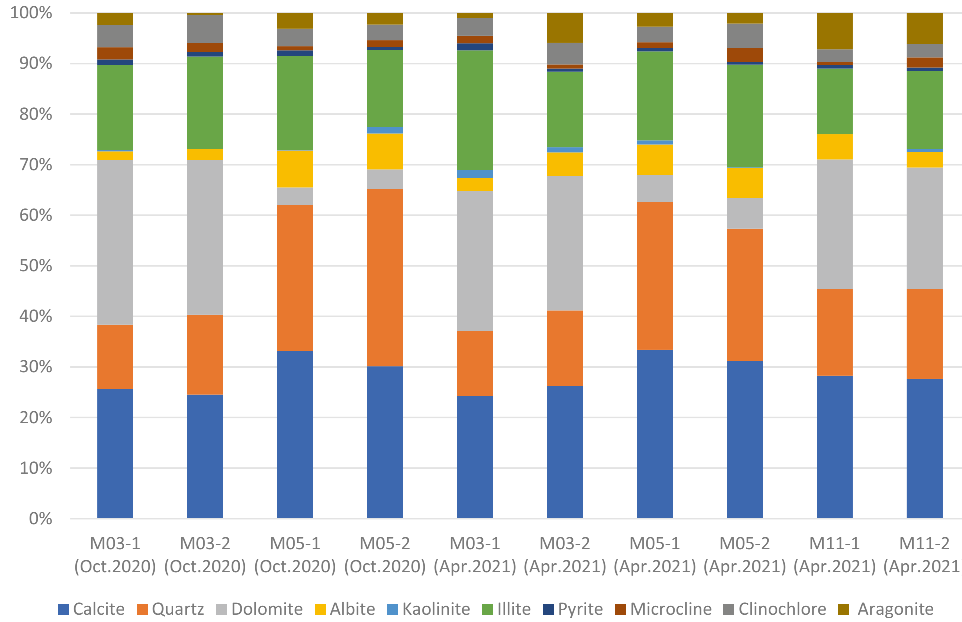

Fig. 4 Mineralogical composition (in %) of sediment samples from M03, M05, and M11 sampling site from both sampling periods (October 2020 and April 2021)

Table 2 Major and minor oxide concentrations (%) and trace elements (mg kg^{-1}) of sediments around sulfur springs M03, M05, and M11

Sampling period	Sample	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	K_2O	TiO_2	P_2O_5	MnO	S	As	Cu	Pb	Rb	Sr	Zn	Zr
	Unit	[%]	[%]	[%]	[%]	[%]	[%]	[%]	[%]	[%]	[%]	[mg kg^{-1}]	[mg kg^{-1}]	[mg kg^{-1}]	[mg kg^{-1}]	[mg kg^{-1}]	[mg kg^{-1}]	[mg kg^{-1}]
October 2020	M03-1	34.95	9.84	3.96	4.28	15.25	2.30	0.50	0.15	0.04	2.04	31	27	13	110	189	41	82
	M03-2	35.24	8.46	3.43	3.94	20.72	1.97	0.48	0.13	0.05	0.92	19	24	17	80	387	26	84
	M05-1	46.50	8.89	3.49	2.28	17.87	1.76	0.55	0.12	0.06	0.87	19	25	22	71	379	30	132
	M05-2	46.16	9.99	3.86	2.58	16.35	2.10	0.62	0.14	0.07	0.66	21	29	23	89	336	46	112
April 2021	M03-1	34.74	9.73	4.03	4.13	15.00	2.34	0.54	0.10	0.04	2.09	29	30	15	112	191	38	83
	M03-2	35.22	8.39	3.40	3.88	21.02	1.98	0.51	0.12	0.05	0.97	19	25	19	83	392	24	105
	M05-1	45.24	8.81	3.53	2.39	17.87	1.82	0.61	0.13	0.07	0.94	20	27	22	71	373	35	129
	M05-2	44.72	9.76	3.81	2.75	16.61	2.11	0.62	0.14	0.07	0.68	21	70	24	87	336	72	118
	M11-1	36.16	7.71	2.72	3.39	23.38	1.64	0.48	0.09	0.05	0.87	14	12	18	65	507	20	93
	M11-2	37.11	8.34	2.94	3.26	22.12	1.80	0.50	0.09	0.05	0.79	14	20	20	73	490	28	90

2022; and references therein). Other common taxa with an average proportion > 5% were *Textularia bocki*, *Porosononion granosum*, and *Reussella spinulosa*. The most abundant miliolid tests belong to the genera *Quinqueloculina* (up to 9.18%) and *Adelosina* (up to 6.14%).

Table 3 Total nitrogen (N_{tot}), total carbon (C_{tot}), organic carbon (C_{org}), and C_{org}/N_{tot} atomic ratio of the surficial sediment samples

Sample	Total nitrogen (wt%)	Organic carbon (wt%)	Total carbon (wt%)	C_{org}/N_{tot} (atomic ratio)
M03-1	0.172	1.142	6.789	7.732
M03-2	0.248	3.167	9.009	14.894
M05-1	0.184	1.018	5.888	6.449
M05-2	0.166	1.694	5.507	11.208
M11-1	0.143	1.013	6.469	8.283
M11-2	0.121	0.941	6.092	9.076

The Shannon–Wiener index ranged from 2.42 to 3.14 (Table 4; these values refer to total and living assemblages of M05-1), Fisher α values ranged from 6.91 to 13.14, and IAE ranged from 31.58 to 73.179%. Foram-AMBI index values ranged from 1.08 (unpolluted, M11-2) to 1.94 (slightly polluted, M05-1). Two sites have EcoQs values below 15 (the threshold between good and excellent EcoQs; Bouchet et al. 2018), namely, the living assemblages at site M05-1 and the total assemblage at site M03-2, while other sites have values above this threshold.

No stained specimens were observed in sample M11-1, and only a single foraminiferal test (of the genus *Porosononion*) was found stained in samples M03-1 and M03-2 (percentage of less than 1% of living foraminifera in the assemblages). Although a higher proportion of living (stained) foraminiferal tests was observed in the assemblage from M011-2, the number of stained tests even in the pooled samples was insufficient for statistical analyses. The living assemblage contained a total of 29 specimens, consisting of

Table 4 The complete list of identified foraminifera species (their relative abundances) from five samples (total assemblages) and from the biocenosis (in bold), with diversity indices and IAE (*Ammonia*/*Elphidium*), Foram-AMBI, and EcoQs indices. The categorization of species into ecological categories according to their sensitivity to organic pollution is based on Jorissen et al. (2018) and Žvab Rožič et al. (2022). The criteria given by O'Malley et al. (2021) were used to interpret the ecological quality of the studied samples, expressed as 0 ˂ Foram-AMBI ˂ 1.2 unpolluted, 1.2 ˂ Foram-AMBI ˂ 3.3 slightly polluted, 3.3 ˂ Foram-AMBI ˂ 4.3 polluted, and ˃4.3 heavily polluted

Species \ Sampling locations	Ecol. category	Izola (M03-1)	Izola (M03-2)	Bele skale (M05-1)	Bele skale (M05-1) LIVING	Ronek (M11-1)	Ronek (M11-2)
Nuria polymorphides (Heron-Allen & Earland)		-	-	1.16	1.06	-	-
Ammoglobigerina globigerinoformis (Parker & Jones)		-	-	1.55	0.53	-	-
Textularia agglutinans (d'Orbigny)	3	0.51	0.40	-	-	-	0.34
Textularia bocki (Höglund)	3	9.69	9.60	3.49	0.53	5.88	5.03
Textularia sp.		-	-	1.16	-	-	-
Adelosina mediterranensis (Le Calvez, J. & Y.)	1	-	-	1.16	-	-	-
Adelosina cliarensis (Heron-Allen & Earland)	1	-	-	0.78	-	-	-
Adelosina sp.	1	2.04	6.40	-	-	0.98	4.03
Quinqueloculina seminula (Linné)	3	-	-	2.71	1.06	-	-
Quiqueloculina sp.		9.18	-	1.16	-	4.41	3.69
Cycloforina sp.		-	-	0.39	-	-	-
Miliolinella subrotunda (Montagu)	1	-	-	1.16	-	-	-
Sigmoilinita costata (Schlumberger)	1	-	-	0.39	-	-	-
Spiroloculina excavata (d'Orbigny)	1	-	-	0.39	-	-	-
Spiroloculina sp.		-	0.40	-	-	0.49	1.34
Triloculina sp.		3.57	4.40	0.78	-	-	-
Reussoolina laevis (Montagu)		-	-	1.16	-	-	-
Bolivna spathulata (Williamson)	3	-	-	0.78	3.72	-	-
Bolivina difformis (Williamson)	2	-	-	0.78	2.66	-	-
Bolivina sp.		0.51	0.40	-	-	0.49	0.34
Bulimina marginata (d'Orbigny)	3	-	-	-	-	0.98	-
Bulimina elongata (d'Orbigny)	3	-	1.20	1.94	3.19	0.49	0.67
Lagena striata (d'Orbigny)		-	-	0.39	-	-	-
Lagena sp.		0.51	0.80	-	-	0.98	0.67
Fissurina sp.		0.51	-	-	-	-	2.68
Hyalinonetrion gracillimum (Seguenza)		-	0.40	0.78	-	-	-
Fursenkonia acuta (d'Orbigny)		-	-	-	-	-	0.34
Asterigerinata sp.		-	7.20	-	-	-	4.36
Asterigerinata mamilla (Williamson)	1	2.55	-	0.78	-	5.39	-
Neocronobina terquemi (Rzehak)	1	-	-	0.39	-	-	-
Reussella spinulosa (Reuss)	1	3.57	4.80	1.16	0.53	6.86	6.38
Valvulineria bradyana (Fornasini)	4	-	-	0.78	-	-	-

Table 4 (continued)

Species \ Sampling locations	Ecol. category	Izola (M03-1)	Izola (M03-2)	Bele skale (M05-1)	Bele skale (M05-1) LIVING	Ronek (M11-1)	Ronek (M11-2)
Rosalina bradyi (Cushman)	1	1.53	-	3.10	8.51	-	-
Rosalina macropora (Hofker)	1	1.53	-	0.39	2.13	-	1.34
Rosalina sp.		-	0.40	-	-	7.35	3.02
Bucccella sp.		-	-	0.78	-	-	-
Lobatula lobatula (Walker & Jakob)	1	0.51	0.40	0.78	0.53	0.98	1.68
Cibicides advenum (d'Orbigny)		-	-	1.55	3.19	-	-
Cibicides sp.		-	-	-	-	-	0.67
Planorbulina mediterranensis (d'Orbigny)	1	-	-	0.78	0.53	-	-
Aubignyana perlucida (Heron-Allen & Earland)	3	-	-	5.43	2.66	0.49	-
Ammonia aberdoveyensis (Haynes)		-	1.20	-	-	-	0.34
Ammonia beccarii (Linné)	2	5.10	1.60	4.65	2.66	0.49	0.34
Ammonia falsobeccarii (Rouvillois)	3	-	0.40	-	-	-	0.67
Ammonia neobeccarii (Shchedrina & Mayer)		10.20	6.00	-	-	7.35	8.72
Ammonia parkinsoniana (d'Orbigny)	1	-	-	8.14	5.32	-	-
Ammonia ex gr. *tepida* (Cushman)	4	3.06	8.80	22.09	26.60	5.88	4.03
Ammonia sp.		-	-	-	-	0.98	1.68
Elphidium crispum (Linné)	1	7.14	2.40	3.10	-	1.47	3.02
Elphidium advenum (Cushman)	2	1.53	-	-	-	1.47	3.69
Elphidium fichtellianum (d'Orbigny)		-		1.55	0.53	-	-
Elphidium translucens (Natland)	2	17.86	32.80	8.14	10.11	26.47	19.13
Elphidium macellum (Fichtel & Moll)	1	0.51	0.40	-	-	0.98	2.35
Elphidium sp.		-	-	-	-	1.47	0.34
Haynesina sp.		2.04	5.60	-	-	2.45	5.7
Haynesina depressula (Walker & Jakob)	2	-	-	7.36	21.81	0.49	-
Porosononion granosum (d'Orbigny)	3	10.2	2.00	-	-	5.39	9.06
Porosononin subgranosum (Egger)	3	-	-	2.33	-	0.98	-
Porosononion sp.		-	-	-	-	4.41	-
Nonion depressulum (Walker & Jacob)	2	2.04	1.60	2.71	1.06	1.47	4.03
Cribroelphidium poeyanum (d'Orbigny)	3	-	-	1.94	1.06	1.96	-
Globigerina calida Parker		2.04	-	-	-	-	-
Globigerina conglobatus (Brady)		2.04	-	-	-	-	-
Globigerina sp		-	-	-	-	0.49	0.34
Globigerinoides sp.		-	0.16	-	-	-	-

Table 4 (continued)

Species \ Sampling locations	Ecol. category	Izola (M03-1)	Izola (M03-2)	Bele skale (M05-1)	Bele skale (M05-1) LIVING	Ronek (M11-1)	Ronek (M11-2)
Species richness		25	25	40	22	30	31
Number of taxa		196	250	258	188	203	293
Simpson Index (1-D)		0.91	0.85	0.92	0.86	0.89	0.92
Shannon		2.75	2.43	3.14	2.41	2.75	2.92
Berger-Parker		0.178	0.33	0.22	0.27	0.27	0.19
Fisher		7.6	6.91	13.25	6.46	9.72	8.79
Evenness (H/S)		0.62	0.45	0.85	0.78	0.52	0.6
Ammonia/*Elphidium* index		40.45%	33.58%	73.17%	76.47%	31.58%	35.61%
EcoQs (Bouchet et al. 2018)		16.61	12.29	24.02	11.53	17.72	19.91
		excellent	**good**	*excellent*	**good**	*excellent*	*excellent*
ForamAMBI (Alve et al. 2016)		1.25	1.31	1.94	2.14	1.21	1.08
		Unpolluted	**Good to slightly polluted**	**Good to slightly polluted**	**Good to slightly polluted**	*Unpolluted*	*Unpolluted*

7 *Elphidium translucens*, 5 *Ammonia neobeccarii*, 5 *Reussella spinulosa*, 4 *A.* ex gr. *tepida*, 3 *Haynesina depressula*, 2 *E. macellum*, 2 *Rosalina* sp., and 1 *Fissurina* sp. Analysis of the biocenosis of sample M05-1 revealed lower diversity (S = 22 species, Fisher $\alpha = 6.46$, H(S) = 2.41), the highest IAE values of 76.473%, Foram-AMBI index values for good to slightly polluted ecological status (2.14), and EcoQs values for good quality.

4 Discussion

4.1 Sediment characteristics

The results of the present study complement the study by Faganeli et al. (2005). The objective of the 2005 study was to obtain a complete geochemical composition of the sulfur spring water at a site designated M03 in our study. Less attention was paid to recent sediment near the spring, and also to the amount and composition of organic matter in the sediment, which was the goal of our study.

In general, the sedimentological, mineralogical, and geochemical composition of sediment around sulfur springs is consistent with all previous studies (Ogorelec et al. 1981, 1987, 1991, 1997; Covelli et al. 2006; Rogan Šmuc et al. 2018; Žvab Rožič et al. 2022) and reflects the geological characteristics of the wider Gulf of Trieste area.

The sediment of the studied depressions where the sulfur spring occurs is granulometrically classified as silty sand and sandy silt, with the largest grains (sand, gravel) represented by shell fragments and particles of organic matter. Sediments from previous studies in Bay of Koper are somewhat finer and were classified in the silty clay textural group, rich in bioclastic fragments (foraminifera and bivalves) (Ogorelec et al. 1987, 1991; Rogan Šmuc et al. 2018). The coarser sediment in the vicinity of sulfur springs can be explained as "washed" due to the outflow of spring water from the sediment.

The sediment from sampling site M05 has comparable mineralogical characteristics to many surface samples from Bay of Koper (Ogorelec et al. 1987; Žvab Rožič et al. 2022), defined as marine sediment of Holocene age (Ogorelec et al. 1987). In contrast, the mineralogy of sampling sites M03 and M11 shows significant differences; the dolomite content is much higher (more than eight times), while the concentrations of quartz (for 55%) and calcite (for 20%) are lower (Fig. 3). Accordingly, the concentrations of some major elements also show a similar pattern, with higher Si concentrations at M05 and lower at M03 and M11, while Ca and especially Mg concentrations are higher at M03 and M11 (Table 3). We interpret this with the depth of the spring depressions. Namely, springs M03 and M11 are located in depressions of 30.8 m and 32.2 m below sea level (bsl)

(Žumer 2004, 2008), while the seabed and the upper edge of the depressions are about 20 m bsl. In the Gulf of Trieste, Quaternary sediments consist of Late Pleistocene alluvial deposits overlain by Holocene marine sediments (Novak et al. 2020). The depth of the base of the Holocene marine sediments in the study area is determined to a depth of 27 m bsl, and the thickness of the Holocene sediments is 5–10 m (Novak et al. 2018). All these facts indicate that the lower part of the depressions M03 and M11 are composed of Late Pleistocene sediments with alluvial characteristics and presumably different mineralogical and geochemical composition. Unfortunately, the mineralogical and geochemical composition of the alluvial sediments in this area has not yet been studied to confirm our interpretation. The only alluvial sediments were studied in this way in a borehole V3, located in the mouth of the Rižana River (Ogorelec et al. 1987), which has exclusively flysch hinterland and cannot be directly compared with our study area, which is more inside the bay. The M05 depression with the sulfur spring is shallower (24.6 m bsl) and was probably formed entirely from marine Holocene sediments, which is why the characteristics of the sediment are comparable to those of the surface sediments of the Bay of Koper (Ogorelec et al. 1981, 1987, 1991, 1997; Rogan Šmuc et al. 2018; Žvab Rožič et al. 2022).

Organic matter is one of the main elements of the early diagenetic processes at the sediment–water interface and in the upper 10 cm of these sediments (Čermelj et al. 2001). Concentrations of C_{org} and N_{tot} decrease from M03 to M05 and then to M11, with concentrations at M03 higher than the average from the region (Čermelj et al. 2019). This is in accordance with the conclusions of Faganeli et al. (2005), who attributed the elevated dissolved inorganic carbon (DIC) content in the spring water to the decomposition of organic matter in the sediment. There were several lines of evidence confirming this fact, including elevated NH_4^+ and PO_4^{3-} concentrations and a low $\delta^{13}C_{DIC}$ value compared to the same values in seawater and groundwater. This only indicates that the OM in the sediments around the springs, even if irregularly distributed, belong to the more reactive and easily degradable fraction of marine origin.

4.2 Benthic foraminifera assemblages

The study revealed moderately diverse and species-rich benthic foraminiferal assemblages. With a total of 61 benthic taxa (33 genera, 44 species, and 16 sp.), the species richness fits well with the distribution of a typical shallow-water benthic foraminiferal fauna in the eastern Adriatic (Vidović et al. 2009; Popadić et al. 2013; Žvab Rožič et al. 2022) and exceeds previous species counts for stressful environments (Felja et al. 2015; Brunović et al. 2019). All samples were dominated by representatives of the genera *Ammonia* and *Elphidium* (Fig. 5), some species of which are known to tolerate a wide range of salinity, temperature, oxygen concentration, and low pH (representatives of the genus *Elphidium* are slightly better adapted to lower pH, Uthicke et al. 2013), and occur in sediments stressed by heavy metals, chemical, and thermal pollution (Martinis et al. 2016). *Ammonia* and *Elphidium* populations show variability in species abundance and dominance from sample to sample (Fig. 5). Numerous studies have confirmed that trace metals (Cr, Cu, Pb, As, Ni, Zn) have a significant impact on the distribution and composition of foraminiferal assemblages in coastal waters (Armynot du Châtelet et al. 2004; Frontalini and Coccioni 2008; Frontalini et al. 2009; El Kateb et al. 2020). Although concentrations of trace metals in the samples studied do not exceed the effect range low (EFL) and therefore have limited effects on the physiology of organisms, there are some trends in abundances and diversity of foraminifera that follow changes in concentrations of these elements. The largest abundances of *A.* ex gr. *tepida* (Fig. 5b, f, g) and the only occurrence of *A. parkinsoniana* were in samples with the highest concentrations of the trace metals Cu and Pb (samples Bele skale, M05-1, Table 2; in living and stained assemblages, Table 4). *A.* ex gr. *tepida* is known from the Adriatic Sea, where it inhabits water depths from the intertidal zone to the inner shelf (Hayward et al. 2021). In contrast, *A. parkinsoniana* is common along the Italian coast in water depths between 10 and 20 m, regardless of the granulometric properties of the substrate or the concentration of organic matter (Jorissen 1988). The highest Zn and As concentrations (M03-1) coincide with a greater abundance of elphiidids over ammonias, especially the species *E. translucens* (Table 4).

The IAE was calculated to estimate the hypoxia level in the whole study area. The index reached 73.17% in the total assemblages and 76.47% in the biocenosis in the Bele skale spring depression (M05-1) (Fig. 1), which should mean that this area is the most depleted in oxygen (Sen Gupta and Plante 2006), but surprisingly, the total carbon and organic carbon content in this station are one of the lowest of the stations studied. This could be related to the spring outbreaks that occurred relatively close to the sampling campaign and resulted in turbid water with a high suspended sediment load. Resuspension of sediments leads to increased release of nutrients into the overlying water column, limits light availability, and negatively affects oxygen concentrations (Spieckermann et al. 2022). Concentrations of trace metals that are indicators of lower oxygen content (Algeo and Maynard 2004), such as Cu and Pb, are higher in these sediments. The higher diversity of both living and total foraminiferal assemblages at the only station where they are present in a significant abundance confirms the opportunistic behavior of the dominant species under conditions where sulfur spring

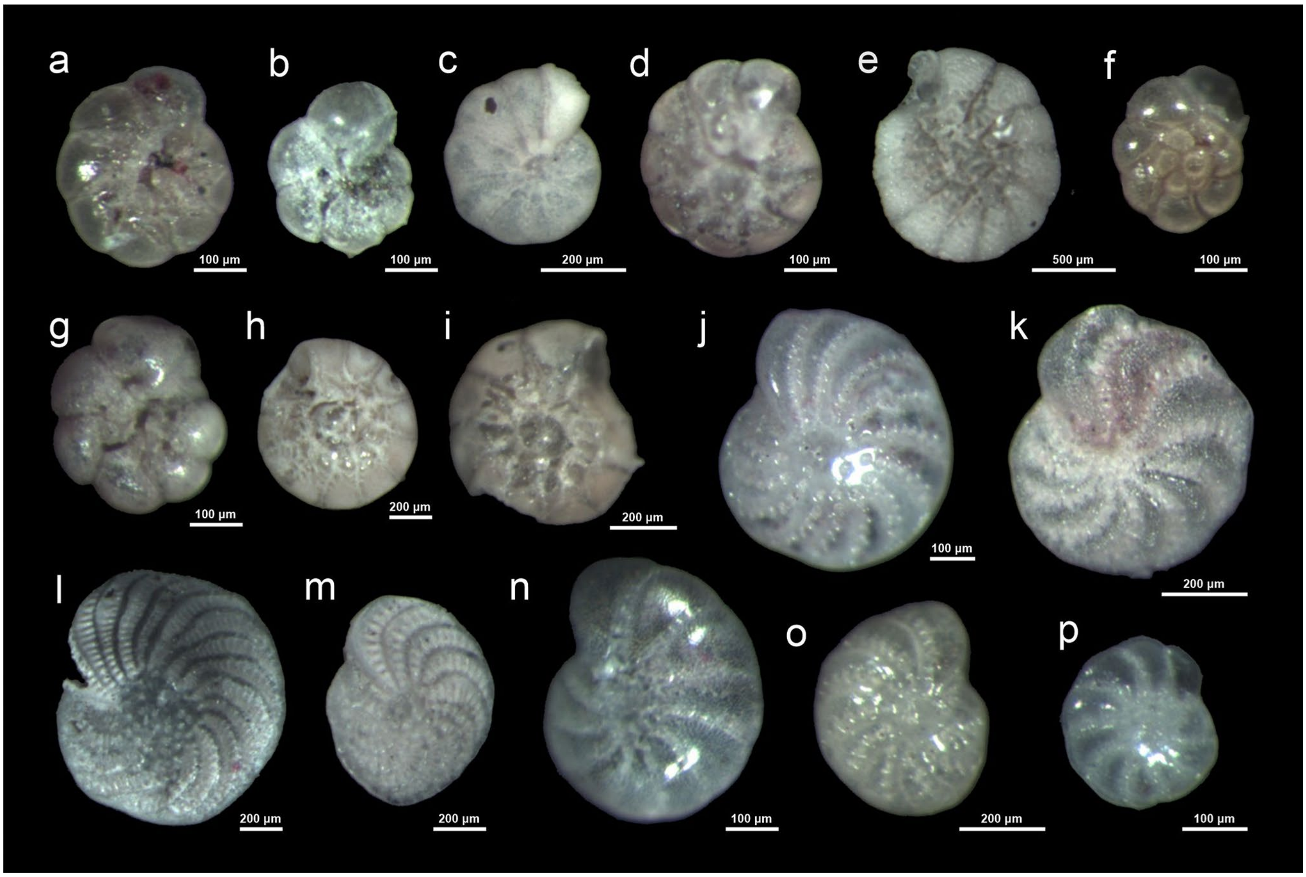

Fig. 5 Microphotographs (by Olympus U TV1XC camera) of representatives of benthic foraminifera: **a** *Ammonia aberdoveyensis* (Haynes), M03-2; **b** *Ammonia* ex gr. *tepida* (Cushman), M05-1; **c** *Ammonia* sp. (Cushman), M03-1; **d** *Ammonia beccarii* (Linné), M03-1; **e** *Ammonia neobeccarii* (Shchedrina & Mayer), M03-2; **f** *Ammonia* ex gr. *tepida* (Cushman), M05-1; **g** *Ammonia* ex gr. *tepida* (Cushman), M03-2; **h** *Ammonia beccarii* (Linné), M03-1; **i** *Ammonia beccarii* (Linné), M03-2; **j** *Elphidium crispum* (Linné), M03-2; **k** *Elphidium* sp., M03-2; **l** *Elphidium crispum* (Linné), M05-1; **m** *Elphidium fichtelianum* (d'Orbigny), M05-1; **n** *Cribroelphidium poyeanum* (d'Orbigny), M05-1: **o** *Elphidium advenum* (Cushman), M03-1; **p** *Cribroelphidium poyeanum* (d'Orbigny), M05-1

discharge disturbs the seafloor from time-to-time. Of 61 benthic species identified, 35 species were assigned according to their sensitivity to organic content and used to calculate Foram-AMBI indices. Unassigned species comprised 18% of the living assemblage (M05-1) and a total of 5.31% of all specimens, while the percentage of unassigned species in the total assemblage M05-1 reached 25% and 12.41% of all specimens. The percentage of unassigned species was well above the threshold for quality assurance in M03-1 and M03-2 (with 36 and 40% and 26.52 and 26.40% of all specimens, respectively) and 33% of unassigned species in M11-1 (30.38% of all specimens) and 41.9% (28.19% of specimens) in M11-2. Only living assemblage was within the threshold of 20% unassigned species, while the values of the total assemblages were slightly higher, so the Foram-AMBI values should be evaluated with caution (Alve et al. 2016; and references therein). The high proportion of unassigned species is due to (i) 16 taxa identified only at the genus level and (ii) the abundance of unclassified *A. neobeccarii*. Although the Foram-AMBI index is not very reliable for most of the studied assemblages, it can be used in correlation with the EcoQs values. Both classify the studied station in the categories of high (unpolluted) and good (slightly polluted) environment (Table 4). The lower values of the indices are consistent with higher C_{org} concentrations due to oxygen depletion and fine-grained sediments. It seems that the geomorphological characteristics of the spring areas play an important role in controlling oxygen contents. The lower oxygen content occurs in the Bele skale spring (accumulation of fine-grained particles from suspended clouds). The higher concentration of C_{org} in sample M03-2 (Table 3) corresponds to lower EcoQs values and thus declares the station as ecologically good, as do the values above the thresholds of sample M03-1. The different ecological class assignments of for site M05-1 could be the result of the calculation of the indices themselves, since all specimens (common and rare) are counted in the calculation

Table 5 Pearson correlation matrix of environmental variables, species diversity expressed as Shannon–Wiener index, total carbon (wt%), *Ammonia/Elphidium* (IAE), EcoQs, and Foram-AMBI indices

	C_{tot}	Foram-AMBI	EcoQs	IAE	H(S)
C_{tot}		− 0.52700	− 0.38952	− 0.50416	− 0.53869
Foram-AMBI	− 0.52700		− 0.093461	0.996080	0.092528
EcoQs	− 0.38952	− 0.093461		− 0.082424	0.970380
IAE	− 0.50416	0.996080	− 0.082424		0.090483
H(S)	− 0.53869	0.092528	0.970380	0.090483	

of EcoQs. The Foram-AMBI indices, on the other hand, consider only those species that have a certain sensitivity to organic matter content. In the interpretation of ecological status, large portions of specimens identified at the generic level (with the exception of *Adelosina* sp.) and all unclassified species are not considered, but they all contribute to a 100% count.

The IAE and Foram-AMBI indices are strongly positively correlated (Table 5, Fig. 6), whereas there is a moderate negative correlation between total carbon content and EcoQs, Shannon–Wiener, and Foram-AMBI indices. This suggests that oxygen depletion in areas of low total and organic carbon is the result of a recent natural stress. The discharge of the spring creates a cloud of suspended sediment that stirs up the seafloor and eventually settles. At other stations where low-oxygen conditions existed based on IAE values, we assumed that the spring discharge occurred sometime before sampling so that the seafloor had time to stabilize and reach such conditions.

The values of ecological indices differ from those known from a previous study in the coastal area of Koper Bay by Žvab Rožič et al. (2022), where sulfur springs were not recorded. Slightly polluted conditions were detected only offshore at the site considered as the reference sampling site (REF), where anthropogenic impacts are lower (Žvab Rožič et al. 2022).

The living foraminifera were found in the Bele skale spring (M05-1) in abundances that allow only ecological interpretations. Lower values occurred for biocenosis diversity, which may be attributed to the fact that the stained specimens belong to one season, while in the total assemblages the accumulation of tests occurred over the seasons. There are at least two possibilities to explain the abundance of stained foraminiferal tests in sample M05-1. First, benthic oxygen depletion

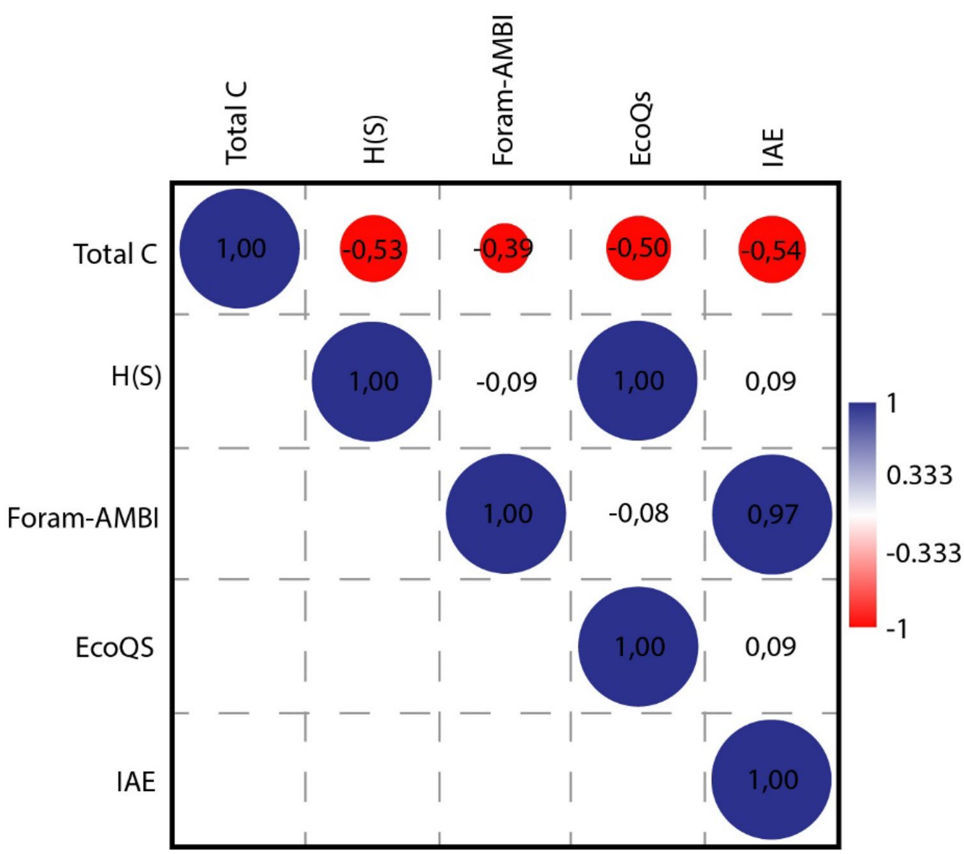

Fig. 6 Pearson correlation coefficient between total carbon, IAE, EcoQs, Foram-AMBI, and species diversity indices. Blue circles mean positive correlation; red circles mean negative correlation. Circle sizes show the *r* (coefficient) values. Bold cells show the strong positive correlation

promoted the preservation of cytoplasm in the foraminiferal tests, resulting in an abundance of stained tests. Second, the sampling campaign coincided with spring outflow activities, and opportunistic species took advantage of conditions unfavorable to most benthic foraminifera and thrived.

The absence or very rare occurrence of infaunal foraminifera indicates that: (1) the pore water below the sediment–water interface is very low in oxygen (due to low oxygen concentration in the overlying water layer) and (2) the periods of oxygen deficiency to anoxic conditions are too long to support infaunal forms.

5 Conclusion

With the aim of determining the effects of specific local conditions on the marine environment, this study investigated the composition of benthic foraminiferal assemblages and the properties of sediment around submarine sulfur springs in the funnel-shaped depression between Izola and Strunjan in the Bay of Koper (northern Adriatic).

In general, sediment characteristics around the sulfur springs do not show and noticeable differences from the uncontaminated sediments in the area; however, some differences do exist. Sampling site M05 has mineralogical and geochemical characteristics comparable to many sediment samples from the region, while sediments from M03 and M11 have higher dolomite content and lower quartz and calcite concentrations. Accordingly, Si concentrations are lower at M03 and M11, while Ca and especially Mg contents are higher. We interpret this with the greater depth of the M03 and M11 spring depression, which in the lower part probably consists of Late Pleistocene continental sediments with alluvial characteristics, while the depression of the sulfur spring M05 is formed entirely in Holocene marine sediments. The coarser sediments near the springs compared to the regional sedimentary features can be explained as “washed.” The distribution of organic matter in the sediments at all three sites is above average for the area. The results also indicate that organic matter is easily degradable, contributing to a higher proportion of degradable inorganic species in the environment.

This study shows that living foraminifera were sparsely distributed near the sulfur springs studied. They were abundant near Bele skale (M05-1), less abundant near Ronek (M11-2), and absent near Izola (M11-1, M11-2). All studied assemblages (total and biocenosis) are dominated by opportunistic representatives of the genera *Ammonia* and *Elphidium*. Epifauna to shallow-infaunal functional groups predominate, while infaunal forms are rare. In contrast to the usual diversity trends reflecting oxygen depletion through lower foraminifera diversity, a comparison of sediments from sulfur spring sites shows higher diversity (in total assemblages) or high diversity (in stained-living assemblages) at sites with lower oxygen levels. This can be explained by several factors: the intensity of spring discharge and sediment mixing/oxygenation, sediment characteristics (e.g., organic matter), depth and shape of the spring depression, and their interactions. A positive correlation was found between the *Ammonia-Elphidium* and Foram-AMBI indices, with slightly polluted environments corresponding to naturally hypoxic conditions near the sulfur spring.

Appendix

The list of identified benthic foraminifera species in alphabetical order:

Adelosina cliarensis (Heron-Allen and Earland 1930).
Adelosina mediterranensis (Le Calvez, J. & Y. 1958).
Ammoglobigerina globigerinoformis (Parker and Jones 1865).
Ammonia aberdoveyensis (Haynes 1973).
Ammonia beccarii (Linné 1758).
Ammonia falsobeccarii (Rouvillois 1974).
Ammonia neobeccarii (Shchedrina and Mayer 1975).
Ammonia parkinsoniana (d’Orbigny 1839).
Ammonia ex gr. *tepida* (Cushman 1926).
Asterigerinata mamilla (Williamson 1858).
Aubignyna perlucida (Heron-Allen and Earland 1913).
Bolivina difformis (Williamson 1858).
Bolivina spathulata (Williamson 1858).
Bulimina elongata (d’Orbigny 1826).
Bulimina marginata (d’Orbigny 1826).
Cibicides advenum (d’Orbigny 1839).
Cribroelphidium poeyanum (d’Orbigny 1839).
Elphidium advenum (Cushman 1922).
Elphidium crispum (Linné 1758).
Elphidium fichtellianum (d’Orbigny 1846).
Elphidium macellum (Fichtel and Moll 1798).
Elphidium translucens (Natland 1938).
Fursenkoina acuta (d’Orbigny 1846).
Haynesina depressula (Walker and Jakob 1798).
Hyalinonetrion gracillimum (Seguenza 1862).
Lagena striata (d’Orbigny 1839).
Lobatula lobatula (Walker and Jakob 1798).
Miliolinella subrotunda (Montagu 1803).
Neoconorbina terquemi (Rzehak 1888).
Nonion depressulum (Walker and Jacob 1798).
Nuria polymorphides (Heron-Allen and Earland 1914).
Planorbulina mediterranensis (d’Orbigny 1826).
Porosononion granosum (d’Orbigny 1846).
Porosononion subgranosum (Egger 1857).
Quinqueloculina seminula (Linné 1758).
Reussella spinulosa (Reuss 1850).
Reussoolina laevis (Montagu 1803).
Rosalina bradyi (Cushman 1915).
Rosalina macropora (Hofker 1951).

Sigmoilinita costata (Schlumberger 1893).
Spiroloculina excavata (d'Orbigny 1846).
Textularia agglutinans (d'Orbigny 1839).
Textularia bocki (Höglund 1947).
Valvulineria bradyana (Fornasini 1900).

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Declarations

Competing interests The authors declare no competing interests.

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