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Shallow water hydrothermal vent field fluids and communities of the D. João de Castro Seamount (Azores)

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Abstract

D. João de Castro seamount has an elevation of 1000 m and is located between the islands of Terceira and São Miguel, Azores, on the hyper-slow spreading Terceira Rift. The summit of the seamount shoals to 13 m below sea level and has hydrothermal vents at a depth of 20 m. This is the first vent system to be described on a hyperslow spreading centre. Gas discharging from the vents is dominated by CO_2 (90%) with lesser H_2S, H_2 and CH_4. Two distinct vent areas were identified that had different physical and chemical characteristics. The white area had vent orifices with white bacterial mats, while the yellow area had yellowish coloured vent openings. Vents in the white area had lower temperatures (≤43 °C), but higher concentrations of H_2S, CH_4 and H_2. *Beggiatoa* sp. was found in this area. The yellow area had vent temperatures up to 63 °C. No typical hydrothermal vent fauna was found at these vents. The macro species present were similar to those found in coastal and seamount areas of the Azorean Archipelago. There was evidence for the presence of deeper vents on the flanks of the D. João de Castro seamount, at depths between 150–400 m.

Keywords: D. João de Castro; Seamount; Shallow hydrothermal vents; Azores

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1. Introduction

The D. João de Castro seamount is located in the Azores archipelago (North Atlantic, 38°13.3′N, 26°36.2′W), between the islands of Terceira and São Miguel (Fig. 1) and classified as an EU-Natura 2000 site. The seamount lies on the Terceira Rift, which is considered to be the world's slowest spreading plate boundary, 4 mm y^{-1} at this location (Vogt and Jung, 2004). The earliest recorded eruptions were in December 1720, when volcanic ejecta formed a small island ~1 km across and 150 m high (Weston, 1964). The island had almost completely disappeared by the following March due to erosion. More recently, a volcanic eruption occurred around June–July 1997, 17 km NW of the 1720 eruption, in a water depth of ~1000 m (Machado and Lemos, 1998). The top of the seamount today lies 13 m below sea level.

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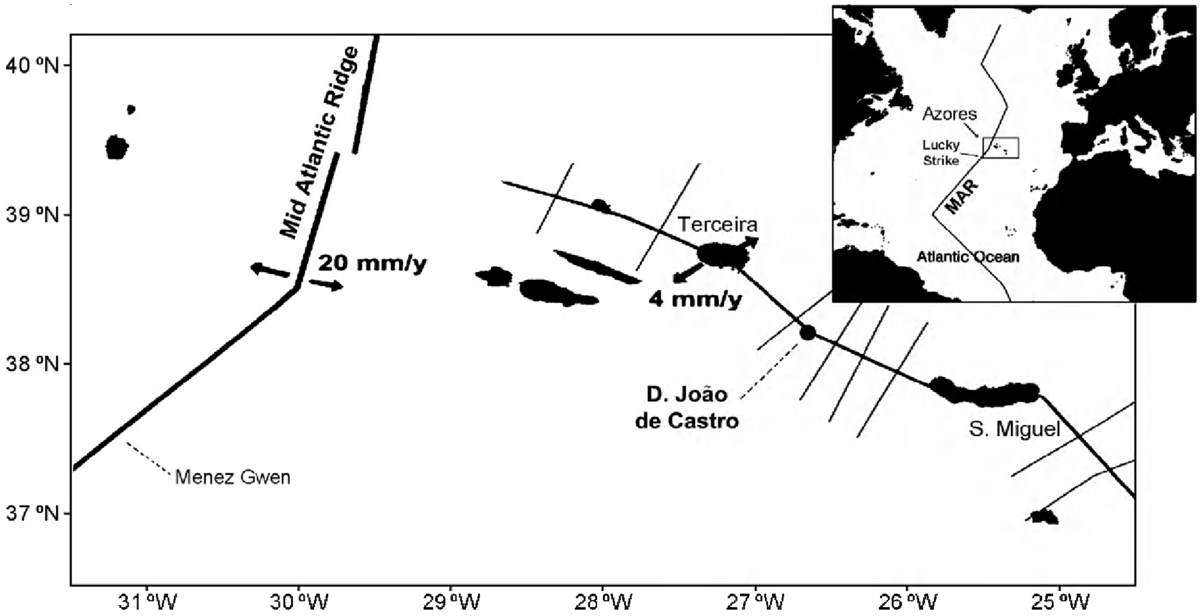

Fig. 1. D. João de Castro seamount is located in the Azores archipelago (North Atlantic: 38°13.3′N, 26°36.2′W), between the islands of Terceira and São Miguel. The positions of the mid Atlantic ridge and the Terceirs Rift are shown. Position of spreading centres adapted from Vogt and Jung (2004).

There have been a number of studies of isolated, hydrothermal-active intraplate volcanic seamounts including the Loihi seamount, offshore of Hawaii (Karl et al., 1988; Hilton et al., 1998), Teahitia volcano in the Society Islands chain (Michard et al., 1993; Stüben et al., 1992), the Macdonald seamount in the Austral Islands chain (Stüben et al., 1992) and the Vailulu'u Seamount in the Samoan chain (Staudigel et al., 2004). Recently a number of hydrothermally active volcanoes in volcanic arc settings have also received attention, including those of the Kermadec arc, off New Zealand (de Ronde et al., 2001) and the Mariana volcanic arc (Embley et al., 2004).

The existence of shallow water submarine hydrothermal venting is well known off volcanic islands and provinces. Such sites are commonly detected by the presence of streams of gas bubbles such as observed offshore from White Island in the Bay of Plenty, New Zealand (Glasby, 1971; Lyon et al., 1977); Kagoshima Bay, Japan (Horibe et al., 1980; Hashimoto et al., 1993); around Iceland (Benjamínsson, 1988; Ólafson et al., 1988); Ushishir Island, the Kuriles (Tarasov and Zhirmunsky, 1989; Tarasov et al., 1990); Milos, Greece (Dando et al., 1995a); Panarea, Italy (Calanchi et al., 1995), Papua New Guinea (Pichler et al., 1990; Pichler and Dix, 1996; Tarasov et al., 1999) and also in lakes, such as Lake Taupo in the Taupo volcanic zone, New Zealand (de Ronde et al., 2002). At deeper sites, water column sampling for Mn and/or CH_4 anomalies has been used to locate vent sites in areas where smokers are absent, and hence particulates in the hydrothermal plumes are low so that plume detection by light attenuation cannot be used (German et al., 1994; Dando et al., 1995b; Dando et al., 2000).

At deep-sea hydrothermal vents on mid-ocean ridges (MORs) there is usually a high biomass of largely endemic, but species poor, fauna that depends on chemosynthesis-based production (Tunnicliffe, 1991). By contrast, at less than 100 m depth, shallow water vents tend to have a low biomass of a more diverse fauna with few, or no, endemic species. (Gallardo et al., 1977; Bianchi and Morri, 1983a,b; Fricke et al., 1989; Tarasov and Zhirmunsky, 1989; Hashimoto et al., 1993; Kamenev et al., 1993; Tarasov et al., 1993, 1999; Dando et al., 1995c; Morri et al., 1999). Only a few examples are known of vent-endemic species occurring in shallow water, e.g., a crab, *Xenograpsus testudinatus*, off Kagoshima Island, Taiwan, 8–20 m (Jeng et al., 2005) and a vestimentiferan, *Lamellibrachia satsuma*, in Kagoshima Bay, Japan (Miura et al., 2002). A detailed discussion of the differences between shallow-water and deep sea hydrothermal vent ecosytems is given by Tarasov et al. (2005). The trophic structure of shallow-water hydrothermal ecosystems, with the exception of those deep in submarine caves (Abbiati et al., 1992; Southward et al., 1996; Airoldi et al., 1997), differs from that of deep-sea hydrothermal ecosystems in that photosynthetic inputs from phytoplankton and benthic organisms are important (Kharlamenko et al., 1995, Dando et al., 1999).

At shallow water hydrothermal vents around Milos the venting had little effect on the epibenthic community structure (De Biasi et al., 2004). However, there was an increase in epibenthic species diversity at venting sites compared with non-venting sites at comparable depths (Morri et al., 1999). In contrast, infaunal communities close to the vents are species and biomass poor (Dando et al., 1995c; Thiermann et al., 1997; Tarasov et al., 1999).

Shallow water venting on the mid-Atlantic ridge (MAR) has been described at a number of sites around Iceland (Benjamínsson, 1988; Botz et al., 1999; Fricke et al., 1989; German et al., 1994; Ólafson et al., 1988). No endemic vent fauna have been found at these sites, which extend to depths of 406 m. It is possible that this is because no vent sites with endemic fauna occur in the vicinity of Iceland. In contrast, the D. João de Castro seamount lies close to sites on the MAR with a diverse range of vent fauna, the closest presently known site is Menez Gwen at ~410 km, at 850 m depth (Colaço et al., 1998). The D. João de Castro seamount is of particular interest for determining the upper depth limit on endemic hydrothermal vents species in the Atlantic.

The hyper-slow Terceira Rift (spreading rate 4 mm yr^{-1}) is comparable to the ultra-slow Southwest Indian (15–16 mm yr^{-1}) and Gakkel (7–13 mm yr^{-1}) ridges (Vogt and Jung, 2004). This study of the D. João de Castro seamount is the first report on the fluid chemistry and biology of vents on a hyperslow spreading centre.

The present paper reports the first studies on the biological communities of the D. João de Castro (DJC) seamount and describes the distribution of organisms in relation to vent fluid chemistry and sediment composition.

2. Surveys and methods

2.1. Expedition dates and site surveys

SCUBA dives were made on the seamount summit in August 1999, August 2000, September 2001, August 2002, September 2003 and September 2004. Bathymetric data were obtained using a number of methods that included a 300 kHz mechanically scanning pencil beam sonar, together with a Doppler unit outputting depth information. The latter proved extremely useful in situations where the gas streaming interfered with the pencil beam sonar, causing the occurrence of outliers due to reflections off the gas bubbles. Both units were installed on-board an Autonomous Surface Vehicle, which executed "lawn mowing" patterns over the seamount in a purely automatic mode (Pascoal et al., 2000). For navigation purposes, the robotic vehicle used an attitude and reference unit coupled with a positioning system built around the Doppler unit and a DGPS (Differential Global Positioning System), the fixed portion of which was installed on Terceira Island. The position of the gas outlets was determined by inspecting the sonar data obtained with the autonomous vehicle and locating the conspicuous bubble plumes. A 28 kHz Furuno echosounder was also used on-board the support vessel *Arquipélago* to verify water depths.

2.2. Chemical and physical measurements

Vent fluid temperatures and water temperatures were measured using a Hydrosphere thermometer (± 0.1 °C accuracy). Long-term temperature was monitored with a Hobo sensor every 30 min for two years, at a bottom depth of 25 m at 38°13.36′N and 26°36.38′W, 1 m from a white vent.

Vent water samples were collected by SCUBA divers in 200 ml vacuum-based titanium bottles. Water samples around the seamount, at depths from 10 to 600 m, were collected using Niskin bottles. The pH of the water samples was measured immediately after sample recovery using a glass electrode. Measurements were made at 25 °C after calibration with NBS buffers (pH 4 and 7) using a WTW model pH 597 pH meter. Metal concentrations were determined by potentiometric stripping analysis using a PSU 22 from Radiometer Analytical (Riso et al., 1997). Concentrations from the different areas were compared using the *T*-Test for independent samples with Statistica 6 software © StatSoft, Inc.

Gas and water samples were collected by SCUBA divers from 20 to 40 m depth, using an inverted funnel, in a plastic bag or glass bottle. Aliquots of the collected gas samples were removed, using Pressure-Lok gas syringes, within 2 h of collection for fixation and analysis. Aliquots of gas were injected into septum vials containing 0.5 ml 1.0 M NaOH for later determination of CO_2. Methane and H_2 were measured on board the research vessel using a portable gas chromatograph fitted with a Figaro TGS 711 solid-state detector. The gases were separated on a 2.15 m column of 13X molecular sieve, using zero-grade N_2 as the carrier. Carbon dioxide was separated by gas chromatography, also using zero grade N_2 as carrier, on a 2 m long, 2 mm i.d. column packed with Unibeads A of 80–100 mesh, and detected using a thermal conductivity detector. Total hydrogen sulphide was determined colorimetrically by the method of Cline (1969).

X-ray diffraction analysis (XRD) was performed on sediments at the Chemistry Department, University of Lisbon, using a Phillips PW 1710 diffractometer. Analytical conditions were as follows: graphite crystal monochromator for CuKθ radiation, 40 Kv, 40 mA and continuous scan for $2° < \theta < 70°$, 2θ increments equal to 0.02° at 1250 s intervals. The samples were crushed and analyzed in an amorphous silicon support.

2.3. Video analyses

Video footage was taken by SCUBA divers and by a Phantom HD2 remotely operated vehicle (ROV). Features were measured by comparison with well-known object sizes. Several parameters were recorded, including the presence or absence of species in the vicinity of vents, the shape and area of the vents, the area occupied by bacteria around the vents, the distance between the fluid outlets and the presence of different species. The ROV was slow-moving and was frequently stopped to take temperature measurements. An initial examination of the videotapes showed that a frame sampling rate of 1 frame every 5 min for detailed analysis ensured that the same field of view was not counted twice. This sampling rate was hence chosen for determining relative fish abundance. The numbers of fish were counted and the presence or absence of venting was noted. Differences in fish abundance were compared using the Chi square statistic.

2.4. Animal collection, mapping and micro-distribution

Thirty five hours of SCUBA diver observations have been made on the D. João de Castro seamount since 1995. Most species were identified visually in situ by the divers, or subsequently from video tapes. Voucher specimens of species difficult to identify in situ were collected and preserved for identification in the laboratory. Rock specimens from around the vent outlets were collected by divers and fixed in 4% formaldehyde in seawater before being transferred to a solution of 70% ethanol, 25% water and 5% 1,2-propanediol. The samples were washed on a sieve of 200 μm mesh and the washings and rock surfaces were examined under a stereomicroscope.

A bongo net, with mesh sizes of 335 and 500 μm, was towed at night on September 1st 1999, at a speed of 2.5 knots above the seamount summit between 38°13.37′N, 26°36.42′W and 38°12.95′N, 26°35.80′W, at 23 m depth. Comparative tows were made north of the seamount between 38°15.86′N, 26°35.98′W and 38°15.64′N, 26°33.07′W, at 70 m depth, over water depths of >800 m, as well as NE of the seamount between 38°14.51′N, 26°33.83′W and 38°13.59′N, 26°34.00′W, at 50m depth, over water depths of 400–800 m. The net samples were fixed in formaldehyde and subsequently transferred to alcohol, as for the benthic samples. The fish post-larvae were removed and identified separately (Sobrinho-Gonçalves and Cardigos, submitted for publication). The remaining zooplankton was identified in sub-samples examined in a Bogorov tray under a stereomicroscope.

3. Results

3.1. Description of the shallow venting area

The seamount today shoals to within 13 m depth of the sea surface. The summit of the volcanic cone is a caldera, 300 × 600 m, 0.18 km^2, at 40 m depth inside (Fig. 2). The area of the D. João de Castro seamount shallower than 50 m is approximately 0.35 km^2, with 0.011 km^2 showing hydrothermal activity. Venting on the seamount can be divided in two main types; 'white' vents and 'yellow' vents, according to the bottom colour around the vents. The white vents cover an area of 9000 m^2 between 20 and 45 m depth, while the yellow area covers an area of 2000 m^2 between 18 and 25 m depth. The 'transition' area covers an area of 100 m^2 between 23 and 25 m depth and has a yellowish-white colour. Two flow-rate measurements made on a white vent in September 1999 gave flow rates of venting water of 773 and 787 ml min^{-1}. Other vents, which were not studied in detail, were observed between 40 and 50 m on the sandy area around the NW part of the D. João de Castro summit, inside the caldera.

Water temperatures, unaffected by vent activity, at 25 m depth, had values, trends, and maxima similar to other shallow water areas in the Azores Archipelago. For example, the summer maximum was 23 °C and in early spring the minimum was 16°. During the period of fluid sampling (August–September) temperatures averaged 35.8 °C (26.5–42.6 °C) at the discharge point of the vents for the white area, and 61.2 °C (58.2–63.3 °C) for vents in the yellow area (Table 1). The two discrete vents that were sampled annually gave temperatures of 26.5 °C (for 2001), 27 °C (for 2002) and 25.9 °C (for 2003) in the white area, and 62.9 °C (for 2001), 64.3 °C (for 2002), 63.0 °C (for 2003) and 63.2 °C (for 2004) in the yellow area.

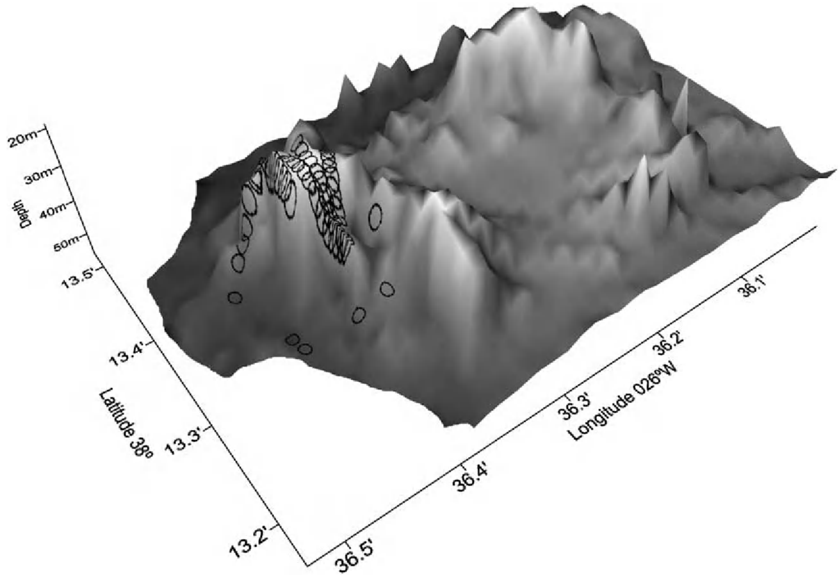

Fig. 2. D. João de Castro seamount is capped by a caldera (300 × 600 m, 18 ha) with a depth of ca. 40 m and surrounding eroding walls that reach 13 m at its shallowest, Circles (O) are the main vent locations as observed by SCUBA divers.

At depths shallower than 50 m there were a number of faults in the rocks through which hydrothermal fluids discharged. Forty four of these vents in rocky substrata were examined, with 4 showing only water discharge. The 40 crevices through which gas bubbles were released averaged 37.9 cm in length by 3.2 cm in width, with 29 averaging 51.9 by 3.5 cm. Twelve of the vents were circular averaging 2.1 by 2.4 cm. The white vents were surrounded by a corona of white bacterial mat that ranged from 0.1–18.5 cm in width (mean 10.5 cm, $n=8$). The white crevices had a rim of 0.4–94.7 cm width (mean 21.5, cm $n=20$). An amorphous material bordered the yellow vents.

3.2. Water composition

The water composition is presented in Table 1 and results from the mixing of the emitted vent fluid with surrounding seawater. The general trend observed between the studied areas was the enrichment in dissolved gases and Pb in the colder "white zone" whereas the yellow zone is warmer and enriched in Ba, Fe and Mn. This trend was significant (confidence level 10%) for temperature, total sulfide, Pb, Ba, Fe and Mn. The salinity of water samples collected from both white and yellow vents was compared onboard the research vessel using a refractometer. All the samples were similar to surface seawater values, ±0.5 PSU. Vent fluids from the yellow zone were warmer by ~20 °C than those from the white zone.

3.3. Geology

X-ray diffraction analyses results on the amorphous material in the yellow area showed no evidence for crystalline mineral phases. The mineral precipitates from the white area gave diffraction lines of Na–Ca–Al silicates (anorthite, sodian ± albite). There were also a few diffraction lines identified as hydrated silicates of the same elements. The large number of diffraction lines present due to the silicate minerals may have obscured other minerals present in minor amounts. During crushing, the samples gave off a strong H_2S smell although no sulphur minerals were conclusively identified by XRD analysis.

3.4. Species present on the top of the seamount

The most common species recorded close to the vents on the D. João de Castro seamount are listed in Table 2 (see Annex 1 for all the species registered on the Seamount). In total, 156 benthic species were identified on the seamount in the 3 active zones, including 41 macro-algae, 10 Porifera, 9 Cnidaria, 5 Annelida, 20 Arthropoda, 44 Mollusca (see Ávila et al., 2004 for details on D. João de Castro Molluscs), 7 Echinodermata, 11 Pisces and 9 other species.

At the white vents, the green alga *Codium elisabethae*, a species endemic to the Macaronesian islands, was the closest macro-alga to the vents and was found at distances of 0–140 cm from the vent outlets. In

Table 1
Location, temperature and composition of D. João de Castro shallow hydrothermal vents waters

Sample	Year	Location	Depth (m)	T (°C)	pH	S (μM)	H_2 (ppm in gas)	CH_4 (ppm in gas)	H_2S (ppm in gas)	Cu (μM)	Pb (nM)	Ba (μM)	Fe (μM)	Mn (μM)	Co (μM)	Cd (μM)
1	1999	White	n.d.	n.d.	5.23	51.0	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
2	1999	White	n.d.	n.d.	5.58	85.0	n.d.	n.d.	12	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
3	2001	White	25.4	n.d.	n.d.	137	n.d.	n.d.	n.d.	0.014	0.92	0.02	l.d.l.	0.10	l.d.l.	l.d.l.
4	2001	White	23.0	n.d.	n.d.	64	n.d.	0.0	n.d.	0.022	2.57	0.19	5	0.66	0.05	l.d.l.
5	2001	White	34.1	n.d.	5.47	65	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
6	2001	White	34.1	n.d.	5.62	34	n.d.	n.d.	n.d.	0.035	3.90	0.10	4	0.37	0.04	l.d.l.
7	2001	White	26.5	42.6	4.64	56	n.d.	n.d.	n.d.	0.039	5.89	0.13	12	0.42	0.04	l.d.l.
8	2001	White	26.5	42.6	4.56	102	6132	84.2	9	0.016	2.71	0.20	4	0.80	0.04	l.d.l.
9	2001	White	25.6	38.1	4.46	93	n.d.	n.d.	n.d.	0.027	4.46	0.10	8	0.57	0.04	l.d.l.
10	2001	White	25.6	38.1	4.52	88	n.d.	n.d.	n.d.	0.038	3.38	0.13	9	0.62	0.05	0.006
11	2001	White	24.6	26.5	n.d.	31	n.d.	n.d.	n.d.	0.052	3.04	0.13	6	0.91	0.04	l.d.l.
12	2001	White	26.0	36.0	4.32	242	n.d.	n.d.	36	0.078	5.20	0.12	22	0.27	0.04	l.d.l.
13	2001	White	n.d.	26.5	4.38	12	235	5.3	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Mean		White	25.8	35.8	5.01	82				0.036	3.56	0.12	9	0.52	0.04	0.006
14	2001	Transition	23.6	50.6	4.87	109	94	42.1	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
15	2001	Transition	23.6	50.6	5.03	108	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
16	2001	Transition	24.7	29.3	4.56	335	21749	42.1	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
17	2001	Transition	24.2	29.5	4.51	404	16479	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
18	2001	Transition	24.2	21.0	4.85	92	4743	42.1	11	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
19	2001	Transition	24.2	21.0	4.79	85	19	31.6	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
20	2001	Transition	23.3	20.4	5.20	73	1982	5.3	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
21	2001	Transition	23.3	20.4	5.08	156	2108	42.1	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Mean		Transition	23.9	30.4	4.88	170	6739	34.2								
22	1999	Yellow	n.d.	n.d.	5.18	0.7	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
23	2001	Yellow	20.3	63.3	5.14	2	n.d.	n.d.	n.d.	0.019	0.80	0.25	88	6.71	0.03	l.d.l.
24	2001	Yellow	20.3	63.3	4.77	3	133	18.4	n.d.	0.024	1.44	0.16	58	4.13	0.03	0.005
25	2001	Yellow	19.2	58.2	n.d.	1	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
26	2001	Yellow	19.2	58.2	5.47	0	94	2.6	n.d.	0.022	3.01	0.22	95	5.66	0.03	l.d.l.
27	2001	Yellow	19.2	58.2	5.29	n.d.	n.d.	n.d.	n.d.	0.037	n.d.	0.61	*7990**	12.88	0.03	n.d.
28	2001	Yellow	20.2	62.9	4.12	1	n.d.	n.d.	n.d.	0.036	2.25	0.19	116	4.83	0.03	n.d.
29	2001	Yellow	20.2	62.9	4.95	1	42	15.8	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
30	2001	Yellow	20.2	62.9	5.27	1	68	14.5	29	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Mean		Yellow	19.9	61.2	5.09	1	84	12.8		0.028	1.88	0.29	89.2	6.84	0.03	0.005
t-test**		White/Yellow		0.00	0.52	0.00		0.50		0.41	0.07	0.03	0.00	0.00	0.00	

* Results on Fe for sample 27 were not used in the average due to possible contamination by particles while sampling. "n.d." = not determined, "l.d.l." = lowest detection limit, ** "*t*-test" = *T*-Test for Independent Samples by Variables. Grey values represent non-equal averages with 0.1 of confidence.

Table 2
Species present near the vents on the D. João de Castro Bank

Group/species	Habitat						Adjacent to the vent	Near the vent i.e., <1.5 m
	Rocky bottom	Block	Walls	Crevices	Water column	Not mentioned/observations		
Bacteria								
Beggiatoa sp.			O	F			P	P
Algae								
Carpomitra costata						O		P
Cladostephus spongiosus	O		R					P
Codium adhaerens	F		O				P	P
Codium elisabethae	A, SA*					*In white active areas until 30m.	P	P
Corallina cf. *elongata*	A		O	O		C, S		P
Coralline crusts	F		F	A		R	P	P
Cf. *Gigartina* sp.						F		P
Halopteris filicina			R			F		P
Padina pavonica	O*		R			*Bellow 20 m	P	P
Sargassum cf. *vulgare*						C	P	P
Ulva cf. *rigida*	R.	R*				*C after 35m		P
Zonaria tournefortii	SA*	SA*				O, *after 30m	P	P
Porifera								
Myxilla rosacea	R		R	O				P
Cnidaria								
Aglaophenia tubulifera	O		O	O				P
Annelida								
Hermodice carunculata	O		O	O			P	P
Arthropoda								
Maja brachydactyla				O				P
Megabalanus azoricus	O		O	O				P
Echinodermata								
Sphaerechinus granularis				F				P
Pisces								
Abudefduf luridus	O						P	P
Apogon imberbis				O				
Balistes carolinensis					A			P
Bodianus scrofa		O						
Chromis limbata	F		A		C		P	P
Coris julis	F						P	P
Kyphosus sp.	F				C		P	P
Muraena augusti				F				
Muraena helena				O				P
Myliobatis aquila		O						
Scorpaena maderensis	F	O						P
Seriola rivoliana					O			
Serranus atricauda	F				O		P	P
Sparisoma cretense	F	F						P
Sphoeroides marmoratus	F	F				C sediment		P
Symphodus mediterraneus		O						
Thalassoma pavo	C	F					P	P
Tripterygion delaisi delaisi	F	F	P	P				P

Classification according to SACFOR index: SA — superabundant, A — abundant, C — common, F — frequent, O — occasional, P — present. Rare species were omitted.

contrast, *Sargassum* cf. *vulgare* was the closest macroalgal species to the yellow vents, at distances of 0–70 cm from the vent outlets. This species had a high density on the seamount, compared to the rest of the Azores. In the same depth range (20–30 m) at other sites, the rocks were colonized by *Dictyota* spp., *Halopteris filicina*, *Padina pavonica* and *Asparagopsis armata*. *P. pavonica* was the next closest macroalga to the vents, at distances of 6–40 cm from the vent outlets (Fig. 3).

Seven rocks samples, all partially covered with bacterial mats, were collected from around the vent outlets in September 1999. The bacteria were mainly an attached form of *Beggiatoa,* with a mean trichome width of 39.1 ± 7.0 (S.D.) µm and a length of 3664 ± 381 (S.D.) µm ($n=100$). The trichomes had a somewhat swollen basal end towards the attachment point and were similar to the similar size group of *Beggiatoa* found in the Grotta Azzurra submarine cave which contained a geothermal spring (Mattison et al., 1998).

The rock samples were found to host 7 species of fauna. The most numerous species was the nematode *Enoplus meridonalis* (116 specimens) followed by an oligochaete, *Lumbricillus* sp. (59 specimens). Both these species were abundant in the thicker *Beggiatoa* mats. Also found in the thick mats was a caprellid, *Caprella* cf. *linearis* (3 specimens) and the hydrozoan *Clytia hemisphaerica* (12 specimens). Harpaticoid copepods, *Harpactus* sp. (20 specimens), and species of Parastenheliidae (51 specimens) and Laophontidae (26 specimens) and a species of Halacarinae (9 specimens) were the most abundant organisms on rocks that had small clumps of *Beggiatoa*. Less common species present on the rocks were *Tellina* sp. (3 specimens) and single specimens of the hydroids *Sertularella polyzonias* and *S. gayi* well as the tanaid *Tanais delongii*.

The most commonly observed fish species within 5 m of the vents in the rocky areas were *Serranus atricauda*, *Coris julis*, *Abudefduf luridus*, *Thalassoma pavo*, *Chromis chromis* and *Chromis limbata*. *Balistes carolinensis*, which were common close to the sea surface, were also occasionally observed close to the gas bubble outlets. Of the six common species, *T. pavo*, *C. julis*, *A. luridus* and *C. limbata* did not appear near yellow vent areas. Thirty five species of fish were found on the seamount distant to the venting areas. A comparison of relative fish density in rocky areas, around the vents, and in rocky areas with no nearby venting was made using video-recordings that were taken continuously using the forward-facing camera on the ROV. For every frame examined (1 frame for every 5 min of tape) it was noted whether the ROV was in a venting or a non-venting area. Most of the ROV video did not show venting and only 95 min of video covered venting rocky areas. Comparing equal numbers of frames (the first 19 in each case) 153 fish were counted in the 19 frames from venting areas over rocks, compared with 51 fish in the frames where no venting was viewed. There were significantly more fish in the venting areas, with a probability, *P*, of <0.001 (Chi square). When viewing all the video, without comparing equal number of frames, on rocky substrate 14 showed (74%) 1 or more fish. In comparison in 79 frames with no vents evident, 36 (46%) showed 1 or more fish, again significantly more fish in the venting area, $P=0.028$ (Chi square).

Very few fish were seen on the sandy bottom, at approximately 40 m depth, with no indication that the venting here attracted fish. Analysis of the ROV videos of the soft bottom, again examining 1 frame every 5 min of tape, showed that in 60 frames only 2 fish were seen.

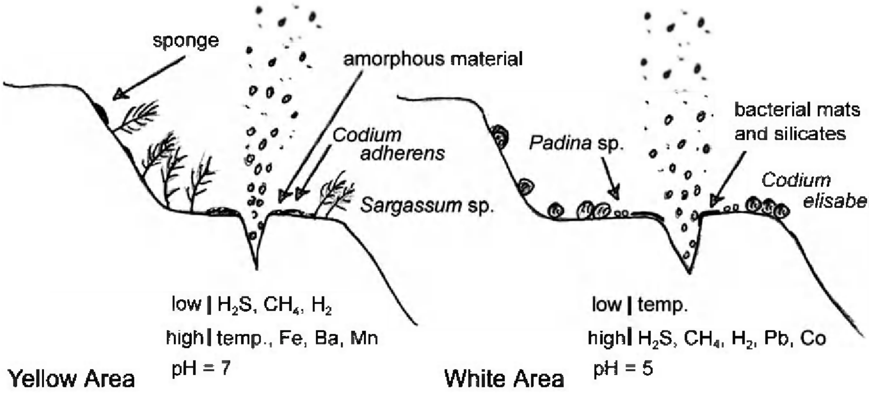

Fig. 3. Scheme of the two main vent types identified in the shallow water area of D. João de Castro seamount.

Townets for zooplankton were collected over the seamount and to the N and NE of the seamount. The invertebrate zooplankton in the 350 μm mesh net towed over the top of the seamount was dominated by copepods (61.0% of the total) followed by siphonophores (21.6%), salps (7.4%), chaetognaths (4.0%), decapods (3.7%) and mollusca, euphasids, amphipods and polychaetes (all<0.6% each). In contrast, samples from N and NW of the seamount contained a higher proportion of copepods, (79.2% and 89.8% of the zooplankton, respectively) but a greatly reduced proportion of siphonophores, (3.5% and 3.3% of the zooplankton, respectively) and salps (1.9% and 3.6%, respectively).

3.5. Location of deeper vents

Casts using Niskin bottle were made at different depths at a series of stations around the seamount, and the water analysed on board the vessel for dissolved CH_4 and H_2. Some degassing of the water may have occurred during recovery so that the reported concentrations are minima. The combined results of all the casts (Fig. 4) show that, together with the expected high gas concentrations in the upper 50 m of water above the seamount, there were positive anomalies for both gases in deeper water, especially between 150 and 350 m. In some depth profiles the changes in CH_4 and H_2 were similar (Fig. 4c), while at other stations the changes in concentrations of the two gases were not in phase (Fig. 4d and e). A detailed echo-sounding survey showed potential gas bubbles plumes close to the stations with high gas concentrations (e.g., Fig. 5). Plumes were found at ~135 m depth (38° 12.709′N, 26° 34.593′W and 38° 12.721′N, 26° 34.593′W), ~220 m (38° 12.641′N, 26° 34.651′ W, 38° 12.650′N, 26° 34.615′W, 38° 12.71′N, 26° 35.10′W, 38° 12.798′N, 26° 34.441′W, 38° 12.570′N, 26° 34.764′W and 38°12.77′N, 26° 34.23′W).

Attempts were made using the ROV to view and sample the deeper vents located by water sampling and echo-sounding at 38°12.733′N, 26°34.618′W and 38°12.707′N, 26°34.602′W. However, strong bottom currents made it impossible to hold the ROV on station. Bottom pictures at depths between 182 and 227 m showed the epifauna to be dominated by whip corals,

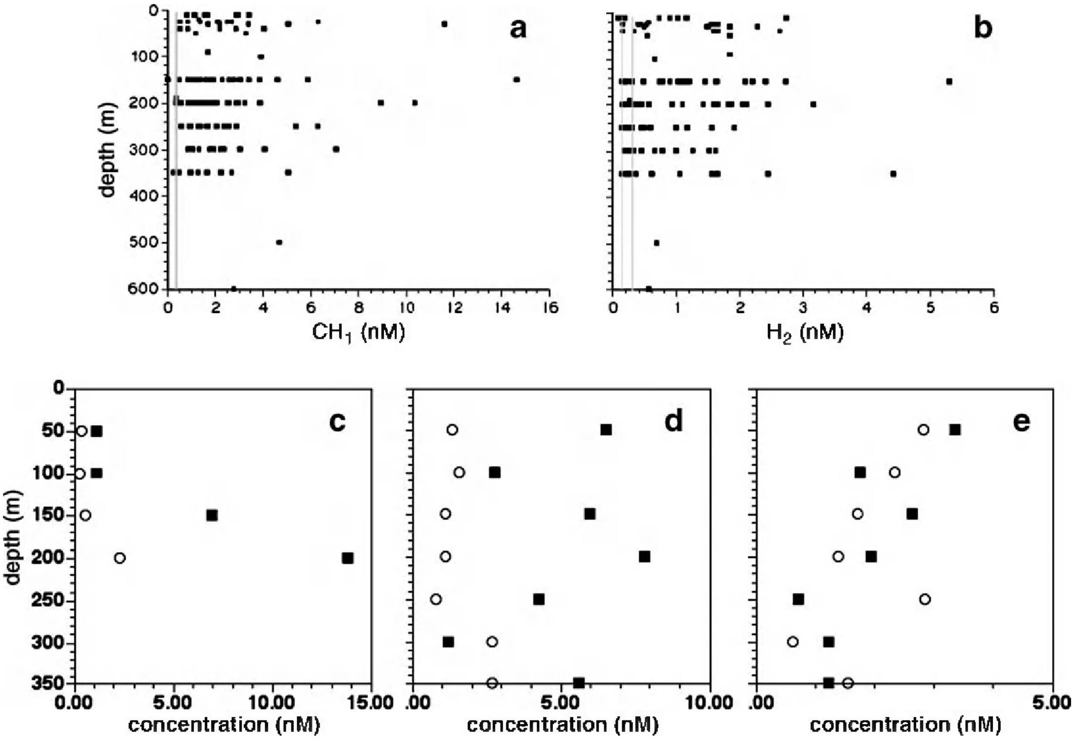

Fig. 4. Vertical profiles from hydrocasts taken at different stations around D. João de Castro. (a) combined profiles for methane from 18 stations, the methane concentration of oceanic seawater is approximately 0.4 nM; (b) combined profiles for hydrogen from the same stations, mid-ocean concentrations are 0.4 to 0.8 nM, being highest in the upper 50 m (Herr and Barger, 1978); (c–e) Methane (■) and hydrogen (○) concentrations profiles at 3 stations, (c) 38° 12.769′N, 26° 36.637′W; (d) 38° 12.884′N, 26° 34.057′W; (e) 38° 14.566′N, 26° 38.082′W.

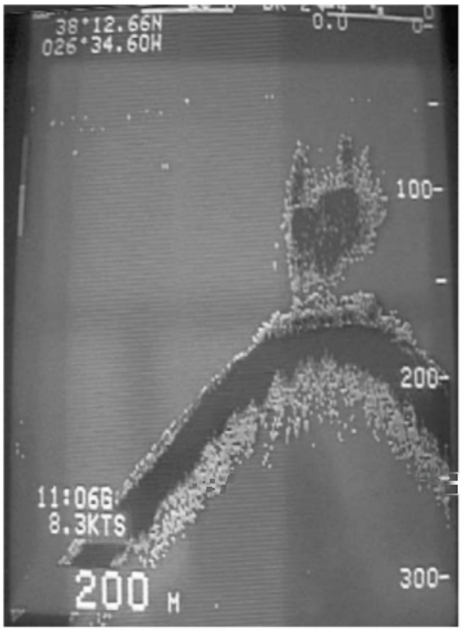

Fig. 5. Sonar image of a vent bubble plume, originating at approximately 170 m deep, detected on a 28 kHz Furuno echosounder.

Stichopathes sp. and other antipatharia, with some gorgonian corals and *Virgularia*. Areas of sediment stained brown were noted, indicating the presence of oxidised iron. White patches, resembling the mats of *Beggiatoa* seen at the shallow sites, were also seen, suggesting areas of active venting were close by. Sponges were observed in close proximity to the presumed bacterial mats.

4. Discussion

The D. João de Castro hydrothermal shallow vents are the first to be described from a hyper-slow spreading centre. The higher H_2, CH_4 and H_2S concentrations and lower metal concentrations in the vents of the white and transition zones, when compared to those of the yellow zone, suggests that the fluid chemistry was affected by phase separation due to subsurface boiling (Charlou et al., 2000; Von Damm et al., 2003). However this suggestion could not be verified as only diluted fluids were sampled and we were not able to estimate the composition of the pure fluids. Iron concentration was high in the yellow area compared to the endmember concentration found in the Menez Gwen deeper vent field (26.1 μM) (Charlou et al., 2000).

Minerals could not be detected in the precipitates around the yellow area, despite the high Fe content of the water. The low concentration of sulphide could prevent the iron sulphide precipitation in the immediate vicinity of the vent. The difference in fluid chemistry between the yellow and the white + transition vents is not easily explained but is significant with respect to H_2S, Pb, Ba and Fe concentrations. Phase separation, as noted above, would explain the higher H_2S and lower metal content but there was no supporting evidence from salinity measurements or by the lower temperatures of the white area vents. The relative venting temperatures were stable over a 3-year period. The yellow vents were at least 3 m higher on the seamount, suggesting that there may be different plumbing systems for the two vent types.

The sulphide concentrations at the white and transition zones, 12–404 μM, with a mean of 120 μM, were in the range of those at diffuse deep sea venting sites on the MAR where there is a chemosynthetic-dependent ecosystem with a high biomass (Desbruyères et al., 2001). The shallow vents thus have the potential to support a chemosynthetic ecosystem; however the strong currents cause rapid dilution of these fluids and probably create an unstable system.

As with other shallow water hydrothermal vents, (e.g., Dando et al., 1995c; Fricke et al., 1989; Tarasov and Zhirmunsky, 1989; Thiermann et al., 1997; Morri et al., 1999; Tarasov et al., 1999) the species found closest to the vents on the D. João de Castro seamount are a subset of temperature- and/or sulphide-tolerant local species with no endemic vent species present. There were similarities between the fauna found close to the vents and those found surrounding hydrothermal vents elsewhere at comparable depths. The hydroid *Clytia hemisphaerica* was found on 3 of the 7 rock samples collected around the vents and was most abundant on a sample covered with the thickest mat of *Beggiatoa*. It has similarly been found, on a variety of substrates, close to vents offshore from Milos (Morri and Bianchi, 1999; Morri et al., 1999). The other hydroids found, *S. polyzonias* and *S. gayi*, were present on the largest rock sample collected, that had only a thin covering of bacteria. The related species, *S. ellisii,* has been found growing on algae surrounding hydrothermal vents offshore from Milos (Morri and Bianchi, 1999).

There were also similarities with fauna found at other shallow vent sites in the Atlantic. Nematodes, including a species of *Enoplus* and harpacticoid copepods, including a species of *Parastenhelia*, were also found at the Kolbeinsey vents (Fricke et al., 1989).

Nematodes and harpacticoids were common around the vents on the seamount and were also the dominant meiofaunal groups in the sediments surrounding the vents in Matupi Harbour, Papua New Guinea (Tarasov et al., 1999) and the gasohydrothermal vents offshore from Panarea, Italy (Colangelo et al., 1996). Nematodes dominated the meiofauna in sediments around vents offshore from White Island, in the Bay of Plenty, New Zealand (Kamenev et al., 1993), in Palaeochori Bay, Milos (Thiermann et al., 1997) and in Lake Taupo, New Zealand (Rota and Manconi, 2004).

Shallow water hydrothermal venting is known to affect the distribution of macroalgal species. *Cystoseira tamariscifolia* was the dominant species at a hydrothermal site off Vulcano Island while 4 other species, including *P. pavonica*, were dominant at a comparable site at 200 m distance (Acunto et al., 1996). On the summit of the D. João de Castro seamount, *Sargassum* cf. *vulgare*, only, was dominant distant from to vent sites (De Biasi et al., 2004). The venting area at Milos was home to exotic thermophilous species, especially macro-alga (De Biasi and Aliani, 2003).

Invertebrate plankton found directly over the seamount differed from the samples collected over deeper water in having a higher proportion of tunicates+salps (29.0% over the seamount compared with 5.5% and 6.9% in the other two samples). Since the depths of the net tows were variable, the changes could be due to differences in the vertical distribution of the species. However, a higher count of bacteria might be expected in the water above the seamount, which, in turn, could account for the higher proportion of micro-plankton feeders. In Matupi Harbour, Papua New Guinea, the zooplankton was most dense in the subsurface layer in the vicinity of the vent fields there (Tarasov et al., 1999).

The white area at D. João de Castro seamount was characterised by filamentous bacteria and the algae *Codium elisabetae*. *C. elisabethae* has usually been reported in flat coastal shallow areas between 17 and 25 m and for one offshore area (Formigas Bank, W of the Azores) at ~ 45 m. At D. João de Castro, *C. elisabethae* was not found below 40 m. Overall, the macro-species composition at the D. João de Castro seamount was typical of that found in shallow water environments of the Azores region (Morton et al., 1998).Despite the low CH_4 content of the D. João de Castro vents, CH_4 together with H_2, was a good tracer for venting activity. The composite vertical profiles for CH_4 and H_2 (Fig. 4) showed similar positive anomalies to those above the Steinahóll vent field on the Reykjanes Ridge (German et al., 1994). Gas plumes seen on the 28 kHz echosounder extended approximately 50 m up into the water column, as seen at other gas-rich sites (German et al., 1994; Dando et al., 1995a). The different relative concentrations of CH_4 and H_2 seen in different water casts, for example those shown in Fig. 3 (c, d and e), are probably due to a combination of factors. H_2 has a very short half-life, of the order of a few hours, in seawater around shallow vents (P. Dando, unpublished studies) and will disappear faster than CH_4. Differential migration through the rocks, due to different molecular sizes, and different sub-surface oxidation rates will affect the composition of the released gas. The higher solubility of CH_4 in seawater (Wiesenberg and Guinasso, 1979) will also cause a difference in distribution due to solution from rising gas bubbles.

The deeper vent sites located on the D. João de Castro seamount were not investigated in detail due to strong bottom currents at the time of our study. The water column profiles for CH_4 and H_2, together with echo-sounder records, indicate vent sites in the depth range of 150 to more than 400 m. Brown staining of bottom sediments and patches of white 'bacterial' mat seen on the ROV videos indicated nearby venting at 182–193 m. Since no vents were directly observed at these depths, it is not known whether vent-endemic fauna are present at these deeper sites. However, the D. João de Castro seamount is clearly a site requiring more detailed investigation in order to study the influence of depth on the presence of endemic hydrothermal vent fauna.

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Appendix A. Annex 1

List of species recorded on the D. João de Castro Seamount

Bacteria
Beggiatoa sp.

Macro-Algae
Acrosorium uncinatum
Carpomitra costata
Ceramiales (not identified)
Cf. *Cladophora* sp.
Cf. *Chylocladia verticillata*
Cladostephus spogiosus
Codium adhaerens
Codium elisabethae
Colpomenia sinuosa or *Leathesia difformis*
Corallina cf. *elongata*
cf. *Cutleria multifida*
Dictyopteris membranacea
Dictyota adnata
Dictyota dichotoma
cf. *Gellidium* sp.
cf. *Gigartina* sp.
Halopteris filicina
Halymenia sp.
Hypnea sp.
Jania rubens
Liagora viscida
Cf. *Lithophyllum incrustans*
Cf. *Lithothamnion calcareum*
cf. *Lobophora variegata*
Meredithia microphyla or *Rhodymesia holmesii*
Mesophylum lichenoides
Microdictyon calodictyon
Padina pavonica
Peyssonelia cf. *squamaria*
Porphyra sp.
Pterocladiella capilacea
cf. *Rhodymenia* sp.
Rhodophyta (translucent blade, not identified)
Rhodophyta (coralline crusts, not identified)
Rhodophyta indet. (non-calcareous crusts)
Sargassum cf. *vulgare*
Sargassum sp.
Sphaerococcus coronopifolius
Stypocaulum scoparium
Taonia atomaria
Ulva cf. *rigida*
Valonia utricularis
Zonaria tournefortii

Porifera
Cliona viridis
Cliona sp.
Cliona celata
cf. *Timea unistellata*
Phorbas fictitius

Appendix A (*continued*)

Hexadella racovitzai
Myxilla rosacea
Polimastia mamilaris
Sycon ciliatum
Tethya aurantium
Terpios sp.

Ctenophora
Cestus veneris
Beroe forskali

Cnidaria
cf. *Actina equina*
Aglaophenia kirchenpaueri
Aglaophenia tubulifera
Antipathes wollastoni
Aurelia aurita
Bolinopsis infundibulum
Caryophyllia smithi
Clytia hemisphaerica
Corynactis viridis
Hydrozoa indet. sp. 1
Obelia sp.
Pelagia noctiluca
Sertularella polyzonias
Sertularella gayi
Stichopathes sp.
Virgularia sp.

Pycnogonida
(Unidentified species)

Bryozoa
(Unidentified species)

Nematoda
Enoplus meridionalis

Annelida
Hermodice carunculata
Lumbricillus sp.
Sabella spallanzanii
Serpulidae
Spirorbidae

Mollusca
Alvania angioyi
Alvania cancellata
Alvania sleursi
Anachis avaroides
Anomia ephippium
Arca tetragona
Bittium laterallii
Bursa scrobilator
Caecum sp.
Calliostoma sp.
Cavolinia inflexa
Charonia lampas lampas
Columbella adansoni
Coralliophila meyendorffi

Appendix A (*continued*)

Mollusca
Crassadoma pusio
Cymatium pathenopeum parthenopeum
Discodoris atromaculata
Ervilia castanea
Gibbula sp.
Haliotis tuberculata coccinea
Jujubinus pseudogravinae
Lamellaria latens
Limacina inflata
Limaria hians
Marshallora adversa
Mitra cornea
Mitromorpha crenipicta
Nassarius incrassatus
Ocinebrina aciculata
Octopus vulgaris
Omalogyra atomus
Palliolum incomparabile
Patella aspera
Phalium granulatum
Pinna rudis
Pseudochama gryphina
Raphitoma linearis
Sinezona cingulata
Stramonita haemastoma haemastoma
Tellina sp.
Thylaeodus cf. *rugulosus*
Trichomusculus semigranatus
Tricolia pullus azorica
Vermetus cf. *triquetrus*

Arthropoda
Calcinus tubularis
Caprellidae
Caprella cf. *linearis*
Dardanus calidus
Dromia marmorea
Gammaridae
Halacarinae
Harpactus sp.
Herbstia condyliata
Laophontidae
Liocarcinus corrugatus
Lysmata sp.
Maja brachydactyla
Megabalanus azoricus
Pagurus cuanensis
Parastenheliidae
Tanais delongii
Xantho incisus

Echinodermata
Arbacia lixula
Holothuria spp.
Ophidiaster ophidianus
Ophiocomina nigra
Paracentrotus lividus
Sphaerechinus granularis

Tunicata
Salps

Appendix A (*continued*)

Pisces
Abudefduf luridus
Acanthocybium solandri
Alepisaurus ferox
Alopias superciliosus
Aphanopus carbo
Apletodon incognitus
Apogon imberbis
Balistes carolinensis
Beryx decadactylus
Beryx splendens
Boops boops
Caranx crysos
Centrolabrus caeruleus
Chromis limbata
Conger conger
Coris julis
Coryphaena hippurus
Dalatias licha
Dasyatis pastinaca
Diplodus sargus cadenati
Epinephelus marginatus
Enchelycore anatina
Galeorhinus galeus
Helicolenus dactylopterus dactylopterus
Isurus oxyrinchus
Katswonus pelamis
Kyphosus sp.
Labrus bergylta
Lepidocybium flavobrunneum
Lepidopus caudatus
Lophius piscatorius
Masturus lanceolatus
Mobula tarapacana
Mola mola
Molva dipterygia macrophthalma
Mora moro
Gymnothorax unicolor
Muraena augusti
Muraena helena
Myliobatis aquila
Ophioblennius atlanticus atlanticus
Pagellus bogaraveo
Pagrus pagrus
Parablennius ruber
Phycis phycis
Polyprion americanus
Pontinus khuli
Bodianus scrofa
Prionace glauca
Remora remora
Remorina albescens
Ruvettus pretiosus
Sarda sarda
Sarpa salpa
Schedophilus ovalis
Scorpaena maderensis
Scorpaena scrofa
Scomber japonicus

(continued on next page)

Appendix A (*continued*)

Pisces
Seriola dumerili
Seriola rivoliana
Serranus atricauda
Sparisoma cretense
Sphoeroides marmoratus
Sphyrna zygaena
Sphyraena viridensis
Symphodus mediterraneus
Taeniura grabata
cf. *Taractes rubescens*
Thalassoma pavo
Thunnus alalunga
Thunnus albacares
Thunnus obesus
Trachinotus ovatus
Trachurus picturatus
Tripterygion delaisi delaisi
Xiphias gladius
Zeus faber

Reptilia
Caretta caretta
Chelonia mydas
Dermochelys coriacea

Aves
Calonectris diomedea borealis
Oceanodroma castro
Puffinus gravis

Mamalia
Tursiops truncatus

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